NASA TECHNICAL MEMORANDUM

NASA TM X-64589

TERRESTRIAL ENVIRONMENT (CLIMATIC) CRITERIA GUIDELINES FOR USE IN SPACE VEHICLE DEVELOPMENT, 1971 REVISION

Glenn E. Daniels, Editor
Aero-Astrodynamics Laboratory

May 10, 1971

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

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APPROVAL

TM X-64589

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

WILLIAM W. VAUGHAN
Chief, Aerospace Environment Division

E. D. GEISSLER
Director, Aero-Astrodynamics Laboratory

ERRATA

NASA Technical Memorandum X-64589

TERRESTRIAL ENVIRONMENT (CLIMATIC) CRITERIA GUIDELINES FOR USE IN SPACE VEHICLE DEVELOPMENT, 1971 REVISION

Glenn E. Daniels, Editor

May 10, 1971

Page 1.13: Reference 1.2 should read, "Daniels, Glenn E.: "Terrestrial Environment (Climatic) Criteria Guidelines for Use in Space Vehicle Development, 1969 Revision," Second printing, March 15, 1970, NASA TM X-53872, NASA-Marshall Space Flight Center, Alabama."

Page 5.37: Table 5.2.25, —z_0 (ft) should read "z_0 (ft)".

Pages 5.56, 5.57, and 5.61 through 5.68: Units for τ are minutes.

Page 5.59: Table 5.2.40, the T at the top of the second column should read "T_D".

Page 5.61: Table 5.2.41, the title should read, "PEAK WINDS (fastest mile value times 1.10) . . . ."

Page 5.87: Figure 5.3.10, the title for Vandenberg, AFB should read, "VANDENBERG, AFB; 9-13km ALTITUDE LAYER".

Page 5.119: Table 5.3.24, column headings, the second P_1 should read "P_2". and the second b_1 should read "b_2".

Page 5.123: Figure 5.3.24, the following should be inserted in the blank upper right corner of the graph:

$$M(y^*)/N_0 = P_1 e^{-|y^*|/Ab_1} + P_2 e^{-|y^*|/Ab_2}$$

Curve	Altitude (ft)	Turbulence Component[a]	P_1	b_1 (ft s^{-1})	P_2	b_2 (ft s^{-1})	L (ft)
1	0 - 1000	V	1.00	2.7	10^{-5}	10.65	500
2	0 - 1000	L, L	1.00	3.1	10^{-5}	14.06	500

[a]Vertical, lateral, and longitudinal (V, L, L).

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Page 5.124: Figure 5.3.25, the following should be inserted in the blank upper right corner of the graph:

$$M(y^*)/N_t = P_1 e^{-|y^*|/Ab_1} + P_2 e^{-|y^*|/Ab_2}$$

Curve	Altitude (ft)	Turbulence Component[a]	P_1	b_1 (ft s^{-1})	P_4	b_2 (ft s^{-1})	L (ft)
1	0 - 1000	V, L, L	1.00	2.51	0.005	5.04	500
2	1000 - 2500	V, L, L	0.42	3.02	0.0033	5.94	1750
3	2500 - 5000	V, L, L	0.30	3.42	0.0020	8.17	2500
4	5000 - 10000	V, L, L	0.15	3.59	0.00065	9.22	2500
5	10000 - 20000	V, L, L	0.062	3.27	0.00028	10.32	2500
6	20000 - 30000	V, L, L	0.025	3.15	0.00011	11.88	2500
7	30000 - 40000	V, L, L	0.011	2.93	0.000095	9.84	2500
8	40000 - 50000	V, L, L	0.0046	3.28	0.000115	8.81	2500
9	50000 - 60000	V, L, L	0.0020	3.82	0.000078	7.04	2500
10	60000 - 70000	V, L, L	0.00088	2.93	0.000057	4.33	2500
11	70000 - 80000	V, L, L	0.00038	2.80	0.000044	1.60	2500
12	above 80000	V, L, L	0.00025	2.50	0	0	2500

[a] Vertical, lateral, and longitudinal (V, L, L).

Page 5.129: The third line from the bottom should read, "here to be the first 533.4 meters (1750 feet) of the atmosphere".

Page 5.133: The first line of the text should read, "flight mode nor ascend or descend in a strictly vertical flight path. At this time".

Page 5.130: The third line from the bottom should read, ". . . . meters (subsection 5.2.6.2), and".

Page 5.137: Figure 5.4.3 for Cape Kennedy > 50 m/sec, the 15% value should read "25%", and the 25% value should read "35%".

Page 14.6: The second line of text should read, "decreasing to one-half that of the surface at 7 kilometers altitude. Density is".

Page 14.49: Table 14.13, the heading under Low Latitude should read "(37.5° N to 37.5° S)".

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15. Supplementary Notes
This document was prepared based on the engineering problems which have developed or are anticipated for future programs by design and operational personnel of the NASA field centers. Various staff members of the Aerospace Environment Division, Aero-Astrodynamics Laboratory, MSFC contributed to the contents of this document.

16. Abstract

This document provides guidelines on probable climatic extremes and probabilities-of-occurrence of terrestrial environment data specifically applicable for NASA space vehicles and associated equipment development. The geographic areas encompassed are The Eastern Test Range (Cape Kennedy, Florida); Huntsville, Alabama; New Orleans, Louisiana; The Space and Missile Test Center (Vanderberg AFB California); Sacramento, California; Wallops Test Range (Wallops Island, Virginia); White Sands Missile Range, New Mexico; and intermediate transportation areas. In addition, sections have been included to provide information on the general distribution of natural environment extremes in the United States (excluding Alaska and Hawaii), cloud cover, and some worldwide climatic extremes. Although all these areas are covered, the major emphasis is given to the Kennedy Space Center launch area due to importance in NASA's large space vehicle programs.

This document presents the latest available information on probable climatic extremes, and supersedes information presented in TM X-53872. The information in this document is recommended for employment in the development of space vehicles and associated equipment design and operational criteria, unless otherwise stated in contract work specifications.

17. Key Words (Suggested by Author(s))
environment criteria
terrestrial environment
surface extremes
wind, temperature, solar radiation, humidity, precipitation, density, pressure, atmospheric electricity, cloud cover

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In addition, acknowledgment is made to Prof. C. B. Moore, Dr. Marx Brook, Dr. H. Kasimir, Dr. E. Pierce, Dr. M. Uman, Dr. E. Lewis, and many others working in the atmospheric electricity area whose contributions, both directly and indirectly, have provided the information needed to revise Section IX on Atmospheric Electricity.

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TECHNICAL MEMORANDUM X-64589

TERRESTRIAL ENVIRONMENT (CLIMATIC) CRITERIA GUIDELINES FOR USE IN SPACE VEHICLE DEVELOPMENT, 1971 REVISION

Glenn E. Daniels, Editor

SUMMARY

This document provides guidelines on probable climatic extremes of terrestrial environment data specifically applicable for NASA space vehicles and associated equipment development. The geographic areas encompassed are the Eastern Test Range (Cape Kennedy, Florida); Huntsville, Alabama; New Orleans, Louisiana; The Space and Missile Test Center (Vandenberg AFB, California); Sacramento, California; Wallops Test Range (Wallops Island, Virginia); White Sands Missile Range, New Mexico; and intermediate transportation areas. In addition, a section has been included to provide information on the general distribution of natural environmental extremes in the continental United States that may be needed to specify design criteria in the transportation of space vehicle components. Although not considered as a specific space vehicle design criterion, a section on atmospheric attenuation has been added, since certain earth orbital experiment missions are influenced by the earth's atmosphere. Some climatic extremes for worldwide operational conditions are included, however, it is recognized that launching and test areas are restricted due to the nonavailability of facilities and real estate.

Design guideline values are established for the following environmental parameters: (1) thermal (temperature and solar radiation), (2) humidity, (3) precipitation, (4) winds, (5) pressure, (6) density, (7) electricity (atmospheric), (8) corrosion (atmospheric), (9) sand and dust, (10) fungi and bacteria, (11) atmospheric oxidants, (12) composition of the atmosphere, and (13) inflight thermodynamic properties. Data are presented and discussions

of these data are given relative to interpretation as design guidelines. Additional information on the different parameters may be located in the numerous references cited in the text following each section.

FOREWORD

For climatic extremes, there is no known physical upper or lower bound, except for certain conditions; that is, for wind speed, there does exist a strict physical lower bound of zero. Therefore, for any observed extreme condition, there is a finite probability of its being exceeded. Consequently, climatic extremes for design must be accepted with the knowledge there is some risk of the values being exceeded. Also, the accuracy of measurement of many environmental parameters is not as precise as desired. In some cases, theoretical estimates of extreme values are believed to be more representative than those indicated by empirical distributions from short periods of record. Therefore, theoretical values are given considerable weight in selecting extreme values for some parameters, i.e., the peak surface winds.

With regard to surface and inflight winds, shears, and turbulence, it is understood that the space vehicle will not be designed for launch and flight in severe weather conditions; that is, hurricanes, thunderstorms, and squalls. Wind conditions are presented for various percentiles based on available data samples. Caution should be exercised in the interpretation of these percentiles in vehicle studies to ensure consistency with physical reality and the specific design and operational problems of concern.

Environment data in this document are limited to information below 90 kilometers. Reference 1.1 provides information above 90 kilometers. Specific space vehicle natural environmental design criteria are normally specified in the appropriate organizational space vehicle design ground rules and design criteria data documentation. The information in this document is recommended for use in the development of space vehicles and associated equipment, unless otherwise stated in contract work specifications.

Considerably more information is available, but not in final form, on some of the topics in this document, viz., solar radiation, surface and inflight winds, and thermodynamic properties. Users of this document who have questions or require further information on the data provided shall direct their requests to the Aerospace Environment Division (S&E-AERO-Y), Aero-Astrodynamics Laboratory, Marshall Space Flight Center.

The data in all sections are based on conditions which have actually occurred, or are statistically probable in nature, over a longer period than the available data. When possible, cycles (diurnal or other) are given to provide information for environmental testing in the laboratory. In many cases, the natural test cycles do not agree with standard laboratory tests, frequently being less severe; although occasionally the natural cycle as given is more severe than the laboratory test. Such cycles need careful consideration to determine whether the laboratory tests need adjustment.

Assesment of the natural environment in early stages of a space vehicle development program will be advantageous in developing a space vehicle with a minimum operational sensitivity to the environment. For those areas of the environment that need to be monitored prior to and during tests and operations, this early planning will permit development of the required measuring and communication systems for accurate and timely monitoring of the environment. Reference 1. 2A is an example of this type of study.

The environment criteria data presented in this document were formulated based on discussions and requests from engineers involved in space vehicle development and operations; therefore, they represent responses to actual engineering problems and are not just a general compilation of environmental data. This report is used extensively by the Marshall Space Flight Center (MSFC), the Manned Spacecraft Center (MSC), and the Kennedy Space Center (KSC) in design and operational studies. Inquiries may be directed through appropriate channels to the following persons:

Scientific Area	MSFC	MSC	KSC
Atmospheric Thermodynamic Models	O. E. Smith C. Brown	R. H. Bradley	
Ground Winds and Inflight Winds	O. E. Smith G. H. Fichtl	A. C. Mackey R. H. Bradley	P. Claybourne J. Spears
Atmospheric Conditions (General)	O. E. Smith G. H. Fichtl G. E. Daniels	R. H. Bradley	

1.4

SECTION I. INTRODUCTION

By

Glenn E. Daniels and William W. Vaughan

1.1 General

A knowledge of the earth's atmospheric environmental parameters is necessary for the establishment of design requirements for space vehicles and associated equipment. Such data are required to define the design condition for fabrication, storage, transportation, test, pre-flight, and in-flight design conditions and should be considered for both the whole system and the components which make up the system. The purpose of this document is to provide guideline data on natural environmental conditions for the various major geographic locations which are applicable to the design of space vehicles and associated equipment for the National Aeronautics and Space Administration. The publications MIL-STD-210A (Ref. 1.3), U.S. Standard Atmosphere, 1962 (Ref. 1.4), the U.S. Standard Atmosphere Supplements (Ref. 1.5), and the Range Reference Atmospheres (Ref. 1.6), are suggested for use as sources of data for geographic areas not given in this document.

Good engineering judgment must be exercised in the application of the earth's atmospheric data to space vehicle design analysis. Consideration must be given to the overall vehicle mission and performance requirements. Knowledge still is lacking on the relationships between some of the atmopheric variates which are required as inputs to the design of space vehicles. Also, interrelationships between space vehicle parameters and atmospheric variables cannot always be clearly defined. Therefore, a close working relationship and team philosophy should exist between the design/operational engineer and the respective organization's aerospace meteorologists. Although a space vehicle design should accommodate all expected operational atmospheric conditions, it is neither economically nor technically feasible to design space vehicles to withstand all atmospheric extremes. For this reason, consideration should be given to protection of space vehicles from some extremes by use of support equipment, and by using specialized forecast personnel to advise of the expected occurrence of critical environmental conditions. The services of specialized forecast personnel may be very economical in comparison with more expensive designing which would be necessary to cope with all environmental possibilities.

This document does not specify how the designer should use the data in regard to a specific space vehicle design. Such specifications may be established only through analysis and study of a particular design problem. Although of operational significance, descriptions of some atmospheric conditions have been omitted since they are not of direct concern for structural and control system design. Induced environments (vehicle caused) may be more critical than natural environments for certain vehicle operational situations, and in some cases the combination of natural and induced environments will be more severe than either environment alone. Induced environments are considered in other space vehicle criteria documents which should be consulted for such data.

Reports such as the "Marine Climatic Guide" (Ref. 1.7) may be consulted for reentry landing area information.

1.2 Geographical Areas Covered (Fig. 1.1)

a. Huntsville, Alabama.

b. River transportation: Between Huntsville, Alabama (via Tennessee, Ohio, and Mississippi Rivers) and New Orleans, Louisiana.

c. New Orleans, Louisiana; Mississippi Test Operations, Mississippi; Houston, Texas; and transportation zones between these locations.

d. Gulf transportation: Between New Orleans, Louisiana (via Gulf of Mexico and up east coast of Florida) and Cape Kennedy, Florida.

e. Panama Canal transportation: Between Los Angeles or SAMTEC, California (via West Coast of California and Mexico, through the Panama Canal, and Gulf of Mexico) and New Orleans, Louisiana.

f. Eastern Test Range (ETR), Cape Kennedy, Florida.

g. Space and Missile Test Center (SAMTEC), (Vandenberg AFB), California.

h. Sacramento, California.

i. Wallops Test Range, Wallops Island, Virginia.

j. West coast transportation: Between Los Angeles, California, and Sacramento, California.

k. White Sands Missile Range, New Mexico.

l. Edwards Air Force Base, California.

FIGURE 1. MAIN GEOGRAPHICAL AREAS COVERED IN DOCUMENT

1.3 Units of Conversion

Numerical values in this document are given in the International System of Units (Ref. 1.8, 1.9). The values in parentheses are equivalent U.S. Customary Units.* The metric and U. S. Customary Units employed in this report are those normally used for measuring and reporting atmospheric data.

By definition, the following fundamental conversion factors are exact (Ref. 1.8, 1.9, 1.10).

Type	U. S. Customary Units	Metric
Length	1 U. S. yard (yd)	0.9144 meter (m)
Mass	1 avoirdupois pound (lb)	453.59237 gram (g)
Time	1 second (s)	1 second (s)
Temperature	1 degree Rankine (°R)	5/9 degrees Kelvin (°K)
Electric current	1 ampere (A)	1 ampere (A)
Light intensity	1 candela (cd)	1 candela (cd)

To aid in conversion of units given in this document, conversion factors based on the above fundamental conversion factors are given in Table 1.1. Geometric altitude as employed herein is with reference to mean sea level (MSL) unless otherwise stated.

1.4 Definition of Percentiles

The values of the data corresponding to the cumulative percentage frequencies are called percentiles. The relationship between percentiles and probability is as follows: Given that the 90th percentile of the wind speed is, say, 60 m/s means that there is a probability of 0.90 that this value of the wind speed will not be exceeded, and there is probability of 0.10 that it will be exceeded for the sample of data from which the percentile was computed. Stated in another way: There is a 90 percent chance that the given wind speed of 60 m/s will not be exceeded or there is a 10 percent chance that it will be exceeded. If one considers the 10th and 90th percentiles for the wind speeds, it is clear that 80 percent of the wind speeds occur within the 10-90 percentiles range.

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* English Units adopted for use by the United States of America.

TABLE 1.1 CONVERSION OF UNITS

TYPE OF DATA		METRIC		U.S. CUSTOMARY		CONVERSION		
		UNIT	ABBREVIATION	UNIT	ABBREVIATION	MULTIPLY	BY	TO GET
SOLAR RADIATION	Solar Intensity	langley (per minute)	ly (min^{-1})	watt per square foot	watt ft^{-2}	ly (min^{-1})	0.69733	kJ m^{-2} (s^{-1})
		gram-calorie per square centimeter (per minute)	g-cal cm^{-2} (min^{-1})	British Thermal Unit per square foot (per minute)	B.T.U. ft^{-2} (min^{-1})	kJ m^{-2} (s^{-1})	1.4340	ly (min^{-1})
		watt per square meter	watt m^{-2}			ly (min^{-1})	1.000*	g-cal cm^{-2} (min^{-1})
		kilojoule per square meter (per second)	kJ m^{-2} (s^{-1})			g-cal cm^{-2} (min^{-1})	1.000*	ly (min^{-1})
						watt m^{-2}	0.09290304*	watt ft^{-2}
						watt ft^{-2}	10.7639	watt m^{-2}
						g-cal cm^{-2} (min^{-1})	64.784	watt ft^{-2}
						g-cal cm^{-2} (min^{-1})	697.33	watt m^{-2}
						watt ft^{-2}	0.015436	g-cal cm^{-2} (min^{-1})
						watt m^{-2}	0.0014340	g-cal cm^{-2} (min^{-1})
						g-cal cm^{-2} (min^{-1})	3.6867	B.T.U. ft^{-2} (min^{-1})
						B.T.U. ft^{-2} (min^{-1})	0.27125	g-cal cm^{-2} (min^{-1})
	Solar Insolation	gram-calorie per square centimeter per minute	g-cal cm^{-2} min^{-1}	British Thermal Unit per square foot per hour	B.T.U. ft^{-2} hr^{-1}	g-cal cm^{-2} min^{-1}	221.20	B.T.U. ft^{-2} hr^{-1}
						B.T.U. ft^{-2} hr^{-1}	0.0045208	g-cal cm^{-2} min^{-1}
TEMPERATURE	Ambient Temperature	degree Celsius	$^{\circ}C$	degree Fahrenheit	$^{\circ}F$	$^{\circ}F - 32$	0.5556	$^{\circ}C$
		degree Kelvin	$^{\circ}K$	degree Rankine	$^{\circ}R$	$^{\circ}C$	1.8*	$^{\circ}F - 32$
						$^{\circ}R$	1.00*	$^{\circ}F + 459.67$
						$^{\circ}R - 459.67$	1.00*	$^{\circ}F$
						$^{\circ}K$	1.00*	$^{\circ}C + 273.15$
						$^{\circ}K - 273.15$	1.00*	$^{\circ}C$
	Temperature Change	degree Celsius	$^{\circ}C$	degree Fahrenheit	$^{\circ}F$	$^{\circ}C$ or $^{\circ}K$	1.8*	temp. change $^{\circ}F$ or $^{\circ}R$
		degree Kelvin	$^{\circ}K$	degree Rankine	$^{\circ}R$	$^{\circ}F$ or $^{\circ}R$	0.5556	temp. change $^{\circ}C$ or $^{\circ}K$

* Defined exact conversion factor

TABLE 1.1 CONVERSION OF UNITS (Contiued)

TYPE OF DATA		METRIC UNIT	METRIC ABBREVIATION	U.S. CUSTOMARY UNIT	U.S. CUSTOMARY ABBREVIATION	CONVERSION MULTIPLY	CONVERSION BY	CONVERSION TO GET
DENSITY	Water Vapor Vapor Concentration (Absolute Humidity)	gram per cubic meter	$g\ m^{-3}$	grain per cubic foot	$gr\ ft^{-3}$	$g\ m^{-3}$	0.43700	$gr\ ft^{-3}$
		gram per cubic centimeter	$g\ cm^{-3}$			$gr\ ft^{-3}$	2.2883	$g\ m^{-3}$
						$g\ m^{-3}$	10^{-6}*	$g\ cm^{-3}$
						$g\ cm^{-3}$	4.370×10^{5}	$gr\ ft^{-3}$
						$gr\ ft^{-3}$	2.288×10^{-6}	$g\ cm^{-3}$
	Air, Dust, and Hail	gram per cubic centimeter	$g\ cm^{-3}$	pound per cubic foot	$lb\ ft^{-3}$	$g\ cm^{-3}$	62.43	$lb\ ft^{-3}$
						$lb\ ft^{-3}$	1.6018×10^{-2}	$g\ cm^{-3}$
PRECIPITATION	Snow Unit Depth Mass	kilogram per square meter per centimeter (of depth)	$kg\ m^{-2}\ cm^{-1}$	pound per square foot per inch (of depth)	$lb\ ft^{-2}\ in.^{-1}$	$kg\ m^{-2}\ cm^{-1}$	0.5202	$lb\ ft^{-2}\ in.^{-1}$
						$lb\ ft^{-2}\ in.^{-1}$	1.922	$kg\ m^{-2}\ cm^{-1}$
	Snow Storm Total Mass	kilogram per square meter	$kg\ m^{-2}$	pound per square foot	$lb\ ft^{-2}$	$kg\ m^{-2}$	0.2048	$lb\ ft^{-2}$
						$lb\ ft^{-2}$	4.882	$kg\ m^{-2}$
	Depth	centimeter	cm	inch	in.	cm	0.3937	in.
						in.	2.54*	cm
WIND	Wind Speed	meter per second	$m\ s^{-1}$	mile per hour	mph	$m\ s^{-1}$	2.2369	mph
				knots	knots	mph	0.44704*	$m\ s^{-1}$
				feet per second	$ft\ s^{-1}$	$m\ s^{-1}$	1.9438	knots
						knots	0.51444	$m\ s^{-1}$
						mph	0.868976	knots
						knots	1.15078	mph
						$m\ s^{-1}$	3.2808	$ft\ s^{-1}$
						$ft\ s^{-1}$	0.3048*	$m\ s^{-1}$

*Defined exact conversion factor

TABLE 1.1 CONVERSION OF UNITS (Continued)

TYPE OF DATA		METRIC		U.S. CUSTOMARY		CONVERSION		
		UNIT	ABBREVIATION	UNIT	ABBREVIATION	MULTIPLY	BY	TO GET
PRESSURE	Atmospheric	newton per square meter	newton m^{-2}	pound force per square inch	lbf in. $^{-2}$	mb	10^{-3*}	bar
						bar	10^{3*}	mb
		millimeter of Mercury	mmHg	inch of Mercury	in.Hg	newton m^{-2}	10^{-2*}	mb
						newton m^{-2}	$1.4504X10^{-4}$	lbf in. $^{-2}$
						lbf in. $^{-2}$	$6.8948X10^{3}$	newton m^{-2}
		bar	bar			mb	$1.4504X10^{-2}$	lbf in. $^{-2}$
		millibar	mb			lbf in. $^{-2}$	68.948	mb
		dyne per square centimeter (microbar)	dyne cm^{-2}			mb	10^{3*}	dyne cm^{-2}
						dyne cm^{-2}	10^{-3*}	mb
		kilogram force per square meter	kgf m^{-2}			lbf in. $^{-2}$	$6.8948X10^{4}$	dyne cm^{-2}
						dyne cm^{-2}	$1.4504X10^{-5}$	lbf in. $^{-2}$
						mb	10.1972	kgf m^{-2}
						kgf m^{-2}	0.0980665	mb
						lbf in. $^{-2}$	703.0696	kgf m^{-2}
						kgf m^{-2}	0.0014223	lbf in. $^{-2}$
						mb	$2.9530X10^{-2}$	in.Hg (32° F)
						mb	0.75006	mmHg (0° C)
						in.Hg(32° F)	25.40^{*}	mmHg (0° C)
						mmHg(0° C)	1.33322	mb
						in.Hg(32° F)	33.8639	mb

* Defined exact conversion factor

TABLE 1.1 CONVERSION OF UNITS (Concluded)

TYPE OF DATA		METRIC		U.S. CUSTOMARY		CONVERSION		
		UNIT	ABBREVIATION	UNIT	ABBREVIATION	MULTIPLY	BY	TO GET
DISTANCE	Length	meter	m	feet	ft	m	3.2808	ft
		micron	μ	inch	in.	ft	0.3048*	m
		Ångstrom unit	Å			in.	$2.54X10^{+4*}$	μ
						in.	$2.54X10^{+8*}$	Å
						m	10^{+6*}	μ
						m	10^{+10*}	Å
						μ	10^{-6*}	m
						μ	$3.937X10^{-5}$	in.
						Å	10^{-10*}	m
						Å	$3.937X10^{-9}$	in.
MASS	Weight	gram	g	grain	gr	lb	0.45359237*	kg
		kilogram	kg	pound	lb	lb	453.59237*	g
						kg	2.20462	lb
						g	15.4324	gr
						gr	0.06480	g

* Defined exact conversion factor

REFERENCES

1.1 Weidner, Don K., Editor: "Space Environment Criteria Guidelines for Use in Space Vehicle Development (1969 Revision)." TM X-53957, Second Edition August 26, 1970. NASA-Marshall Space Flight Center, Huntsville, Alabama. (To be revised in Fall 1971)

1.2 Daniels, Glenn E.: "Terrestrial Environment (Climatic) Criteria Guidelines for Use in Space Vehicle Development, 1969 Revision." Second Printing, March 15, 1970. NASA-Marshall Space Flight Center, Alabama.

1.2A Carter, E. A.: "Natural Environment Support for Space Shuttle Tests and Operations," NASA CR-61346, Marshall Space Flight Center, Alabama, 1971.

1.3 "Climatic Extremes for Military Equipment." MIL-STD-210A, 1957, with change notice 1, 1958.

1.4 "U. S. Standard Atmosphere, 1962." United States Government Printing Office, Washington, D. C., 1962.

1.5 "U. S. Standard Atmosphere Supplements, 1966." United States Government Printing Office, Washington, D. C., 1966.

1.6 IRIG Document No. 104-63, Range Reference Atmosphere Documents published by Secretariat, Range Commander's Council, White Sands Missile Range, New Mexico. The following reference atmospheres have been published under this title:

(1) Atlantic Missile Range Reference Atmosphere for Cape Kennedy, Florida (Part I), 1963.

(2) White Sands Missile Range Reference Atmosphere (Part I), 1964.

(3) Fort Churchill Missile Range Reference Atmosphere for Fort Churchill, Canada (Part I), 1964.

(4) Pacific Missile Range Reference Atmosphere for Eniwetok, Marshall Islands (Part I), 1964.

(5) Fort Greely Missile Range Reference Atmosphere (Part I), 1964.

(6) Eglin Gulf Test Range Reference Atmosphere for Eglin, AFB, Florida (Part I), 1965.

(7) Pacific Missile Range Reference Atmosphere for Point Arguello, California (Part I), 1965.

(8) Wallops Island Test Range Reference Atmosphere (Part I), 1965.

(9) Eastern Test Range Reference Atmosphere for Ascension Island, South Atlantic (Part I), 1966.

(10) Lihue, Kauai, Hawaii Reference Atmosphere (Part I), 1970

(11) Johnson Island Test Site Reference Atmosphere (Part I), 1970

1.7 "Marine Climatic Guide," NASA-CR-95014, NASA, Manned Space Flight Center, Houston, Texas. Prepared by Spaceflight Meteorology Group, Weather Bureau, Houston, Texas, Jan. 1968.

1.8 "International System of Units, Resolution No. 12." NASA-TT-F-8365, NASA, Washington, D. C., 1963.

1.9 Mechtly, E. A.: "The International System of Units, Physical Constants and Conversion Factors." NASA SP-7012, National Aeronautics and Space Administration, Washington, D. C., 1964.

1.10 "Units of Weight and Measure (United States Customary and Metric) Definitions and Tables of Equivalents." United States Department of Commerce, National Bureau of Standards, Miscellaneous Publication 233, 1960.

SECTION II. THERMAL

By

Glenn E. Daniels

2.0 Introduction

One of the more important environmental influences on a vehicle is the thermal environment. Combinations of air temperature, solar radiation, and sky radiation can cause various structural problems. Some examples of potential problems are: (1) Heating of one side of the vehicle by the sun while the other side is cooled by a clear sky causes stresses since the vehicle sides will be of different length; (2) the temperature of the fuel influences the volume/mass relationship; and (3) too high a temperature may destroy the usefulness of a lubricant. The heating or cooling of a surface by air temperature and radiation is a function of the heat transfers taking place; therefore, methods of determining these relationships are presented in this section.

2.1 Definitions

The following terms and meanings are used in this section.

Absorption bands are those portions of the solar (or other continuous) spectrum which have lesser intensity because of absorption by gaseous elements or molecules. In general, elements give sharp lines, but molecules such as water vapor or carbon dioxide in the infrared give broad diffuse bands.

Air mass is the amount of atmosphere that the solar radiation passes through, whereas one air mass is referenced to when the sun is at its zenith.

Air temperature (surface) is the free or ambient air temperature measured under standard conditions of height, ventilation, and radiation shielding. The air temperature is normally measured with liquid-in-glass thermometers in a louvered wooden shelter, painted white inside and outside, with the base of the shelter normally 1.22 meter (4 ft) above a close-cropped grass surface (Ref. 2.1, page 59). Unless an exception is stated, surface air temperatures given in this report are temperatures measured under these standard conditions.

Astronomical unit is a unit of length defined as equal to the mean distance between the earth and sun. The current accepted value is 1.495978930 x 10^8 kilometers.

Atmospheric transmittance is the ratio between the intensity of the extraterrestrial solar radiation and intensity of the solar radiation after passing through the atmosphere.

Black body is an ideal emitter which radiates energy at the maximum possible rate per unit area at each wavelength for any given temperature and which absorbs all incident radiation at all wavelengths.

Diffuse sky radiation is the solar radiation reaching the earth's surface after having been scattered from the direct solar beam by molecules or suspensoids in the atmosphere. It is measured on a surface after the direct solar radiation is subtracted from the total horizontal radiation.

Direct solar radiation is the solar radiation received on a surface directly from the sun, and does not include diffuse sky radiation.

Emittance is the ratio of the energy emitted by a body to the energy which would be emitted by a black body at the same temperature. All real bodies will emit energy in different amounts from a black body at various wavelengths; i.e., colored bodies are colored because of higher emittance at specific wavelengths. In this document, the assumption is made that the absorptivity of an object is numerically equal to the emittance of the object at the same wavelengths. Therefore, the value of the emittance can be used to determine the portion of the energy received by the object which heats (or energy lost which cools) the object.

Extraterrestrial solar radiation is that solar radiation received outside the earth's atmosphere at one astronomical unit from the sun. The term "solar spectral irradiance" is used when the extraterrestrial solar radiation at small wavelength intervals is considered.

Fraunhofer lines are the dark absorption bands in the solar spectrum caused by gases in the outer portions of the sun and earth's atmosphere.

Horizontal solar radiation is the solar radiation measured on a horizontal surface. This is frequently referred to as "global radiation" when solar and diffuse sky radiation are included.

Irradiation is often used to mean solar radiation received by a surface.

Normal incident solar radiation is the radiation received on a surface, normal to the direction of the sun, direct from the sun, and does not include diffuse sky radiation.

Radiation temperature is the absolute temperature of a radiating black body determined by Wien's displacement law, expressed as

$$T_R = \frac{w}{\lambda\,max} \quad , \qquad (2.1)$$

where

T_R = absolute temperature of the radiating body

w = Wien's displacement constant (0. 2880 cm °K)

$\lambda\,max$ = the wavelength of the maximum radiation intensity for the black body.

Sky radiation temperature is the average radiation temperature of the sky when it is assumed to be a black body. Sky radiation is the radiation to and through the atmosphere from outer space. While this radiation is normally termed nocturnal radiation, it takes place under clear skies even during daylight hours.

Solar radiation in this document will be defined as the radiant energy from the sun between 0. 22 and 20. 0 microns (subsection 2. 2. 2).

Surface temperature is the temperature which a given surface will have when exposed to air temperature and radiation within the approximate wavelength interval of 0. 22 to 20. 0 microns.

2. 2 Special Distribution of Radiation

2. 2. 1 Introduction

All objects radiate energy in the electromagnetic spectrum. The amount and frequency of the radiation distribution is a function of temperature. The higher the temperature, the greater the amount of total energy emitted and the higher the frequency (shorter the wavelength) of the peak energy emission.

2.2.2 Solar Radiation

The sun emits energy in the electromagnetic spectrum from 10^{-7} to greater than 10^5 microns. This radiation ranges from cosmic rays through the very long wave radio waves. The total amount of radiation from the sun is nearly constant in intensity with time.

Of the total electromagnetic spectrum of the sun, only the radiant energy from that portion of the spectrum between 0.22 and 20.0 microns (the light spectrum) will be considered in this document since it contains 99.8 percent of the total electromagnetic energy. The spectral distribution of this region closely resembles the emission of a gray body radiating at 6000°K. This is the spectral region which causes nearly all of the heating or cooling of an object.

Solar radiation outside the earth's atmosphere is distributed in a continuous spectrum with many narrow absorption bands caused by the elements and molecules in the colder solar atmosphere. These absorption bands are the Fraunhofer lines, whose widths are usually very small ($< 10^{-4}\mu$ in most cases).

The earth's atmosphere also absorbs a part of the solar radiation such that the major portion of the solar radiation reaching the earth's surface is between about 0.35 μ and 4.00 microns. The distribution of the energy in this region of the spectrum outside the earth's atmosphere (extraterrestrial) is as follows:

Region (μ)	Distribution (%)	Solar Intensity g-cal cm^{-2} (min^{-1})
Ultraviolet below 0.38	7.003	0.136
0.38 to 0.75	44.688	0.867
Infrared above 0.75	48.309	0.937

The first detailed information published for use by engineers on the distribution of solar radiation energy (solar irradiation) wavelength was that by Parry Moon in 1940 (Ref. 2.2). These data were generally based on theoretical curves, but are still used as the basic solar radiation in design by many engineers.

2. 2. 3 Intensity Distribution

Table 2. 1 presents data on the distribution with wavelength of solar radiation outside the earth's atmosphere and at the earth's surface after 1 atmosphere absorption. The solar radiation distribution data outside the earth's atmosphere (solar spectral irradiance) are based on recent extraterrestrial data obtained by high-flying aircraft and published by Thekarkara (Ref. 2. 3). The values of solar radiation for 1 atmosphere absorption are representative of a very clear atmosphere which provides a minimum of atmospheric absorption. This gives a total normal solar radiation value (area under the spectral curve) equal to the highest values measured at the earth's surface in mid-latitudes. These data are for use in solar radiation design studies when extreme solar radiation effects are desired at the earth's surface.

2. 2. 4 Atmospheric Transmittance of Solar Radiation

The atmosphere of the earth is composed of a mixture of gases, aerosols, and dust which absorb radiation in different amounts at various wavelengths. If the ratio is taken of the solar spectral irradiance I_o to that of the solar radiation after absorption through one air mass $I_{1.00}$, an atmospheric transmittance factor M can be found [equation (2. 2)]:

$$M = \frac{I_o}{I_{1.00}} \qquad (2.2)$$

The atmospheric transmittance constant can be used in the following equation for computations of intensities for any other number of air masses:

$$I_N = I_o (M^N) \quad , \qquad (2.3)$$

where

I_N = intensity of solar radiation for N air mass thickness

N = number of air masses.

Equation (2. 3) can also be used to obtain solar radiation intensities versus wavelengths for other total normal incident solar radiation intensities

TABLE 2. 1 SOLAR SPECTRAL IRRADIANCE (outside atmosphere) AND SOLAR RADIATION AFTER ABSORPTION BY CLEAR ATMOSPHERE

Wavelength (microns) λ	Solar Spectral Irradiance (watts cm^{-2} μ^{-1})	Area Under Solar Spectral Irradiance Curve (watts cm^{-2})	Solar Radiation After One Atmosphere Absorption (watts cm^{-2} μ^{-1})	Area Under One Atmosphere Solar Radiation Curve (watts cm^{-2})	Percentage of Solar Radiation After One Atmosphere Absorption for Wavelengths Shorter than λ (%)
0.120	0.000010	0.00000060	0.000000	0.000000	0.00
0.140	0.000003	0.00000073	0.000000	0.000000	0.00
0.150	0.000007	0.00000078	0.000000	0.000000	0.00
0.160	0.000023	0.00000093	0.000000	0.000000	0.00
0.170	0.000063	0.00000136	0.000000	0.000000	0.00
0.180	0.000125	0.00000230	0.000000	0.000000	0.00
0.190	0.000271	0.00000428	0.000000	0.000000	0.00
0.200	0.00107	0.000010	0.000001	0.000000	0.00
0.210	0.00229	0.000027	0.000003	0.000000	0.00
0.220	0.00575	0.000067	0.000007	0.000000	0.00
0.225	0.00649	0.000098	0.000007	0.000000	0.00
0.230	0.00667	0.000131	0.000008	0.000000	0.00
0.235	0.00593	0.000162	0.000007	0.000000	0.00
0.240	0.00630	0.000193	0.000007	0.000000	0.00
0.245	0.00723	0.000227	0.000008	0.000000	0.00
0.250	0.00704	0.000263	0.000008	0.000000	0.00
0.255	0.0104	0.000306	0.000012	0.000000	0.00
0.260	0.0130	0.000365	0.000015	0.000000	0.00
0.265	0.0185	0.000443	0.000021	0.000000	0.00
0.270	0.0232	0.000548	0.000026	0.000000	0.00
0.275	0.0204	0.000657	0.000023	0.000000	0.00
0.280	0.0222	0.000763	0.000025	0.000000	0.00
0.285	0.0315	0.000897	0.000036	0.000001	0.00
0.290	0.0482	0.001097	0.000055	0.000001	0.00
0.295	0.0584	0.001363	0.000066	0.000001	0.00
0.300	0.0514	0.001638	0.006677	0.000035	0.03
0.305	0.0603	0.001917	0.019830	0.000134	0.12
0.310	0.0689	0.002240	0.029084	0.000279	0.25
0.315	0.0764	0.002603	0.038941	0.000474	0.42
0.320	0.0830	0.003002	0.047684	0.000712	0.64
0.325	0.0975	0.003453	0.062018	0.001022	0.92
0.330	0.1059	0.003961	0.073829	0.001392	1.25
0.335	0.1081	0.004496	0.080896	0.001796	1.61
0.340	0.1074	0.005035	0.084636	0.002219	1.99
0.345	0.1069	0.005571	0.087080	0.002655	2.39
0.350	0.1093	0.006111	0.091327	0.003111	2.80
0.355	0.1083	0.006655	0.092186	0.003572	3.40
0.360	0.1068	0.007193	0.092857	0.004036	3.63
0.365	0.1132	0.007743	0.099873	0.004536	4.08
0.370	0.1181	0.008321	0.105507	0.005063	4.55
0.375	0.1157	0.008906	0.104596	0.005586	5.03
0.380	0.1120	0.009475	0.102971	0.006101	5.49
0.385	0.1098	0.010030	0.102273	0.006613	5.95
0.390	0.1098	0.010579	0.103977	0.007132	6.42
0.395	0.1189	0.011150	0.114309	0.007704	6.93
0.400	0.1429	0.011805	0.137403	0.008391	7.55
0.405	0.1644	0.012573	0.158076	0.009181	8.26
0.410	0.1751	0.013422	0.168365	0.010023	9.02
0.415	0.1774	0.014303	0.170576	0.010876	9.79
0.420	0.1747	0.015183	0.167980	0.011716	10.54
0.425	0.1693	0.016043	0.162788	0.012530	11.28
0.430	0.1639	0.016876	0.157596	0.013318	11.99
0.435	0.1663	0.017702	0.159903	0.014117	12.71
0.440	0.1810	0.018570	0.174038	0.014988	13.40
0.445	0.1922	0.019503	0.184807	0.015912	14.30
0.450	0.2006	0.020485	0.192884	0.016876	15.19
0.455	0.2057	0.021501	0.195904	0.017656	16.07
0.460	0.2066	0.022532	0.196761	0.018839	16.96
0.465	0.2048	0.023560	0.196923	0.019824	17.84
0.470	0.2033	0.024580	0.195480	0.020801	18.72

TABLE 2.1 SOLAR SPECTRAL IRRADIANCE (outside atmosphere) AND SOLAR RADIATION AFTER ABSORPTION BY CLEAR ATMOSPHERE (Continued)

Wavelength (microns) λ	Solar Spectral Irradiance (watts $cm^{-2}\mu^{-1}$)	Area Under Solar Spectral Irradiance Curve (watts cm^{-2})	Solar Radiation After One Atmosphere Absorption (watts $cm^{-2}\mu^{-1}$)	Area Under One Atmosphere Solar Radiation Curve (watts cm^{-2})	Percentage of Solar Radiation After One Atmosphere Absorption for Wavelengths Shorter than λ (%)
0.475	0.2044	0.025600	0.196538	0.021784	19.61
0.480	0.2074	0.026629	0.197523	0.022772	20.50
0.485	0.1976	0.027642	0.186415	0.023704	21.34
0.490	0.1950	0.028623	0.183962	0.024624	22.17
0.495	0.1960	0.029601	0.183177	0.025539	22.99
0.500	0.1942	0.030576	0.179814	0.026439	23.80
0.505	0.1920	0.031542	0.176146	0.027319	24.60
0.510	0.1882	0.032492	0.172660	0.028183	25.37
0.515	0.1833	0.033421	0.168165	0.029023	26.13
0.520	0.1833	0.034337	0.168165	0.029864	26.88
0.525	0.1852	0.035259	0.169908	0.030714	27.65
0.530	0.1842	0.036182	0.168990	0.031559	28.41
0.535	0.1818	0.037097	0.166788	0.032393	29.16
0.540	0.1783	0.037997	0.163977	0.033211	29.90
0.545	0.1754	0.038882	0.160917	0.034015	30.62
0.550	0.1725	0.039751	0.158256	0.034806	31.33
0.555	0.1720	0.040613	0.157798	0.035595	32.05
0.560	0.1695	0.041466	0.155504	0.036373	32.75
0.565	0.1705	0.042316	0.156422	0.037155	33.45
0.570	0.1712	0.043171	0.157064	0.037940	34.16
0.575	0.1719	0.044028	0.157726	0.038729	34.87
0.580	0.1715	0.044887	0.157339	0.039516	35.57
0.585	0.1712	0.045744	0.157064	0.040301	36.28
0.590	0.1700	0.046597	0.155963	0.041081	36.98
0.595	0.1682	0.047442	0.154311	0.041852	37.68
0.600	0.1666	0.048279	0.152844	0.042616	38.37
0.605	0.1647	0.049107	0.151100	0.043372	39.05
0.610	0.1635	0.049928	0.150000	0.044122	39.72
0.620	0.1602	0.051546	0.146972	0.045592	41.05
0.630	0.1570	0.053132	0.145370	0.047045	42.30
0.640	0.1544	0.054689	0.144299	0.048488	43.66
0.650	0.1511	0.056217	0.142547	0.049914	44.94
0.660	0.1486	0.057715	0.141523	0.051329	46.22
0.670	0.1456	0.059186	0.140000	0.052729	47.48
0.680	0.1427	0.060628	0.137211	0.054101	48.71
0.690	0.1402	0.062042	0.134807	0.055449	49.93
0.700	0.1369	0.063428	0.131634	0.056766	51.11
0.710	0.1344	0.064784	0.129230	0.058058	52.27
0.720	0.1314	0.066113	0.126346	0.059321	53.41
0.730	0.1290	0.067415	0.124038	0.060562	54.53
0.740	0.1260	0.068690	0.121153	0.061773	55.62
0.750	0.1235	0.069938	0.118750	0.062961	56.69
0.800	0.1107	0.075793	0.106442	0.068283	61.48
0.850	0.0988	0.081030	0.095000	0.073033	65.76
0.900	0.0889	0.085723	0.080090	0.077037	69.36
0.950	0.0835	0.090033	0.077314	0.080903	72.84
1.000	0.0746	0.093985	0.071730	0.084490	76.07
1.100	0.0592	0.100675	0.056923	0.090182	81.20
1.200	0.0484	0.106055	0.046538	0.094836	85.39
1.300	0.0396	0.110455	0.036000	0.098436	88.63
1.400	0.0336	0.114115	0.002240	0.098660	88.83
1.500	0.0287	0.117230	0.027333	0.101393	91.29
1.600	0.0244	0.119885	0.023461	0.103739	93.40
1.700	0.0202	0.122115	0.019423	0.105681	95.15
1.800	0.0159	0.123920	0.013826	0.107064	96.40
1.900	0.0126	0.125345	0.000126	0.107077	96.41
2.000	0.0103	0.126490	0.009809	0.108057	97.29
2.100	0.0090	0.127455	0.008653	0.108923	98.07
2.200	0.0079	0.128300	0.007596	0.109682	98.76
2.300	0.0068	0.129035	0.006538	0.110336	99.34

TABLE 2. 1 SOLAR SPECTRAL IRRADIANCE (outside atmosphere) AND SOLAR RADIATION AFTER ABSORPTION BY CLEAR ATMOSPHERE (Concluded)

Wavelength (microns) λ	Solar Spectral Irradiance (watts cm^{-2} μ^{-1})	Area Under Solar Spectral Irradiance Curve (watts cm^{-2})	Solar Radiation After One Atmosphere Absorption (watts cm^{-2} μ^{-1})	Area Under One Atmosphere Solar Radiation Curve (watts cm^{-2})	Percentage of Solar Radiation After One Atmosphere Absorption for Wavelengths Shorter than λ (%)
2.4	0.0064	0.129695	0.006153	0.110951	99.90
2.5	0.0054	0.130285	0.001080	0.111059	100.00
2.6	0.0048	0.130795	0.000005	0.111060	100.00
2.7	0.0043	0.131250	0.000004	0.111060	100.00
2.8	0.00390	0.131660	0.000004	0.111061	100.00
2.9	0.00350	0.132030	0.000004	0.111061	100.00
3.0	0.00310	0.132360	0.000003	0.111061	100.00
3.1	0.00260	0.132645	0.000002	0.111062	100.00
3.2	0.00226	0.132888	0.000002	0.111062	100.00
3.3	0.00192	0.133097	0.000002	0.111062	100.00
3.4	0.00166	0.133276	0.000001	0.111062	100.00
3.5	0.00146	0.133432	0.000001	0.111062	100.00
3.6	0.00135	0.133573	0.000001	0.111062	100.00
3.7	0.00123	0.133702	0.000001	0.111062	100.00
3.8	0.00111	0.133819	0.000001	0.111063	100.00
3.9	0.00103	0.133926	0.000001	0.111063	100.00
4.0	0.00095	0.134025	0.000001	0.111063	100.00
4.1	0.00087	0.134116	0.000001	0.111063	100.00
4.2	0.00078	0.134198	0.000000	0.111063	100.00
4.3	0.00071	0.134273	0.000000	0.111063	100.00
4.4	0.00065	0.134341	0.000000	0.111063	100.00
4.5	0.00059	0.134403	0.000000	0.111063	100.00
4.6	0.00053	0.134459	0.000000	0.111063	100.00
4.7	0.00048	0.134509	0.000000	0.111063	100.00
4.8	0.00045	0.134556	0.000000	0.111063	100.00
4.9	0.00041	0.134599	0.000000	0.111063	100.00
5.0	0.0003830	0.13463906	0.000000	0.111063	100.00
6.0	0.0001750	0.13491806	0.000000	0.111063	100.00
7.0	0.0000990	0.13505506	0.000000	0.111063	100.00
8.0	0.0000600	0.13513456	0.000000	0.111063	100.00
9.0	0.0000380	0.13518356	0.000000	0.111063	100.00
10.0	0.0000250	0.13521506	0.000000	0.111063	100.00
11.0	0.0000170	0.13523606	0.000000	0.111063	100.00
12.0	0.0000120	0.13525056	0.000000	0.111063	100.00
13.0	0.0000087	0.13526091	0.000000	0.111063	100.00
14.0	0.0000055	0.13526801	0.000000	0.111063	100.00
15.0	0.0000049	0.13527321	0.000000	0.111063	100.00
16.0	0.0000038	0.13527756	0.000000	0.111063	100.00
17.0	0.0000031	0.13528101	0.000000	0.111063	100.00
18.0	0.0000024	0.13528376	0.000000	0.111063	100.00
19.0	0.0000020	0.13528596	0.000000	0.111063	100.00
20.0	0.0000016	0.13528776	0.000000	0.111063	100.00
25.0	0.000000610	0.13529328	0.000000	0.111063	100.00
30.0	0.000000300	0.13529556	0.000000	0.111063	100.00
35.0	0.000000160	0.13529671	0.000000	0.111063	100.00
40.0	0.000000094	0.13529734	0.000000	0.111063	100.00
50.0	0.000000038	0.13529800	0.000000	0.111063	100.00
60.0	0.000000019	0.13529829	0.000000	0.111063	100.00
80.0	0.000000007	0.13529855	0.000000	0.111063	100.00
100.0	0.000000003	0.13529865	0.000000	0.111063	100.00
1000.0	0.000000000	0.13530000	0.000000	0.111063	100.00

(area under curve) by computation of new values of atmospheric transmittance as follows:

$$M_N = M \frac{I_{TN}}{0.1111} , \quad (2.4)$$

where

I_{TN} = new value of total normal incident solar radiation intensity in $W\,cm^{-2}$

M = value for atmospheric transmittance given in Table 2.1

M_N = new value of atmospheric transmittance.

Equations (2.3) and (2.4) are valid only for locations relatively near the earth's surface (below 5 km altitude). For higher altitudes, corrections would be needed for the change of the amount of ozone and water vapor in the atmosphere. Also, equation (2.4) should be used only for values of I_{TN} greater than 0.0767 $W\,cm^{-2}$ (1.10 g-cal $cm^{-2}\,min^{-1}$) since values lower than this would indicate a considerably higher ratio of water vapor to ozone in the atmosphere and require that the curve be adjusted to give more absorption in the infrared water vapor bands at long wavelengths (infrared) and a smaller increase for the ozone at shorter wavelengths.

2.2.5 Sky (Diffuse) Radiation

When solar radiation, which is a nearly parallel beam of light, enters the atmosphere of the earth, molecules of air, dust particles, and aerosols such as water vapor droplets either diffuse or absorb a part of the radiation. The diffuse radiation then reaches the earth as nonparallel light from all directions.

2.2.5.1 Scattered Radiation

The scattered radiation gives the sky its brightness and color. The color is a result of selective scattering at certain wavelengths as a function of the size of the molecules and particles.

On a clear day the amount of scattering is very low because there are few particles and water droplets. The clear sky can be as little as 10^{-6} as bright as the surface of the sun. This sky radiation is called "diffuse radiation" in this document. The total energy contribution from the diffuse radiation from the entire sky hemisphere to a horizontal surface is only between 0.0007 and 0.014 W cm^{-2} (0.01 and 0.20 g-cal cm^{-2}).

As a black body radiator, the clear sky is considered equivalent to a cold source (about -15°C). The temperature of the clear sky is the same during the daytime as at nightime. Values of sky radiation for several localities are given in Table 2.5. It is the clear sky at night acting as a cold sink, without the solar radiation heating the surface of the earth, that causes air temperatures to be lower than the daytime values.

With clouds the amount of diffuse radiation is greater. The total hemisphere during an overcast day may contribute as much as 0.069 W cm^{-2} (1.0 g-cal cm^{-2}) of radiation to a horizontal surface.

The greater scattering by clouds makes the effective temperature of the clouds warmer than the clear air. At night the clouds act as a barrier to the outgoing radiation. Since they are warmer than the clear sky, the air near the ground will not cool to as low a temperature.

2.2.5.2 Absorbed Radiation

The various gases in the atmosphere selectively absorb some of the incoming radiation. Absorption changes some of the radiation into heat or radiation at wavelengths different from that received. Absorption by gases is observed in the solar spectrum as bands of various widths. The major gases in the earth's atmosphere, which show as absorption bands in the solar spectrum, are water vapor, carbon dioxide, ozone, and molecular oxygen.

2.3 Average Emittance of Colored Objects

In thermal engineering studies, the color of a painted surface is not important when one considers low-temperature radiation, i.e., from 10° to 68°C, since most painted surfaces have the same absorptivity at these low temperatures. Colored surfaces may differ in absorptivity. In Reference 2.4, a table on page 38 lists values of emissivity and absorptivity for various surfaces and different colors of paint exposed to solar radiation. Similar data are given in other publications but give either a range of values or mean values for the type of surface. The change of temperature (above or below the air temperature), which is the amount of heating or cooling, is proportional to the emissivity or absorptivity; therefore, the accuracy of determining the temperature of a surface is related to the accuracy of the emissivity and absorptivity. Spectral distribution curves of emittance are available for many surfaces.

The average emittance of any surface can be computed by the following method:

a. Divide the spectral emittance curve (i. e. , Figure 2. 1) into small intervals that have little or no change of emittance within the interval.

b. Using the same intervals from the spectral distribution of radiation (i. e. from Table 2. 1), multiply each value of emittance over the selected interval by the percentage of radiation over the interval.

c. Sum the resultant products to give the average emittance.

Table 2. 2 is an example of such computations. Data from Figure 2. 1 and Table 2. 1 are used. Similar computations can be accomplished for other sources of radiation such as the night sky or from cloudy skies.

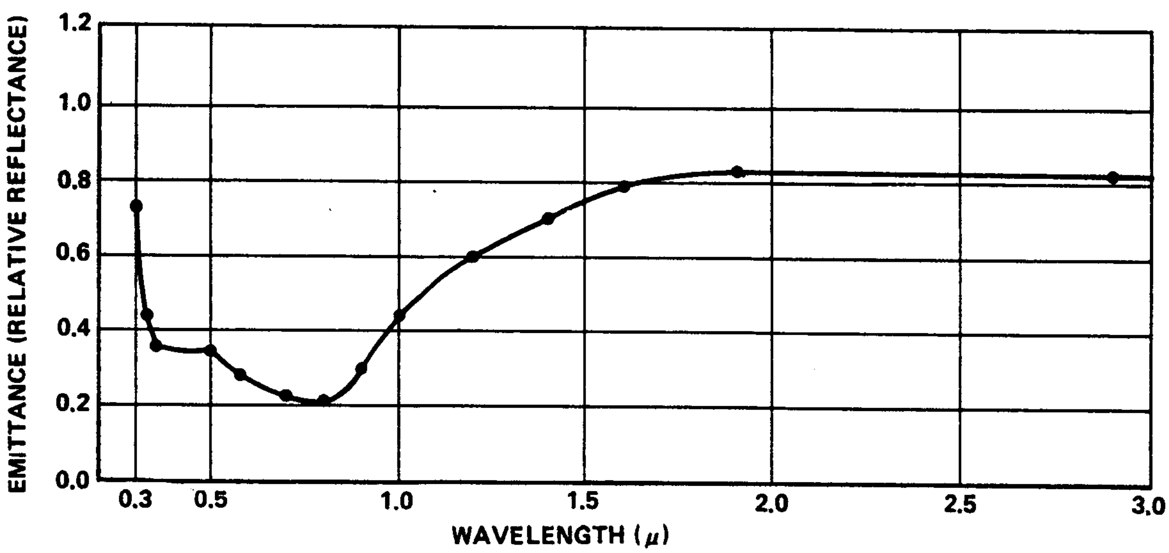

FIGURE 2. 1 EMITTANCE OF BARIUM SULPHATE AND MAGNESIUM OXIDE VERSUS WAVELENGTH

2. 4 Computation of Surface Temperature for Several Simultaneous Radiation Sources

The extreme value of temperature which a surface may reach when exposed to daytime (solar) or nighttime (night sky) radiation with no wind (calm), assuming it has no mass or heat transfer within the object, is

$$T_S = T_A + E(\Delta T_{BS}) \quad , \qquad (2.5)$$

TABLE 2.2 COMPUTATION OF EMITTANCE OF WHITE PAINT EXPOSED TO DIRECT SOLAR RADIATION AT THE EARTH'S SURFACE

Wavelength (μ)	Emittance	Average Emittance	Solar Radiation, 1 Atmosphere (%)	Solar Radiation over Interval (%)	Product of Average Emittance and Percent Solar Radiation over Interval Divided by 100
0.300	0.73		0.03		
		0.590		1.22	0.0072
0.330	0.45		1.25		
		0.410		1.55	0.0063
0.350	0.37		2.80		
		0.365		21.00	0.0766
0.500	0.36		23.80		
		0.325		11.77	0.0382
0.580	0.29		35.57		
		0.260		15.54	0.4040
0.700	0.23		51.11		
		0.225		10.37	0.0233
0.800	0.22		61.48		
		0.260		7.88	0.0205
0.900	0.30		69.36		
		0.370		6.71	0.0248
1.000	0.44		76.07		
		0.520		9.32	0.0485
1.200	0.60		85.39		
		0.650		3.44	0.0224
1.400	0.70		88.83		
		0.745		4.57	0.0340
1.600	0.79		93.40		
		0.810		3.01	0.0244
1.900	0.83		96.41		
		0.830		3.59	0.0298
50.000	0.83		100.00		
			Sum = average emittance = 0.396		

where

T_S = surface temperature (°K)

T_A = air temperature (°K)

E = emittance of surface

ΔT_{BS} = increase in black body temperature (°K) from daytime solar radiation (plus) or decrease in black body temperature (°K) from nighttime sky radiation (minus), calculated from

$$\Delta T_{BS} = \left(\frac{I_{TS}}{\sigma} \right)^{\frac{1}{4}} - T_A \quad . \tag{2.6}$$

Extreme values of ΔT_{BS} can be obtained from Figure 2.4A or Table 2.8, where

I_{TS} = total radiation (solar by day) (sky for night) received at surface. These values can be extremes from Tables 2.3, 2.4, or 2.6 from this report.

σ = Stefan-Boltzmann constant

= 8.1296×10^{-11} g-cal cm^{-2} K^{-4}

= 5.6692×10^{-12} W cm^{-2} K^{-4}

The term $\left(\frac{I_{TS}}{\sigma} \right)^{\frac{1}{4}}$ is equal to the extreme black body surface temperature.

If a correction for wind speed is desired, equation (2.5) can be used as follows:

$$T_S = T_A + E(\Delta T_{BS}) \frac{Wc}{100} \quad , \tag{2.5A}$$

where Wc is the correction for wind speed in percent from Figure 2.4B. Equations (2.5), (2.6), and (2.5A) are only for computing the effect of one source of radiation on a surface. When more than one radiation source is received by an object, then a more complex method must be used, as given in the following discussion.

If we have a black body with several radiation sources and no convection, then

$$\sigma T^4 = \sum_{1}^{n} I_i \qquad i = 1, 2, 3 \ldots n \quad . \tag{2.7}$$

Then

$$T - T_A = \Delta T = \frac{\sum_{1}^{n} I_i}{\sigma}^{\frac{1}{4}} - T_A \quad , \qquad (2.8)$$

where T_A is the air temperature.

For any object exposed to radiation in the earth's atmosphere

$$\Delta T = f_w \left(\frac{\sum_{1}^{n} E_i I_i}{\sigma} \right)^{\frac{1}{4}} - T_A \quad , \qquad (2.9)$$

where

E_i = emittance of object for corresponding radiation source I_i

$\Delta T = T - T_A$ (2.10)

f_w = wind effect (convection)

$$f_w = \frac{0.325}{\sqrt{w}} \qquad (2.11)$$

w = wind speed (m/sec) .

2.5 Total Solar Radiation

2.5.1 Introduction

The standard solar radiation sensors measure the intensity of direct solar radiation from the sun falling on a horizontal surface plus the diffuse (sky) radiation from the total sky hemisphere. Diffuse radiation is lowest with dry clear air; it increases with increasing dust and moisture in the air. With extremely dense clouds or fog, the measured horizontal solar radiation will be nearly all diffuse radiation. The higher (≥ 95 percentile) values of measured horizontal solar radiation occur under clear skies or under conditions of scattered fair weather cumulus clouds which reflect additional solar radiation onto the measuring sensor.

In this document all solar radiation values given are intensitites. Solar radiation intensities are measured in gram calories per square centimeter (same as langleys per square centimeter) by stations of the National Oceanic and Atmospheric Administration, National Weather Service; therefore, these units are used in this section. Intensities of solar radiation are numerically equal to solar insolation per minute; i. e. , gram calories per square centimeter per minute.

2. 5. 2 Use of Solar Radiation in Design

When radiation data are used in design studies, the direct solar radiation should be applied from one direction as parallel rays, and at the same time, the diffuse radiation should be applied as rays from all directions of a hemisphere (Figure 2. 2).

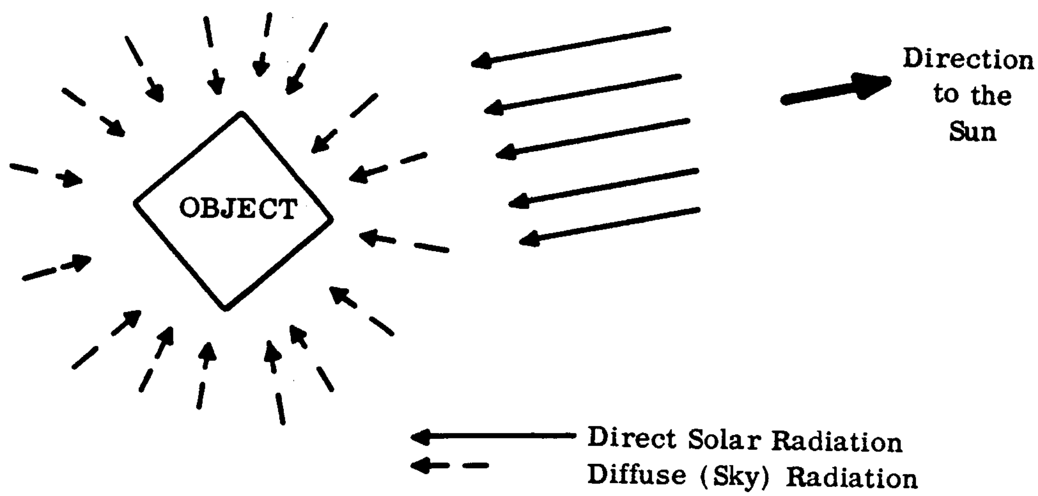

FIGURE 2. 2 METHOD OF APPLYING RADIATION FOR DESIGN

Because the sun provides heat (from radiation) from a specific direction, differential heating of an object occurs; i. e. , one part is heated more than another, resulting in stress and deformation. As an example, the sun heats the side of the Apollo/Saturn V vehicle facing the sun, while the sky cools the opposite side. This differential heating causes the vehicle to bend away from the sun sufficiently at the top to require consideration in design of platforms surrounding the vehicle. These platforms are used to ready the vehicle on the launch pad and must be designed so as to prevent damage to the vehicle skin as the vehicle bends away from the sun.

2.5.3 Total Solar Radiation Extremes

Ten years of total horizontal solar and sky radiation data at two stations were selected for analysis to determine the frequency distribution of solar radiation for use in design. The data analysis was made by The National Oceanic and Atmospheric Administration, National Climatic Center, under contract to NASA-Marshall Space Flight Center.

2.5.3.1 Basic Data Computations

The basic data used were hourly totals of horizontal solar and sky radiation (I_{TH}) for each hour of the day for 10-year periods at each of two stations: Apalachicola, Florida, and Santa Maria, California. The hourly totals were divided by 60 to obtain the average solar radiation values per minute for each hour. The average values per minute are numerically equal to intensity, and these values were used in the computations of frequency distributions. The diffuse sky radiation intensities I_{DH} were empirically estimated for each value based on the amount of total horizontal solar and sky radiation and solar altitude, similar to the method used in Reference 2.5. After the diffuse sky radiation is subtracted from the total horizontal solar and sky radiation, the resultant horizontal solar radiation I can be used to compute the direct normal incident solar radiation I_{DN} by using the following equation (Refs. 2.6 and 2.7):

$$I_{DN} = \frac{I}{\sin b} \quad , \qquad (2.12)$$

where

I_{DN} = direct normal incident solar radiation

I = horizontal solar radiation = $I_{TH} - I_{dH}$

b = sun's altitude[1] (Ref. 2.8).

The total normal incident solar radiation I_{TN} values were found by adding the direct normal incident solar radiation I_{DN} and the diffuse sky radiation I_{dH} previously estimated. This method of finding the total normal

1. Horizon system of coordinates such as those used by surveyors and astronomers.

incident solar radiation may result in a slight overestimate of the value for low solar altitudes because the sky hemisphere is intercepted by the ground surface. This error is insignificant, however, when extreme values are used and would be small for values equal to or greater than the mean plus one standard deviation.

Total solar radiation intensities on a south-facing surface, with the normal to the surface at 45 degrees to the horizontal, are calculated as follows:

$$I_{D45} = I\,(\sin 45\text{ deg} + \cot b \cos a \cos 45\text{ deg}) \quad , \qquad (2.13)$$

where

I_{D45} = intensity of direct solar radiation on a south-facing surface, with normal 45 degrees to the horizontal

I = horizontal solar radiation = $I_{TH} - I_{dH}$

a = sun's azimuth measured from south direction

b = sun's altitude.

2.5.3.2 Solar Radiation Extreme and 95 Percentile

To present the solar radiation data in a simplified form, the month of June was selected to represent the summer and the longest period of daylight and December for the winter and shortest period of daylight. The June data for normal incident solar radiation from Santa Maria, California, were increased for the period from 1100 to 1900 hours to reflect the higher values which occur early in July (first week) during the afternoon. Tables 2.3 and 2.4 give the frequency distributions for the extreme[2] values and the 95 percentile values of solar radiation for hours of the day. The values given for diffuse radiation are the values which occurred associated with the other extreme and 95 percentile values of the other solar radiations given. Since the diffuse radiation decreases with increasing horizontal radiation, the values given in Tables 2.3 and 2.4 are considerably lower than the highest values of diffuse radiation occurring during the period of record. Figure 2.3 shows the June total horizontal and total normal incident data for the Eastern Test Range, New Orleans, Gulf Transportation, and Huntsville.

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2. Extreme as used in this section is the highest measured value of record.

TABLE 2.3 EXTREME VALUES OF SOLAR RADIATION FOR THE SPACE AND MISSILE TEST CENTER, WEST COAST TRANSPORTATION, SACRAMENTO, WHITE SANDS MISSILE RANGE, AND EDWARDS AFB

TIME OF DAY (Local Standard Time)	Total Horizontal Solar Radiation g-cal cm^{-2}		Diffuse Radiation Associated with Total Horizontal Solar Radiation Extremes g-cal cm^{-2}		Total Normal Incident Solar Radiation g-cal cm^{-2}		Total 45° Surface Solar Radiation g-cal cm^{-2}	
	JUNE							
	EXTREME	95 Percentile	EXTREME	95 Percentile	EXTREME	95 Percentile	EXTREME	95 Percentile
0500	0	0	0	0	0	0	0	0
0600	0.16	0.11	.02	.04	1.14	0.78	0.04	0
0700	0.46	0.40	.05	.08	1.34	1.08	0.19	0.16
0800	0.82	0.76	.06	.09	1.54	1.38	0.34	0.31
0900	1.16	1.11	.04	.08	1.74	1.62	0.84	0.77
1000	1.45	1.42	0	.03	1.79	1.71	1.19	1.12
1100	1.64	1.56	0	.10	1.79	1.69	1.39	1.31
1200	1.69	1.63	0	.08	1.74	1.68	1.49	1.38
1300	1.69	1.64	0	.07	1.74	1.68	1.49	1.40
1400	1.59	1.54	.06	.12	1.74	1.68	1.34	1.29
1500	1.45	1.39	0	.06	1.79	1.70	1.14	1.09
1600	1.21	1.19	0	.02	1.79	1.71	0.89	0.78
1700	0.87	0.83	.03	.05	1.69	1.60	0.34	0.18
1800	0.46	0.42	.05	.08	1.39	1.23	0.19	0.13
1900	0.14	0.12	.02	.04	1.19	0.93	0.04	0
2000	0	0	0	0	0	0	0	0
	DECEMBER							
	EXTREME	95 Percentile	EXTREME	95 Percentile	EXTREME	95 Percentile	EXTREME	95 Percentile
0800	0	0	0	0	0	0	0	0
0900	0.35	0.32	0.04	0.05	1.59	1.39	0.99	0.85
1000	0.65	0.60	0.03	0.05	1.64	1.53	1.29	1.21
1100	0.86	0.80	0	0.04	1.84	1.64	1.64	1.49
1200	0.96	0.89	0.02	0.06	1.79	1.69	1.74	1.63
1300	0.99	0.89	0	0.06	1.84	1.70	1.79	1.64
1400	0.85	0.80	0.01	0.04	1.79	1.64	1.59	1.49
1500	0.66	0.60	0.02	0.05	1.69	1.54	1.34	1.21
1600	0.38	0.31	0.02	0.05	1.64	1.38	1.04	0.87
1700	0	0	0	0	0	0	0	0

TABLE 2.4 EXTREME VALUES OF SOLAR RADIATION FOR EASTERN TEST RANGE, NEW ORLEANS, GULF TRANSPORTATION, AND HUNTSVILLE

TIME OF DAY (Local Standard Time)	Total Horizontal Solar Radiation g-cal cm^{-2}		Diffuse Radiation Associated with Total Horizontal Solar Radiation Extremes g-cal cm^{-2}		Total Normal Incident Solar Radiation g-cal cm^{-2}		Total 45° Surface Solar Radiation g-cal cm^{-2}	
	JUNE							
	EXTREME	95 Percentile	EXTREME	95 Percentile	EXTREME	95 Percentile	EXTREME	95 Percentile
0500	0	0	0	0	0	0	0	0
0600	0.12	0.07	0	0	1.09	1.00	0	0
0700	0.42	0.36	0.05	0.07	1.29	1.04	0.19	0.16
0800	0.82	0.71	0.04	0.10	1.59	1.30	0.34	0.27
0900	1.23	1.02	0	0.10	1.59	1.48	0.49	0.41
1000	1.35	1.30	0.02	0.06	1.59	1.54	0.99	0.95
1100	1.52	1.45	0.03	0.09	1.59	1.54	1.19	1.14
1200	1.58	1.53	0.10	0.16	1.64	1.55	1.29	1.24
1300	1.58	1.50	0.10	0.20	1.64	1.53	1.29	1.24
1400	1.50	1.44	0.05	0.12	1.59	1.52	1.19	1.09
1500	1.35	1.30	0.02	0.06	1.59	1.52	1.04	0.95
1600	1.10	1.01	0.05	0.12	1.54	1.44	0.54	0.44
1700	0.77	0.72	0.05	0.09	1.49	1.33	0.34	0.30
1800	0.48	0.40	0.03	0.06	1.44	1.14	0.19	0.18
1900	0.11	0.08	0	0	1.14	1.00	0.14	0.03
2000	0	0	0	0	0	0	0	0
	DECEMBER							
	EXTREME	95 Percentile	EXTREME	95 Percentile	EXTREME	95 Percentile	EXTREME	95 Percentile
0700	0	0	0	0	0	0	0	0
0800	0.16	0.10	0	0	1.34	1.12	0.64	0.50
0900	0.46	0.42	0.04	0.06	1.44	1.36	0.94	0.89
1000	0.79	0.71	0.01	0.07	1.69	1.60	1.39	1.29
1100	0.95	0.92	0.02	0.04	1.79	1.68	1.64	1.56
1200	1.09	1.02	0	0.03	1.79	1.70	1.74	1.66
1300	1.05	1.02	0	0.03	1.79	1.78	1.74	1.66
1400	0.94	0.89	0.02	0.05	1.74	1.67	1.59	1.63
1500	0.79	0.70	0	0.03	1.74	1.57	1.39	1.27
1600	0.46	0.41	0.04	0.06	1.54	1.40	0.99	0.91
1700	0.16	0.10	0	0	1.34	1.12	0.64	0.50
1800	0	0	0	0	0	0	0	0

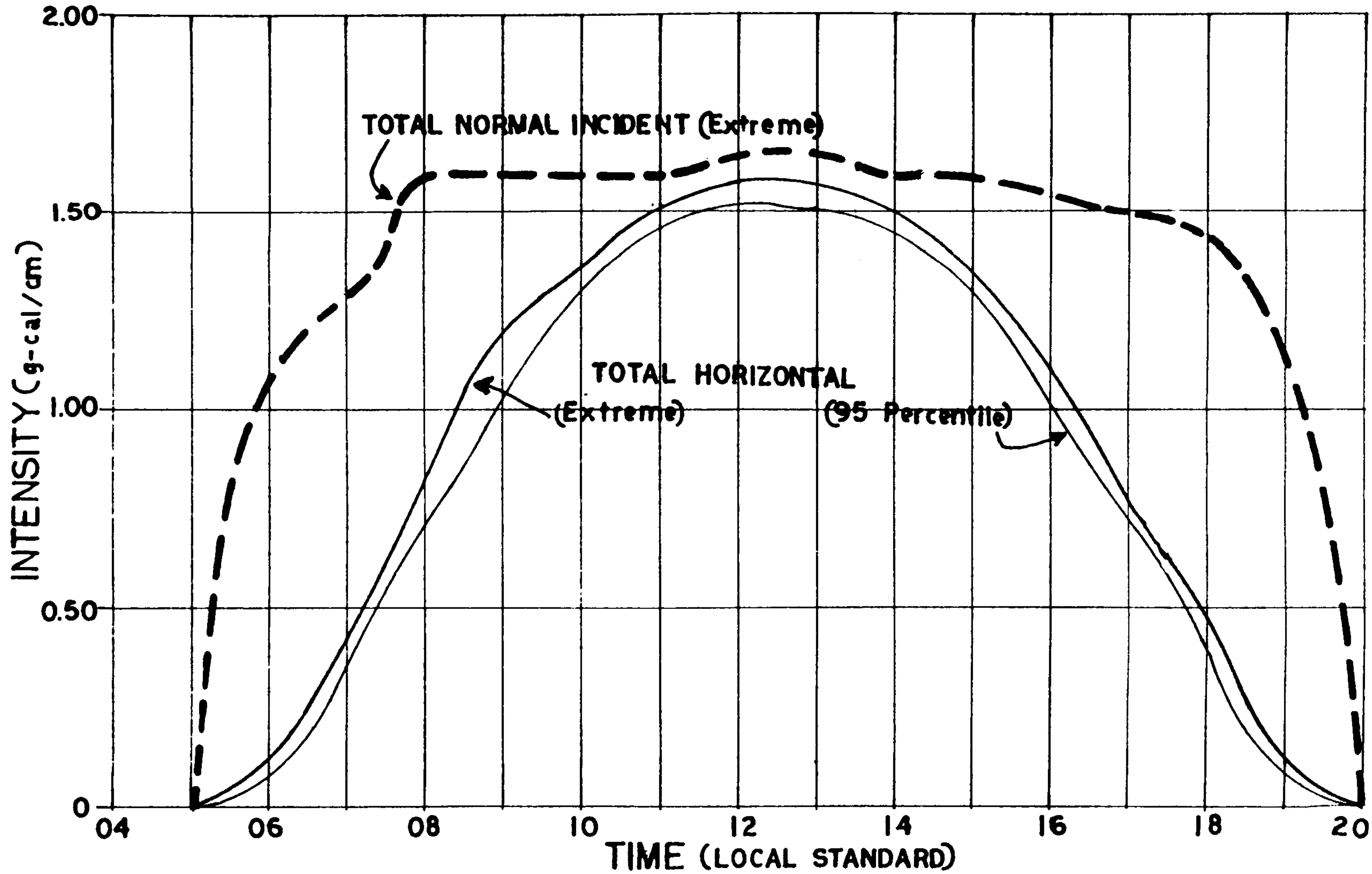

FIGURE 2. 3 JUNE EXTREME VALUES OF SOLAR RADIATION FOR EASTERN TEST RANGE, NEW ORLEANS, GULF TRANSPORTATION, AND HUNTSVILLE

2.5.3.3 Variation with Altitude

Solar radiation intensity on a surface will increase with altitude above the earth's surface, with clear skies, according to the following equation:

$$I_H = I_{DN} + (1.94 - I_{DN}) \left(1 - \frac{\rho_H}{\rho_S}\right) \quad , \qquad (2.14)$$

where

I_H = intensity of solar radiation normal to surface at required height

I_{DN} = intensity of solar radiation normal to surface at the earth's surface assuming clear skies ($I_{DN} = I_{TN} - I_{dH}$)

ρ_H = atmospheric density at required height (from U. S. Standard, U.S. Supplemental Atmospheres, or this document) (kg m^{-3})

ρ_S = atmospheric density at sea level (from U. S. Standard, U.S. Supplemental Atmospheres, or this document) (kg m^{-3})

1.94 = solar constant (g-cal cm^{-2}).

The diffuse radiation I_{dH} decreases with altitude above the earth's surface, with clear skies. A good estimate of the value can be obtained from the following equation[3]:

$$I_{dH} = 0.7500 - 0.4076\, I_H \quad , \qquad (2.15)$$

where

I_{dH} = intensity of diffuse radiation

I_H = intensity of solar radiation normal to surface.

Equation (2.15) is valid for values of I_H from equation (2.14) up to 1.84 g-cal cm^{-2}. For values of I_H greater than 1.84 g-cal cm^{-2}, $I_{dH} = 0$.

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3. Equation (2.15) is based on a cloudless and dust free atmosphere.

2. 5. 3. 4 Solar Radiation during Extreme Conditions

When ground winds occur exceeding the 95, 99, or 99. 9 percentile design winds given in this document in Section V, the associated weather normally is such that clouds, rain, or dust are generally present; therefore, the intensity of the incoming solar radiation will be less than the maximum values given in Tables 2. 3 and 2. 4. Maximum values of solar radiation intensity to use with corresponding wind speeds are given in Table 2. 5.

TABLE 2. 5 SOLAR RADIATION MAXIMUM VALUES ASSOCIATED WITH EXTREME WIND VALUES

Maximum Solar Radiation (Normal Incident)						
Steady-State Ground Wind Speed at 18 m Height	Huntsville, New Orleans River Transportation, Gulf Transportation, Eastern Test Range, Western Test Range, Sacramento, West Coast Transportation and Wallops Test Range			White Sands Missile Range		
($m\ sec^{-1}$)	($kJm^{-2}\ sec^{-1}$)	($g\text{-}cal\ cm^{-2}\ min^{-1}$)	($BTU\ ft^{-2}\ hr^{-1}$)	($kJm^{-2}\ sec^{-1}$)	($g\text{-}cal\ cm^{-2}\ min^{-1}$)	($BTU\ ft^{-2}\ hr^{-1}$)
10	0. 84	1. 20	265	1. 05	1. 50	332
15	0. 56	0. 80	177	0. 70	1. 00	221
≥20	0. 35	0. 50	111	0. 56	0. 80	177

2. 6 Temperature

Several types of temperatures at the earth's boundary layer may be considered in design. These are as follows:

a. Air temperature normally measured at 1. 22 meters (4 ft) above a grass surface.

b. Changes of air temperature (Usually the rapid changes which occur in less than 24 hours are considered.)

c. Surface or skin temperature measured of a surface exposed to radiation.

d. Temperatures within a closed compartment.

All of the above will be discussed in the following subsections.

2. 6. 1 Air Temperature Near the Surface

Surface air temperatures are presented in Table 2. 6 for various geographic areas. The maximum extremes and minimum extremes and the 95 percentile values are given for the worst month based on 50 years of record. Values for extreme minimum sky radiation (equal to outgoing radiation) are also given in Table 2. 6. Maximum and minimum temperature values should be expected to last only a few hours during a daily period. Generally, the extreme maximum temperature is reached after 12 noon and before 5 p. m., while the minimum temperature is reached just before sunrise. Table 2. 7 shows the maximum and minimum air temperatures which have occurred on each hour at the Eastern Test Range (Cape Kennedy), but not necessarily on the same day, although these curves represent a cold and hot extreme day. The method of sampling the day (frequency of occurrence of observations) will result in the same extreme values if the same period of time for the data is used, but the 95 percentile values will be different for hourly, daily, and monthly data reference periods. Selection of the reference period depends on engineering application.

2. 6. 2 Extreme Air Temperature Change

a. For all areas the design values of extreme air temperature changes (thermal shock) are:

(1) An increase of air temperature of 10°C (18°F) with a simultaneous increase of solar radiation (measured on a normal surface) from 0. 50 g-cal cm^{-2} min^{-1} (110 BTU ft^{-2} hr^{-1}) to 1. 85 g-cal cm^{-2} min^{-1} (410 BTU ft^{-2} hr^{-1}) may occur in a 1-hour period. Likewise, the reverse change of the same magnitude may occur for decreasing air temperature and solar radiation.

(2) A 24-hour change may occur with an increase of 27. 7° C (50°F) in air temperature in a 5-hour period, followed by 4 hours of constant air temperature, then a decrease of 27. 7°C (50°F) in a 5-hour period, followed by 10 hours of constant air temperature.

b. For Eastern Test Range (Cape Kennedy, Florida), the 99. 9 percentile air temperature changes are as follows:

(1) An increase of air temperature of 5. 6°C (11°F) with a simultaneous increase of solar radiation (measured on a normal surface) from 0. 50 g-cal cm^{-2} min^{-1} (110 BTU ft^{-2} hr^{-1}) to 1. 60 g-cal cm^{-2} min^{-1} (354 BTU ft^{-2} hr^{-1}), or a decrease of air temperature of 9. 4°C (17°F) with a simultaneous decrease of solar radiation from 1. 60 g-cal cm^{-2} min^{-1} (354 BTU ft^{-2} hr^{-1}) to 0. 50 g-cal cm^{-2} min^{-1} (110 BTU ft^{-2} hr^{-1}) may occur in a 1-hour period.

TABLE 2. 6 SURFACE AIR AND SKY RADIATION TEMPERATURE EXTREMES

Area		Surface Air Temperature Extremes[a]				Sky Radiation	
		Maximum		Minimum		Equivalent Temperature Minimum Extreme	Equivalent Radiation (g-cal cm^{-2} min^{-1})
		Extreme	95%	Extreme	95%		
Huntsville	°C	43. 9	41. 7[b]	-23. 3	-21. 7[b]	-30. 0	0. 28
	°F	111	107[b]	-10	-7[b]	-22	
River Transporatation	°C	43. 9	NA	-30. 6	NA	-37. 2	0. 25
	°F	111	NA	-23	NA	-35	
New Orleans	°C	37. 8	31. 7[c]	-12. 8	7. 8[c]	-17. 8	0. 35
	°F	100	89[c]	9	46[c]	0	
Gulf Transportation	°C	40. 6	NA	-12. 8	NA	-17. 8	0. 35
	°F	105	NA	9	NA	0	
Eastern Test Range	°C	37. 2	30. 0[c]	-3. 9	12. 2[c]	-15. 0	0. 36
	°F	99	86[c]	25	54[c]	5	
	°C	37. 2	31. 7[d]	-3. 9	6. 7[d]		
	°F	99	89[d]	25	44[d]		
Panama Canal Transportation	°C	41. 7	NA	-12. 8	NA	15. 0	0. 36
	°F	107	NA	9	NA	5	
Space and Missile Test Center	°C	41. 7	31. 1[c]	-2. 2	3. 9[c]	-15. 0	0. 36
	°F	107	88[c]	28	39[c]	5	
West Coast Transportation	°C	46. 1	NA	-6. 1	NA	-17. 8	0. 35
	°F	115	NA	21	NA	0	
Sacramento	°C	46. 1	e	-6. 1	e	-17. 8	0. 35
	°F	115	e	21	e	0	
White Sands Missile Range	°C	41. 1	e	-21. 1	e	-30. 0	0. 28
	°F	106	e	-6	e	-22	
Wallops Test Range	°C	39. 4	e	-11. 7	e	-17. 8	0. 35
	°F	103	e	11	e	0	
Edwards AFB	°C	43. 3	39. 4[d]	-15. 0	-3.9[d]	-30. 0	0. 28
	°F	110	103[d]	5	25[d]	-22	

a. The extreme maximum and minimum temperatures will be encountered during periods of wind speeds less than about 1 meter per second.

b. Based on worst month extreme

c. Based on hourly observations

d. Based on daily extreme (maximum or minimum) observations.

e. To be determined

TABLE 2. 7 MAXIMUM AND MINIMUM SURFACE AIR TEMPERATURES AT EACH HOUR FOR EASTERN TEST RANGE[4]

Time	Annual Maximum		Annual Minimum	
	°C	°F	°C	°F
1 a. m.	28. 9	84	1. 1	34
2	28. 9	84	0. 6	33
3	29. 4	85	-1. 1	30
4	28. 3	83	-0. 6	29
5	28. 3	83	-1. 1	28
6	29. 4	85	-1. 1	27
7	30. 6	87	-1. 7	26
8	30. 6	87	-2. 2	25
9	31. 7	89	-0. 6	28
10	33. 9	93	1. 1	30
11	35. 0	95	2. 2	35
12 noon	35. 6	96	5. 0	41
1 p. m.	37. 2	99	5. 6	42
2	35. 6	97	5. 0	41
3	35. 6	97	5. 6	42
4	35. 6	97	5. 6	42
5	35. 6	97	5. 6	42
6	35. 0	95	3. 9	39
7	33. 3	92	2. 2	36
8	31. 7	89	2. 2	36
9	30. 0	86	1. 7	35
10	30. 0	86	1. 7	35
11	30. 0	86	1. 1	34
12 mid	30. 0	86	1. 1	34

4. Based on 10 years of record for Patrick Air Force Base and Cape Kennedy.

(2) A 24-hour temperature change may occur as follows: An increase of 16. 1°C (29° F) in air temperature (wind speed under 5 m/sec) in an 8-hour period, followed by 2 hours of constant air temperature (wind speed under 5 m/sec), then a decrease of 21. 7°C (39° F) in air temperature (wind speed between 7 and 10 m/sec) in a 14-hour period.

2. 6. 3 Surface (Skin) Temperature

The temperature of the surface of an object exposed to solar, day sky, or night sky radiation is usually different from the air temperature (Refs. 2. 9 and 2. 10). The amount of the extreme difference in temperature between the object and the surrounding air temperature is given in Table 2. 8 and Figure 2. 4, Part A, for exposure to a clear night (or day)[5] sky or to the sun on a clear day. Since the flow of air across an object changes the balance between the heat transfers from radiation and convection-conduction between the air and the object, the difference in the temperature between the air and the object will decrease with increasing wind speed (Ref. 2. 9). Part B of Figure 2. 4 provides information for making the corrections for wind speed. Values are tabulated in Table 2. 8 for various wind speeds.

2. 6. 4 Compartment Temperature

2. 6. 4. 1 Introduction

A cover of thin material enclosing an air space will conduct heat to (or remove heat from) the inside air when the cover is heated by solar radiation (or cooled by the night sky). This results in the compartment air space being frequently considerably hotter or cooler than the surrounding air. The temperature reached in a compartment is dependent on the location of the air space with respect to the heated surface, the type and thickness of the surface material, the type of construction, and the insulation; i. e., an addition of a layer of insulation on the inside surface of the compartment will greatly reduce the heating or cooling of the air in the compartment space (Refs. 2. 11 and 2. 12).

2. 6. 4. 2 Compartment Extreme High Temperature

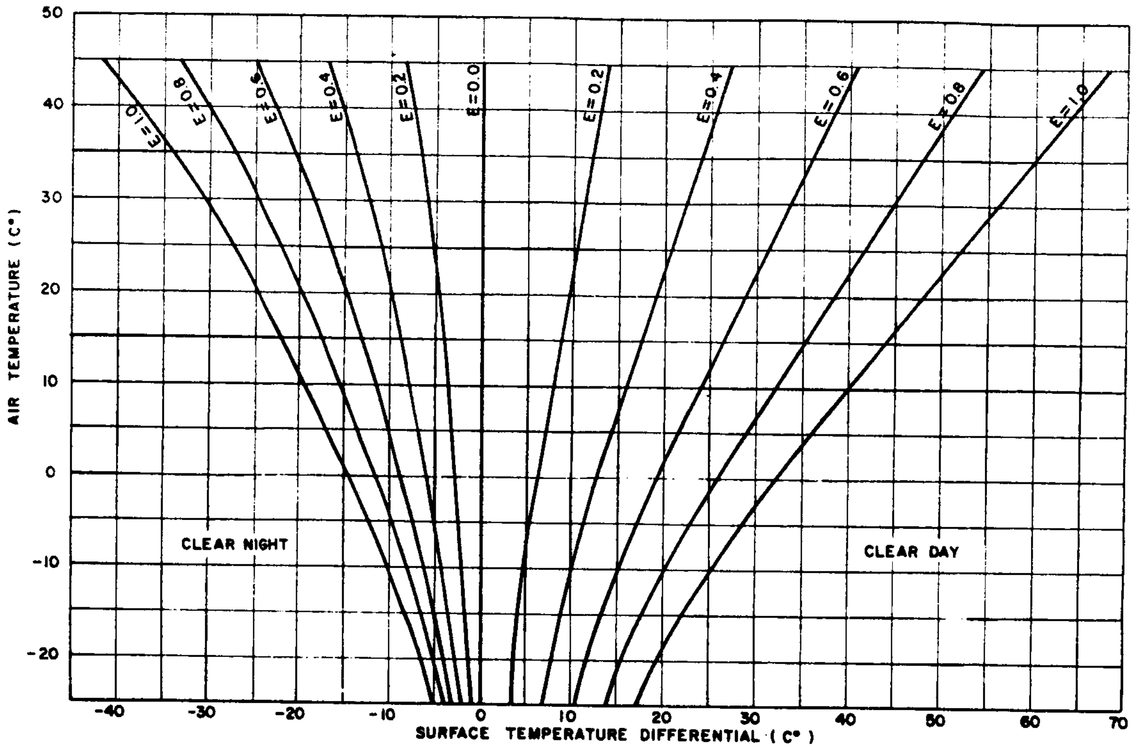
A compartment probable extreme high temperature of 87. 8°C (190° F) for a period of 1 hour and 65. 6°C (150° F) for a period of 6 hours must be considered at all geographic locations while aircraft or other transportation equipment are stationary on the ground without air conditioning in the compartment. These extremes will be found at the top and center of the compartment.

5. Without the sun's rays striking, the daytime sky is about as cold as the nighttime sky.

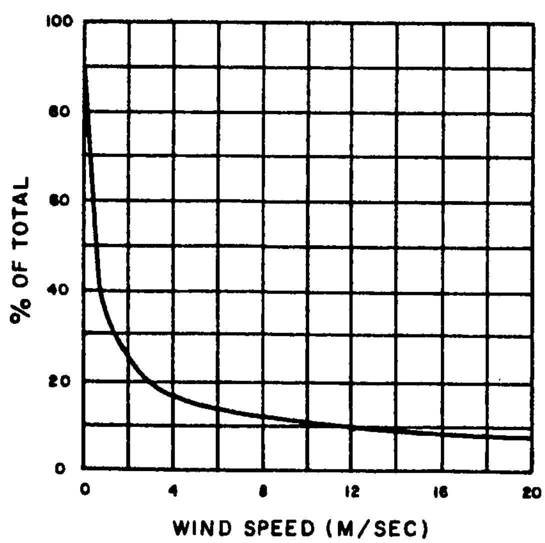
TABLE 2.8 EXTREME SURFACE (skin) TEMPERATURE ABOVE OR BELOW AIR TEMPERATURE OF AN OBJECT NEAR THE EARTH'S SURFACE

Air Temperature	Surface Temperature (°C)									
	Clear Night					Clear Day				
	Wind Speed (m sec^{-1})					Wind Speed (m sec^{-1})				
	0	2	4	10	20	0	2	4	10	20
(°C)	Correction Factor					Correction Factor				
	1.00	0.25	0.17	0.11	0.08	1.00	0.25	0.17	0.11	0.08
-25	-5.0	-1.2	-0.8	-0.6	-0.4	16.9	4.2	2.9	1.9	1.4
-20	-6.5	-1.6	-1.1	-0.7	-0.5	19.2	4.8	3.3	2.1	1.5
-15	-8.2	-2.0	-1.4	-0.9	-0.6	22.0	5.5	3.7	2.4	1.8
-10	-10.2	-2.6	-1.7	-1.1	-0.8	25.1	6.3	4.3	2.8	2.0
- 5	-12.2	-3.0	-2.1	-1.3	-1.0	28.5	7.1	4.8	3.1	2.3
0	-14.5	-3.6	-2.5	-1.6	-1.2	32.0	8.0	5.4	3.5	2.6
5	-16.9	-4.2	-2.9	-1.9	-1.4	36.0	9.0	6.1	4.0	2.9
10	-19.4	-4.8	-3.3	-2.1	-1.6	40.0	10.0	6.8	4.4	3.2
15	-21.9	-5.5	-3.7	-2.4	-1.8	44.0	11.0	7.5	4.8	3.5
20	-24.6	-6.2	-4.2	-2.7	-2.0	48.0	12.0	8.2	5.3	3.8
25	-27.4	-6.8	-4.6	-3.0	-2.2	52.0	13.0	8.8	5.7	4.2
30	-30.5	-7.6	-5.2	-3.4	-2.4	56.0	14.0	9.5	6.2	4.5
35	-34.0	-8.5	-5.8	-3.7	-2.7	60.0	15.0	10.2	6.6	4.8
40	-37.7	-9.4	-6.4	-4.1	-3.0	64.0	16.0	10.9	7.0	5.1
45	-41.7	-10.4	-7.1	-4.6	-3.3	68.0	17.0	11.6	7.5	5.4

NOTE: Values are given for an emittance value of 1.0 Temperature differences for other emittance can be determined by multiplying tabular value by the appropriate emittance.



A. Surface temperature differentials with respect to air temperature for surface of emittance from 0. 0 to 1. 0 for calm wind conditions. Temperature difference after correction for wind is to be added or subtracted to the air temperature to give surface (skin) temperature.



B. Correction for wind speed obtained from Graph A. Valid only for a pressure of one atmosphere.

FIGURE 2. 4 EXTREME SURFACE (skin) TEMPERATURE OF AN OBJECT NEAR THE EARTH'S SURFACE (0 to 300m) FOR CLEAR SKY

2.7 Data on Air Temperature Distribution with Altitude

Data on air temperature distribution with altitude are given in Section XIV

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SECTION III. HUMIDITY

By

Glenn E. Daniels

3.1 Definitions. (Ref. 3.1)

Dew point is the temperature to which a given parcel of air must be cooled at constant pressure and constant water vapor content in order for saturation to occur. Further cooling below the dew point normally produces condensation or sublimation.

Relative humidity is the ratio of the actual amount of water vapor in a given volume of air to the amount of water vapor that the same volume of air at the same temperature holds if saturated. Values given are in percent.

Vapor concentration [previously called absolute humidity (Ref. 3.2)] is the ratio of the mass of water vapor present to the volume occupied by the mixture, i.e., the density of the water vapor content. This is expressed in grams of water vapor per cubic meter of air.

Water vapor is water in gaseous state.

3.2 Vapor Concentration.

Water in vapor form in the atmosphere is invisible; however, the amount of liquid water available from a volume of warm air near saturation is considerable and must be considered in design of space vehicles because:

a. Small solid particles (dust) which settle on surfaces cause condensation (frequently when the atmosphere is not at the saturation level) and will dissolve. The resultant solution may be corrosive. Galvanic corrosion resulting from contact of dissimilar metals also takes place at a rapid rate in the presence of moisture. The rate of corrosion of the surface increases with higher humidity (Ref. 3.3). See Section X of this document for further details.

b. Humidity conditions can impair the performance of electrical equipment. This may be by an alteration of the electrical constants of tuned circuits, deterioration of parts (resistors, capacitors, etc.), electrical breakdown of air gaps in high-voltage areas, or shorting of sections by conductive solutions formed from solid particles dissolving in the liquid formed.

c. To grow well, bacteria and fungi usually require high humidities associated with high temperatures.

d. A decrease in the temperature of the air to the dew point will result in condensation of water from the atmosphere in liquid or frozen form. Considerable difficulty may result from ice forming on space vehicles when moist air is cooled by the low temperature of the fuel, especially if pieces of this ice should drop into equipment areas of the vehicle or supporting ground equipment before or during takeoff. Optical surfaces (such as lenses of television cameras) may become coated with water droplets or ice crystals.

Test specifications still use an accelerated humidity test of temperature of 71.1°C (160°F) at a relative humidity of 95 percent ±5 percent for 10 cycles of 6 hours each spread over a total period of 240 hours. This represents a dew point of 68.9°C (156°F), values that are much higher than any natural extreme in the world. Dew points above 32.2°C (90°F) are extremely unlikely in nature (Ref. 3.4), since the dew point temperature is limited by the source of the water vapor; i.e., the surface temperature of the water body from which the water evaporates (Ref. 3.5). These tests with high temperatures can be advantageously used only as an aggravated test if high temperatures are not significant in the test after correlation of deterioration with that encountered in natural extremes. Also, if the mass of the test object is large, moisture may not condense on the test object because of thermal lag in the test object. Therefore, referenced specifications for tests which require high temperature must be carefully evaluated and should be used as guidelines along with this document.

3.2.1 High Vapor Concentration at Surface.

a. Huntsville, River Transportation, New Orleans, Gulf Transportation, Eastern Test Range, and Wallops Test Range:

(1) The following extreme humidity cycle of 24 hours with a wind of less than 5 m sec^{-1} (9.7 knots) should be considered in design: Three hours of 37.2°C (99°F) air temperature at 50 percent relative humidity and a vapor concentration of 22.2 g m^{-3} (9.7 gr ft^{-3}); six hours of decreasing air temperature to 24.4°C (76°F) with relative humidity increasing to 100 percent (saturation); eight hours of decreasing air temperature to 21.1°C (70°F), with a release of 3.8 grams of water as liquid per cubic meter of air (1.7 gr

of water per cubic foot of air),* humidity remaining at 100 percent; and seven hours of increasing air temperature to 37.2°C (99°F) and a decrease to 50 percent relative humidity (Fig. 3.1).

(2) An extreme relative humidity between 75 and 100 percent and air temperature between 22.8°C (73°F) and 27.8°C (82°F), which would result in corrosion and bacterial and fungal growths, can be expected for a period of 15 days. A humidity of 100 percent occurs one-fourth of the time at the lower temperature in cycles not exceeding 24 hours. Any loss of water vapor from the air by condensation is replaced from outside sources to maintain at least 75 percent relative humidity at the higher temperature.

b. Panama Canal Transportation:

(1) The following extreme humidity cycle of 24 hours with a wind of less than 5 m sec^{-1} (9.7 knots) should be considered in design: Three hours of 32.2°C (90°F) air temperature at 75 percent relative humidity, and a vapor concentration of 25.4 g m^{-3} (11.1 gr ft^{-3}); six hours of decreasing air temperature to 26.7°C (80°F) with relative humidity increasing to 100 percent; eight hours of decreasing air temperature to 21.7°C (71°F) with a release of 6.3 grams of water as liquid per cubic meter of air (2.8 gr of water per cubic foot of air),* humidity remaining at 100 percent; four hours of increasing air temperature to 26.7°C (80°F) and a decrease to 75 percent relative humidity; and three hours of increasing air temperature to 32.2°C (90°F) with the relative humidity remaining at 75 percent (moisture added to air by evaporation, mixing, or replacement with air of higher vapor concentration). See Figure 3.2.

(2) An extreme relative humidity between 85 and 100 percent and air temperature between 23.9°C (75°F) and 26.1°C (79°F), which would result in corrosion and bacterial and fungal growth, can be expected for a period of 30 days. The humidity should be 100 percent during one-fourth of the time at the lower temperature in cycles not exceeding 24 hours. Any loss of water vapor from the air by condensation is replaced from outside sources to maintain at least 85 percent relative humidity at the higher temperature.

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* The release of water as a liquid on the test object may be delayed for several hours after the start of this part of the test because of thermal lag in a large test object. If the lag is too large, the test should be extended in time for each cycle to allow condensation.

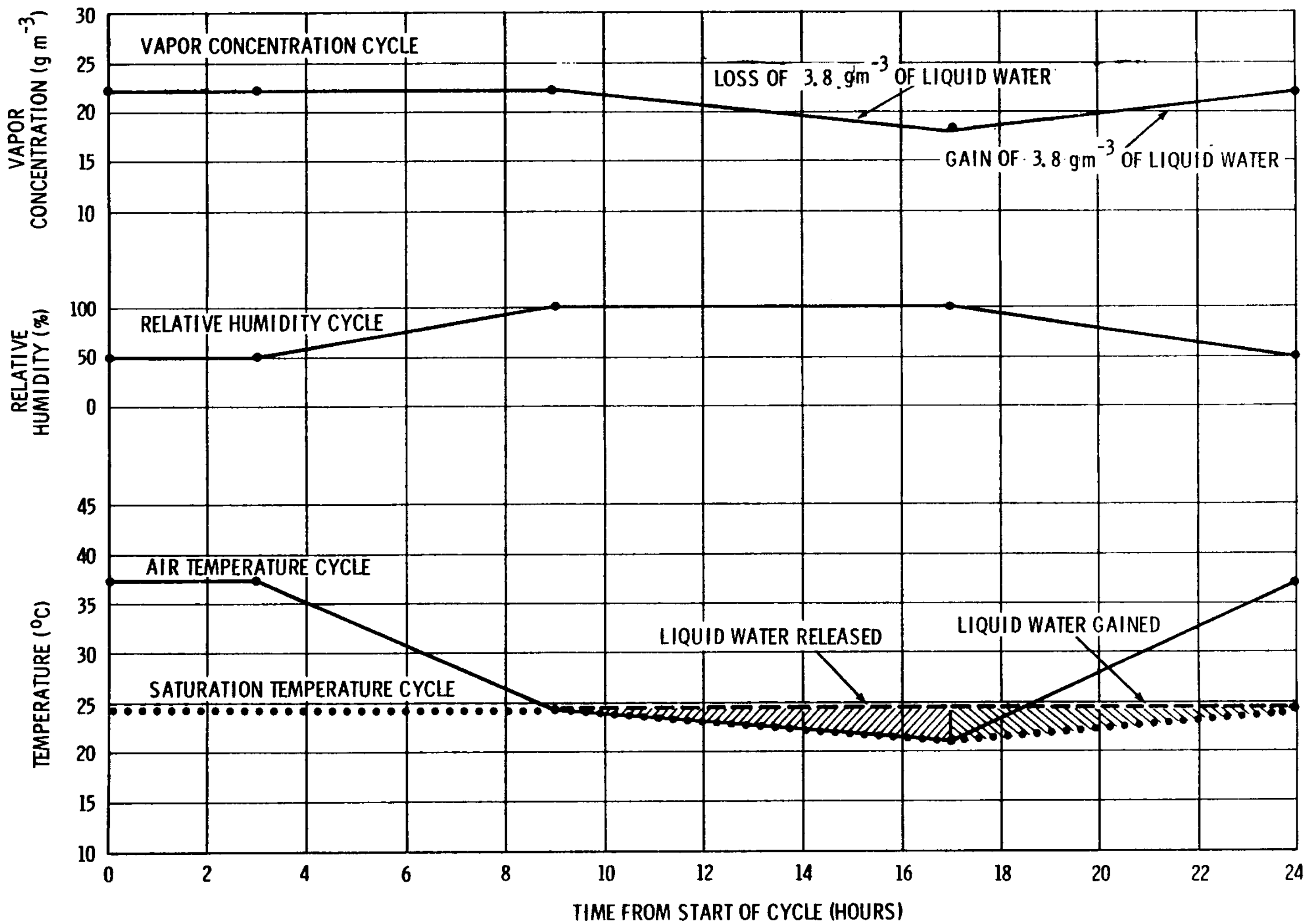

FIGURE 3.1 EXTREME HIGH VAPOR CONCENTRATION CYCLE FOR HUNTSVILLE, RIVER TRANSPORTATION, NEW ORLEANS, GULF TRANSPORTATION, EASTERN TEST RANGE, AND WALLOPS TEST RANGE

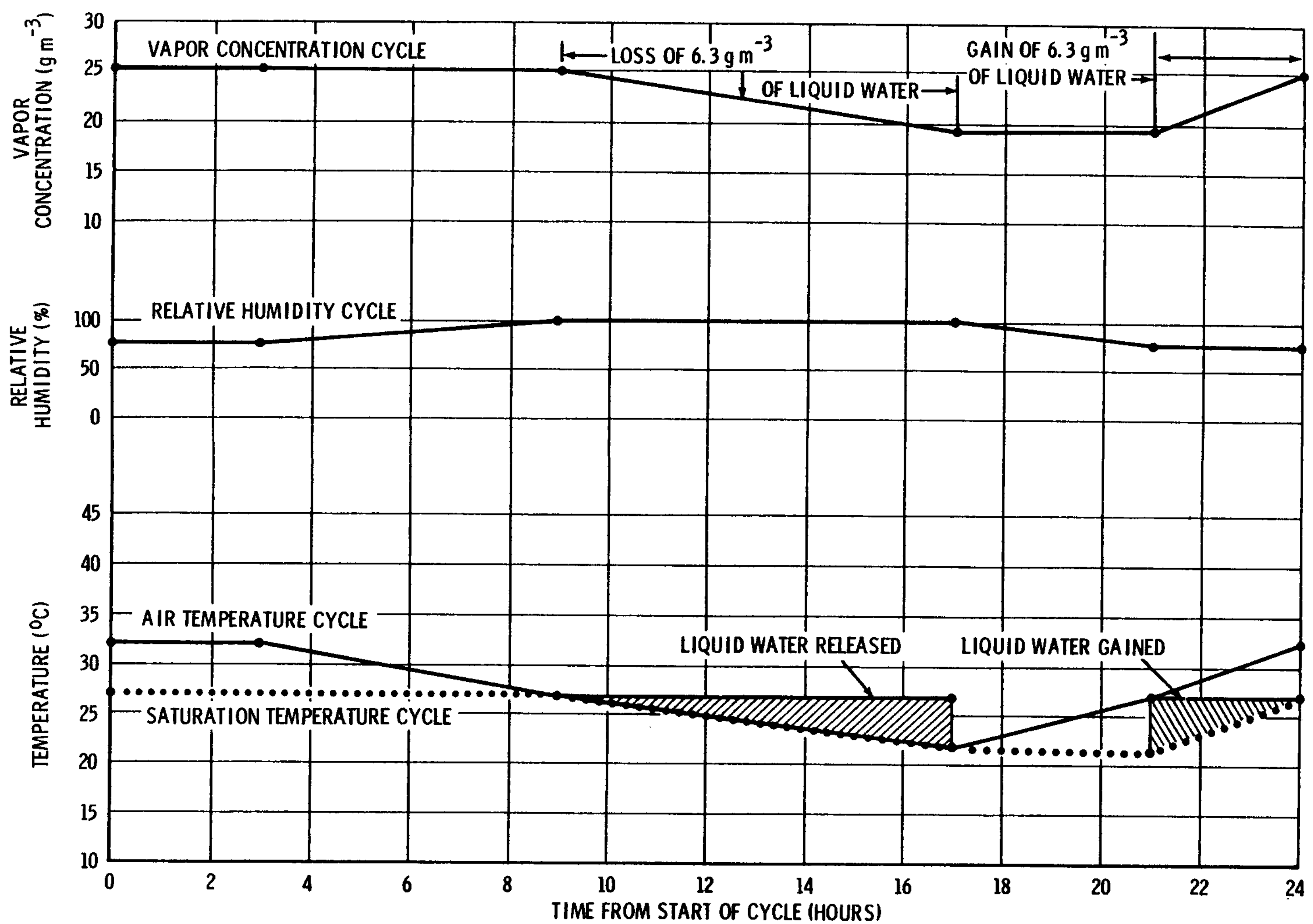

FIGURE 3.2 EXTREME HIGH VAPOR CONCENTRATION CYCLE FOR PANAMA CANAL TRANSPORTATION

(3) Equipment shipped from the West Coast, through the Panama Canal by ship may accumulate moisture (condensation) while in the ship's hold because of the increasing moisture content of the air while traveling south to the Panama Canal, and the slower increase of temperature of the equipment being transported. This condensation may result in corrosion, rusting, or other deterioration of the equipment (Ref. 3.6). Extreme values of condensation are:

(a) Maximum condensation conditions occur during the period between December and March, but condensation conditions may occur during all months.

(b) The maximum dew point expected is 30.0° C (86° F), with dew points over 21.1° C (70°F) for ship travel of 6 days prior to arrival at the Panama Canal from the west coast, and for the remainder of the trip to Cape Kennedy.

c. The Space and Missile Test Center, West Coast Transportation, and Sacramento:

(1) The following extreme humidity cycle of 24 hours with a wind of less than 5 m sec^{-1} (9.7 knots) should be considered in design: Three hours of 23.9° C (75° F) air temperature at 75 percent relative humidity and a vapor concentration of 16.2 g m^{-3} (7.9 gr ft^{-3}); six hours of decreasing air temperature to 18.9°C (66° F) with relative humidity increasing to 100 percent; eight hours of decreasing air temperature to 12.8°C (55° F) with a release of 5.0 grams of water as liquid per cubic meter of air (2.2 gr of water per cubic foot of air),* humidity at 100 percent; and seven hours of increasing air temperature to 23.9°C (75° F) and the relative humidity decreasing to 75 percent (Fig. 3.3).

(2) Bacterial and fungal growth should present no problem because of the lower temperatures in this area. For corrosion, an extreme humidity of between 75 and 100 percent relative humidity and air temperature between 18.3°C (65° F) and 23.3°C (74° F) can be expected for a period of 15 days. The humidity should be 100 percent during one-fourth of the time at the lower temperature in cycles not exceeding 24 hours. Any loss of water vapor from the air condensation is replaced from outside sources to maintain at least 75 percent relative humidity at the higher temperature.

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* See footnote, page 3.3

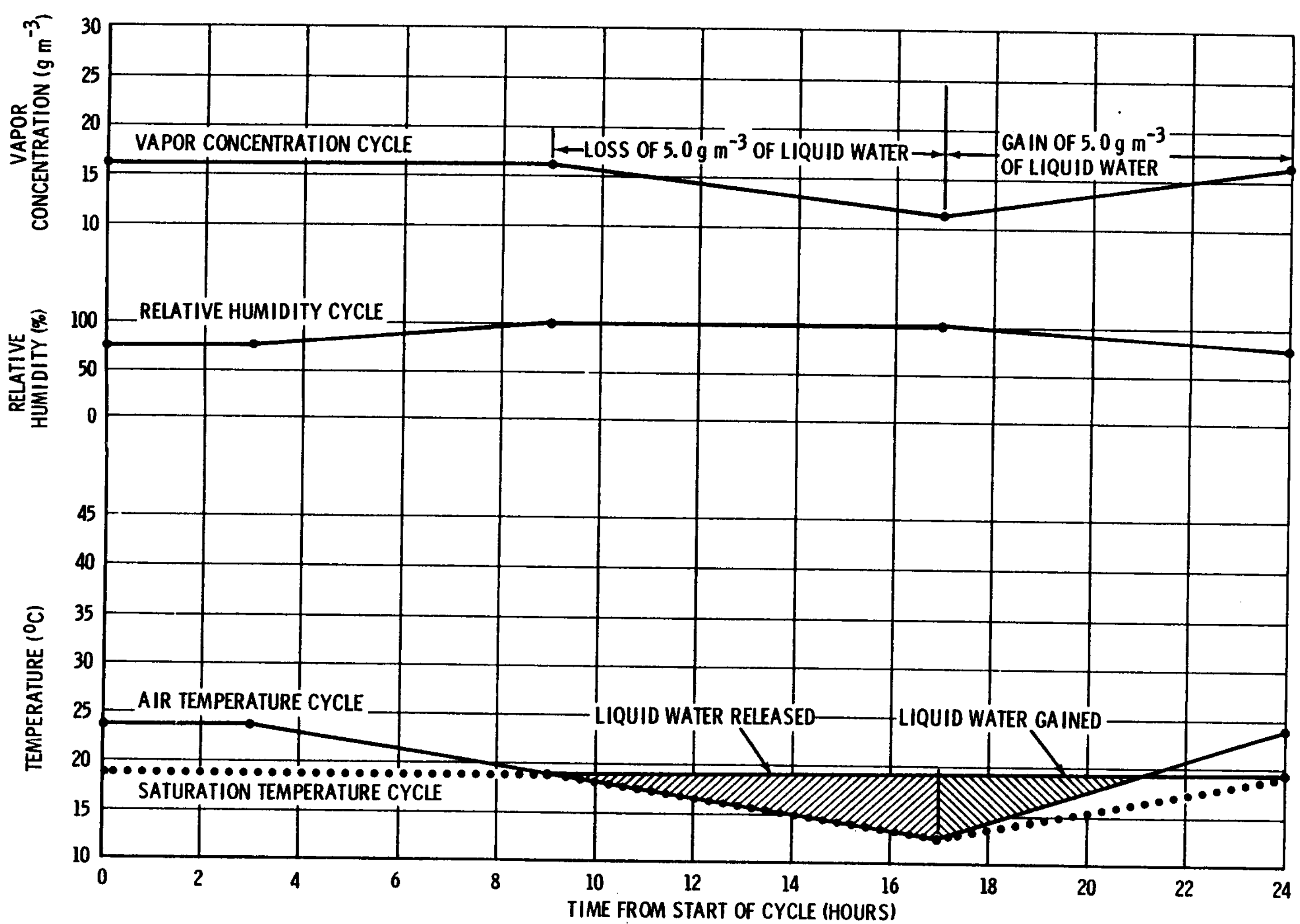

FIGURE 3.3 EXTREME HIGH VAPOR CONCENTRATION CYCLE FOR SAMTEC, WEST COAST TRANSPORTATION AND SACRAMENTO

d. White Sands Missile Range: This area is located at 1216 meters (4000 ft) above sea level, and is on the eastern side of higher mountains. The mean annual rainfall of 250 cm (10 inches) is rapidly absorbed in the sandy soil. Fog rarely occurs. Therefore, at this location, a high-vapor concentration need not be considered.

3.2.2 Low Vapor Concentration at Surface.

3.2.2.1 Introduction. Low water-vapor concentration can occur at very low or at high temperatures when the air is very dry. In both cases, the dew points are very low. However, in the case of low dew points and high temperatures, the relative humidity is low. When any storage area or compartment of a vehicle is heated to temperatures well above the ambient air temperature (such as the high temperatures of the storage area in an aircraft standing on the ground in the sun), the relative humidity will be even lower than the relative humidity of the ambient air. These two types of low water-vapor concentrations have entirely different environment effects. In the case of low air temperatures, ice or condensation may form on equipment while in the high temperature-low humidity condition; organic materials may dry and split or otherwise deteriorate. When a storage area (or aircraft) is considerably warmer than the ambient air (even when the air is cold), the drying increases even more. Low relative humidities may also result in another problem — that of static electricity. Static electrical charges on equipment may ignite fuel or result in shocks to personnel when discharged. Because of this danger two types of low water-vapor concentrations (dry extremes) are given for the surface.

3.2.2.2 Surface Extremes of Low Vapor Concentration.

a. Huntsville, River Transportation, Wallops Test Range, and White Sands Missile Range:

(1) A vapor concentration of 2.1 g m^{-3} (0.9 gr ft^{-3}), with an air temperature of -11.7°C (+11°F) and a relative humidity between 98 and 100 percent for a duration of 24 hours, must be considered.

(2) A vapor concentration of 4.5 g m^{-3} (2.0 gr ft^{-3}), corresponding to a dew point of -1.1°C (30°F) at an air temperature of 28.9°C (84°F) and a relative humidity of 15 percent occurring for 6 hours each 24 hours, and a maximum relative humidity of 34 percent at an air temperature of 15.6°C (60°F) for the remaining 18 hours of each 24 hours for a 10-day period, must be considered.

b. New Orleans, Gulf Transportation, Panama Canal Transportation, and Eastern Test Range:

(1) A vapor concentration of 4.2 g m^{-3} (1.8 gr ft^{-3}), with an air temperature of -2.2° C (28° F) and a relative humidity of 98 to 100 percent for a duration of 24 hours, must be considered.

(2) A vapor concentration of 5.6 g m^{-3} (2.4 gr ft^{-3}) corresponding to a dew point of 2.2° C (36° F) at an air temperature of 22.2° C (72° F) and a relative humidity of 29 percent occurring for 8 hours, and a maximum relative humidity of 42 percent at an air temperature of 15.6° C (60° F) for the remaining 16 hours of each 24 hours for 10 days, must be considered.

c. Space and Missile Test Center:

(1) A vapor concentration of 4.2 g m^{-3} (1.8 gr ft^{-3}), with an air temperature of -2.2° C (28° F) and a relative humidity of 98 to 100 percent for a duration of 24 hours, must be considered.

(2) A vapor concentration of 4.8 g m^{-3} (2.1 gr ft^{-3}), corresponding to a dew point of 0.0° C (32° F) at an air temperature of 37.8° C (100° F) and a maximum relative humidity of 26 percent at an air temperature of 21.1° C (70° F) for the remaining 20 hours of each 24 hours for 10 days, must be considered.

d. West Coast Transportation and Sacramento:

(1) A vapor concentration of 3.1 g m^{-3} (1.4 gr ft^{-3}), with an air temperature of -6.1° C (21° F) and a relative humidity of 98 to 100 percent for a duration of 24 hours, must be considered.

(2) A vapor concentration of 10.1 g m^{-3} (4.4 gr ft^{-3}), corresponding to a dew point of 11.1° C (52 °F) at an air temperature of 37.8° C (100° F) and a relative humidity of 22 percent occurring for 4 hours each 24 hours, and a maximum relative humidity of 55 percent at an air temperature of 21.1° C (70° F) for the remaining 20 hours of each 24 hours for 10 days, must be considered.

3.2.3 Compartment Vapor Concentration at Surface.

A low water-vapor concentration extreme of 10.1 g m^{-3} (44. gr ft^{-3}), corresponding to a dew point of 11.1° C (52 °F) at a temperature of 87.8 °C (190° F) and a relative humidity of two percent occurring for one hour, a linear change over a four-hour period to an air temperature of 37.8° C (100°F) and a relative humidity of 22 percent occurring for 15 hours, then a linear change over a four-hour period to the initial conditions, must be considered at all locations.

3.3 Vapor Concentration at Altitude.

In general, the vapor concentration decreases with altitude in the troposphere because of the decrease of temperature with altitude. The data given in this section on vapor concentration are appropriate for design purposes.

3.3.1 High Vapor Concentration at Altitude.

The following table present the relationship between maximum vapor concentration and the associated temperature normally expected as a function of altitude (Ref. 3.7).

a. Maximum Vapor Concentrations for Eastern Test Range, Table 3.1.

b. Maximum Vapor Concentrations for Wallops Test Range, Table 3.2.

c. Maximum vapor concentrations for White Sands Missile Range, Table 3.3.

TABLE 3.1. MAXIMUM VAPOR CONCENTRATION FOR EASTERN TEST RANGE

Geometric Altitude		Vapor Concentration		Temperature Associated with Maximum Vapor Concentration	
(km)	(ft)	(g m^{-3})	(gr ft^{-3})	(°C)	(°F)
SRF (0.005 MSL)	(16)	27.0	11.8	30.5	87
1	3,300	19.0	8.3	24.5	76
2	6,600	13.3	5.8	18.0	64
3	9,800	9.3	4.1	12.0	54
4	13,100	6.3	2.8	5.5	42
5	16,400	4.5	2.0	-0.5	31
6	19,700	2.9	1.3	-6.8	20
7	23,000	2.0	0.9	-13.0	9
8	26,200	1.2	0.5	-20.0	-4
9	29,500	0.6	0.3	-27.0	-17
10	32,800	0.3	0.1	-34.5	-30
16.2	53,100	0.025	0.01	-57.8	-72
20	65,600	0.08	0.03	-47.8	-54

TABLE 3.2. MAXIMUM VAPOR CONCENTRATION FOR WALLOPS TEST RANGE

Geometric Altitude		Vapor Concentration		Temperature Associated with Maximum Vapor Concentration	
(km)	(ft)	(g m^{-3})	(gr ft^{-3})	(°C)	(°F)
SRF (0.002 MSL)	(8)	22.5	9.8	27.5	81
1	3,300	20.0	8.7	26.1	79
2	6,600	13.9	6.1	17.2	63
3	9,800	10.3	4.5	12.8	55
4	13,100	7.4	3.2	7.8	46
5	16,400	6.0	2.6	2.8	37
6	19,700	3.9	1.7	-1.1	30
7	23,000	2.6	1.1	-5.0	23
8	26,200	1.7	0.7	-11.1	12
9	29,500	0.9	0.4	-17.8	0
10	32,800	0.4	0.2	-27.8	-18
16.5	54,100	0.08	0.03	-47.2	-44
20	65,600	0.09	0.04	-46.2	-43

TABLE 3.3. MAXIMUM VAPOR CONCENTRATION FOR WHITE SANDS MISSILE RANGE

Geometric Altitude		Vapor Concentration		Temperature Associated with Maximum Vapor Concentration	
(km)	(ft)	(g m^{-3})	(gr ft^{-3})	(°C)	(°F)
SRF (1.2 MSL)	(3,989)	16.0	7.0	21.5	70
2	6,600	13.2	5.8	18.9	66
3	9,800	9.0	3.9	12.8	55
4	13,100	6.8	3.0	7.8	46
5	16,400	4.9	2.1	2.2	36
6	19,700	3.4	1.5	-2.2	28
7	23,000	2.2	1.0	-10.0	14
8	26,200	1.3	0.6	-16.1	3
9	29,500	0.6	0.3	-22.8	-9
10	32,800	0.2	0.1	-30.0	-22
16.5	54,100	0.08	0.03	-47.8	-44
20	65,600	0.05	0.02	-52.2	-47

3.3.2 Low Vapor Concentration at Altitude

The values presented as low extreme vapor concentrations in the following tables are based on data measured by standard radiosonde equipment.

a. Minimum Vapor Concentrations for Eastern Test Range, Table 3.4.

b. Minimum Vapor Concentrations for Wallops Test Range, Table 3.5.

c. Minimum Vapor Concentrations for White Sands Missile Range, Table 3.6.

TABLE 3.4. MINIMUM VAPOR CONCENTRATIONS FOR EASTERN TEST RANGE

Geometric Altitude		Vapor Concentration		Temperature Associated with Minimum Vapor Concentration	
(km)	(ft)	($g\ m^{-3}$)	($gr\ ft^{-3}$)	(°C)	(°F)
SRF (0.005 MSL)	(16)	4.0	1.7	29	84.2
1	3,300	0.5	0.2	6	42.8
2	6,600	0.2	0.1	0	32.0
3	9,800	0.1	0.04	-11	12.2
4	13,100	0.1	0.04	-14	6.8

TABLE 3.5. MINIMUM VAPOR CONCENTRATION FOR WALLOPS TEST RANGE

Geometric Altitude		Vapor Concentration		Temperature Associated with Minimum Vapor Concentration	
(km)	(ft)	($g\ m^{-3}$)	($gr\ ft^{-3}$)	(°C)	(°F)
SRF (0.002 MSL)	(8)	0.5	0.2	-4	24.8
1	3,300	0.3	0.1	-11	12.2
2	6,600	0.2	0.1	-17	1.4
3	9,800	0.2	0.1	-23	-9.4
4	13,100	0.2	0.1	-31	-23.8
5	16,400	0.1	0.04	-39	-38.2
7.5	24,600	0.08	0.03	-47	-43.9
10	32,800	0.017	0.007	-61	-51.7

TABLE 3.6. MINIMUM VAPOR CONCENTRATION FOR WHITE SANDS MISSILE RANGE

Geometric Altitude		Vapor Concentration		Temperature Associated with Minimum Vapor Concentration	
(km)	(ft)	(g m^{-3})	(gr ft^{-3})	(°C)	(°F)
SRF (1.2 MSL)	(3,989)	1.2	0.5	-1	30.2
2	6,600	0.9	0.4	-5	23.0
3	9,800	0.6	0.3	-12	10.4
4	13,100	0.4	0.2	-20	-4.0
5	16,400	0.2	0.1	-26	-14.8
6	19,700	0.1	0.04	-36	-37.8
7	23,000	0.09	0.03	-42	-41.1
8	26,200	0.07	0.03	-49	-45.0
9	29,500	0.03	0.01	-55	-48.3
10	32,800	0.02	0.01	-60	-51.1

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SECTION IV. PRECIPITATION

By

Glenn E. Daniels

4.1 Definitions. (Ref. 4.1)

Precipitation is defined as all forms of hydrometeors, whether liquid or solid, which are free in the atmosphere and which may or may not reach the ground. Accumulation is reported in inches of depth for liquid, or in inches of depth of water equivalent, for frozen water particles.

Snow is defined as all forms of frozen precipitation except large hail; it encompasses snow pellets, snow grains, ice crystals, ice pellets, and small hail.

Hail is precipitation in the form of balls or irregular lumps of ice, and is always produced by convective clouds. Through established convention, the diameter of the ice must be 5 mm or more, and the specific gravity between 0.60 and 0.92 to be classified as hail.

Ice pellets are precipitation in the form of transparent, more or less globular, hard grains of ice under 5 mm in diameter, that rebound when striking hard surfaces.

Small hail is precipitation in the form of semitransparent, round or conical grains of frozen water under 5 mm in diameter. Each grain consists of a nucleus of soft hail (ball of snow) surrounded by a very thin ice layer. They are not crisp and do not usually rebound when striking a hard surface.

Precipitable water is the total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending between any two specified levels. It is usually given as inches of water (if vapor were completely condensed).

4.2 Rain.

Although most long-duration rainfall world records (monthly or yearly) have been for regions far removed from the areas of interest for large space vehicle launch and test operations, the world maximum amount of short-duration rainfall has occurred in the thunderstorms or tropical storms within the United States, in the Gulf of Mexico, or in Canal Zone areas. A study of the rate of rainfall, compared with duration, shows that the average rate (per hour) decreases as the duration increases. Equipment must withstand both prolonged soaking rain and brief downpours. The following precipitation values at an air temperature between 21.1°C (70°F) (night) and 32.2°C (90°F) (day) are adequate for most design problems, although considerably less than world record extremes.

4.2.1 Rainfall at Surface.

a. Extreme Amounts. The design rainfall for the areas of interest are as follows:

(1) Huntsville, Eastern Test Range, SAMTEC, Sacramento, West Coast Transportation, River Transportation, White Sands Missile Range, and Wallops Test Range, rainfall information is given in Table 4.1.

(2) Gulf Transportation, Panama Canal Transportation, and New Orleans rainfall information is given in Table 4.2.

TABLE 4.1 DESIGN RAINFALL RATES FOR HUNTSVILLE, EASTERN TEST RANGE, SAMTEC, SACRAMENTO, WEST COAST TRANSPORTATION, RIVER TRANSPORTATION, WALLOPS TEST RANGE, AND WHITE SANDS MISSILE RANGE

Time Period	1 min	1 hour	24 hours
Total Amount (mm)	7.6	64	305
(in.)	0.3	2.5	12
Rate (mm/hr)	456	64	13
(in./hr)	18.0	2.5	0.5
Average Drop Diameter (mm)	3.8	2.6	2.0
Average Rate of Fall (m/sec)	8.5	7.3	6.4
Peak Wind Speed (m/sec)	20	20	20
Average Wind Speed (m/sec)	6	6	4.5

TABLE 4.2 DESIGN RAINFALL RATES FOR GULF TRANSPORTATION, PANAMA CANAL, AND NEW ORLEANS

Time Period	1 min	1 hour	24 hours
Total Amount (mm)	12.7	102	508
(in.)	0.5	4	20
Rate (mm/hr)	762	102	21
(in./hr)	30.0	4.0	0.8
Average Drop Diameter (mm)	4.1	2.9	1.8
Average Rate of Fall (m/sec)	8.8	7.6	6.1
Peak Wind Speed (m/sec)	20	20	20
Average Wind Speed (m/sec)	6	6	4.5

b. Probability of Precipitation Not Exceeding Selected Amounts. The probability of precipitation not exceeding selected amounts on any one day was determined by a study of six years of data at Cape Kennedy, Florida. This information is given in Table 4.3.

4.2.2 Rainfall at Altitude.

Rainfall rates normally decrease with altitude when rain is striking the ground. The rainfall rates at various altitudes in percent of the surface rates are given in Table 4.4 for all areas (Ref. 4.2).

The precipitation above the ground is generally colder than at the ground and frequently occurs as supercooled drops which can cause icing on any object moving through the drops. Such icing can be expected to occur when the air temperature is -2.2°C (28°F). The amount of icing (i.e., rate of formation) is related to the speed and shape of the object. For the geographic areas considered in this report, these conditions usually occur between 3 and 10 km altitude.

TABLE 4.3 PROBABILITY THAT PRECIPITATION WILL NOT EXCEED A SPECIFIC AMOUNT IN ANY ONE DAY, EASTERN TEST RANGE

AMOUNT (Inches)	MONTH					
	JAN %	FEB %	MAR %	APR %	MAY %	JUNE %
0.00	79.0	75.7	68.8	75.6	76.3	59.4
0.05	86.6	82.8	73.7	85.5	84.4	68.9
0.20	90.3	86.4	80.1	90.0	91.4	74.4
0.50	93.0	89.3	87.1	95.0	95.7	86.1
1.00	96.2	96.4	95.7	97.8	99.5	96.1
2.00	98.9	100.0*	98.9	100.0*	100.0*	98.9
5.00	100.0*	100.0*	99.5	100.0*	100.0*	100.0*

AMOUNT (Inches)	MONTH					
	JULY %	AUG %	SEPT %	OCT %	NOV %	DEC %
0.00	61.8	59.1	52.8	65.6	75.0	75.8
0.05	69.4	66.1	63.3	73.1	81.7	86.6
0.20	79.6	74.7	73.3	82.3	89.4	92.5
0.50	87.1	83.9	83.9	90.3	92.8	95.7
1.00	94.1	92.5	93.9	96.8	96.7	98.4
2.00	97.3	98.4	97.8	100.0*	100.0*	100.0*
5.00	100.0*	100.0*	100.0*	100.0*	100.0*	100.0*

* Although the available data records indicate no chance of exceeding certain amounts of precipitation during most of the months, it should be realized that the length of data studied is not long and that there is always a chance of any meteorological extreme of record being exceeded.

TABLE 4.4 DISTRIBUTION OF RAINFALL RATES WITH HEIGHT FOR ALL LOCATIONS

Height (Geometric) Above Surface (km)	Percent of Surface Rate
SRF	100
1	90
2	75
3	57
4	34
5	15
6	7
7	2
8	1
9	0.1
10 and over	< 0.1

4.3 Snow.

The accumulation of snow on a surface produces stress. For a flat horizontal surface, the stress is proportional to the weight of the snow directly above the surface. For long narrow objects, such as pipes or wires lying horizontally above a flat surface (which can accumulate the snow), the stress can be figured as approximately equal to the weight of the wedge of snow with the sharp edge along the object and extending above the object in both directions at about 45 degrees to the vertical. (In such cases, the snow load would be computed for the weight of the snow wedge above the object and not the total snow depth on the ground.) The weight of new fallen snow on a surface varies between 0.5 kg m^{-2} per cm of depth (0.25 lb ft^{-2} $in.^{-1}$) and 2.0 kg m^{-2} per cm of depth (1.04 lb ft^{-2} $in.^{-1}$), depending on the weather situation at the time of snowfall. When the amount is sufficient to be important in load design, the weight on the surface is near 1.0 kg m^{-2} cm^{-1} (0.52 lb ft^{-2} $in.^{-1}$). Snow on the ground becomes more dense, and the depth decreases with time.

4.3.1 Snow Loads at Surface.

Maximum snow loads for the following areas are:

a. Huntsville, Wallops Test Range, and River Transportation areas. For horizontal surfaces a snow load of 25 kg m^{-2} (5.1 lb ft^{-2}) per 24-hour period (equivalent to a 10-inch snowfall) to a maximum of 50 kg m^{-2} (10.2 lb ft^{-2}) in a 72-hour period, provided none of the snow is removed from the surface during the period, should be considered for design purposes.

b. New Orleans, West Coast Transportation, White Sands Missile Range, and Sacramento areas. For horizontal surfaces, a maximum snow load of 10 kg m^{-2} (2.0 lb ft^{-2}) per one 24-hour period, should be considered for design purposes.

4.3.2 Snow Particle Size.

Snow particles may penetrate openings (often openings of minute size) in equipment and cause malfunction of mechanical or electrical components, either before or after melting. Particle size, associated wind speed, and air temperature to be considered are as follows:

a. Huntsville, Wallops Test Range, and River Transportation areas. Snow particles 0.1 mm (0.0039 in.) to 5 mm (0.20 in.) diameter; wind speed 10 m sec^{-1} (19 knots); air temperature -17.8°C (0°F).

b. New Orleans, West Coast Transportation, White Sands Missile Range, and Sacramento areas. Snow particles 0.5 mm (0.020 in.) to 5 mm (0.20 in.) diameter; wind speed 10 m sec^{-1} (19 knots); air temperature -5.0°C (23°F).

4.4 Hail.

Hail is one of the most destructive weather forces in nature, being exceeded only by hurricanes and tornadoes. Hail normally forms in extremely well-developed thunderstorms during warm weather and rarely occurs in winter months or when the air temperature is below 0°C (32°F). Although the average diameter of hailstones is 8 mm (0.31 in.) (Ref. 4.3), hailstones larger than 12.7 mm (0.5 in.) in diameter frequently fall, while stones 50 mm (2.0 in.) in diameter can be expected annually somewhere in the United States. The largest measured hailstone in the United States was 137 mm (5.4 in.) in diameter and had a weight of 0.68 kg (1.5 lb) (Refs. 4.4, 4.5 and 4.6). Three environmental effects on equipment must be considered:

The accumulation of hail, as with snow, stresses the object by its weight. Although hail has a higher density than snow, 2.4 kg m^{-2} cm^{-1} (1.25 lb ft^{-2} $in.^{-1}$), the extreme load from hail will not exceed the extreme snow load at any area of interest; therefore, the snow load design will adequately cover any hail loads expected.

Large hailstones, because of weight and velocity of fall, are responsible for structural damage to property (Ref. 4.7). To actually designate locations where hailstones, with specific sizes of hail, will fall is not possible. However, the following information can be used as a guide for design and scheduling (these values are most applicable to the design of ground support equipment and protective covering for the space vehicles during the transporting of vehicles between Huntsville and New Orleans). Hail as an abrasive is discussed in Section VI.

4.4.1 Hail at Surface.

a. Huntsville, River Transportation, Gulf Transportation, New Orleans, Wallops Test Range, and White Sands Missile Range.

(1) A maximum hailstone size of 50 mm (2 in.) in diameter with an occurrence probability of one time in 15 years.

(2) Damaging hailstorms occur most frequently between 3 p.m. and 9 p.m. during May through September. April is the month of highest frequency-of-occurrence of hailstorms for Huntsville, River Transportation, and Gulf Transportation. March is the month of highest frequency-of-occurrence of hailstorms for White Sands Missile Range, and May is the month of highest frequency-of-occurrence of hailstorms for Wallops Test Range.

(3) The period of large hail (over 25 mm in diameter) will not be expected to last more than 15 minutes and should have a maximum total accumulation of 50 mm (2 in.) for depth of hailstones on horizontal surfaces.

(4) Velocity of fall equals 30.5 m sec^{-1} (100 ft sec^{-1}) for each stone.

(5) Wind speed equals 10 m sec^{-1} (33 ft sec^{-1}).

(6) Density of hailstones equals 0.80 g cm^{-3} (50 lb ft^{-3}).

b. Eastern Test Range.

(1) A maximum hailstone size of 25.4 mm (1 in.) in diameter with an occurrence probability of one time in 30 years may be expected.

(2) Damaging hailstones occur most frequently between 3 p.m. and 9 p.m. during April through June. May is the month of highest frequency-of-occurrence for hailstorms.

(3) The period of large hail will not be expected to last more than 15 minutes and should have a maximum total accumulation of 12.5 mm (0.5 in.) for depth of hailstones on horizontal surfaces.

(4) Velocity of fall equals 20 m sec^{-1} (66 ft sec^{-1}) for each stone.

(5) Wind speed equals 10 m sec^{-1} (33 ft sec^{-1}).

(6) Density of hailstones equals 0.80 g cm^{-3} (50 lb ft^{-3}).

4.4.2 Distribution of Hail with Altitude.

Although it is not the current practice to design space vehicles for flight in thunderstorms, data on distribution with altitude are presented as an item of importance. The probability of hail increases with altitude from the surface to 5 km and then decreases rapidly with increasing height. Data on Florida thunderstorms, giving the number of times hail was encountered at various altitudes during aircraft flights (Ref. 4.8), are given in Table 4.5 for areas specified in paragraph 4.4.1.

TABLE 4.5 DISTRIBUTION OF HAIL WITH HEIGHT FOR ALL LOCATIONS (Ref. 4.8)

Height (Geometric) Above Surface (km)	Occurrence of Hail (percent of flights through thunderstorms)
2	0
3	3.5
5	10
6	4
8	3

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SECTION V. WIND

By

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5.0 Introduction

A space vehicle's response to atmospheric disturbances cannot be reduced to the evaluation of one set of response criteria, such as vehicle loads, but it must include many response parameters, the choice of criteria (parameters) depending upon the vehicle configuration and the specific mission. It is also impractical to use only one response calculation method for all phases of vehicle design. Therefore, the studies must be separated into their various phases and parts, using different approaches and methods of evaluation, as the particular phase demands. Although not independent, these phases include (1) preliminary design, (2) final structural design, (3) guidance and control system design and optimization (preliminary and final), and (4) establishment of limits and procedures for launch and flight operations. Thus, the proper selection, representation, and use of wind information require the skillfully coordinated efforts of aerospace meteorologists and engineers.

Winds are characterized by three-dimensional motions of the air, accompanied by large temporal and spatial variations. The characteristics of these variations are a function of synoptic conditions, atmospheric stability, and season, as well as the geographic location of the launch site. It is necessary, therefore, to use good technical judgment and to consider the engineering application of the wind data in preparing criteria that are descriptive and yet concise. The wind environment affects the various vehicle design and operational problem areas in a different manner and requires a unique interpretation and application of the data for each analysis.

During the initial and intermediate phases of the development cycle, the synthetic ground and inflight wind criteria concept has its major value and contribution to the design. Although a certain overall vehicle performance capability in terms of probability may be mentioned as a guideline, it is not realistic to expect a design to be developed that will precisely meet this specified performance capability because of the many unknowns in the vehicle characteristics and design criteria. With the status of current space vehicle technology it is not possible to make, as a result of design procedures or tests, a candid statement about the specific calculated overall design risk or operational capability of a space vehicle. Therefore, it makes good engineering sense to establish a set of idealized or synthetic ground and inflight wind characteristics, which include such features as wind magnitude versus height of profile, gust factors, turbulence spectra, wind shears, and directional features of the wind. They may then be referenced and used in a consistent manner to establish the preliminary and intermediate designs necessary to ensure accomplishment of the expected range of missions for the vehicle development. Furthermore, they assist in isolating those aspects of the wind structure critical to a vehicle design area.

It is currently the accepted practice, which is further endorsed by this report, to use the synthetic wind criteria approach described herein for NASA space vehicle developments during the preliminary and intermediate design phases. These criteria should be carefully formulated to ensure that the appropriate data are employed for vehicle studies in order to be consistent with the degree of resolution available from other vehicle input criteria and the structural/control system simulation models. The synthetic wind profile features may readily be employed to isolate specific design problem areas without resorting to elaborate computations, which are not justified with respect to the other unknown system parameters. In addition, by use of this approach, the designer may, for example, closely approximate the steady-state wind limits for a design or operational configuration. The other features of the wind forcing function may be accommodated with a specified risk level. Using these steady-state wind limits, a multitude of mission and performance analysis studies can rapidly be accomplished relative to launch windows, etc., using the entire available historical record from the steady-state inflight wind (rawinsonde) or ground wind measurement systems. Such records, described in this section, are available for all major launch areas. These statistical records and the synthetic profile concept are also adequate for bias of pitch and yaw programs, range safety studies, preliminary abort analysis, and related space vehicle operational problems.

When adequately documented and referenced, the synthetic wind criteria concept provides a powerful tool for ensuring consistent design inputs for all users, and it essentially avoids the problem of any oversight errors, which may be very costly to correct in later development phases. Furthermore, they enable various design teams to simultaneously conduct studies and to compare their results on a common basis.

During the latter stages of a vehicle development program, when adequate vehicle response data are available, it is considered highly desirable, if not mandatory, to simulate the vehicle flight and response to actual wind velocity profiles. However, these wind profiles should contain an adequate frequency content through at least the vehicle's first bending moment frequency. Otherwise, only another preliminary design approximation is derived, and no specific new design information is obtained relative to the synthetic wind profile concept. The current acceptable practice is to use a selection of detailed inflight wind profiles (resolution to at least one cycle per 100 meters) obtained by the FPS-16 Radar/Jimsphere technique for the major launch range(s) of concern. These data and their availability are discussed elsewhere in this document. The number of flight performance simulations and detailed wind profiles selected will depend upon the particular vehicle and the design problem involved and how well the vehicle characteristics were established during the preliminary and intermediate design work. The vehicle simulation to detailed inflight wind profiles should constitute, essentially, a verification of the design. It should provide the design organization with added confidence in the capability of the vehicle design and enable them to isolate any critical areas requiring further indepth study to refine the control and structural systems. The profiles used should constitute a selection from the available detailed wind profile records. This selection should be based upon the mission objectives and should be established through discussions between the affected design group and the cognizant organization concerned with wind criteria.

For the prelaunch simulation and flight evaluation of a space vehicle relative to the inflight wind environment, it is recommended that established ground wind reference height anemometers and detailed inflight wind profiles measured by the FPS-16 Radar/Jimsphere system be used to provide adequate resolution, accurate data, timely measurements, and rapid reduction scheme, ensuring a prompt input into the prelaunch simulation program and flight evaluation. It is during the prelaunch phase that accurate and near real-time wind data are mandatory, especially if an almost critical launch wind condition exists. The consequences are obvious. Furthermore, adequate flight evaluations cannot be made without timely and accurate launch wind data.

The above remarks are intended to reflect some currently accepted engineering practices for use of available wind data in the design, development, mission analysis, prelaunch, and flight evaluation phases of a space vehicle program. It is apparent that the wind input employed in terms of resolution, accuracy, representativeness, etc., will depend upon the status of the space vehicle design's use of reliable data that are consistent with the design requirements at the particular stage of development. An understanding of the use and limitations of wind data in making engineering decisions is required for the design of a space vehicle for a given mission objective(s). This can only be accomplished through a team relationship between the design engineer and meteorologist concerned with wind criteria.

5. 4

The information given in this section constitutes guidelines for data that are applicable to various design problems. The selected risk levels employed to determine those characteristics of the ground and inflight winds used in the design are a matter of organizational design philosophy and management decision. To maximize performance flexibility, it is considered best to utilize those data associated with the minimum acceptable risk levels. In addition, such critical mission related parameters as vehicle free-standing period, launch windows, and launch turnaround period should be carefully considered. Initial design work using unbiased (wind) trajectories on the basis of nondirectional ground or inflight winds is recommended unless the vehicle and its mission are well known and the exact launch azimuth and time(s) are established and rigidly adhered to throughout the project. In designs that use wind-biased trajectories and directional wind criteria, rather severe wind constraints can result if the vehicle is used for another mission, different flight azimuths, or in another configuration. Therefore, caution must be exercised in the employment of wind data to ensure consistency with the physical interpretation relative to the specific design problem. References 5. 1, 5. 2, 5. 3, 5. 4, and 5. 5 are a few of the many works related to the problems involved in using wind in space vehicle design programs.

5.1 Definitions

The following terms are used in this section with the meanings specified here.

5.1.1 Ground Winds

Ground winds are, for purposes of this document, winds below a height of about 150 meters above the natural grade.

Average wind speed — See steady-state wind speed.

Gust is a sudden increase in the ground wind speed. It is frequently stated with respect to a mean wind speed. A sudden decrease in the wind speed is sometimes referred to as a gust (negative).

Free-standing winds are the ground winds that are applied when the vehicle is standing on the launch pad (with or without fuel), after any service structure, support, or shelter has been removed.

Gust factor is the ratio of peak ground wind speed to the average or mean ground wind speed over a finite time period.

Launch design winds are the peak ground winds for which the vehicle can be launched, normally involving a stated design wind at a reference height plus the associated 3σ ($\sim$ 99.9%) peak wind profile shape.

On-Pad winds are the ground winds that are applied when the vehicle is on the launch pad with protective measures in place, i.e., service structures, support, or shelter.

Peak wind speed is the maximum (essentially, instantaneous) wind speed measured during a specified reference period, such as hour, day, or month.

Steady-state or average wind speed is the mean over a period of about 10 minutes or longer, of the wind speed measured at a fixed height. It is usually assumed constant as, for example, in spectrum calculations. Thus, the steady-state or average wind should be the mean which filters out, over a sufficient duration, the effects that would very definitely contribute to the random responses of aerospace vehicles and structures. The average wind speed is sometimes referred to as quasi-steady-state winds.

Reference height (ground winds) is the height above the ground surface (natural grade) at which wind speeds are referred for establishing climatological conditions, reference for construction of design wind profiles, and statements of a space vehicle's wind constraints. Normally during the design and development phase a reference height near the base of the vehicle is used. After completion of vehicle development, the operational constraints are stated with respect to a reference height near the top of the vehicle, the height of which is now established.

Causes of high groundwinds are summarized as follows:

a. Tornadoes: Upper limit unknown; estimated ~103 m/sec (200 knots).

b. Hurricanes: By definition, a tropical storm with winds > 33 m/sec (64 knots), upper limit unknown; estimated ~ 82 m/sec (160 knots).

c. Tropical Storms: By definition, a storm with winds < 33 m/sec (64 knots) and > 17 m/sec (34 knots).

d. Thunderstorms: Upper limit not defined; typical values ~ 23 m/sec (45 knots); severe thunderstorm by definition > 26 m/sec (50 knots).

e. Frontal Passages: Without thunderstorms; typical to 18 m/sec (35 knots), with squalls same as for thunderstorms.

f. Pressure Gradients: Long duration winds; wind to ~ 31 m/sec (60 knots).

5.1.2 Inflight Winds

Inflight winds are those winds above a height of about 150 meters.

Design verification data tapes are a selection of detail wind profile data compiled from FPS-16 Radar/Jimsphere data records for use in vehicle final design verification analysis. They consist of a representative monthly selection of wind profiles from which the integrated response of a vehicle to the combined effect of speed, direction, shear, and turbulence (gusts) may be derived. It has application to computation of absolute values of launch probability for a given vehicle.

Design wind speed profile envelopes are envelopes of scalar or component wind speeds representing the extreme steady-state inflight wind value for any selected altitude that will not be exceeded by the probability selected for a given reference period.

Detail wind profile is a wind profile measured by the FPS-16 Radar/Jimsphere or equivalent technique and having a resolution to at least one cycle per 100 meter. Application intended for final design verification purposes and launch delay risk calculations.

Steady-state inflight wind, in this document, refers to the mean wind speed as computed by the rawinsonde system and averaged over approximately 600 meters in the vertical direction.

Reference height (inflight winds) is that referred to in constructing a synthetic wind profile.

Scale-of-distance is the vertical distance between two wind measurements (thickness of layer) used in computing wind shears.

Serial complete data represent the completion of a sample of rawinsonde data (selected period) by filling in (inserting) missing data by interpolation, by extropolation, or by use of data from nearby stations. Such an operation is performed by professional meteorological personnel familiar with the data.

Shear build-up envelope is the curve determined by combining the reference height wind speed from the wind speed profile envelope with the shears (wind speed change) below the selected altitude (reference height). The shear build-up envelope curve starts at zero altitude difference (scale of distance) and zero wind speed and ends at the design wind speed value at the referenced altitude for inflight wind response studies.

Synthetic wind speed profile is a design wind profile representing the combination of a reference height design wind with associated envelope shears (wind speed change) and gusts for engineering design and mission analysis purposes.

Wind shear wind speed change envelopes represents the value of the change in wind speed over various increments of altitude (100 to 5000 m), computed for a given probability level and associated reference height or related wind speed value at the reference height. These values are combined, and an envelope of the wind speed change is found useful in constructing synthetic wind profiles. Usually the 99 percentile or larger probability levels are used for design purposes.

5.1.3 General

Calm winds are these with a wind speed of less than 0.5 m/sec (1 knot).

Component wind speed is the equivalent wind speed that any selected wind vector would have if resolved to a specific direction, that is, a wind from the northeast (45-deg azimuth) of 60 m/sec would have a component from the east (90-deg azimuth) of (60) cos 45 deg = 42. 4 m/sec. This northeast wind would be equivalent to a 42. 4 m/sec head wind on the vehicle, if the vehicle is launched on an east (90-deg) azimuth.

Percentile is the percentage of time that a variable does not exceed a given magnitude. Section I, page 1. 8 of this document should also be consulted for more details on percentiles and probabilities. The following relationships exist between probabilities and percentiles in a normal distribution function:

Probability Level	Percentile
Minimum	0.000
Mean - 3σ (standard deviation)	0.135
Mean - 2σ (standard deviation)	2.275
Mean - 1σ (standard deviation)	15.866
Mean $\pm$ 0σ (standard deviation)	50.000
Mean + 1σ (standard deviation)	84.134
Mean + 2σ (standard deviation)	97.725
Mean + 3σ (standard deviation)	99.865
Maximum	100.000

Scalar wind speed is the magnitude of the wind vector without regard to direction.

Wind direction is the direction from which the wind is blowing, measured clockwise from true North.

Windiest monthly reference period is any month that has the highest wind speeds at a given probability level.

Wind shear is equal to the difference between wind speeds measured at two specific locations, that is, the rate of change of wind speed with height (vertical wind shear) or distance (horizontal wind shear).

5. 2 Ground Winds (0-150 m)

5. 2. 1 Introduction

Ground winds for space vehicle application are defined in this report as those winds in the lowest 150 meters of the atmosphere. A vehicle positioned vertically on-pad may penetrate this entire region. Therefore, it is necessary to model the structure of the atmosphere in the vehicle's vicinity. This requirement exists because of the complicated and possibly critical manner in which a vehicle responds to certain wind profile configurations, both while it is stationary on the launch pad and while in the first few seconds of launch, especially for vehicle clearance of the service structure. The problem, therefore, may be resolved initially into the basic identification of the wind speed profile and its behavior within the 150-meter layer.

Until recently, several years of average wind speed data measured at the 10-meter level above ground were the only available records with which to develop design and launch ground wind profile criteria. With the evolution of larger and more sophisticated space vehicles, the requirements for more adequate wind profile information have increased. For example, to fulfill the need to provide improved ground wind data, a 150-meter ground wind tower facility was constructed on Merritt Island, Kennedy Space Center, Florida, in close proximity to the Apollo/Saturn launch complex 39. Wind and temperature profile data from this facility have been used in many new studies that have contributed to a significant portion of the information in this chapter on wind profile shaping, gusts, and turbulence spectra. Similar towers are in operation at the various national ranges.

Since ground wind data are applied by space vehicle engineers in various ways and degrees, dependent upon the specific problem, there are several analytical techniques utilized to obtain the results presented here. Program planning, for instance, requires considerable climatological insight to determine the frequency and persistence distributions for wind speeds and wind directions. However, for design purposes the space vehicle must withstand certain unique predetermined structural loads that are generated from exposure to known peak ground wind conditions. Ground wind profiles and the ground wind turbulence spectra contribute to the development of the design ground wind models. Surface roughness, thermal environment, and various transient local and large-scale meteorological systems influence the ground wind environment for each launch site. Other pertinent ground wind studies have been performed on wind gusts and associated duration times that directly affect the response characteristics of space vehicles.

In general during the early design and development phase of a space vehicle the ground wind criteria should be referenced to a level near the base of the vehicle when standing vertical on the launch pad; for example, an 18.3-meter level is frequently used for the Cape Kennedy area. This presents a reference level design wind speed and associated wind profile to be defined that is readily usable during the design phase when length of vehicle is not well established. During the operational phase, after the vehicle length has been fixed at a specific height above the launch pad, then the ground wind operational constraint should be referenced to a level near the top of the vehicle.

5.2.2 Considerations in Ground Wind Design Criteria

To establish the ground wind design criteria for aerospace vehicles, several important factors must be considered.

a. Where is the vehicle to operate? What is the launch location?

b. What are the proposed vehicle missions?

c. How many hours, days, or months will the vehicle be exposed to ground winds?

d. What are the consequences of operational constraints that may be imposed upon the vehicle because of wind constraints?

e. What are the consequences if the vehicle is destroyed or damaged by ground winds?

f. What are the cost and engineering practicalities for designing a functional vehicle to meet the desired mission requirements?

g. What is the risk that the vehicle will be destroyed or damaged by excessive wind loading?

In view of this list of questions or any similar list that a design group may enumerate, it becomes obvious that in establishing the ground wind environment design criteria for a space vehicle an interdisciplinary approach between the several engineering and scientific disciplines is required; furthermore, the process is an iterative one. To begin the iterative process, specific information on ground winds is required.

5.2.3 Introduction to Exposure Period Analysis

Valid, quantitative answers to such questions as the following are of primary concern in the design, mission planning, and operations of space vehicles.

a. How probable is it that the peak surface wind at some specified reference height will exceed (or not exceed) a given magnitude in some specified time period?

b. Given a design wind profile in terms of peak wind speed versus height from 10 to 150 meters, how probable is it that the design wind profile will be exceeded in some specified time period?

Given a statistical sample of peak wind measurements for a specific location, the first question can be answered in as much detail as a statistical analyst finds necessary and sufficient. This first question has been thoroughly analyzed for Cape Kennedy, but only partially for the other locations of interest.

The analysis becomes considerably more complex in answering the second question. A wind profile model is required, and, to develop the model, measurements of the wind profiles by properly instrumented ground wind towers are required as well as a program for scheduling the measurements and data reduction. Every instantaneous wind profile is unique; similarity is a matter of degree. Given the peak wind speed at one height, there is a whole family of possible profiles extending from the specified wind. For each specified wind speed at a given height, there is a statistical distribution of wind profiles. Recommended profile shapes for Cape Kennedy and other locations are given in this report. The analysis needed to answer the second question is not complete, but we can assume that, given a sufficient period of time, the design wind profile shape will occur for a specified wind speed at a given height. In the event that a thunderstorm passes over the vehicle, it is logical to assume that the design wind profile shape will occur and that the chance of the design wind profile being exceeded is the same as the probability that the peak wind during the passage of the thunderstorm will strike the vehicle or point of interest.

From a statistical 10-year sample of thunderstorm events for Cape Kennedy, including the beginning and ending times of thunderstorms, the peak winds during each thunderstorm event, a code indicating whether more than one thunderstorm was observed for each event, weather, and other related phenomena, the percentage of days that had one or more thunderstorm events and the statistical values for samples of (1) daily peak winds for nonthunderstorm days, (2) daily peak winds for thunderstorm days, (3) daily peak winds on all days, and (4) daily peak thunderstorm wind speeds for monthly and seasonal reference periods have been computed. Reference 5. 5A contains these data and additional data on the subject.

5. 2. 4 Development of Extreme Value Samples

It has been estimated from wind tunnel tests that only a few seconds are required for the wind to produce steady drag loads on a vehicle such as the Saturn V in an exposed condition on the launch pad. Because of vortex shedding, a steady wind as low, for example, as 9 m/sec (18 knots) blowing for 15 or more seconds may introduce dynamic loads on a vehicle while it is in some configurations. For these and other reasons (subsection 5. 2. 5), we have adopted the peak wind speed as our fundamental measurement of wind. More important, when the engineering applications of winds can be made in terms of peak wind speeds, it is possible to obtain an appropriate statistical sample that conforms to the fundamental principles of extreme value theory. One hour is a convenient time interval from which to select the peak wind.

5. 2. 4.1 Envelope of Distributions

In the development of the statistics for peak winds, it was recognized that the probability of hourly, daily, and monthly peak winds exceeding (or not exceeding) specified values varied with time of day and from month to month. In other words, the distributions of like variables were different for the various reference periods. Even so, the Gumbel distribution was an excellent fit to the samples of all hourly, daily, monthly, bimonthly (in two combinations), and trimonthly (in three combinations) periods taken over the complete period of record, justifying the presentation of these distributions; they serve as a basic reference for the statistics of peak wind for the annual reference period. However, in establishing vehicle wind design criteria for the peak winds versus exposure time, it is desired to present a simple set of wind statistics in such a manner that every reference period and exposure time would not have to be examined to determine the probability that the largest peak wind during the exposure time would exceed some specified magnitude. To accomplish this objective, envelopes of the distributions of the largest peak winds for various time increments from which the extremals were taken for the various reference periods were constructed.

From the continuously recording charts, the highest instantaneous wind speed (and associated direction) that occurred during each hour was selected for the data sample. The resulting sample of hourly peak wind speeds (and associated directions) has only been completed for Cape Kennedy.

Selected envelopes of distributions are given in subsection 5.2.5. It is recommended that these envelopes of distributions be used for vehicle wind design considerations. This recommendation is made under the assumption that it is not known what time of day or season of year critical vehicle operations are to be conducted; furthermore, it is not desirable to design a vehicle to operate only during selected hours or months. Should all other design alternatives fail to lead to a functionally engineered vehicle with an acceptable risk of not being over stressed by wind loads, then distributions for peak winds by time of day for monthly reference periods may be considered for limited missions. For vehicle operations, detailed statistics of peak winds for specific missions are meaningful for management decisions, in planning the mission, and in establishing mission rules and alternatives to the operational procedures. To present the wind statistics for these purposes is beyond the scope of this document. Each space mission has many facets that make it difficult to generalize and to present the statistics in brief form. Specific data for these applications are available upon request.

5.2.5 Design Wind Profiles (Vehicles)

Specific information about the wind profile is required to calculate ground wind loads on space vehicles. The earth's surface is a rigid boundary that exerts a frictional force on the lower layers of the atmosphere, causing the wind to vanish on the boundary. In addition, the characteristic length and velocity scales of the mean (steady-state) flow in the first 150 meters (boundary layer) of the atmosphere combine to yield extremely high Reynolds numbers with values that range between approximately 10^6 and 10^8, so that for most conditions (wind speeds > 1 m/sec) the flow is turbulent. The lower boundary condition, the thermal and dynamic stability properties of the boundary layer, the distributions of the large scale pressure and Coriolis forces, and the structure of the turbulence combine to yield an infinity of wind profiles.

Data on basic wind speed profiles given in this section are to be used for vehicle design. With respect to design practices, the application of peak winds and the associated turbulence spectra and discrete gusts should be considered. The maximum response obtained for the selected risk levels for each physically realistic combination of conditions should be employed in the design, but not the sum of all individual response calculations, for example, to the peak wind, discrete gust, turbulence spectra, and steady state wind. Also consideration should be given to the appropriate exposure period for on-pad and free standing risk wind value selection.

The application of design ground wind profiles for aircraft landing and takeoff analyses and simulation requires that the wind be applied from the direction contained within the two quadrants perpendicular to and up wind of the runway.

5. 2. 5. 1 Philosophy

The fundamental wind statistics sample was constructed by selecting the peak wind speed that occurred in each hour of record read from original wind records. An example of a peak wind speed is given in Figure 5. 2. 1. Peak wind statistics have three advantages over mean wind statistics. First, peak wind statistics do not depend upon an averaging operation as do mean wind statistics. Second, to construct a mean wind sample, a chart reader or weather observer must perform an "eyeball" average of the wind data, causing the averaging process to vary from day to day according to the mood of the observer, and from observer to observer. Hourly peak wind speed readings avoid this subjective averaging process. Third, to monitor winds during the countdown phase of a space vehicle launch, it is easier to monitor the peak wind speed than the mean wind speed.

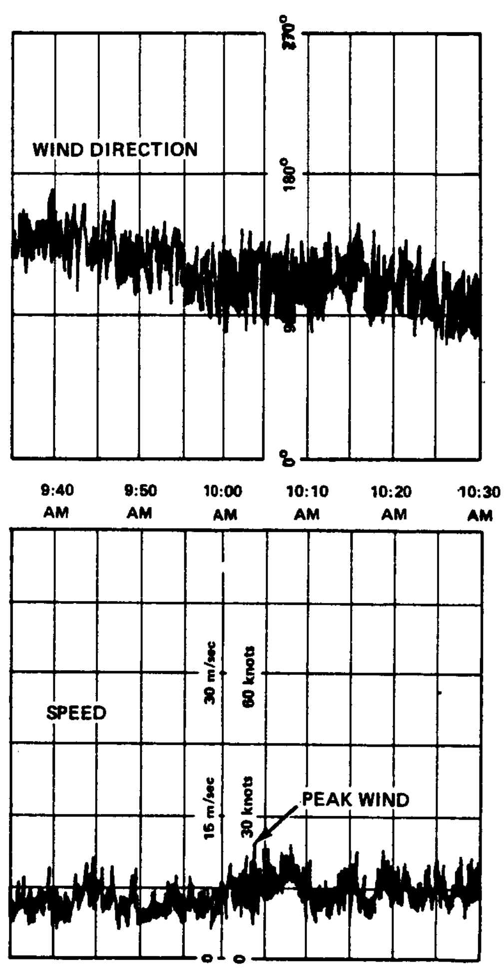

FIGURE 5. 2. 1 EXAMPLE OF PEAK WIND SPEED RECORDS

Smith et al. (Ref. 5. 6) have performed extensive statistical analyses with peak wind speed samples. In the course of the work, he and his collaborators introduced the concept of exposure period probabilities into the design and operation of space vehicles. By determining the distribution functions of peak wind speeds for various periods of exposure (hour, day, month, year, etc.), it is possible to determine the probability of occurrence of a certain wind speed magnitude occurring during a prescribed period of exposure of a space vehicle to the natural environment. Thus, if an operation requires, for example, 1 hour to complete, and if the critical wind loads on the space vehicle can be defined in terms of the peak wind speed, then it is the probability of occurrence of the peak speed during a 1-hour period that gives a measure of the probable risk of the occurrence of structural failure. Similarly, if an operation requires 1 day to complete, then it is the probability of occurrence of the peak wind speed during a 1-day period that gives a measure of the probable risk of structural failure.

All probability statements concerning the capabilities of the space vehicles that are launched at NASA's Kennedy Space Center are prescribed in terms of Smith's peak wind speed exposure statistics.[1] However, to perform loading and response calculations resulting from steady-state and random turbulence drag loads and von Karman vortex shedding loads, the engineer requires information about the vertical variation of the mean wind and the structure of turbulence in the atmospheric boundary layer. The philosophy is to extrapolate the peak wind statistics up into the atmosphere via a peak wind profile, and the associated steady-state or mean wind profile is obtained by applying a gust factor that is a function of wind speed and height.

5.2.5.2 Peak Wind Profile Shapes

To develop a peak wind profile model, approximately 6000 hourly peak wind speed profiles measured during 1967 at NASA's ground wind tower facility at Kennedy Space Center have been analyzed. The sample, comprised of profiles of hourly peak wind speeds measured at the 18-, 30-, 60-, 90-, 120-, and 150-meter levels, appeared to show that the variation of the peak wind speed in the vertical, below 150 meters, could be described with a power law relationship given by

$$u(z) = u_{18.3}\left(\frac{z}{18.3}\right)^{k} , \tag{5.1}$$

where $u(z)$ is the peak wind speed at height z in meters above natural grade and $u_{18.3}$ is a known peak wind speed at $z = 18.3$ meters. The peak wind is referenced to the 18.3-meter level because this level has been selected as the standard reference for the Kennedy Space Center launch area. A reference level should always be stated when discussing ground winds to avoid confusion in interpretation of risk statements and structural load calculations.

A statistical analysis of the peak wind speed profile data revealed that, for engineering purposes, k is distributed normally for any particular value of the peak wind speed at the 18.3-meter level. Thus, for a given percentile level of occurrence, k is approximately equal to a constant for $u_{18.3} > 2$ m/sec. For $u_{18.3} > 2$ m/sec,

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1. A transformation to the 18.3-meter design reference level (or higher level for operational vehicles) is made for Kennedy Space Center applications of risk statement (subsection 5.2.5.5.1).

$$k = c u_{18.3}^{-3/4} \quad , \tag{5.2}$$

where $u_{18.3}$ has the units of meter per second. The parameter, c, for engineering purposes, is distributed normally with mean value 0.52 and standard deviation 0.36. The distribution of k as a function $u_{18.3}$ is depicted in Figure 5.2.2. The $\bar{k} + 3\sigma$ values are used in design studies.

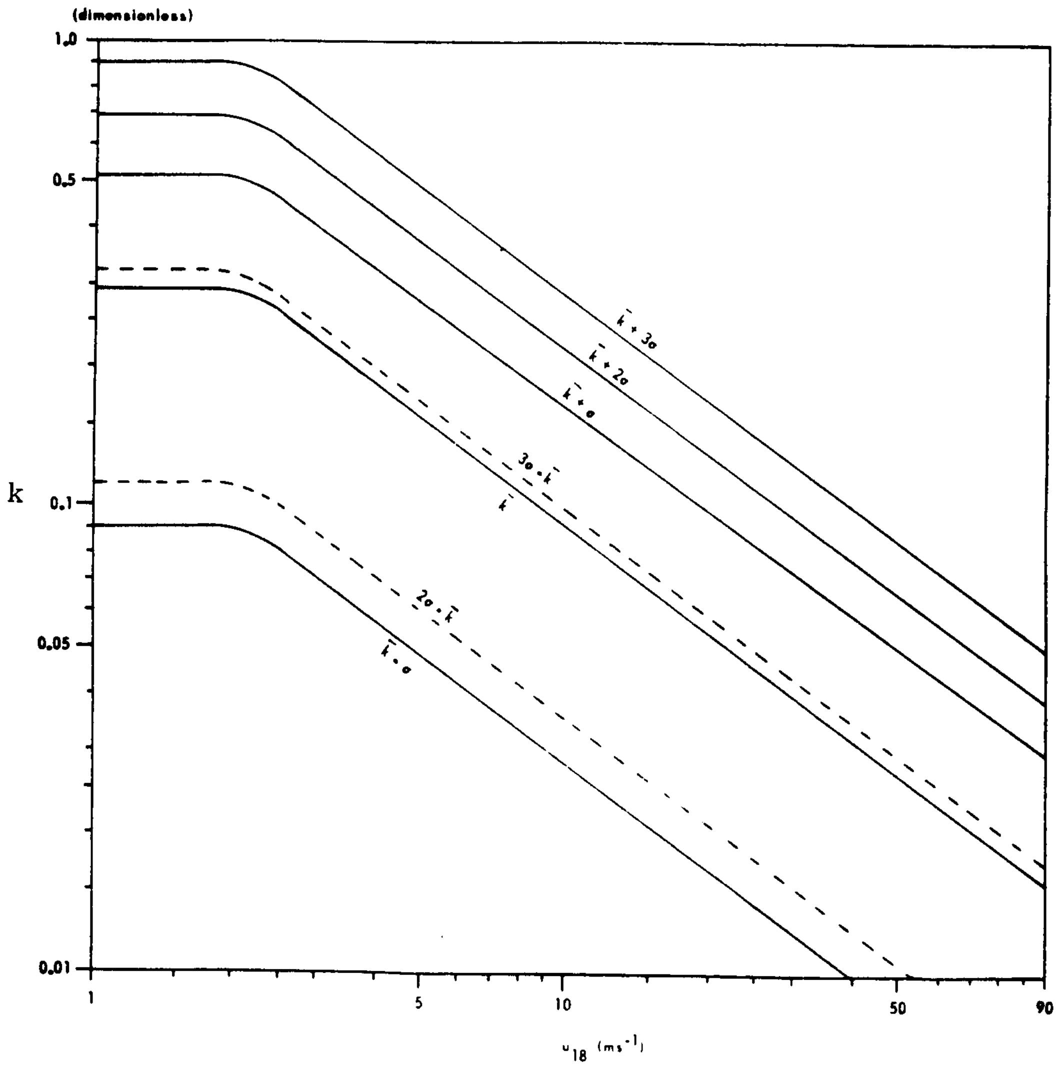


FIGURE 5.2.2 DISTRIBUTION OF THE PEAK WIND PROFILE PARAMETER k FOR VARIOUS WIND SPEEDS AT THE 18.3-m LEVEL FOR THE EASTERN TEST RANGE

5. 2. 5. 3 Instantaneous Extreme Wind Profiles

The probability that the hourly peak wind speeds at all levels occur simultaneously is small. Accordingly, the practice of using peak wind profiles introduces some conservatism into the design criteria; however, the probability is relatively large that when the hourly peak wind occurs at the 18. 3-meter level, the winds at the other levels almost take on the hourly peak values.

To gain some insight into this question, approximately 35 hours of digitized magnetic tape data were analyzed. The data were digitized at 0. 1-second intervals in real time and partitioned into 0. 5-, 2-, 5-, and 10-minute samples. The vertical average peak wind speed $\bar{u}_P$ and the 18-meter mean wind $\bar{u}_{18}$ were calculated for each sample. In addition, the instantaneous vertical average wind speed time history at 0. 1-second intervals was calculated for each sample, and the peak instantaneous vertical average wind speed $\bar{u}_I$ was selected from each sample. The quantity $\bar{u}_I/\bar{u}_P$ was then interpreted to be a measure of how well the peak wind profile approximates the instantaneous extreme wind profile. Figure 5. 2. 3 is a plot of $\bar{u}_I/\bar{u}_P$ as a function of $\bar{u}_{18}$. The data points tend to scatter about a mean value of $\bar{u}_I/\bar{u}_P \simeq 0.93$, which could mean that the peak wind profile will result in an overestimate of ground wind loads by approximately 14 percent. However, some of the data points have values equal to 0. 98, which could mean an overestimate of the loads by only 4 percent. Figure 5. 2. 4 gives the average values of $\bar{u}_I/\bar{u}_P$ as a function of $\bar{u}_{18}$ for different averaging times (0. 5, 2, 5, and 10 min).

5. 2. 5. 4 Peak Wind Profile Shapes for Other Test Ranges and Sites

Detailed analyses of wind profile statistics are not available for other test ranges and sites. The exponent k in equation (5. 1) is a function of wind speed, surface roughness, etc. For moderate surface roughness conditions, the extreme value of k is usually equal to 0. 2 or less during high winds ($\gtrsim$ 15 m/sec). For design and planning purposes for test ranges and sites other than the Eastern Test Range, it is recommended that the values of k given in Table 5. 2. 1 be used. These values of k are the only values used in this report for sites other than the Eastern Test Range and represent estimates for 99. 87 percentile-mean + 3σ (0. 13 percent risk) values for the profile shape.

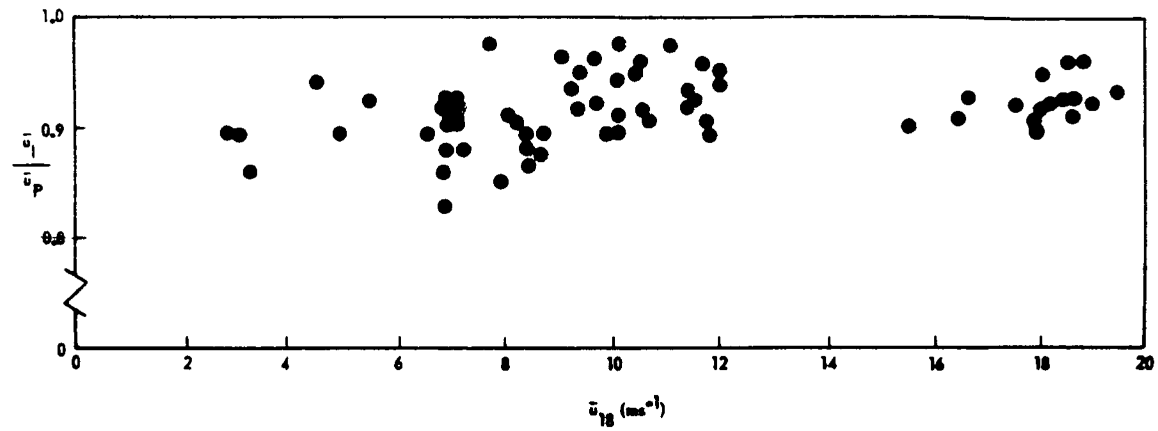


FIGURE 5.2.3 THE RATIO $\bar{u}_I/\bar{u}_P$ AS A FUNCTION OF THE 18.3-m MEAN WIND SPEED ($\bar{u}_{18}$) FOR A 10-min SAMPLING PERIOD

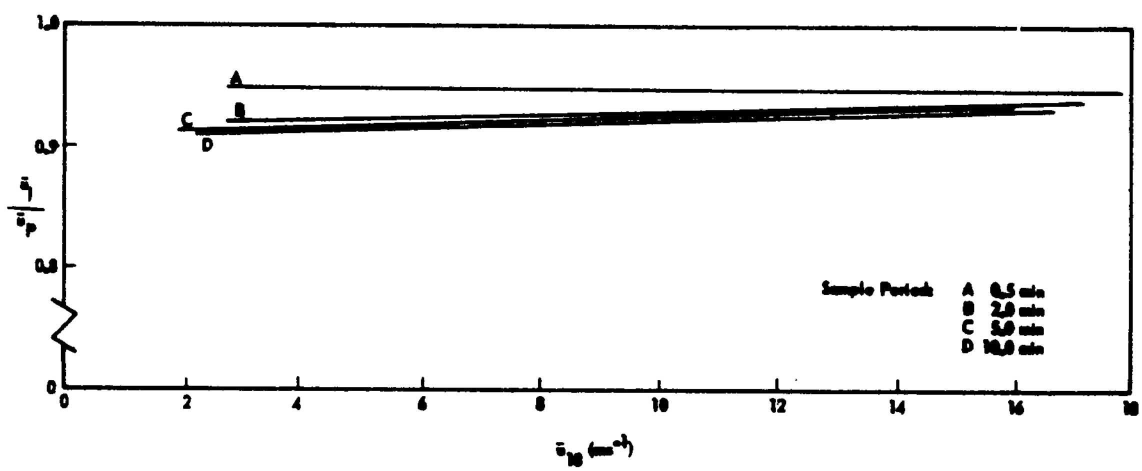


FIGURE 5.2.4 THE RATIO $\bar{u}_I/\bar{u}_P$ AS A FUNCTION OF THE 18.3-m MEAN WIND SPEED ($\bar{u}_{18}$) FOR VARIOUS SAMPLING PERIODS

TABLE 5.2.1 VALUES OF k TO USE FOR TEST RANGES OTHER THAN THE EASTERN TEST RANGE

k Value	18.3-Meter Level Peak Wind Speed (ms^{-1})
k = 0.2	$7 \leq u_{18.3} < 22$
k = 0.14	$22 \leq u_{18.3}$

5.2.5.5 Aerospace Vehicle Design Wind Profiles

The data presented in this section provide basic peak wind speed profile (envelope) information for use in studies to determine load factors for test, free-standing, launch, and lift-off conditions to ensure satisfactory performance of the space vehicle. To establish vehicle response requirements, the peak design surface winds are assumed to act normal to the longitudinal axis of the vehicle on the launch pad and to be from the most critical direction.

5.2.5.5.1 Design Wind Profiles for the Eastern Test Range

Peak wind profiles are characterized by two parameters, the peak wind speed at the 18.3-meter level and the shape parameter k. Once these two quantities are defined, the peak wind speed profile envelope is completely specified. Accordingly, to construct a peak wind profile envelope for the Eastern Test Range, in the context of launch vehicle loading and response calculations, two pieces of information are required. First, the risk of exceeding the design wind peak speed at the reference level for a given period must be specified. Once this quantity is given, the design peak wind speed at the reference level is automatically specified (Figure 5.2.5). Second, the risk associated with compromising the structural integrity of the vehicle, once the reference level design wind occurs, must be specified. This second quantity and the reference level peak wind speed will determine the value of k that is to be used in equation (5.1). To apply equations (5.1) and (5.2) to the peak wind statistics valid at 10 meters, equation (5.1) is evaluated at $z = 10$ meters, and the resulting relationship inverted to yield $u_{18.3}$ as a function of the 10-meter level peak wind speed u_{10} for a fixed value of c. This function is then combined with equation (5.2) to yield k as a function of u_{10} for a given value of c. The validity of this inversion process is open to question because equation (5.1) is a stochastic relationship. However, analysis with profiles that include peak wind information obtained at the 10-meter level appear to show that this inversion is valid for engineering applications.

It is recommended that the $\bar{k} + 3\sigma$ value of k be used for the design of space vehicles. Thus, if a space vehicle designed to withstand a particular value of the peak wind speed at the 18.3-meter reference level is exposed to that peak wind speed, the vehicle has at least a 99.87-percent chance of withstanding possible peak wind profile conditions.

Operational ground wind contraints for established vehicles should be determined for a reference level (above natural grade) near the top of the vehicle while on the launch pad. The profile may be calculated using equations (5.1) and (5.2) with a value of $k = \bar{k} - 3\sigma$. This will produce a peak wind

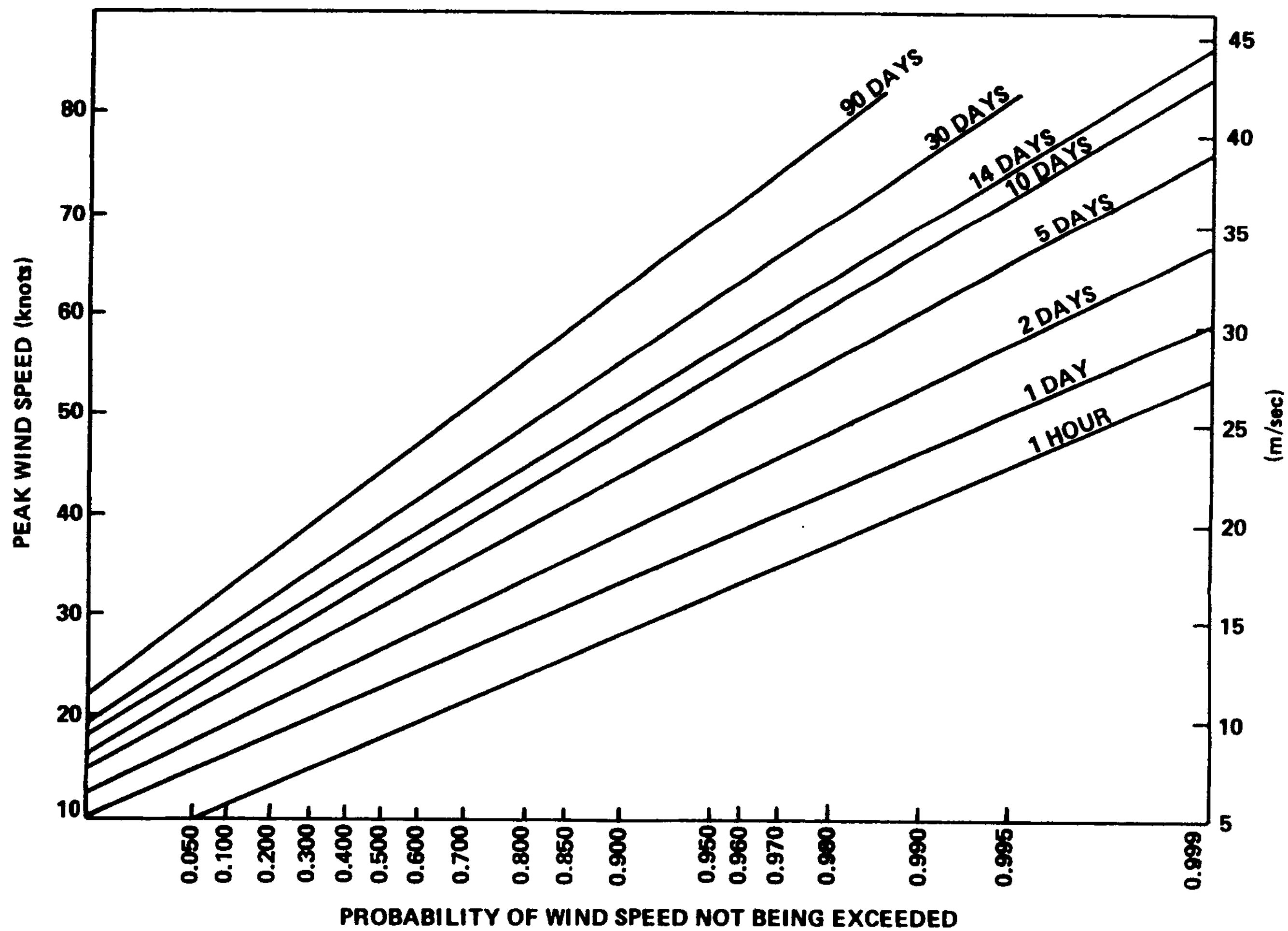


FIGURE 5.2.5 18.3-m REFERENCE LEVEL; CAPE KENNEDY PEAK WIND SPEED, WINDIEST PERIOD, PROBABILITY VERSUS WIND SPEED FOR SEVERAL EXPOSURE PERIODS APPLICABLE TO VEHICLE DESIGN CRITERIA DEVELOPMENT

profile envelope associated with an upper reference level ground wind constraint. Tables for these calculations and those associated with the design reference level are available for various wind speeds and k values applicable to Cape Kennedy upon request to the Aerospace Environment Division, NASA, Marshall Space Flight Center, Alabama.

Table 5.2.2 contains peak wind speed profiles for various envelope values of peak wind speed at the 10-meter level for fixed values of risk for the worst monthly-hourly reference periods of the year for a 1-hour exposure. To construct these profiles, the 1-hour exposure period statistics for each hour in each month were constructed. This exercise yielded 288 distribution functions (12 months times 24 hours), which were enveloped to yield the largest or "worst" 10-meter level peak wind speed associated with a given level of risk for all monthly-hourly reference periods. Thus, for example, according to Table 5.2.2 there is at most a 10-percent risk that the peak wind speed will exceed 13.8 m/sec (26.9 knots) during any particular hour in any particular month at the 10-meter level, and if 13.8 m/sec (26.9 knots) occur at the 10-meter level, then there is only a 0.135-percent chance that the peak wind speed will exceed 24.1 m/sec (46.8 knots) at the 152.4-meter level or the corresponding values given at the other heights.

Tables 5.2.3 through 5.2.5 contain peak wind profile envelopes for various values of peak wind speed at the 10-meter level and fixed values of risk for various exposure periods. The 1-day exposure values of peak wind speed were obtained by constructing the daily peak wind statistics for each month and then enveloping these distributions to yield the worst 1-day exposure, 10-meter level peak wind speed for a specified value of risk (daily-monthly reference period). The 30-day exposure envelope peak wind speeds were obtained by constructing the monthly peak wind statistics for each month and then constructing the envelope of the distributions (monthly-annual reference period). The 10-day exposure statistics were obtained by interpolating between the 1- and 30-day exposure period results. The envelopes of the 90-day exposure period statistics were the 90-day exposure statistics associated with the 12 trimonthly periods (January-February-March, February-March-April, March-April-May, and so forth) (90-day-annual reference period). Finally, the 365-day exposure period statistics were calculated with the annual peak wind sample (17 data points) to yield one distribution (90-day-annual reference period). Tables 5.2.3 through 5.2.5 contain the largest or "worst" 10-meter level peak wind speed associated with a given level of risk for the stated exposure periods.

It is recommended that the data in Tables 5.2.2 through 5.2.5 be used as the basis for space vehicle design for Cape Kennedy/Kennedy Space Center Operations. Wind profile statistics for the design of permanent ground support equipment are discussed in subsection 5.2.6.

TABLE 5. 2. 2 PEAK WIND SPEED PROFILE ENVELOPES FOR VARIOUS VALUES OF RISK OF EXCEEDING THE 10-m LEVEL PEAK WIND SPEED FOR 1-hr EXPOSURE (hourly-monthly reference period) FOR CAPE KENNEDY[2]

Height		Risk (%)									
		20		10		5		1		0.1	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	22.9	11.8	27.0	13.9	30.8	15.8	39.5	20.3	51.9	26.7
18.3	60	26.3	13.5	30.5	15.7	34.4	17.7	43.4	22.3	56.0	28.8
30.5	100	29.5	15.2	33.8	17.4	37.9	19.5	47.0	24.2	59.8	30.8
61.0	200	34.5	17.8	38.9	20.0	43.0	22.1	52.3	26.9	65.4	33.6
91.4	300	37.8	19.5	42.2	21.7	46.4	23.9	55.7	28.7	68.9	35.4
121.9	400	40.4	20.8	44.7	23.0	48.9	25.2	58.3	30.0	71.5	36.8
152.4	500	42.5	21.9	46.8	24.1	51.0	26.2	60.3	31.0	73.6	37.8

TABLE 5. 2. 3 PEAK WIND SPEED PROFILE ENVELOPES FOR A 10-PERCENT RISK VALUE OF EXCEEDING THE 10-m LEVEL PEAK WIND SPEED FOR VARIOUS REFERENCE PERIODS OF EXPOSURE, FOR CAPE KENNEDY[2]

Height		Exposure (days)									
		1		10		30		90		365	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	32.1	16.5	46.9	24.1	53.9	27.7	61.0	31.4	70.0	36.0
18.3	60	35.8	18.4	51.0	26.2	58.2	29.9	65.3	33.6	74.5	38.3
30.5	100	39.2	20.2	54.7	28.1	62.0	31.9	69.3	35.7	78.5	40.4
61.0	200	44.4	22.8	60.2	31.0	67.6	34.8	75.0	38.6	84.4	43.4
91.4	300	47.8	24.6	63.6	32.7	71.1	36.6	78.5	40.4	88.0	45.3
121.9	400	50.3	25.9	66.2	34.1	73.7	37.9	81.1	41.7	90.6	46.6
152.4	500	52.4	27.0	68.3	35.1	75.8	39.0	83.2	42.8	92.8	47.7

2. Recommended for design criteria development.

TABLE 5.2.4 PEAK WIND SPEED PROFILE ENVELOPES FOR A 5-PERCENT RISK VALUE OF EXCEEDING THE 10-m LEVEL PEAK WIND SPEED FOR VARIOUS REFERENCE PERIODS OF EXPOSURE FOR CAPE KENNEDY[3]

Height		Exposure (days)									
		1		10		30		90		365	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	36.1	18.5	52.3	26.9	60.1	30.9	67.8	34.9	77.7	40.0
18.3	60	39.8	20.5	56.5	29.1	64.4	33.1	72.3	37.2	82.4	42.4
30.5	100	43.3	22.3	60.3	31.0	68.3	35.1	76.3	39.3	86.5	44.5
61.0	200	48.6	25.0	65.9	33.9	74.0	38.1	82.1	42.2	92.5	47.6
91.4	300	52.0	26.8	69.4	35.7	77.6	40.0	85.7	44.1	96.1	49.4
121.9	400	54.5	28.0	72.0	37.0	80.2	41.3	88.4	45.5	98.8	50.8
152.4	500	56.6	29.1	74.1	38.1	82.3	42.3	91.0	46.8	101.0	52.0

TABLE 5.2.5 PEAK WIND SPEED PROFILE ENVELOPES FOR A 1-PERCENT RISK VALUE OF EXCEEDING THE 10-m LEVEL PEAK WIND SPEED FOR VARIOUS REFERENCE PERIODS OF EXPOSURE FOR CAPE KENNEDY[3]

Height		Exposure (days)									
		1		10		30		90		365	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	45.0	23.1	65.4	33.6	74.0	38.1	83.4	42.9	95.4	49.1
18.3	60	49.0	25.2	69.9	36.0	78.6	40.4	88.2	45.4	100.3	51.6
30.5	100	52.6	27.1	73.9	38.0	82.8	42.6	92.4	47.5	104.7	53.9
61.0	200	58.1	30.0	79.7	41.0	88.6	45.6	98.4	50.6	110.9	57.1
91.4	300	61.5	31.6	83.2	42.8	92.3	47.5	102.1	52.5	114.6	59.0
121.9	400	64.1	33.0	85.9	44.2	95.0	48.9	104.8	53.9	117.4	60.4
152.4	500	66.1	34.0	88.0	45.3	97.1	50.0	107.0	55.0	119.6	61.5

3. Recommended for design criteria development.

Mean wind profiles or steady-state wind profiles can be obtained from the peak wind profiles by dividing the peak wind by the appropriate gust factor (subsection 5.2.7). It is recommended that the 10-minute gust factors be used for structural design purposes. Application of the 10-minute gust factors to the peak wind profile corresponds to averaging the wind speed over a 10-minute period. This averaging period appears to result in a stable mean value of the wind speed. Within the range of variation of the data, the 1-hour and 10-minute gust factors are approximately equal for sufficiently high wind speed. This occurs because the spectrum of the horizontal wind speed near the ground is characterized by a broad energy gap centered at a frequency approximately equal to 0.000278 hertz (1 cycle/hr) and typically extends over the frequency domain 0.000139 hertz (0.5 cycles/hr) $< \omega <$ 0.00139 hertz (5 cycles/hr) (Ref. 5.7). The Fourier spectral components associated with frequencies less then 0.0166 hertz (1 cycle/hr) correspond to the meso- and synoptic-scale motions, while the remaining high-frequency spectral components correspond to mechanically and thermally produced turbulence. Thus, a statistically stable estimate of the mean or steady-state wind speed can be obtained by averaging over a period in the range from 10 minutes to an hour. Davenport (Ref. 5.5) points out that this period for averaging is also suitable for structural analysis. Since this period is for longer than any natural period of structural vibration, it assures that effects caused by the mean wind properly represent steady-state, nontransient effects. The steady-state wind profiles, calculated with the 10-minute gust factors, that correspond to those in Tables 5.2.2 through 5.2.5 are given in Tables 5.2.6 through 5.2.9.

5.2.5.5.2 Design Ground Wind Profiles for Other Locations

Tables 5.2.10 through 5.2.21 contain recommended design ground wind profiles for several different risks of exceeding the 10-meter level peak wind speed and 10-minute mean wind speed for a 1-hour exposure period. These tables are based on the same philosophy as Table 5.2.2 and Table 5.2.6 for the Eastern Test Range. The locations for which data are provided include Wallops Island, Virginia; White Sands Missile Range, New Mexico; Air Force Flight Center, Edwards AFB, California; Space and Missile Test Center, Vandenberg AFB, California; Huntsville, Alabama; and the New Orleans, Louisiana-Mississippi Test Facility area. Data for 1-day and longer exposure periods are currently being established for several of these locations and will be made available on request. Detailed hourly peak wind records similar to those for Cape Kennedy are not available at this time for other locations. Therefore, it was necessary to develop Tables 5.2.10 through 5.2.21 from the existing data records. This was accomplished by developing the 10-meter wind statistics for each of these locations plus Cape Kennedy from a common type data record. After extensive cross checks and analysis a scaling factor was developed with the special Cape Kennedy hourly peak wind records as a base line relative to the common type data record also available for Cape

TABLE 5.2.6 10-min MEAN WIND SPEED PROFILE ENVELOPES FOR VARIOUS VALUES OF RISK OF EXCEEDING THE 10-m LEVEL MEAN WIND SPEED FOR A 1-hr EXPOSURE (hourly-monthly reference period) FOR CAPE KENNEDY

Height		Risk (%)									
		20		10		5		1		0.1	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	14.1	7.2	16.6	8.6	19.1	9.8	24.6	12.7	32.4	16.7
18.3	60	17.1	8.8	19.9	10.3	22.6	11.7	28.7	14.8	37.2	19.1
30.5	100	20.0	10.3	23.1	11.9	26.0	13.4	32.6	16.8	41.6	21.4
61.0	200	24.7	12.7	28.1	14.5	31.3	16.1	38.3	19.7	48.1	24.7
91.4	300	27.8	14.3	31.3	16.1	34.7	17.9	42.0	21.6	52.1	26.8
121.9	400	30.3	15.6	33.9	17.4	37.3	19.2	44.8	23.0	55.1	28.3
152.4	500	32.3	16.6	35.9	18.5	39.4	20.3	47.0	24.2	57.5	29.6

TABLE 5.2.7 10-min MEAN WIND SPEED PROFILE ENVELOPES FOR A 10-PERCENT RISK VALUE OF EXCEEDING THE 10-m LEVEL MEAN WIND SPEED FOR VARIOUS REFERENCE PERIODS OF EXPOSURE FOR CAPE KENNEDY

Height		Exposure (days)									
		1		10		30		90		365	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	20.0	10.3	29.3	15.1	33.7	17.3	38.1	19.6	43.8	22.5
18.3	60	23.6	12.1	33.8	17.4	38.7	19.9	43.3	22.3	49.5	25.5
30.5	100	27.1	13.9	38.0	19.5	43.1	22.2	48.2	24.8	54.6	28.1
61.0	200	32.4	16.7	44.2	22.7	49.6	25.5	55.1	28.3	62.1	31.9
91.4	300	35.8	18.4	48.1	24.7	53.8	27.7	59.4	30.6	66.6	34.3
121.9	400	38.5	19.8	51.0	26.2	56.8	29.2	62.6	32.2	69.9	36.0
152.4	500	40.6	20.9	53.3	27.4	59.2	30.5	65.1	33.5	72.6	37.3

TABLE 5.2.8 10-min MEAN WIND SPEED PROFILE ENVELOPES FOR A 5-PERCENT RISK VALUE OF EXCEEDING THE 10-m LEVEL MEAN WIND SPEED FOR VARIOUS REFERENCE PERIODS OF EXPOSURE FOR CAPE KENNEDY

Height		Exposure (days)									
		1		10		30		90		365	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	22.5	11.6	32.7	16.8	37.6	19.3	42.5	21.9	48.6	25.0
18.3	60	26.3	13.5	37.5	19.3	42.8	22.0	48.1	24.7	54.8	28.2
30.5	100	30.0	15.4	41.9	21.6	47.5	24.4	53.2	27.4	60.2	31.0
61.0	200	35.5	18.3	48.4	24.9	54.5	28.0	60.4	31.1	68.1	35.0
91.4	300	39.2	20.2	52.5	27.0	58.7	30.2	64.9	33.4	72.9	37.5
121.9	400	41.9	21.6	55.5	28.6	61.9	31.8	68.2	35.1	76.3	39.3
152.4	500	44.0	22.6	57.9	29.8	64.4	33.1	70.9	36.4	79.1	40.7

TABLE 5.2.9 10-min MEAN WIND SPEED PROFILE ENVELOPES FOR A 1-PERCENT RISK VALUE OF EXCEEDING THE 10-m LEVEL MEAN WIND SPEED FOR VARIOUS REFERENCE PERIODS OF EXPOSURE FOR CAPE KENNEDY

Height		Exposure (days)									
		1		10		30		90		365	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	28.1	14.5	40.9	21.0	46.3	23.8	52.2	26.9	59.7	30.7
18.3	60	32.5	16.7	46.5	23.9	52.2	26.9	58.6	30.1	66.7	34.3
30.5	100	36.6	18.8	51.4	26.4	57.6	29.6	64.3	33.1	72.9	37.5
61.0	200	42.6	21.9	58.6	30.1	65.2	33.5	72.5	37.3	81.6	42.0
91.4	300	47.2	24.3	63.0	32.4	69.9	36.0	77.4	39.8	86.9	44.7
121.9	400	49.4	25.4	66.3	34.1	73.4	37.8	81.0	41.7	90.7	46.7
152.4	500	51.7	26.6	68.9	35.4	76.1	39.1	83.8	43.1	93.7	48.2

TABLE 5.2.10 PEAK WIND SPEED PROFILE ENVELOPES FOR VARIOUS VALUES OF RISK OF EXCEEDING THE 10-m LEVEL PEAK WIND SPEED FOR 1-hr EXPOSURE (hourly-monthly reference period) FOR HUNTSVILLE, ALABAMA

Height		Risk (%)									
		20		10		5		1		0.1	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	19.1	9.8	21.6	11.1	24.0	12.4	31.5	16.2	47.5	24.5
18.3	60	21.5	11.1	24.4	12.5	27.1	14.0	35.6	18.3	51.7	26.7
30.5	100	23.9	12.3	27.0	13.9	30.0	15.5	39.4	20.3	55.5	28.6
61.0	200	27.4	14.1	31.0	15.9	34.5	17.8	45.2	23.3	61.0	31.5
91.4	300	29.7	15.3	33.6	17.3	37.4	19.3	49.1	25.2	64.7	33.4
121.9	400	31.5	16.2	35.6	18.3	39.6	20.5	52.0	26.7	67.4	34.7
152.4	500	33.0	16.9	37.3	19.2	41.5	21.4	54.4	28.0	69.5	35.8

TABLE 5.2.11 10-min MEAN WIND SPEED PROFILE ENVELOPES FOR VARIOUS VALUES OF RISK OF EXCEEDING THE 10-m LEVEL MEAN SPEED FOR 1-hr EXPOSURE (hourly-monthly reference period) FOR HUNTSVILLE, ALABAMA

Height		Risk (%)									
		20		10		5		1		0.1	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	13.6	7.0	15.4	7.9	17.1	8.8	22.5	11.6	33.9	17.5
18.3	60	15.4	7.9	17.4	9.0	19.4	10.0	25.4	13.1	36.9	19.0
30.5	100	17.1	8.8	19.3	9.9	21.4	11.1	28.1	14.5	39.6	20.4
61.0	200	19.6	10.1	22.2	11.4	24.6	12.7	32.3	16.6	43.6	22.5
91.4	300	21.3	10.9	24.0	12.4	26.7	13.8	35.0	18.0	46.2	23.8
121.9	400	22.5	11.6	25.5	13.1	28.3	14.6	37.1	19.1	48.1	24.8
152.4	500	23.6	12.1	26.7	13.7	29.6	15.3	38.9	20.0	49.6	25.6

TABLE 5.2.12 SURFACE PEAK WIND SPEED PROFILE ENVELOPES FOR VARIOUS VALUES OF RISK OF EXCEEDING THE 10-m LEVEL PEAK WIND SPEED FOR 1-hr EXPOSURE (hourly-monthly reference period) FOR NEW ORLEANS AND MISSISSIPPI TEST FACILITY AREA

Height		Risk (%)									
		20		10		5		1		0.1	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	19.8	10.2	23.9	12.3	27.6	14.2	37.2	19.1	53.0	27.3
18.3	60	22.4	11.5	27.0	13.9	31.2	16.0	42.0	21.5	57.7	29.7
30.5	100	24.8	12.8	29.9	15.4	34.5	17.8	46.5	23.9	61.9	31.8
61.0	200	28.4	14.6	34.3	17.7	39.6	20.4	53.4	27.4	68.1	35.1
91.4	300	30.8	15.9	37.2	19.2	43.0	22.1	57.9	29.8	72.2	37.2
121.9	400	32.7	16.8	39.4	20.3	45.5	23.4	61.4	31.5	75.2	38.7
152.4	500	34.2	17.6	41.3	21.3	47.7	24.5	64.3	33.0	77.5	39.9

TABLE 5.2.13 SURFACE MEAN WIND SPEED PROFILE ENVELOPES FOR VARIOUS VALUES OF RISK OF EXCEEDING THE 10-m LEVEL 10-min MEAN WIND SPEED FOR 1-hr EXPOSURE (hourly-monthly reference period) FOR NEW ORLEANS AND MISSISSIPPI TEST FACILITY AREA

Height		Risk (%)									
		20		10		5		1		0.1	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	14.1	7.3	17.1	8.8	19.7	10.1	26.6	13.7	37.9	19.5
18.3	60	16.0	8.2	19.3	9.9	22.3	11.4	30.0	15.4	41.2	21.2
30.5	100	17.7	9.1	21.4	11.0	24.7	12.7	33.2	17.1	44.2	22.8
61.0	200	20.3	10.5	24.5	12.6	28.3	14.6	38.2	19.6	48.6	25.0
91.4	300	22.0	11.3	26.6	13.7	30.7	15.8	41.4	21.3	51.6	26.6
121.9	400	23.3	12.0	28.2	14.5	32.5	16.7	43.8	22.5	53.7	27.7
152.4	500	24.4	12.6	29.5	15.2	34.1	17.5	45.9	23.6	55.4	28.5

TABLE 5.2.14 SURFACE PEAK WIND SPEED PROFILE ENVELOPES FOR VARIOUS VALUES OF RISK OF EXCEEDING THE 10-m LEVEL PEAK WIND SPEED FOR 1-hr EXPOSURE (hourly-monthly reference period) FOR THE SPACE AND MISSILE TEST CENTER,[4] VANDENBERG AFB, CALIFORNIA

Height		Risk (%)									
		20		10		5		1		0.1	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	18.3	9.4	23.1	11.9	27.6	14.2	36.5	18.8	45.0	23.2
18.3	60	20.7	10.6	26.1	13.4	31.2	16.0	41.2	21.2	49.0	25.2
30.5	100	22.9	11.8	28.9	14.9	34.5	17.8	45.7	23.5	52.6	27.1
61.0	200	26.3	13.5	33.2	17.1	39.6	20.4	52.4	27.0	57.8	29.8
91.4	300	28.5	14.6	36.0	18.5	43.0	22.1	56.9	29.3	61.3	31.6
121.9	400	30.2	15.5	38.1	19.6	45.5	23.4	60.2	31.0	63.8	32.9
152.4	500	31.6	16.2	39.9	20.6	47.7	24.5	63.1	32.5	65.8	33.9

TABLE 5.2.15 SURFACE MEAN WIND SPEED PROFILE ENVELOPES FOR VARIOUS VALUES OF RISK OF EXCEEDING THE 10-m LEVEL 10-min MEAN WIND SPEED FOR 1-hr EXPOSURE (hourly-monthly reference period) FOR THE SPACE AND MISSILE TEST CENTER, VANDENBERG AFB, CALIFORNIA

Height		Risk (%)									
		20		10		5		1		0.1	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	13.1	6.7	16.5	8.5	19.7	10.1	26.1	13.4	32.1	16.5
18.3	60	14.8	7.6	18.6	9.6	22.3	11.4	29.4	15.2	35.0	18.0
30.5	100	16.4	8.4	20.6	10.6	24.7	12.7	32.6	16.8	37.5	19.4
61.0	200	18.8	9.6	23.7	12.2	28.3	14.6	37.4	19.3	41.3	21.3
91.4	300	20.4	10.5	25.7	13.2	30.7	15.8	40.6	20.9	43.8	22.6
121.9	400	21.6	11.1	27.2	14.0	32.5	16.7	43.0	22.2	45.6	23.5
152.4	500	22.6	11.6	28.5	14.7	34.1	17.5	45.1	23.2	47.0	24.2

4. Formerly Western Test Range.

TABLE 5.2.16 SURFACE PEAK WIND SPEED PROFILE ENVELOPES FOR VARIOUS VALUES OF RISK OF EXCEEDING THE 10-m LEVEL PEAK WIND SPEED FOR 1-hr EXPOSURE (hourly-monthly reference period) FOR WALLOPS TEST RANGE

Height		Risk (%)									
		20		10		5		1		0.1	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	22.9	11.8	27.1	13.9	31.2	16.1	38.6	19.9	55.0	28.3
18.3	60	25.9	13.3	30.6	15.7	35.2	18.2	43.6	22.5	59.8	30.8
30.5	100	28.6	14.8	33.9	17.4	39.0	20.1	48.3	24.9	64.3	33.1
61.0	200	32.9	16.9	38.9	20.0	44.8	23.1	55.4	28.6	70.6	36.3
91.4	300	35.7	18.4	42.2	21.7	48.6	25.1	60.1	31.0	74.9	38.6
121.9	400	37.8	19.5	44.7	22.9	51.5	26.6	63.7	32.8	78.0	40.1
152.4	500	39.6	20.4	46.8	24.0	53.9	27.8	66.7	34.4	80.5	41.4

TABLE 5.2.17 SURFACE MEAN WIND SPEED PROFILE ENVELOPES FOR VARIOUS VALUES OF RISK OF EXCEEDING THE 10-m LEVEL 10-min MEAN WIND SPEED FOR 1-hr EXPOSURE (hourly-monthly reference period) FOR WALLOPS TEST RANGE

Height		Risk (%)									
		20		10		5		1		0.1	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	16.4	8.4	19.3	9.9	22.3	11.5	27.6	14.2	39.3	20.2
18.3	60	18.5	9.5	21.9	11.2	25.2	13.0	31.1	16.1	42.7	22.0
30.5	100	20.5	10.5	24.2	12.4	27.9	14.4	34.5	17.8	45.9	23.6
61.0	200	23.5	12.1	27.8	14.3	32.0	16.5	39.6	20.4	50.4	26.0
91.4	300	25.5	13.1	30.2	15.5	34.7	17.9	42.9	22.1	53.5	27.5
121.9	400	27.0	13.9	31.9	16.4	36.8	19.0	45.5	23.5	55.7	28.7
152.4	500	28.3	14.6	33.5	17.2	38.5	19.9	47.7	24.6	57.5	29.6

TABLE 5.2.18 SURFACE PEAK WIND SPEED PROFILE ENVELOPES FOR VARIOUS VALUES OF RISK OF EXCEEDING THE 10-m LEVEL PEAK WIND SPEED FOR 1-hr EXPOSURE (hourly-monthly reference period) FOR WHITE SANDS MISSILE RANGE

Height		Risk (%)									
		20		10		5		1		0.1	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	15.3	7.9	20.9	10.7	24.7	12.7	34.3	17.7	52.1	26.8
18.3	60	17.3	8.9	23.6	12.1	27.9	14.3	38.7	20.0	56.7	29.2
30.5	100	19.1	9.9	26.1	13.4	30.9	15.9	42.9	22.1	60.9	31.3
61.0	200	22.0	11.3	30.0	15.4	35.5	18.2	49.3	25.4	66.9	34.4
91.4	300	23.8	12.3	32.6	16.7	38.5	19.8	53.4	27.6	71.0	36.5
121.9	400	25.2	13.0	34.5	17.7	40.8	21.0	56.6	29.2	73.9	38.0
152.4	500	26.4	13.7	36.1	18.5	42.7	22.0	59.3	30.6	76.2	39.2

TABLE 5.2.19 SURFACE MEAN WIND SPEED PROFILE ENVELOPES FOR VARIOUS VALUES OF RISK OF EXCEEDING THE 10-m LEVEL 10-min MEAN WIND SPEED FOR 1-hr EXPOSURE (hourly-monthly reference period) FOR WHITE SANDS MISSILE RANGE

Height		Risk (%)									
		20		10		5		1		0.1	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	10.9	5.6	14.9	7.7	17.6	9.1	24.5	12.6	37.2	19.2
18.3	60	12.3	6.4	16.9	8.6	19.9	10.2	27.7	14.3	40.5	20.8
30.5	100	13.7	7.1	18.7	9.6	22.1	11.3	30.7	15.8	43.4	22.4
61.0	200	15.7	8.1	21.4	11.0	25.3	13.0	35.2	18.2	47.8	24.6
91.4	300	17.0	8.8	23.3	11.9	27.5	14.1	38.2	19.7	50.7	26.1
121.9	400	18.0	9.3	24.6	12.6	29.1	15.0	40.4	20.9	52.8	27.1
152.4	500	18.9	9.8	25.8	13.2	30.5	15.7	42.3	21.9	54.4	28.0

TABLE 5.2.20 SURFACE PEAK WIND SPEED PROFILE ENVELOPES FOR VARIOUS VALUES OF RISK OF EXCEEDING THE 10-m LEVEL PEAK WIND SPEED FOR 1-hr EXPOSURE (hourly-monthly reference period) FOR EDWARDS AIR FORCE BASE

Height		Risk (%)									
		20		10		5		1		0.1	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	24.4	12.6	28.3	14.6	31.5	16.2	38.4	19.8	47.0	24.2
18.3	60	27.6	14.2	32.0	16.5	35.6	18.3	43.4	22.4	51.1	26.3
30.5	100	30.5	15.8	35.4	18.3	39.4	20.3	48.0	24.8	54.9	28.3
61.0	200	35.0	18.1	40.6	21.0	45.2	23.3	55.1	28.4	60.3	31.1
91.4	300	38.0	19.6	44.1	22.7	49.1	25.2	59.8	30.8	64.0	33.0
121.9	400	40.3	20.8	46.7	24.1	52.0	26.7	63.4	32.7	66.6	34.3
152.4	500	42.2	21.8	48.9	25.2	54.4	28.0	66.4	34.2	68.8	35.4

TABLE 5.2.21 SURFACE MEAN WIND SPEED PROFILE ENVELOPES FOR VARIOUS VALUES OF RISK OF EXCEEDING THE 10-m LEVEL 10-min MEAN WIND SPEED FOR 1-hr EXPOSURE (hourly-monthly reference period) FOR EDWARDS AIR FORCE BASE

Height		Risk (%)									
		20		10		5		1		0.1	
(m)	(ft)	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}	knots	ms^{-1}
10.0	33	17.4	9.0	20.2	10.4	22.5	11.6	27.4	14.1	33.6	17.3
18.3	60	19.7	10.2	22.8	11.8	25.4	13.1	31.0	16.0	36.5	18.8
30.5	100	21.8	11.3	25.3	13.0	28.1	14.5	34.4	17.7	39.2	20.2
61.0	200	25.0	12.9	29.0	15.0	32.3	16.6	39.4	20.3	43.1	22.2
91.4	300	27.1	14.0	31.5	16.2	35.0	18.0	42.7	22.0	45.7	23.5
121.9	400	28.8	14.9	33.4	17.2	37.1	19.1	45.3	23.3	47.6	24.5
152.4	500	30.1	15.6	34.9	18.0	38.9	20.0	47.4	24.4	49.1	25.3

Kennedy. Although the resulting design ground wind profiles for the various locations are subject to change if and when a special hourly peak wind record can be developed, for engineering design application the data given in Tables 5.2.10 through 5.2.21 are acceptable. The peak/mean wind profiles were constructed with a 1.4 gust factor and mean $+3\sigma$ value of k, as given in subsection 5.2.5.5.1. Some additional general ground wind data are given in References 5.7A and 5.7B for several other locations.

5.2.5.5.3 Frequency of Calm Winds

Generally, design criteria wind problems are concerned with high wind speeds, but a condition of calm or very low speeds may also be important. For example, with no wind to disperse venting vapors such as LOX, a poor visibility situation could develop around the vehicle. Table 5.2.22 shows the frequency of calm winds at the 10-meter reference height for Cape Kennedy as a function of time of day and month. The maximum percentage of calms appears in the summer and during the early morning hours, with the minimum percentage appearing throughout the year during the afternoon. Similar tables for other location are available upon request.

5.2.6 Spectral Ground Wind Turbulence Model

Under most conditions ground winds are fully developed turbulent flows. This is particularly true when the wind speed is greater than a few meters per second, the atmosphere is unstable, or when both conditions exist. During nighttime conditions when the wind speed is low and the stratification is stable, the intensity of turbulence is small if not nil. Spectral methods are a particularly useful way of representing the turbulent portion of the ground wind environment for launch vehicle design purposes, as well as for use in diffusion calculations of toxic fuels and atmospheric pollutants. At the present time, a spectral turbulence model of the longitudinal and horizontal lateral components of turbulence that is valid for all conditions, except for the case of a nighttime stable stratification, is available.

5.2.6.1 Introduction

At a fixed point in the atmospheric boundary layer, the instantaneous wind vector fluctuates in time about the horizontal quasi-steady wind vector. The vector departure of the horizontal component of the instantaneous wind vector from the quasi-steady wind vector is the horizontal vector component of turbulence. This vector departure can be represented by two components, the longitudinal and the lateral components of turbulence that are parallel and perpendicular to the quasi-steady wind vector in the horizontal plane (Figure 5.2.6). The model contained herein is a spectral representation

TABLE 5. 2. 22 FREQUENCY (%) OF CALM WIND AT THE 10-m LEVEL, CAPE KENNEDY

Hour EST	Month												Annual
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	
00	4.8	4.0	3.6	1.3	7.3	9.2	11.7	13.7	6.3	6.9	6.3	6.0	6.8
01	2.8	1.3	2.4	1.7	8.9	8.3	10.9	14.1	7.1	4.8	6.3	6.5	6.3
02	4.8	2.2	3.6	2.9	7.7	10.0	11.7	13.7	10.4	7.3	5.4	4.0	7.0
03	5.2	3.1	2.0	3.8	8.5	12.1	11.3	17.3	12.1	5.2	2.9	3.2	7.3
04	2.8	4.4	2.4	3.8	5.2	13.8	14.5	13.7	10.8	5.2	4.6	2.8	7.0
05	4.4	4.0	3.2	2.9	9.7	16.3	15.3	18.5	13.3	3.6	4.6	4.4	8.4
06	4.4	4.0	4.4	2.9	8.9	16.3	19.8	19.0	13.3	3.2	5.0	5.2	8.9
07	3.6	4.4	4.8	6.3	10.5	16.7	18.1	19.4	15.8	4.4	5.4	5.6	9.6
08	3.6	6.6	6.5	2.9	2.4	5.4	6.0	6.9	4.6	4.0	8.8	4.4	5.2
09	3.6	1.8	2.0	2.1	2.8	3.8	4.8	1.6	4.2	0.8	4.6	5.6	3.1
10	0.4	1.8	1.6	1.7	0.4	3.8	4.0	2.8	2.1	a	1.3	2.4	1.8
11	0.4	1.3	1.2	1.7	0.8	1.3	2.4	0.8	2.9	0.8	1.7	0.8	1.3
12	1.6	0.4	a	a	a	0.8	0.8	0.4	1.3	0.4	2.1	1.2	0.8
13	2.0	0.4	a	a	0.4	1.3	0.4	1.6	0.8	0.4	1.7	0.4	0.8
14	0.8	4.0	0.8	0.4	0.4	0.8	1.2	1.6	1.3	0.8	a	0.4	0.7
15	0.4	1.3	a	a	a	0.8	0.4	1.6	2.5	0.4	0.4	0.4	0.7
16	0.4	0.4	0.4	a	0.8	0.4	0.8	0.4	1.3	0.8	a	0.8	0.5
17	1.6	0.4	a	0.4	0.4	2.1	0.8	3.2	2.1	1.6	1.7	2.0	1.4
18	4.0	1.8	0.8	0.4	1.6	2.5	3.2	4.0	2.9	1.2	5.0	7.7	2.9
19	2.8	3.5	2.0	a	1.6	5.0	2.8	5.2	4.6	1.2	7.1	6.5	3.5
20	4.4	3.5	2.8	1.7	3.2	6.7	5.6	8.5	7.5	1.6	6.3	6.0	4.8
21	5.2	4.0	3.2	1.3	4.8	7.5	10.5	8.9	8.3	4.4	5.0	6.0	5.8
22	3.6	2.2	2.4	1.7	6.0	7.5	7.7	12.9	7.9	4.8	6.3	5.2	5.7
23	5.6	3.5	4.8	0.8	6.5	8.3	10.5	15.3	10.0	5.6	4.6	5.2	6.8
All Hours	3.1	2.5	2.3	1.7	4.1	6.7	7.3	8.6	6.4	2.9	4.0	3.9	4.5

a. values < 0.4 percent

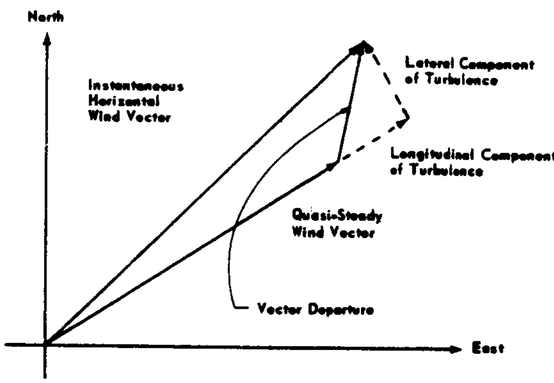


FIGURE 5. 2. 6 THE RELATIONSHIP BETWEEN THE QUASI-STEADY AND THE HORIZONTAL INSTANTANEOUS WIND VECTORS AND THE LONGITUDINAL AND LATERAL COMPONENTS OF TURBULENCE

of the characteristics of the longitudinal and lateral components of turbulence. The model analytically defines the spectra of these components of turbulence for the first 200 meters of the boundary layer. In addition, it defines the longitudinal and lateral cospectra, quadrature spectra, and the corresponding coherence functions associated with any pair of levels in the boundary layer. Details concerning the model herein can be found in References 5. 8, 5. 9, and 5. 10.

5. 2. 6. 2 Turbulence Spectra

The longitudinal and lateral spectra of turbulence at frequency ω and height z can be represented by a dimensionless function of the form

$$\frac{\omega\, S(\omega)}{\beta\, u_*^{\,2}} = \frac{c_1\, f/f_m}{\left[1 + 1.5\,(f/f_m)^{c_2}\right]^{5/3\, c_2}} \qquad (5.3)$$

where

$$f = \frac{\omega z}{u(z)} \qquad (5.4)$$

$$f_m = c_3 \left(\frac{z}{z_r}\right)^{c_4} \qquad (5.5)$$

$$\beta = \left(\frac{z}{z_r}\right)^{c_5} \qquad (5.6)$$

$$u_* = c_6\, u(z_r) \qquad (5.7)$$

In these equations z_r is a reference height equal to 18. 3 meters (60 ft); $\bar{u}(z)$ is the quasi-steady wind speed at height z; and the quantities c_i (i = 1, 2, 3, 4, 5) are dimensionless constants that depend upon the site and

TABLE 5.2.23 DIMENSIONLESS CONSTANTS FOR THE LONGITUDINAL SPECTRUM OF TURBULENCE FOR THE EASTERN TEST RANGE

Condition	c_1	c_2	c_3	c_4	c_5
Light Wind Daytime Conditions	2.905	1.235	0.04	0.87	-0.14
Strong Winds	6.198	0.845	0.03	1.00	-0.63

TABLE 5.2.24 DIMENSIONLESS CONSTANTS FOR THE LATERAL SPECTRUM OF TURBULENCE FOR THE EASTERN TEST RANGE

Condition	c_1	c_2	c_3	c_4	c_5
Light Wind Daytime Conditions	4.599	1.144	0.033	0.72	-0.04
Strong Winds	3.954	0.781	0.1	0.58	-0.35

the stability. The frequency ω is defined with respect to a structure or vehicle at rest relative to the earth. To apply the spectral model to the Shuttle or aircraft landing problem, the mean wind speed $u(z)$ at height z shall be replaced with the mean wind speed relative to the vehicle. The longitudinal and lateral spectra shall then be applied in the longitudinal and lateral directions relative to the vehicle flight path. The lateral spectrum can also be used for the vertical power spectrum. The spectrum $S(\omega)$ is defined so that integration over the domain $0 \leq \omega \leq \infty$ yields the variance of the turbulence. For the launch sites at the Eastern Test Range,[5] it is permissible for engineering purposes to use the values of c_i given in Table 5.2.23 for the longitudinal spectrum and Table 5.2.24 for the lateral spectrum. The constant c_6 can be estimated with the equation

$$c_6 = \frac{0.4}{\ln\left(\frac{z_r}{z_0}\right) - \Psi} , \qquad (5.8)$$

where z_0 is the surface roughness length of the site and Ψ is a parameter that depends upon the stability. If z_0 is not available for a particular site, then an estimate of z_0 can be obtained by taking 10 percent of the typical height of the surface obstructions (grass, shrubs, trees, rocks, etc.) over

5. Eastern Test Range, Kennedy Space Center, and Cape Kennedy are synonymous in this report.

TABLE 5.2.25 TYPICAL VALUES OF SURFACE ROUGHNESS LENGTH (z_0) FOR VARIOUS TYPES OF SURFACES

Type of Surface	z_0 (m)	—z_0 (ft)
Mud flats, ice	10^{-5} - $3 \cdot 10^{-5}$	$3 \cdot 10^{-5}$ - 10^{-4}
Smooth sea	$2 \cdot 10^{-4}$ - $3 \cdot 10^{-4}$	$7 \cdot 10^{4}$ - 10^{-3}
Sand	10^{-4} - 10^{-3}	$3 \cdot 10^{-4}$ - $3 \cdot 10^{-3}$
Snow surface	10^{-3} - $6 \cdot 10^{-3}$	$3 \cdot 10^{-4}$ - $2 \cdot 10^{-2}$
Mown grass (~ 0.01 m)	10^{-3} - 10^{-2}	$3 \cdot 10^{-3}$ - $3 \cdot 10^{-2}$
Low grass, steppe	10^{-2} - $4 \cdot 10^{-2}$	$3 \cdot 10^{-2}$ - 10^{-1}
Fallow field	$2 \cdot 10^{-2}$ - $3 \cdot 10^{-2}$	$6 \cdot 10^{-2}$ - 10^{-1}
High grass	$4 \cdot 10^{-2}$ - 10^{-1}	10^{-1} - $3 \cdot 10^{-1}$
Palmetto	10^{-1} - $3 \cdot 10^{-1}$	$3 \cdot 10^{-1}$ - 1
Suburbia	1 - 2	3 - 6
City	1 - 4	3 - 13

a fetch from the site with length equal to approximately 1500 meters. The parameter Ψ vanishes for strong wind conditions and is of order unity for light wind unstable daytime conditions at the Kennedy Space Center. Typical values of z_0 for various surfaces are given in Table 5.2.25. The value of z_0 given for Palmetto is recommended for Kennedy Space Center design studies.

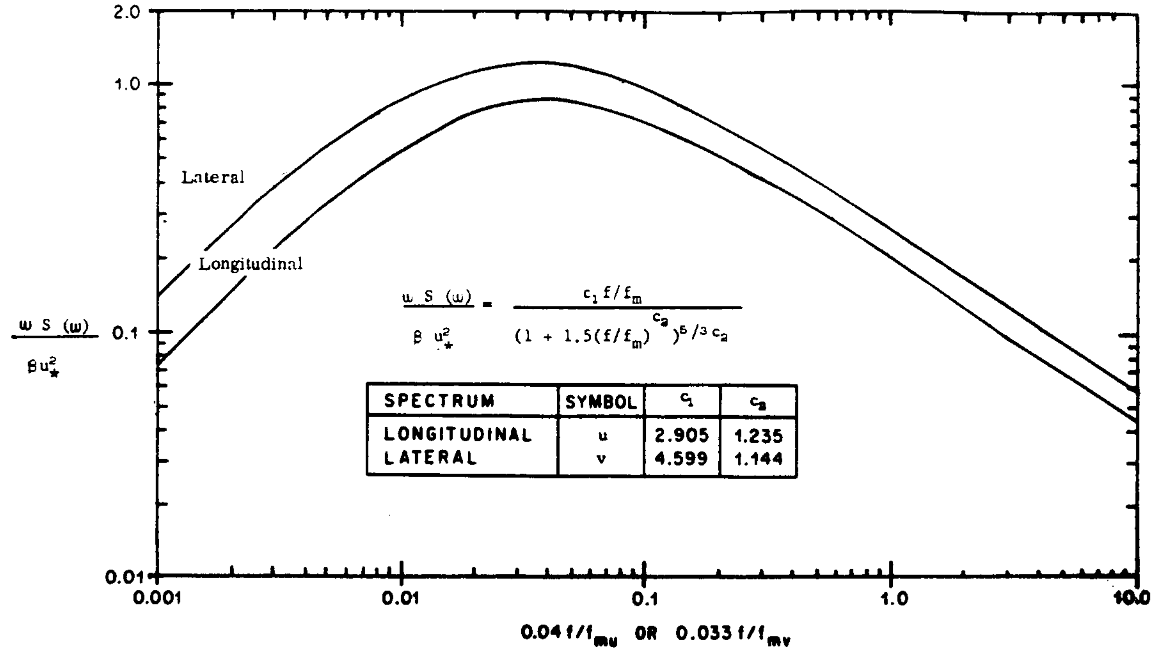
The functions given by equations (5.3), (5.5), and (5.6) are depicted in Figures 5.2.7 through 5.2.12. Upon prescribing the steady-state wind profile $\bar{u}(z)$ and the site (z_0), the longitudinal and lateral spectra are completely specified functions of height z and frequency ω. A discussion of the units of the various parameters mentioned above is given in subsection 5.2.6.4.

5.2.6.3 The Cospectrum and Quadrature Spectrum

The cospectrum and the quadrature spectrum associated with either the longitudinal or lateral components of turbulence at levels z_1 and z_2 can be represented by the following:

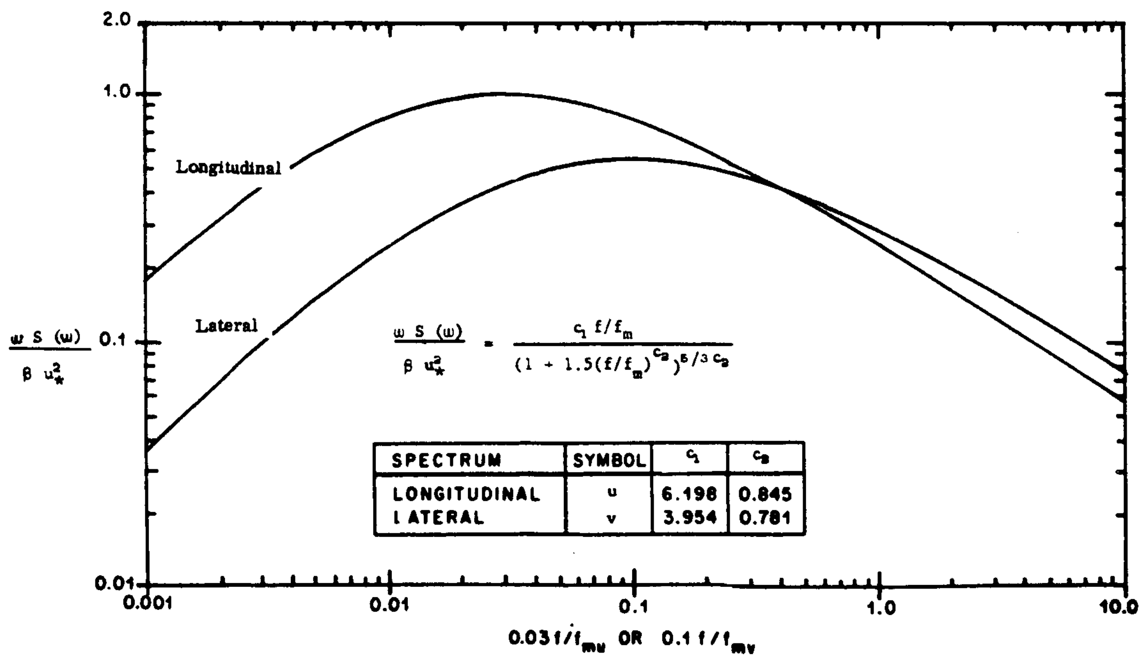
$$C(\omega, z_1, z_2) = \sqrt{S_1 S_2} \; \exp\left(-0.3465 \frac{\Delta f}{\Delta f_{0.5}}\right) \cos(2\pi\gamma\Delta f) \qquad (5.9)$$

$$Q(\omega, z_1, z_2) = \sqrt{S_1 S_2} \; \exp\left(-0.3465 \frac{\Delta f}{\Delta f_{0.5}}\right) \sin(2\pi\gamma\Delta f) \;, \qquad (5.10)$$



SPECTRUM	SYMBOL	c_1	c_2
LONGITUDINAL	u	2.905	1.235
LATERAL	v	4.599	1.144

FIGURE 5.2.7 $\frac{\omega S(\omega)}{\beta u_*^2}$ VERSUS $\frac{0.04f}{f_m}$ (longitudinal) AND $\frac{0.033f}{f_m}$ (lateral) FOR LIGHT WIND DAYTIME CONDITIONS, CAPE KENNEDY



SPECTRUM	SYMBOL	c_1	c_2
LONGITUDINAL	u	6.198	0.845
LATERAL	v	3.954	0.781

FIGURE 5.2.8 $\frac{\omega S(\omega)}{\beta u_*^2}$ VERSUS $\frac{0.03f}{f_m}$ (longitudinal) AND $\frac{0.1f}{f_m}$ (lateral) FOR STRONG WIND CONDITIONS, CAPE KENNEDY

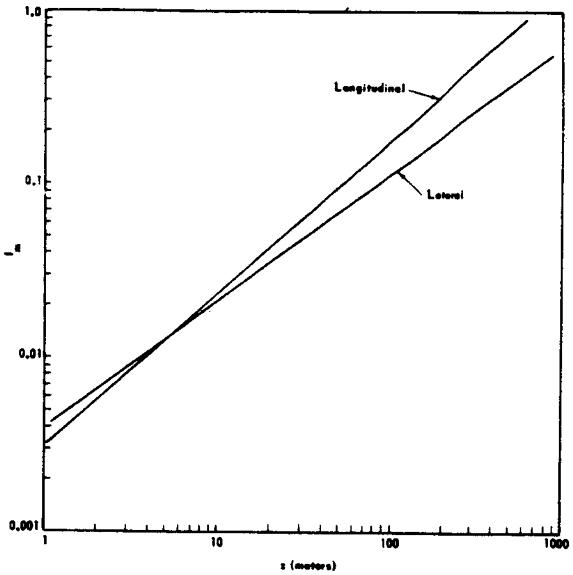


FIGURE 5.2.9 f_m VERSUS z FOR LIGHT WIND DAYTIME CONDITIONS, CAPE KENNEDY

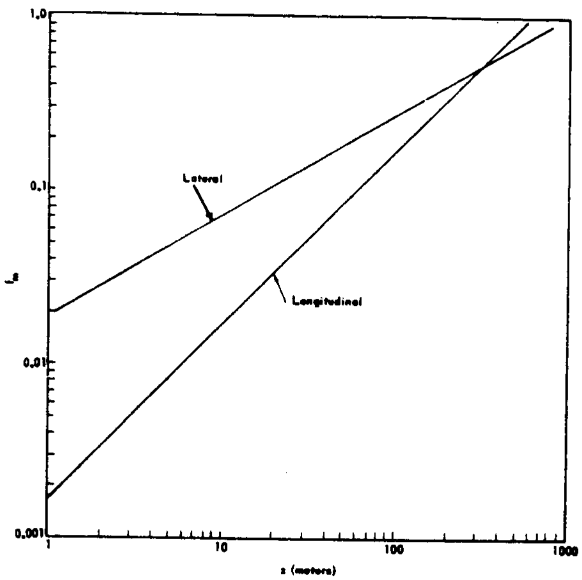


FIGURE 5.2.10 f_m VERSUS z FOR STRONG WIND CONDITIONS, CAPE KENNEDY

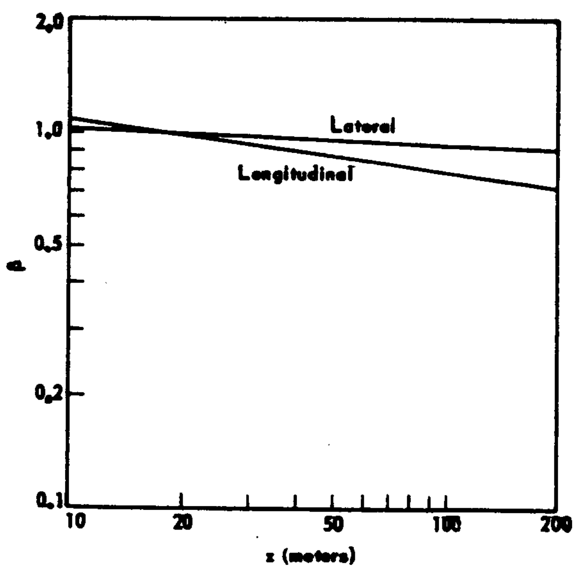


FIGURE 5.2.11 β VERSUS z FOR LIGHT WIND DAYTIME CONDITIONS

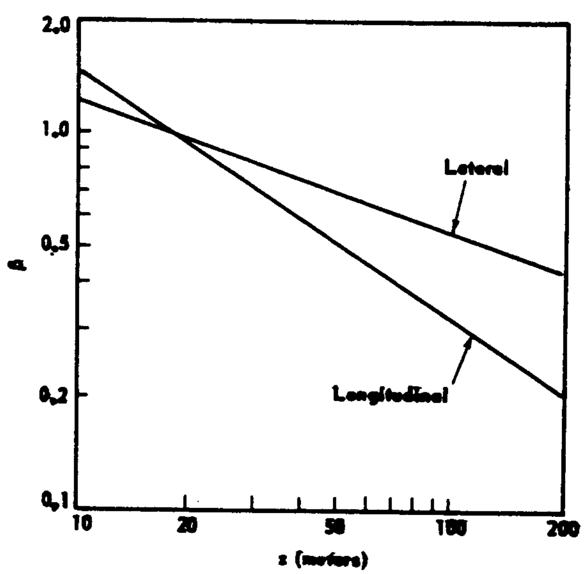


FIGURE 5.2.12 β VERSUS z FOR STRONG WIND CONDITIONS

where

$$\Delta f = \frac{\omega z_2}{\bar{u}(z_2)} - \frac{\omega z_1}{\bar{u}(z_1)} \quad . \tag{5.11}$$

TABLE 5. 2. 26 VALUES OF $\Delta f_{0.5}$ FOR THE EASTERN TEST RANGE

Turbulence Component	Light Wind Daytime Conditions	Strong Winds
Longitudinal	0.04	0.036
Lateral	0.06	0.045

TABLE 5. 2. 27 VALUES OF γ FOR THE EASTERN TEST RANGE

Turbulence Component	$(z_1 + z_2)/2 \leq 100m$	$(z_1 + z_2)/2 > 100m$
Longitudinal	0.7	0.3
Lateral	1.4	0.5

S_1 and S_2 are the longitudinal or lateral spectra at levels z_1 and z_2, respectively, and $\bar{u}(z_1)$ and $\bar{u}(z_2)$ are the steady-state wind speeds at levels z_1 and z_2. The quantity $\Delta f_{0.5}$ is a dimensionless function of stability, and values of this parameter for the Eastern Test Range are given in Table 5. 2. 26. The dimensionless quantity γ should depend upon height and stability. However, it has only been possible to detect a dependence on height at the Eastern Test Range. Based upon an analysis of turbulence data measured at the NASA 150-meter meteorological tower facility, the values of γ in Table 5. 2. 27 are suggested for the Eastern Test Range. The quantity $\Delta f_{0.5}$ can be interpreted by constructing the coherence function, which is defined to be

$$\mathrm{coh}(\omega, z_1, z_2) = \frac{C^2 + Q^2}{S_1 S_2} \quad . \qquad (5.12)$$

Substituting equations (5. 9) and (5. 10) into equation (5. 12) yields

$$\mathrm{coh}(\omega, z_1, z_2) = \exp\left(-0.693 \frac{\Delta f}{\Delta f_{0.5}}\right) \quad . \qquad (5.13)$$

It is clear from this relationship that $\Delta f_{0.5}$ is that value of Δf for which the coherence (coh) is equal to 0. 5.

5. 2. 6. 4 Units

The spectral model of turbulence presented in subsections 5. 2. 6. 2 and 5. 2. 6. 3 is a dimensionless model. Accordingly, the user is free to select the system of units he desires, except that ω must have the units of cycles per unit time. Table 5. 2. 28 gives the appropriate metric and U. S. customary units for the various quantities in the model.

TABLE 5.2.28 METRIC AND U. S. CUSTOMARY UNITS OF VARIOUS QUANTITIES IN THE TURBULENCE MODEL

Quantity	Metric Units	U. S. Customary Units
ω	Hz	Hz
$S(\omega)$, $Q(\omega)$, $C(\omega)$	$m^2 s^{-2}/Hz$	$ft^2 s^{-2}/Hz$
f, f_m, Δf, $\Delta f_{0.5}$	Dimensionless	Dimensionless
z, z_r, z_0	m	ft
u, u_*	ms^{-1}	$ft\ s^{-1}$
β	Dimensionless	Dimensionless
Coh	Dimensionless	Dimensionless
γ	Dimensionless	Dimensionless
Ψ	Dimensionless	Dimensionless

5.2.7 Ground Wind Gust Factors

The solutions of problems dealing with surface winds for the design and launch of space vehicles include analyses of wind gustiness or gust factor. Previous Marshall Space Flight Center ground wind gust factor design criteria adopted a gust factor of 1.4 and treated the gust as acting over the entire length of the vehicle. Revised ground wind mean gust factor design criteria were derived from data obtained during 1967 and 1968 at the 150-meter ground wind tower facility at Kennedy Space Center. To more precisely determine gust factors to a height of 150 meters, analyses have been made relating gust factors to height, steady-state or mean wind speed, peak wind speed at reference height 18.3 meters, and length of time used to obtain the mean wind speed. A study was made of 181 hours of data recorded when the atmosphere was generally unstable (daytime). The gust factor G is defined to be

$$G = u/\bar{u} \quad , \qquad (5.14)$$

where

u = maximum wind speed at height h within an averaging period of length τ in time

$\bar{u}$ = mean wind speed associated with the averaging period τ, given by

$$\bar{u} = \frac{1}{\tau} \int_{-\tau/2}^{\tau/2} v(t)\, dt \tag{5.15}$$

$v(t)$ = instantaneous wind speed at time t

t = time reckoned from the beginning of the averaging period.

If $\tau = 0$, then $\bar{u} = u$ according equation (5.15), and it follows from equation (5.14) that $G = 1.0$. As τ increases, $\bar{u}$ departs from u, and $\bar{u} \leq u$ and $G > 1.0$. Also, as τ increases, the probability of finding a maximum wind of a given magnitude increases. In other words, the maximum wind speed increases as τ increases. In the case of $\bar{u} = 0$ and $u \geq 0$ ($\bar{u} = 0$ might correspond to windless free convection), $G = \infty$. As $\bar{u}$ or u increases, G tends to decrease for fixed $\tau > 0$; while for very high wind speeds (neutral stratification), G tends to approach a constant value for given values of z and τ. Finally, as z increases, G decreases. Thus, the gust factor is a function of the averaging time τ over which the mean wind speed is calculated, the height z, and the wind speed (mean or maximum).

5.2.7.1 Gust Factor as a Function of Peak Wind Speed at Reference Height ($u_{18.3}$) for Cape Kennedy

Representation of the first factor G as a function of height h, averaging period τ, and the 18.3-meter peak wind speed $u_{18.3}$ is based upon the fact that the design wind statistics are calculated in terms of peak winds. Thus G will be given as a function of $u_{18.3}$, z and τ.

Investigations of the mean gust factor data revealed that the variation of the gust factor in the first 150 meters of the atmosphere could be described with the following relationships:

$$G = 1 + \frac{1}{g_0} \left(\frac{18.3}{z}\right)^p , \tag{5.16}$$

where h is the height in meters above natural grade. The parameter p, a function of the 18.3-meter peak wind speed in meters per second, is given by

$$p = 0.283 - 0.435\, e^{-0.2\, u_{18.3}} . \tag{5.17}$$

The parameter g_0, depends on the averaging time and the 18.3-meter peak wind speed and is given by

$$g_0 = 0.085 \left(\ln \frac{\tau}{10}\right)^2 - 0.329 \left(\ln \frac{\tau}{10}\right) + 1.98 - 1.887\, e^{-0.2\, u_{18.3}} , \qquad (5.18)$$

where τ is given in minutes and, $u_{18.3}$ in meters per second.

These relationships are valid for $u_{18.3} \geq 4$ m/sec and $\tau \leq 10$ min. In the interval 10 min $\leq \tau \leq$ 60 min, G is a slowly increasing monotonic function of τ, and for all practical purposes the 10-minute gust factors (τ = 10 min) can be used as estimates of the gust factors associated with averaging times greater than 10 minutes and less than 60 minutes (10 min $\leq \tau \leq$ 60 min).

The dependence of the 18.3-meter height gust factor upon the averaging time and the peak wind speed is shown in Figure 5.2.13. Figure 5.2.14 illustrates the dependence of the 10-minute gust factors upon the peak wind speed and height.

The calculated mean gust factors for 10 minutes for values of $u_{18.3}$ in the interval 4.63 m/sec $\leq u_{18.3} \leq \infty$ are presented in Table 5.2.29 in both the U. S. customary and metric units for $u_{18.3}$ and h. The gust factor profile for τ = 10 minutes and $u_{18.3}$ = 9.27 m/sec (18 knots) is given by Table 5.2.30. These values are valid only for the Cape Kennedy area.

Since the basic wind statistics are given in terms of hourly peak winds, use the τ = 10 minute gust factors to convert the peak winds to mean winds by dividing by G. All gust factors in these sections are expected values for any particular set of values for u, τ, and h.

5.2.7.2 Gust Factors for Other Locations

For design purposes, the gust factor value of 1.4 will be used over all altitudes of the ground wind profile at other test ranges. This gust factor should correspond to approximately a 10-minute averaging period.

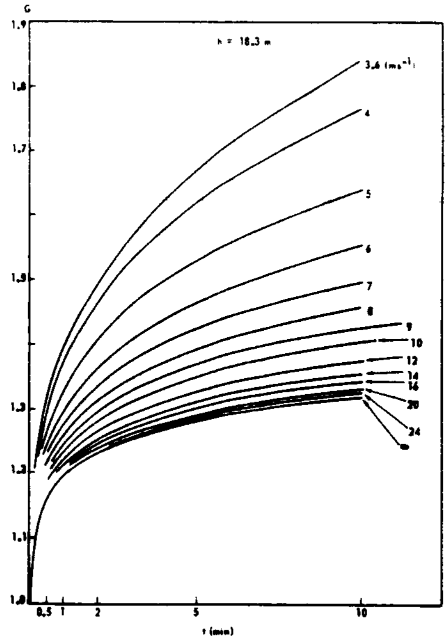


FIGURE 5. 2. 13 GUST FACTOR AS A FUNCTION OF TIME FOR VARIOUS VALUES OF $u_{18.3}$ IN THE INTERVAL

$3.6 \le u_{18.3} \le \infty$

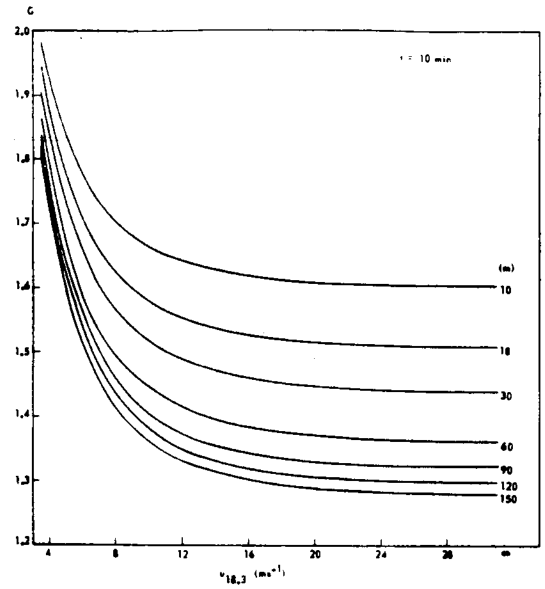


FIGURE 5. 2. 14 GUST FACTOR AS A FUNCTION OF PEAK WIND (u) FOR VARIOUS HEIGHTS

5. 2. 8 Ground Wind Shear

Local or point values of wind shear can be obtained by differentiating equation (5. 1) with respect to height z. When the 18. 3-meter level is used as a reference and the 99. 97-percentile values of k are employed, the equation for local wind shear is given by

$$\frac{du}{dz} = \frac{1.6\, u_{18.3}^{1/4}}{z} \left(\frac{z}{18.3}\right)^{1.6\, u_{18.3}^{-3/4}} . \qquad (5.19)$$

Figure 5. 2. 15 presents the shears as computed with the above equation for six levels. Wind shear near the surface, for design purposes, is a shear that acts upon a space vehicle, free-standing on the pad, or at time of lift-off. For overturning moment calculations, the 10-minute mean wind at the height of the vehicle base and the peak wind profile value at the height of the vehicle top is employed in the calculations.

TABLE 5. 2. 29 10-min GUST FACTORS FOR CAPE KENNEDY

60-ft (18.3-m) peak wind kts (ms^{-1})	Height Above Natural Grade in Feet (meters)						
	33 (10.0)	60 (18.3)	100 (30.5)	200 (61.0)	300 (91.4)	400 (121.9)	500 (152.4)
9.0 (4.63)	1.868	1.812	1.767	1.710	1.679	1.658	1.642
10.0 (5.15)	1.828	1.766	1.718	1.657	1.624	1.602	1.585
11.0 (5.66)	1.795	1.729	1.678	1.614	1.580	1.556	1.539
12.0 (6.18)	1.768	1.699	1.645	1.579	1.544	1.520	1.502
13.0 (6.69)	1.746	1.674	1.618	1.550	1.514	1.489	1.471
14.0 (7.21)	1.727	1.652	1.595	1.525	1.488	1.464	1.446
15.0 (7.72)	1.712	1.634	1.576	1.505	1.467	1.442	1.424
16.0 (8.24)	1.698	1.619	1.559	1.487	1.449	1.424	1.406
17.0 (8.75)	1.686	1.606	1.545	1.472	1.434	1.409	1.390
18.0 (9.27)	1.676	1.594	1.532	1.459	1.421	1.395	1.377
19.0 (9.78)	1.668	1.584	1.522	1.447	1.409	1.384	1.365
20.0 (10.30)	1.660	1.575	1.512	1.437	1.399	1.374	1.355
25.0 (12.87)	1.634	1.545	1.480	1.403	1.365	1.339	1.321
30.0 (15.44)	1.619	1.528	1.462	1.385	1.346	1.321	1.302
∞ (∞)	1.599	1.505	1.437	1.359	1.320	1.295	1.277

TABLE 5. 2. 30 GUST FACTOR PROFILE FOR τ = 10 min AND $u_{18.3}$ = 9. 27 m/sec (18 knots)

Height		Gust Factor (G)
(ft)	(m)	
33	10. 0	1. 676
60	18. 3	1. 594
100	30. 5	1. 532
200	61. 0	1. 459
300	91. 4	1. 421
400	121. 9	1. 395
500	152. 4	1. 377

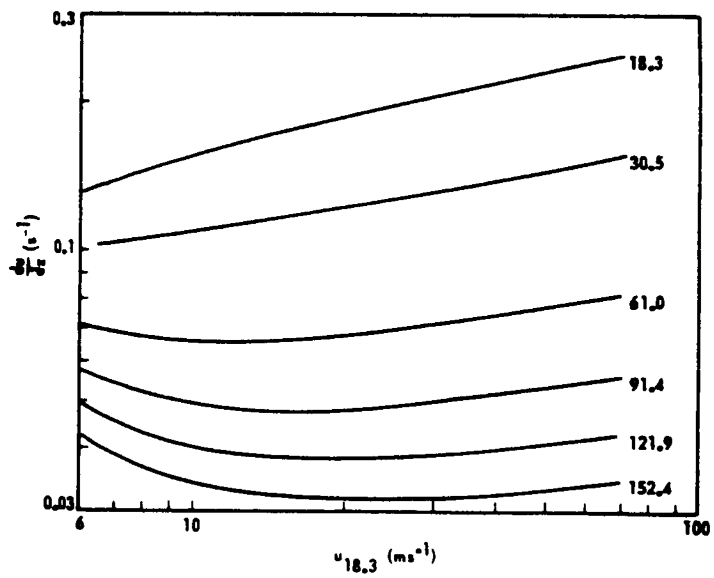


FIGURE 5. 2. 15 LOCAL WIND SHEARS FOR SIX LEVELS

5. 2. 9 Ground Wind Direction Characteristics

Figure 5. 2. 1 (Subsection 5. 2. 5) shows a time trace of wind direction (a section of a wind direction recording chart). This wind direction trace may be visualized as being composed of a mean wind direction plus fluctuations about the mean. An accurate measure of wind direction in the free

atmosphere near the ground is difficult to obtain because of the interference of the structure that supports the instrumentation and other obstacles in the vicinity of the measurement location (Ref. 5.11). The measured wind directions represent conditions existing at a given place, and they are directly applicable in vehicle-response-to-ground-winds studies.

General information such as that which follows is available and may be used to specify conditions for particular studies. For instance, in Reference 5.12 is discussed the variation of lateral wind-direction for various stability regimes. A graph is shown in Reference 5.12 that gives values of the standard deviation of the lateral wind direction σ_θ as a function of height for a sampling time of about 10 minutes. It states that σ_θ for sampling periods greater than 1 minute with some given stability condition will always be larger when the wind is light than when it is strong. In general, the more stable the air, the smaller the σ_θ, except for the case of meandering wind directions for very low wind speeds and very stable conditions.

5.2.10 Design Winds for Facilities and Ground Support Equipment

5.2.10.1 Introduction

In this section, the important relationships between desired lifetime N, calculated risk U, design return period T_D, and design wind W_D will be described for use in facilities design for several locations.

a. The desired lifetime N is expressed in years, and preliminary estimates must be made as to how many years the proposed facility is to be used.

b. The calculated risk U is a probability expressed either as a percentage or as a decimal fraction. Calculated risk, sometimes referred to as design risk, is a probability measure of the risk the designer is willing to accept that the facility will be destroyed by wind loading in less time than the desired lifetime.

c. The design return period T_D is expressed in years and is a function of desired lifetime and calculated risk.

d. The design wind W_D is a function of the desired lifetime and calculated risk and can be derived either through the design return period and a probability distribution function of yearly peak winds or from an analytical expression.

5. 2. 10. 2 Development of Relationships

From the theory of repeated trial probability we can derive the following expression:

$$N = \frac{\ln(1 - U)}{\ln\left(1 - \frac{1}{T_D}\right)} \qquad . \qquad (5.20)$$

Equation (5. 20) gives the important relationships for the three variables, calculated risk U, design return period T_D, and desired lifetime N. If estimates for any two variables are available, the third can be determined.

From the derivation of equation (5. 20), solutions for the design return period versus desired lifetime for various design risks are given in Table 5. 2. 31. In Table 5. 2. 31, the exact and adopted values for design return period versus desired lifetime for various design risk are presented. The adopted values for T_D are in some cases greatly oversized to facilitate a convenient use of the tabulated probabilities for the distributions of yearly peak winds.

FIGURE 5. 2. 31 EXACT AND ADOPTED VALUES FOR DESIGN RETURN PERIOD (T_D, years) VERSUS DESIRED LIFETIME (N, years FOR VARIOUS DESIGN RISKS (U)

N (years)	Design Return Period (years)									
	U = 0.50%		U = 0.20%		U = 10%		U = 5%		U ≠ 1%	
	Exact	Adopted	Exact	Adopted	Exact	Adopted	Exact	Adopted	Exact	Adopted
1	2	2	15	5	10	10	20	20	100	100
10	15	15	45	50	95	100	196	200	996	1000
20	29	30	90	100	190	200	390	400	1991	2000
25	37	40	113	125	238	250	488	500		
30	44	50	135	150	285	300	585	600		
50	73	100	225	250	475	500	975	1000		
100	145	150	449	500	950	1000	1950	2000		

5.2.10.3 Design Winds for Facilities at Cape Kennedy

To obtain the design wind, it is required that the wind speed corresponding to the design return period be determined. Since the design return period can be expressed in terms of probability, either of two procedures can be used to determine the design wind: One is through a graphical or numerical interpolation procedure; The second is from an analytical function. A knowledge of the distribution of yearly peak winds is required for both procedures. For the greatest statistical efficiency in arriving at a knowledge of the probability that peak winds will be less than or equal to some specified value of yearly peak winds {that is, $P(W \leq W*)$ or for exceedance probabilities, $P(W > W*) = [1 - P(W \leq W*)]$}, the choice of an appropriate probability distribution function is made, and the parameters for the function are estimated from the sample of yearly peak winds. From the investigation leading to the distribution of hourly, daily, monthly, and yearly peaks it was learned that the Gumbel distribution was an excellent fit for the 17 years of yearly peak ground winds at the 10-meter level for Cape Kennedy. (The Fréchet, a special case of Fisher-Tippett Type II, distribution, was also an adequate fit to this sample.) The distribution of yearly peak wind (10-meter level), as obtained by the Gumbel distribution, is tabulated for various percentiles along with the corresponding return periods in Table 5.2.32. The values for the parameters α and μ for this distribution are also given in this table.

The design wind can now be determined by making a choice for desired lifetime and design risk and by taking the design return period from Table 5.2.31 and looking up the wind speed corresponding to the return period given in Table 5.2.32. For combinations not tabulated in Tables 5.2.31 and 5.2.32, the design return period can be interpolated.

5.2.10.4 Procedure to Determine Design Winds for Facilities

It is desired to show an analytical form for the design wind W_D as a function of desired lifetime N and calculated risk U, given a Gumbel distribution. This expression for W_D as a function of N and U for the Gumbel distribution of peak winds at the 10-meter reference level can be derived as

$$W_D = \frac{1}{\alpha}\{-\ell n[-\ell n(1-U)] + \ell n\ N\} + \mu \quad , \qquad (5.21)$$

where α and μ are estimated from the sample of yearly peak winds.

TABLE 5.2.32 GUMBEL DISTRIBUTION FOR YEARLY PEAK WIND SPEED, 10-m REFERENCE LEVEL, INCLUDING HURRICANE WINDS, CAPE KENNEDY

Return Period (years)	Probability	y	m/sec	Knots
2	0.50	0.36651	25.45	49.47
5	0.80	1.49994	31.79	61.79
10	0.90	2.25037	35.98	69.95
15	0.933	2.66859	38.33	74.50
20	0.95	2.97020	40.01	77.77
30	0.967	3.39452	42.38	82.39
45	0.978	3.80561	44.68	86.86
50	0.98	3.90191	45.22	87.90
90	0.9889	4.49523	48.54	94.35
100	0.99	4.60015	49.12	95.49
150	0.9933	5.00229	51.37	99.86
200	0.995	5.29581	53.01	103.05
250	0.996	5.51946	54.26	105.48
300	0.9967	5.71218	55.34	107.58
400	0.9975	5.99021	56.90	110.60
500	0.9980	6.21361	58.14	113.02
600	0.9983	6.37628	58.75	114.20
1 000	0.9990	6.90726	62.02	120.56
10 000	0.9999	9.21029	74.90	145.60

α = 0.1788 m/sec^{-1} (0.0920 knots)$^{-1}$ $\frac{1}{\alpha}$ = 5.5917 m/sec (10.8675 knots)

μ = 23.4 m/sec (45.49 knots)

Taking the values for $\frac{1}{\alpha}$ = 5.5917 m/sec (10.8695 knots) and for μ = 23.4 m/sec (45.49 knots) from Table 5.2.32 and evaluating equation (5.21) for selected values of N and U, yields the data in Table 5.2.33.

TABLE 5.2.33 FACILITY DESIGN WIND $\left(W_{D_{10}}\right)$ WITH RESPECT TO THE 10-m REFERENCE LEVEL PEAK WIND SPEED FOR VARIOUS LIFETIMES (N), CAPE KENNEDY

U	1 - U	ln [ln (1 - U)]	Design Wind $(W_{D_{10}})$ for Various Lifetimes (N)[a]							
			N = 1		N = 10		N = 30		N = 100	
			(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
0.63212	0.36788	0	23.40	45.49	36.28	70.52	42.42	82.46	49.15	95.55
0.50	0.50	0.36651	25.45	49.47	38.33	74.50	44.47	86.44	51.20	99.53
0.4296	0.5704	0.57722	26.62	51.76	39.50	76.79	45.65	88.73	52.38	101.82
0.40	0.60	0.67173	27.16	52.79	40.03	77.82	46.18	89.76	52.92	102.85
0.30	0.70	1.03093	29.17	56.70	42.04	81.72	48.19	93.67	54.92	106.75
0.20	0.80	1.49994	31.79	61.79	44.66	86.82	50.81	98.76	57.54	111.85
0.10	0.90	2.25037	35.99	69.95	48.86	94.98	55.00	106.92	61.74	120.01
0.05	0.95	2.97020	40.01	77.77	52.88	102.80	59.03	114.74	65.76	127.83
0.01	0.99	4.60016	49.12	95.49	62.00	120.52	68.14	132.46	74.88	145.55

a. Values of N are given in years.

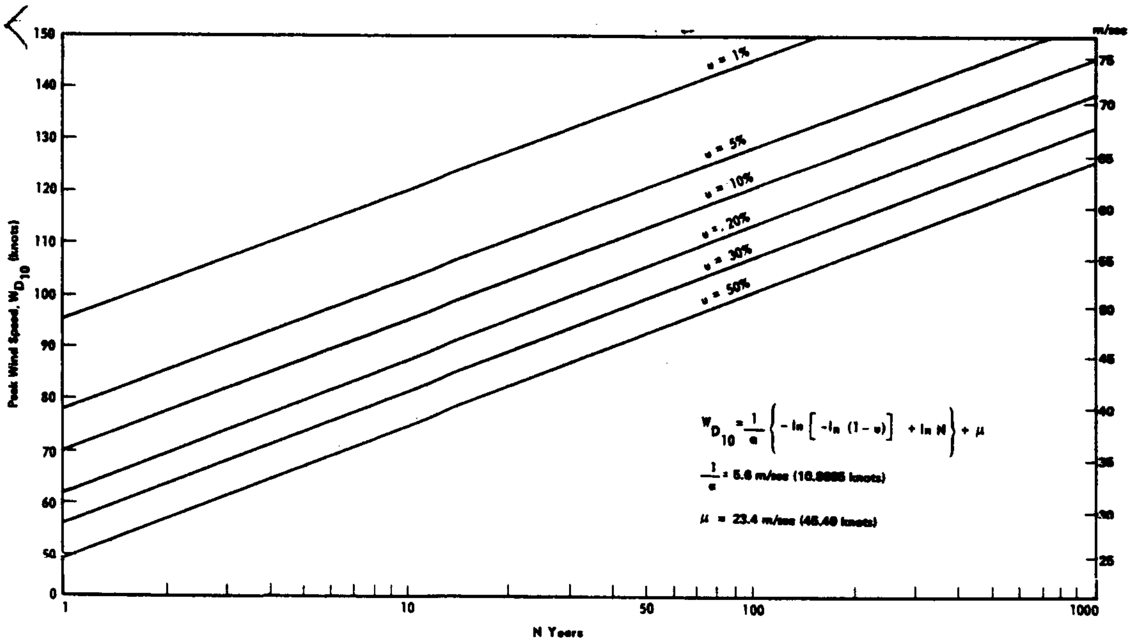


FIGURE 5.2.16 FACILITY DESIGN WIND $\left(W_{D_{10}}\right)$ WITH RESPECT TO THE 10-m REFERENCE LEVEL PEAK WIND SPEED FOR VARIOUS LIFETIMES (N), CAPE KENNEDY

An inspection of equation (5.21) reveals that the design wind $W_{D_{10}}$ is a linear function of the logarithm of the desired lifetime for given values of α and μ. Thus, a convenient plot for design wind versus desired lifetime can be illustrated as in Figure 5.2.16. The slope of all curves in Figure 5.2.16 is the same; therefore $\frac{\partial W_D}{\partial N}$ is a constant equal to $\frac{1}{\alpha}$ for all risk levels.

5.2.10.5 Requirements for Wind Load Calculations

The design wind for a structure cannot be determined solely by wind statistics at a particular height. Estimates of wind loads are required, for which a wind profile is needed. The design engineer is most interested in designing a structure which satisfies the users' requirements for utility, which will have a minimum risk of failure within the desired lifetime of the structure, and which can carry the maximum wind load and be constructed at a minimum cost. The total wind loading on a structure is composed of two interrelated components, drag wind loads and dynamic wind loads. The time required for a structure to respond to the drag wind loads dictates the averaging time for the wind profile. In general, the structure response time depends upon the shape and size of the structure. The natural frequency of the structure and the size and shape of the structure and its components are important in estimating the dynamic wind load. It is conceivable that a structure could be designed to withstand very high wind speeds without structural failure and still oscillate in moderate wind speeds. If such a structure, for example, is to be used to support a precision tracking radar, then there may be little danger of overloading the structure by high winds; but the structure might be useless for its intended purpose if it were to oscillate in a moderate wind. Also, a building may have panels or small members that could respond to dynamic loading in such a way that long-term vibrations could cause failure, without any structural failure of the main supporting members. Since dynamic wind loading requires an intricate knowledge of the particular facility and its components, no attempt is made here to state generalized design criteria for dynamic wind loading. The emphasis in this section is upon winds for estimating drag wind loads in establishing design wind criteria for structures. Reference is made to subsection 5.2.5 for some information appropriate to dynamic wind loads.

5.2.10.6 Wind Profile Construction

Given the peak wind at the 10-meter level, the peak wind profile can be constructed with the peak wind profile law from subsection 5.2.5. Equation (5.1) can be obtained by using the appropriate gust factors which are discussed in subsection 5.2.7.

To illustrate the procedures and operations in deriving the wind profile and the application of the gust factors, three examples are worked out for Cape Kennedy. The peak wind speed at the 10-meter level of 36, 49, and 62 m/sec (70, 95, and 120 knots) have been selected for these examples. These three wind speeds were selected because they correspond to a return period of 10, 100, and 1000 years for a peak wind at the 10-meter level at Cape Kennedy.

Now, let us consider 36-, 49-, and 62-m/sec (70-, 95-, and 120-knot) peak wind at the 10-meter level to be the design wind relative to the peak wind at the 10-meter level $\left(W_{D_{10}}\right)$, and the corresponding return periods to be the design return periods. Then the calculated risks versus the desired lifetimes are given in Table 5. 2. 34.

FIGURE 5. 2. 34 CALCULATED RISK (U) VERSUS DESIRED LIFETIME (N, years) FOR ASSIGNED DESIGN WINDS RELATED TO PEAK WINDS AT THE 10-m REFERENCE LEVEL, CAPE KENNEDY

N (years)	$W_{D_{10}}$ = 36 m/sec (70 knots) T_D = 10 years u%	$W_{D_{10}}$ = 49 m/sec (95 knots) T_D = 100 years u%	$W_{D_{10}}$ = 62 m/sec (120 knots) T_D = 1000 years u%
1	10	1. 0	0. 1
10	65	10	1
20	88	18	2
25	93	22	2. 5
30	95. 8	26	3
50	99. 5	39. 5	5
100	99. 997	63. 397	10

T_D = Design return period

From an evaluation of equation (5.1) for z = 10, 18.3, 30.5, 61.0, 91.4, 121.9, and 152.4 meters, the peak wind profiles corresponding to the peak winds of 36, 49, and 62 m/sec (70, 95, and 120 knots) at the 10-meter level, shown in Table 5.2.35, were obtained by a table look-up. Table 5.2.35 gives the peak design wind profiles corresponding to the desired lifetimes and calculated risks presented in Table 5.2.34.

5.2.10.7 Use of Gust Factors Versus Height

In estimating the drag load on a particular structure, it may be determined that wind force of a given magnitude must act on the structure for some period (for example, 1 min) to produce a critical drag load. To obtain the wind profile corresponding to a time averaged wind, the peak wind profile values are divided by the required gust factors. The gust factors for winds > 15 m/sec (30 knots) versus height given in Table 5.2.36 are taken from subsection 5.2.7. This operation may seem strange to those engineers who are accustomed to multiplying the given wind by a gust factor in establishing the design wind. This is because most literature on this subject gives the reference wind as averaged over some time increment (for example, 1, 2, or 5 min) or in terms of the "fastest mile" of wind that has a variable averaging time depending upon the wind speed. The design wind profiles for the three examples, that is, in terms of the peak winds of 36, 49, and 62 m/sec (70, 95, and 120 knots) at the 10-meter level, for various averaging times τ, given in minutes, are illustrated in Tables 5.2.37, 5.2.38, and 5.2.39. Following the procedures presented by this example, the design engineer can objectively derive several important design parameters that can be used in meeting the objective of designing a facility that will (1) meet the requirements for utility and desired lifetime, (2) withstand the maximum wind loading with a known calculated risk of failure, caused by wind loads, and (3) allow him to proceed with trade-off studies between the design parameters and to estimate the cost of building a structure to best meet these design objectives.

5.2.10.8 Recommended Design Risk Versus Desired Lifetime

Unfortunately, there is not a clear-cut precedent from building codes to follow in recommending design risk for a given desired lifetime of a structure. This could be because the consequences of total loss of a structure due to wind forces differ according to the purpose of the structure. Conceivably, a value analysis in terms of original investment cost, replacement cost, safety of property and human life, loss of national prestige, and many other factors could be made to give a measure of the consequences for the loss of a particular structure in arriving at a decision as to what risk the management is willing to accept for the loss within the desired lifetime of the structure. If the structure

TABLE 5.2.35 DESIGN[6] PEAK WIND PROFILES FOR DESIGN WIND RELATIVE TO THE 10-m REFERENCE LEVEL, CAPE KENNEDY

Height		$W_{D_{10}}$ = 36 m/sec (70 knots)		$W_{D_{10}}$ = 49 m/sec (95 knots)		$W_{D_{10}}$ = 62 m/sec (120 knots)	
(ft)	(m)	(knots)	(ms^{-1})	(knots)	(ms^{-1})	(knots)	(ms^{-1})
33	10	70.0	36.0	95.0	48.9	120.0	61.8
60	18.3	74.5	38.4	99.9	51.4	125.2	64.5
100	30.5	78.6	40.4	104.2	53.7	129.8	66.8
200	61.0	84.4	43.4	110.4	56.8	136.2	70.1
300	91.4	88.0	45.3	114.2	58.8	140.2	72.2
400	121.9	90.7	46.7	117.0	60.2	143.0	73.62
500	152.4	92.8	47.8	119.1	61.3	145.3	74.8

TABLE 5.2.36 GUST FACTORS FOR VARIOUS AVERAGING TIMES (τ) FOR PEAK WINDS > 15 m/sec (30 knots) AT THE 10-m REFERENCE LEVEL VERSUS HEIGHT, CAPE KENNEDY

Height		Various Averaging Times (τ, min)				
(ft)	(m)	τ=0.5	τ=1	τ=2	τ=5	τ=10
33	10	1.318	1.372	1.435	1.528	1.599
60	18.3	1.268	1.314	1.366	1.445	1.505
100	30.5	1.232	1.271	1.317	1.385	1.437
200	61.0	1.191	1.223	1.261	1.316	1.359
300	91.4	1.170	1.199	1.232	1.282	1.320
400	121.9	1.157	1.183	1.214	1.260	1.295
500	152.4	1.147	1.172	1.201	1.244	1.277

6. See Table 5.2.34 for calculated risk values versus desired lifetime for these design winds.

TABLE 5.2.37 DESIGN[7] WIND PROFILES FOR VARIOUS AVERAGING TIMES (τ) FOR PEAK DESIGN WIND OF 36.0 m/sec (70 knots) RELATIVE TO THE 10-m REFERENCE LEVEL, CAPE KENNEDY

Height		Design Wind Profiles for Various Averaging Times (τ)											
(ft)	(m)	τ=0		τ=0.5		τ=1		τ=2		τ=5		τ=10	
		(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
33	10	36.0	70.0	27.3	53.1	26.2	51.0	25.1	48.8	23.6	45.8	22.5	43.8
60	18.3	38.3	74.5	30.2	58.8	29.2	56.7	28.0	54.5	26.5	51.6	25.5	49.5
100	30.5	40.4	78.6	32.8	63.8	31.8	61.8	30.7	59.7	29.2	56.8	28.1	54.7
200	61.0	43.4	84.4	36.5	70.9	35.5	69.0	34.4	66.9	33.0	64.1	31.9	62.1
300	91.4	45.3	88.0	38.7	75.2	37.8	73.4	36.7	71.4	35.3	68.6	34.3	66.7
400	121.9	46.7	90.7	40.3	78.4	39.5	76.7	38.4	74.7	37.0	72.0	36.0	70.0
500	152.4	47.7	92.8	41.6	80.9	40.7	79.2	39.8	77.3	38.4	74.6	37.4	72.7

TABLE 5.2.38 DESIGN[7] WIND PROFILES FOR VARIOUS AVERAGING TIMES (τ) FOR PEAK DESIGN WIND OF 48.9 m/sec (95 knots) RELATIVE TO THE 10-m REFERENCE LEVEL, CAPE KENNEDY

Height		Design Wind Profiles for Various Averaging Times (τ)											
(ft)	(m)	τ=0		τ=0.5		τ=1		τ=2		τ=5		τ=10	
		(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
33	10	48.9	95.0	37.1	72.1	35.6	69.2	34.1	66.2	32.0	62.2	30.6	59.4
60	18.3	51.4	99.9	40.5	78.8	39.1	76.0	37.6	73.1	35.5	69.1	34.2	66.4
100	30.5	53.6	104.2	43.5	84.6	42.2	82.0	40.7	79.1	38.7	75.2	37.3	72.5
200	61.0	56.8	110.4	47.7	92.7	46.5	90.3	45.0	87.5	43.2	83.9	41.8	81.2
300	91.4	58.7	114.2	50.2	97.6	49.0	95.2	47.7	92.7	45.8	89.1	44.5	86.5
400	121.9	60.2	117.0	52.0	101.1	50.9	98.9	49.6	96.4	47.8	92.9	46.5	90.3
500	152.4	61.3	119.1	53.4	103.8	52.3	101.6	51.0	99.2	49.2	95.7	48.0	93.3

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7. See Table 5.2.34 for calculated risk values versus desired lifetime for these design winds.

TABLE 5. 2. 39 DESIGN WIND[8] PROFILES FOR VARIOUS AVERAGING TIMES (τ) FOR PEAK DESIGN WIND OF 61. 7 m/sec (120 knots) RELATIVE TO THE 10-m REFERENCE LEVEL, CAPE KENNEDY

Height		Design Wind Profiles for Various Averaging Times (τ)											
(ft)	(m)	τ=0		τ=0. 5		τ=1		τ=2		τ=5		τ=10	
		(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
33	10	61. 7	120. 0	46. 8	91. 0	45. 0	87. 5	43. 0	83. 6	40. 4	78. 5	38. 6	75. 0
60	18. 3	64. 4	125. 2	50. 8	98. 7	49. 0	95. 3	47. 2	91. 7	44. 6	86. 6	42. 8	83. 2
100	30. 5	66. 8	129. 8	54. 2	105. 4	52. 5	102. 1	50. 7	98. 6	48. 2	93. 7	46. 5	90. 3
200	61. 0	70. 1	136. 2	58. 9	114. 4	57. 3	111. 4	55. 6	108. 0	53. 2	103. 5	51. 5	100. 2
300	91. 4	72. 1	140. 2	61. 6	119. 8	60. 1	116. 9	58. 5	113. 8	56. 3	109. 4	54. 6	106. 2
400	121. 9	73. 6	143. 0	63. 6	123. 6	62. 2	120. 9	60. 6	117. 8	58. 4	113. 5	56. 8	110. 4
500	152. 4	74. 7	145. 3	65. 2	126. 7	63. 8	124. 0	62. 2	121. 0	60. 1	116. 8	58. 5	113. 8

is an isolated shed then obviously its loss is not as great as a structure that would house many people or a structure that is critical to the mission of a large organization; nor is it as potentially unsafe as the loss of a nuclear power plant or storage facility for explosives or highly radioactive materials. To give a starting point for design studies aimed at meeting the design objectives, it is recommended that a design risk of 10 percent for the desired lifetime be used in determining the wind loading on structures that have a high replacement cost. Should the loss of the structure be extremely hazardous to life or property, or critical to the mission of a large organization, then a design risk of five percent or less for the desired lifetime is recommended. These are subjective recommendations involving arbitrary assumptions about the design objectives. Note that the larger the desired lifetime, the greater the design risk is for a given wind speed (or wind loading). Therefore, realistic appraisals should be made for desired lifetimes.

5. 2. 10. 9 Design Winds for Facilities at The Space and Missile Test Center, (Vandenberg AFB), Wallops Island, White Sands Missile Range, Edwards Air Force Base, New Orleans,[9] and Huntsville

5. 2. 10. 9. 1 The Wind Statistics

The basic wind statistics for these five locations are taken from Reference 5. 13, which presents isotachs, in the form of maps, for the

8. See Table 5. 2. 34 for calculated risk values versus desired lifetime for these design winds.

9. Includes Mississippi Test Facility area.

50, 98, and 99 percentile values for the yearly maximum "fastest mile" of wind in the units miles per hour for the 30-foot (~10-m) reference height above natural grade. By definition, the fastest mile is the fastest wind speed in miles per hour of any mile of wind during a specified period (usually taken as the 24-hour observational day), and the largest of these in a year for the period of record constitutes the statistical sample of yearly fastest mile. From this definition, it is noted that the fastest mile as a measure of wind speed has a variable averaging time; for example, if the wind speed is 60 miles per hour, the averaging time for the fastest mile of wind is 1 minute. For a wind speed of 120 miles per hour, the averaging time for the fastest mile of wind is 0.5 minute. Thom reports that the Fréchet probability distribution function fits his samples of fastest mile very well. The Fréchet distribution function is given as

$$F(x) = e^{-\left(\frac{x}{\beta}\right)^{-\gamma}} \qquad (5.22)$$

where the two parameters β and γ are estimated from the sample by the maximum likelihood method. From Thom's maps of the 50, 98, and 99 percentiles of fastest mile of wind for yearly extremals, we have estimated (interpolated) for these percentiles for the five locations and calculated the values for the parameters β and γ for the Fréchet distribution function and computed several additional percentiles, as shown in Table 5.2.40. To have units consistent with the other sections of this document, the percentiles and the parameters β and γ have been converted from miles per hour to knots and m/sec. Thus, Table 5.2.40 gives the Fréchet distribution for the fastest mile of winds at the 30-foot (~10-m) level for the five locations with the units in knots and m/sec.

The discussion in subsection 5.2.10.2.4, devoted to desired lifetime, calculated risk, and design winds with respect to the wind statistics at a particular height (10-m level) is applicable here, except that the reference statistics are with respect to the fastest mile converted to knots and m/sec.

5.2.10.9.2 Conversion of Fastest Mile to Peak Winds

It was mentioned in subsection 5.2.10.3 that the Fréchet distribution for the 17-year sample of yearly peak winds for Cape Kennedy was an acceptable fit to this sample. The Fréchet distributions for the fastest mile were obtained from Thom's data (maps) for Cape Kennedy. From these two distributions (the Fréchet for the peak winds as well as for the fastest mile), the ratio of the percentiles of the fastest mile to the peak winds were taken.

TABLE 5.2.40 FRECHET DISTRIBUTION OF FASTEST MILE WIND AT THE 10-m HEIGHT OF YEARLY EXTREMES FOR THE INDICATED STATIONS

P Probability	T Return Period (years)	Fastest Mile Wind									
		Huntsville		New Orleans		Space and Missile Test Center[a]		Wallops Island		Edwards AFB	
		(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
0.50	2	20.1	39.0	22.1	42.9	18.0	34.9	24.6	47.9	11.3	22.0
0.80	5	23.9	46.4	26.6	51.8	21.6	42.0	29.6	57.6	15.0	29.1
0.90	10	26.8	52.0	30.1	58.6	24.4	47.4	33.4	65.0	18.1	35.2
0.95	20	29.8	58.0	33.9	65.9	27.4	53.3	37.6	73.0	21.6	42.0
0.98	50	34.5	67.0	39.6	76.9	31.8	61.9	43.7	84.9	27.3	53.0
0.99	100	38.3	74.4	44.4	86.4	35.7	69.4	48.9	95.0	32.4	63.1
0.9933	150	40.7	79.2	47.4	92.2	38.0	73.9	52.2	101.4	35.1	68.3
0.995	200	42.3	82.2	49.7	96.7	39.9	77.6	54.7	106.3	38.6	75.0
0.996	250	44.1	85.7	51.6	100.4	41.4	80.4	56.7	110.2	40.8	79.3
0.99667	300	45.4	88.2	53.2	103.5	42.6	82.9	58.4	113.6	42.7	83.1
0.9975	400	47.4	92.1	55.8	108.4	44.6	86.7	61.2	118.9	45.8	89.1
0.998	500	49.0	95.3	57.9	112.5	46.2	89.9	63.4	123.2	48.5	94.2
0.99833	600	50.2	97.6	59.4	115.5	47.5	92.3	65.1	126.6	50.5	98.1
0.99875	800	52.7	102.4	62.6	121.6	50.3	97.7	68.4	133.0	54.0	105.0
0.999	1000	54.5	106.0	64.9	126.1	51.8	100.6	70.9	137.8	57.6	111.9
γ	Unitless	6.54686		6.08075		6.19591		6.19949		4.02093	
$1/\gamma$	Unitless	0.15274		0.16445		0.16140		0.16130		0.24870	
$\ln \beta$	Unitless	3.60758		3.70093		3.49620		3.81208		2.99989	
β	m/sec	18.979		20.829		16.968		23.274		10.322	
	(knots)	(36.892)		(40.488)		(32.983)		(45.241)		(20.065)	

a. Vandenberg AFB, California.

This ratio varied from 1. 12 to 1. 09, over range of percentiles from the 30th to the 99th. Thus, we adopted 1. 10 as a factor to multiply the statistics of the fastest mile of wind to get the value in knots necessary to obtain peak (instantaneous) wind statistics. This procedure is based upon the evidence of only one station. A gust factor of 1. 10 is often applied to the fastest mile statistics in facility design work to account for gust loads.

5. 2. 10. 9. 3 The Peak Wind Profile

The peak wind profile law adopted for the five locations for peak winds at the 10-meter level greater than 22. 6 m/sec (44 knots) is

$$u_z = u_{10}\left(\frac{z}{10}\right)^{1/7} \tag{5. 23}$$

where u_{10} is the peak wind at the 10-meter height and u_z is the peak wind at height z in meters.

5. 2. 10. 9. 4 The Mean Wind Profile

To obtain the mean wind profile for various averaging times, the gust factors given in subsection 5. 2. 7, are applied to the peak wind profile as determined by equation (5. 23).

5. 2. 10. 9. 5 Design Wind Profiles for Six Station Locations

The design peak wind profiles for the peak winds in Table 5. 2. 41 are obtained from the adopted peak wind power law given by equation (5. 23), and the mean wind profile for various averaging times are obtained by dividing by the gust factors for the various averaging times. (The gust factors versus height and averaging times are presented in Table 5. 2. 36.) The resulting selected design wind profiles for design return periods of 10, 100, and 1000 years for the five stations are given in Tables 5. 2. 42 through 5. 2. 56, in which values of τ are given in minutes. The design risk versus desired lifetime for the design return periods of 10, 100, and 1000 years is presented in Table 5. 2. 47.

TABLE 5.2.41 PEAK WIND (fastest mile values times 1.0) FOR THE 10-m REFERENCE LEVEL FOR 10-, 100-, AND 1000-YEAR RETURN PERIODS

T_D (years)	Peak Winds									
	Huntsville		New Orleans		SAMTEC[a] and White Sands		Wallops Island		Edwards AFB	
	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
10	29.4	57.2	33.2	64.5	26.8	52.1	36.8	71.5	19.9	38.7
100	42.1	81.8	48.9	95.0	39.3	76.3	53.8	104.5	35.7	69.4
1000	60.0	116.6	71.4	138.7	56.9	110.7	78.0	151.6	63.7	123.9

a. Vandenberg AFB, California.

TABLE 5.2.42 FACILITIES DESIGN WIND AS A FUNCTION OF AVERAGING TIME (τ) FOR A PEAK WIND OF 29.4 m/sec (57.2 knots) (10-year return period) FOR HUNTSVILLE, ALABAMA

Height		Facilities Design Wind as a Function of Averaging Time (τ)											
(ft)	(m)	τ=0 (peak)		τ=0.5		τ=1		τ=2		τ=5		τ=10	
		(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
33	10	29.4	57.2	22.3	43.4	21.5	41.7	20.5	39.9	19.2	37.4	18.4	35.8
60	18.3	32.1	62.4	25.3	49.2	24.4	47.5	23.5	45.7	22.2	43.2	21.3	41.5
100	30.5	34.5	67.1	28.0	54.5	27.2	52.8	26.2	50.9	24.9	48.4	24.0	46.7
200	61.0	38.1	74.1	32.0	62.2	31.2	60.6	30.2	58.8	29.0	56.3	28.0	54.5
300	91.4	40.4	78.5	34.5	67.1	33.7	65.5	32.8	63.7	31.5	61.2	30.6	59.5
400	121.9	42.1	81.8	36.4	70.7	31.2	60.7	34.7	67.4	33.4	64.9	32.5	63.2
500	152.4	43.0	83.6	37.5	72.9	36.7	71.3	35.8	69.6	34.6	67.2	33.7	65.5

TABLE 5. 2. 43 FACILITIES DESIGN WIND AS A FUNCTION OF AVERAGING TIME (τ) FOR A PEAK WIND OF 42. 1 m/sec (81. 8 knots) (100-year return period) FOR HUNTSVILLE, ALABAMA

Height (ft)	Height (m)	τ=0 (peak) (m/sec)	τ=0 (peak) (knots)	τ=0. 5 (m/sec)	τ=0. 5 (knots)	τ=1 (m/sec)	τ=1 (knots)	τ=2 (m/sec)	τ=2 (knots)	τ=5 (m/sec)	τ=5 (knots)	τ=10 (m/sec)	τ=10 (knots)
33	10	42. 1	81. 8	31. 9	62. 1	30. 7	59. 6	29. 3	57. 0	27. 5	53. 5	26. 3	51. 2
60	18. 3	45. 9	89. 2	36. 2	70. 3	34. 9	67. 9	33. 6	65. 3	31. 7	61. 7	30. 5	59. 3
100	30. 5	49. 3	95. 9	40. 0	77. 8	38. 8	75. 5	37. 5	72. 8	35. 6	69. 2	34. 3	66. 7
200	61. 0	54. 5	105. 9	45. 7	88. 9	44. 6	86. 6	43. 2	84. 0	41. 4	80. 5	40. 1	77. 9
300	91. 4	57. 7	112. 2	49. 3	95. 9	48. 2	93. 6	46. 9	91. 1	45. 0	87. 5	43. 7	85. 0
400	121. 9	59. 9	116. 5	51. 8	100. 7	50. 7	98. 5	49. 4	96. 0	47. 6	92. 5	46. 3	90. 0
500	152. 4	61. 5	119. 5	53. 6	104. 2	52. 5	102. 0	51. 2	99. 5	49. 4	96. 1	48. 2	93. 6

TABLE 5. 2. 44 FACILITIES DESIGN WIND AS A FUNCTION OF AVERAGING TIME (τ) FOR A PEAK WIND OF 60. 0 m/sec (116. 6 knots) (1000-year return period) FOR HUNTSVILLE, ALABAMA

Height (ft)	Height (m)	τ=0 (peak) (m/sec)	τ=0 (peak) (knots)	τ=0. 5 (m/sec)	τ=0. 5 (knots)	τ=1 (m/sec)	τ=1 (knots)	τ=2 (m/sec)	τ=2 (knots)	τ=5 (m/sec)	τ=5 (knots)	τ=10 (m/sec)	τ=10 (knots)
33	10	60. 0	116. 6	45. 5	88. 5	43. 7	85. 0	41. 8	81. 3	39. 2	76. 3	37. 5	72. 9
60	18. 3	65. 3	127. 0	51. 5	100. 2	49. 7	96. 7	47. 8	93. 0	45. 2	87. 9	43. 4	84. 4
100	30. 5	70. 3	136. 6	57. 1	110. 9	55. 3	107. 5	53. 3	103. 7	50. 7	98. 6	48. 9	95. 1
200	61. 0	77. 6	150. 8	65. 1	126. 6	63. 4	123. 3	61. 5	119. 6	59. 0	114. 6	57. 1	111. 0
300	91. 4	82. 2	159. 8	70. 3	136. 6	68. 6	133. 3	66. 7	129. 7	64. 1	124. 6	62. 3	121. 1
400	121. 9	85. 7	166. 5	74. 0	143. 9	72. 4	140. 7	70. 5	137. 1	68. 0	132. 1	66. 2	128. 6
500	152. 4	88. 4	171. 9	77. 1	149. 9	75. 5	146. 7	73. 6	143. 1	71. 1	138. 2	69. 2	134. 6

TABLE 5. 2. 45 FACILITIES DESIGN WIND AS A FUNCTION OF AVERAGING TIME (τ) FOR A PEAK WIND OF 33. 2 m/sec (64. 5 knots) (10-year return period) FOR NEW ORLEANS

Height		Facilities Design Wind as a Function of Averaging Time (τ)											
(ft)	(m)	τ=0 (peak)		τ=0.5		τ=1		τ=2		τ=5		τ=10	
		(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
33	10	33. 2	64. 5	25. 2	48. 9	24. 2	47. 0	23. 1	44. 9	21. 7	42. 2	20. 7	40. 3
60	18. 3	36. 2	70. 3	28. 5	55. 4	27. 5	53. 5	26. 5	51. 5	25. 1	48. 7	24. 0	46. 7
100	30. 5	38. 9	75. 6	31. 6	61. 4	30. 6	59. 5	29. 5	57. 4	28. 1	54. 6	27. 1	52. 6
200	61. 0	43. 0	83. 5	36. 1	70. 1	35. 1	68. 3	34. 1	66. 2	32. 6	63. 4	31. 6	61. 4
300	91. 4	45. 5	88. 5	38. 9	75. 6	38. 0	73. 8	36. 9	71. 8	35. 5	69. 0	34. 5	67. 0
400	121. 9	47. 4	92. 2	41. 0	79. 7	40. 1	77. 9	39. 0	75. 9	37. 7	73. 2	36. 6	71. 2
500	152. 4	48. 5	94. 3	42. 3	82. 2	41. 4	80. 5	40. 4	78. 5	39. 0	75. 8	38. 0	73. 8

TABLE 5. 2. 46 FACILITIES DESIGN WIND AS A FUNCTION OF AVERAGING TIME (τ) FOR A PEAK WIND OF 48. 9 m/sec (95. 0 knots) (100-year return period) FOR NEW ORLEANS

Height		Facilities Design Wind as a Function of Averaging Time (τ)											
(ft)	(m)	τ=0 (peak)		τ=0. 5		τ=1		τ=2		τ=5		τ=10	
		(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
33	10	48. 9	95. 0	37. 1	72. 1	35. 6	69. 2	34. 1	66. 2	32. 0	62. 2	30. 6	59. 4
60	18. 3	53. 3	103. 6	42. 0	81. 7	40. 5	78. 8	39. 0	75. 8	36. 9	71. 7	35. 4	68. 8
100	30. 5	57. 3	111. 1	46. 5	90. 4	45. 1	87. 6	43. 5	84. 6	41. 4	80. 4	40. 8	79. 3
200	61. 0	63. 3	123. 0	53. 1	103. 3	51. 8	100. 6	50. 2	97. 5	48. 1	93. 5	46. 6	90. 5
300	91. 4	67. 0	130. 3	57. 3	111. 4	55. 9	108. 7	54. 4	105. 8	52. 3	101. 6	50. 8	98. 7
400	121. 9	69. 9	135. 8	60. 4	117. 4	59. 1	114. 8	57. 6	111. 9	55. 5	107. 8	54. 0	104. 9
500	152. 4	71. 4	138. 8	62. 2	121. 0	60. 9	118. 4	59. 5	115. 6	57. 4	111. 6	55. 9	108. 7

TABLE 5.2.47 FACILITIES DESIGN WIND AS A FUNCTION OF AVERAGING TIME (τ) FOR A PEAK WIND OF 71.4 m/sec (138.7 knots) (1000-year return period) FOR NEW ORLEANS

Height		Facilities Design Wind as a Function of Averaging Time (τ)											
(ft)	(m)	τ=0 (peak)		τ=0.5		τ=1		τ=2		τ=5		τ=10	
		(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
33	10	71.4	138.7	54.1	105.2	52.0	101.1	49.7	96.7	46.7	90.8	44.6	86.7
60	18.3	77.8	151.2	61.3	119.2	59.2	115.1	56.9	110.7	53.8	104.6	51.7	100.5
100	30.5	83.7	162.7	68.0	132.1	65.8	128.0	63.5	123.5	60.4	117.5	58.2	113.2
200	61.0	92.4	179.6	77.6	150.8	75.6	146.9	73.3	142.4	70.2	136.5	68.0	132.2
300	91.4	97.9	190.3	83.6	162.6	81.6	158.7	79.5	154.5	76.3	148.4	74.2	144.2
400	121.9	102.0	198.2	88.1	171.3	86.2	167.5	84.0	163.3	80.9	157.3	78.8	153.1
500	152.4	104.3	202.7	90.9	176.7	89.0	173.0	86.8	168.8	83.8	162.9	81.6	158.7

TABLE 5.2.48 FACILITIES DESIGN WIND AS A FUNCTION OF AVERAGING TIME (τ) FOR A PEAK WIND OF 26.8 m/sec (52.1 knots) (10-year return period) FOR THE SPACE AND MISSILE TEST CENTER AND WHITE SANDS MISSILE RANGE

Height		Facilities Design Wind as a Function of Averaging Time (τ)											
(ft)	(m)	τ=0 (peak)		τ=0.5		τ=1		τ=2		τ=5		τ=10	
		(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
33	10	26.8	52.1	20.3	39.5	19.5	38.0	18.7	36.3	17.5	34.1	16.8	32.6
60	18.3	29.2	56.8	23.0	44.8	22.2	43.2	21.4	41.6	20.2	39.3	19.4	37.7
100	30.5	31.4	61.1	25.5	49.6	24.7	48.1	23.9	46.4	22.7	44.1	21.9	42.5
200	61.0	34.7	67.5	29.2	56.7	28.4	55.2	27.5	53.5	26.4	51.3	26.6	49.7
300	91.4	36.8	71.5	31.4	61.1	30.7	59.6	29.8	58.0	28.7	55.8	27.9	54.2
400	121.9	38.3	74.5	33.1	64.4	32.4	63.0	31.6	61.4	30.4	59.1	29.6	57.5
500	152.4	39.1	76.1	34.1	66.3	33.4	64.9	32.6	63.3	31.5	61.2	30.7	59.6

TABLE 5.2.49 FACILITIES DESIGN WIND AS A FUNCTION OF AVERAGING TIME (τ) FOR A PEAK WIND OF 39.3 m/sec (76.3 knots) (100-year return period) FOR THE SPACE AND MISSILE TEST CENTER AND WHITE SANDS MISSILE RANGE

Height		Facilities Design Wind as a Function of Averaging Time (τ)											
(ft)	(m)	τ=0 (peak)		τ=0.5		τ=1		τ=2		τ=5		τ=10	
		(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
33	10	39.3	76.3	29.8	57.9	28.6	55.6	27.4	53.2	25.7	49.9	24.5	47.7
60	18.3	42.8	83.2	33.7	65.6	32.6	63.3	31.3	60.9	29.6	57.6	28.4	55.3
100	30.5	46.0	89.5	37.3	72.6	36.2	70.4	35.0	68.0	33.2	64.6	32.0	62.3
200	61.0	50.8	98.8	42.7	83.0	41.6	80.8	40.3	78.4	38.6	75.1	37.4	72.7
300	91.4	53.9	104.7	46.0	89.5	44.9	87.3	43.7	85.0	42.0	81.7	40.8	79.3
400	121.9	56.1	109.1	48.5	94.3	47.4	92.2	46.2	89.9	44.6	86.6	43.3	84.2
500	152.4	57.4	111.5	50.0	97.2	48.9	95.1	47.7	92.8	46.1	89.6	44.9	87.3

TABLE 5.2.50 FACILITIES DESIGN WIND AS A FUNCTION OF AVERAGING TIME (τ) FOR A PEAK WIND OF 56.9 m/sec (110.7 knots) (1000-year return period) FOR THE SPACE AND MISSILE TEST CENTER AND WHITE SANDS MISSILE RANGE

Height		Facilities Design Wind as a Function of Averaging Time (τ)											
(ft)	(m)	τ=0 (peak)		τ=0.5		τ=1		τ=2		τ=5		τ=10	
		(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
33	10	56.9	110.7	43.2	84.0	41.5	80.7	39.7	77.1	37.2	72.4	35.6	69.2
60	18.3	62.1	120.7	49.0	95.2	47.3	91.9	45.5	88.4	43.0	83.5	41.3	80.2
100	30.5	66.8	129.8	54.2	105.4	52.5	102.1	50.7	98.6	48.2	93.7	46.5	90.3
200	61.0	73.7	143.3	61.9	120.3	60.3	117.2	58.4	113.6	56.0	108.9	54.2	105.4
300	91.4	78.1	151.9	66.8	129.8	65.2	126.7	63.4	123.3	61.0	118.5	59.2	115.1
400	121.9	81.4	158.2	70.3	136.7	68.8	133.7	67.0	130.3	64.6	125.6	62.9	122.2
500	152.4	83.2	161.8	72.6	141.1	71.0	138.1	69.3	134.7	66.9	130.1	65.2	126.7

TABLE 5. 2. 51 FACILITIES DESIGN WIND AS A FUNCTION OF AVERAGING TIME (τ) FOR A PEAK WIND OF 36. 8 m/sec (71. 5 knots) (10-year return period) FOR WALLOPS TEST RANGE

Height		Facilities Design Wind as a Function of Averaging Time (τ)											
(ft)	(m)	τ=0 (peak)		τ=0. 5		τ=1		τ=2		τ=5		τ=10	
		(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
33	10	36. 8	71. 5	27. 9	54. 2	26. 8	52. 1	25. 6	49. 8	24. 1	46. 8	23. 0	44. 7
60	18. 3	40. 1	77. 9	31. 6	61. 4	30. 5	59. 3	29. 3	57. 0	27. 7	53. 9	26. 6	51. 8
100	30. 5	43. 1	83. 8	35. 0	68. 0	33. 9	65. 9	32. 7	63. 6	31. 1	60. 5	30. 0	58. 3
200	61. 0	47. 6	92. 6	40. 0	77. 7	38. 9	75. 7	37. 8	73. 4	36. 2	70. 4	35. 0	68. 1
300	91. 4	50. 5	98. 1	43. 1	83. 8	42. 1	81. 8	40. 9	79. 6	39. 4	76. 5	38. 2	74. 3
400	121. 9	52. 6	102. 2	45. 4	88. 3	44. 4	86. 4	43. 3	84. 2	41. 7	81. 1	40. 6	78. 9
500	152. 4	53. 8	104. 5	46. 9	91. 1	45. 9	89. 2	44. 8	87. 0	43. 2	84. 0	42. 1	81. 8

TABLE 5. 2. 52 FACILITIES DESIGN WIND AS A FUNCTION OF AVERAGING TIME (τ) FOR A PEAK WIND OF 53. 8 m/sec (104. 5 knots) (100-year return period) FOR WALLOPS TEST RANGE

Height		Facilities Design Wind as a Function of Averaging Time (τ)											
(ft)	(m)	τ=0 (peak)		τ=0. 5		τ=1		τ=2		τ=5		τ=10	
		(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
33	10	53. 8	104. 5	40. 8	79. 3	39. 2	76. 2	37. 5	72. 8	35. 2	68. 4	33. 6	65. 4
60	18. 3	58. 6	113. 9	46. 2	89. 8	44. 6	86. 7	42. 9	83. 4	40. 5	78. 8	38. 9	75. 7
100	30. 5	63. 0	122. 5	51. 1	99. 4	49. 6	96. 4	47. 8	93. 0	45. 5	88. 4	43. 8	85. 2
200	61. 0	69. 6	135. 3	58. 4	113. 6	56. 9	110. 6	55. 2	107. 3	52. 9	102. 8	51. 2	99. 6
300	91. 4	73. 8	143. 4	63. 1	122. 6	61. 5	119. 6	59. 9	116. 4	57. 6	111. 9	55. 9	108. 6
400	121. 9	76. 9	149. 4	66. 4	129. 1	65. 0	126. 3	63. 3	123. 1	61. 0	118. 6	59. 4	115. 4
500	152. 4	78. 6	152. 7	68. 5	133. 1	67. 0	130. 3	65. 4	127. 1	63. 1	122. 7	61. 5	119. 6

TABLE 5.2.53 FACILITIES DESIGN WIND AS A FUNCTION OF AVERAGING TIME (τ) FOR A PEAK WIND OF 78.0 m/sec (151.6 knots) (1000-year return period) FOR WALLOPS TEST RANGE

Height		Facilities Design Wind as a Function of Averaging Time (τ)											
(ft)	(m)	τ=0 (peak)		τ=0.5		τ=1		τ=2		τ=5		τ=10	
		(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)
33	10	78.0	151.6	59.2	115.0	56.8	110.5	54.3	105.6	51.0	99.2	48.8	94.8
60	18.3	85.0	165.3	67.1	130.4	64.7	125.8	62.2	121.0	58.9	114.4	56.5	109.8
100	30.5	91.5	177.8	74.2	144.3	72.0	139.9	69.4	135.0	66.1	128.4	63.6	123.7
200	61.0	101.0	196.3	84.8	164.8	82.6	160.5	80.1	155.7	76.8	149.2	74.3	144.4
300	91.4	107.0	208.0	91.5	177.8	89.3	173.5	86.9	168.9	83.4	162.2	81.1	157.6
400	121.9	111.5	216.7	96.4	187.3	94.2	183.2	91.8	178.5	88.5	172.0	86.1	167.3
500	152.4	113.9	221.5	99.3	193.1	97.2	189.0	94.9	184.4	91.6	178.1	89.3	173.5

TABLE 5.2.54 FACILITIES DESIGN WIND AS A FUNCTION OF AVERAGING TIME (τ) FOR A PEAK WIND OF 19.9 m/sec (38.7 knots) (10-year return period) FOR EDWARDS AFB

Height		Facilities Design Wind as a Function of Averaging Time (τ)											
(ft)	(m)	τ=0 (peak)		τ=0.5		τ=1		τ=2		τ=5		τ=10	
		(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)
33	10	38.7	19.9	29.4	15.1	28.2	14.5	27.0	13.9	25.3	13.0	24.2	12.4
60	18.3	42.1	21.7	33.2	17.1	32.0	16.5	30.8	15.8	29.1	15.0	28.0	14.4
100	30.5	45.1	23.2	36.6	18.8	35.5	18.3	34.2	17.6	32.6	16.8	31.4	16.2
200	61.0	50.1	25.8	42.1	21.7	41.0	21.1	39.7	20.4	38.1	19.6	36.9	19.0
300	91.4	53.1	27.3	45.4	23.4	44.3	22.8	43.1	22.2	41.4	21.3	40.2	20.7
400	121.9	55.3	28.4	47.8	24.6	46.7	24.0	45.6	23.5	43.9	22.6	42.7	22.0
500	152.4	57.1	29.4	49.8	25.6	48.7	25.1	47.5	24.4	45.9	23.6	44.7	23.0

TABLE 5. 2. 55 FACILITIES DESIGN WIND AS A FUNCTION OF AVERAGING TIME (τ) FOR A PEAK WIND OF 35. 7 m/sec (69. 4 knots) (100-year return period) FOR EDWARDS AFB

Height		Facilities Design Wind as a Function of Averaging Time (τ)											
(ft)	(m)	τ=0 (peak)		τ=0. 5		τ=1		τ=2		τ=5		τ=10	
		(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)
33	10	69. 4	35. 7	52. 7	27. 1	50. 6	26. 0	48. 4	24. 9	45. 4	23. 4	43. 4	22. 3
60	18. 3	75. 5	38. 8	59. 5	30. 6	57. 5	29. 6	55. 3	28. 4	52. 2	26. 9	50. 2	25. 8
100	30. 5	80. 9	41. 6	65. 7	33. 8	63. 7	32. 8	61. 4	31. 6	58. 4	30. 0	56. 3	29. 0
200	61. 0	89. 9	46. 2	75. 5	38. 8	73. 5	37. 8	71. 3	36. 7	68. 3	35. 1	66. 2	34. 1
300	91. 4	95. 2	49. 0	81. 4	41. 9	79. 4	40. 8	77. 3	39. 8	74. 3	38. 2	72. 1	37. 1
400	121. 9	99. 2	51. 0	85. 7	44. 1	83. 9	43. 2	81. 7	42. 0	78. 7	40. 5	76. 6	39. 4
500	152. 4	102. 4	52. 7	89. 3	45. 9	87. 4	45. 0	85. 3	43. 9	82. 3	42. 3	80. 2	41. 3

TABLE 5. 2. 56 FACILITIES DESIGN WIND AS A FUNCTION OF AVERAGING TIME (τ) FOR A PEAK WIND OF 63. 3 m/sec (123. 0 knots) (1000-year return period) FOR EDWARDS AFB

Height		Facilities Design Wind as a Function of Averaging Time (τ)											
(ft)	(m)	τ=0 (peak)		τ=0. 5		τ=1		τ=2		τ=5		τ=10	
		(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)	(knots)	(m/sec)
33	10	123. 0	63. 3	93. 3	48. 0	89. 7	46. 1	85. 7	44. 1	80. 5	41. 4	76. 9	39. 6
60	18. 3	133. 8	68. 8	105. 5	54. 3	101. 8	52. 4	98. 0	50. 4	92. 6	47. 6	88. 9	45. 7
100	30. 5	143. 2	73. 7	116. 2	59. 8	112. 7	58. 0	108. 7	55. 9	103. 4	53. 2	99. 7	51. 3
200	61. 0	159. 3	82. 0	133. 8	68. 8	130. 3	67. 0	126. 3	65. 0	121. 0	62. 2	117. 2	60. 3
300	91. 4	168. 7	86. 8	144. 2	74. 2	140. 7	72. 4	136. 9	70. 4	131. 6	67. 7	127. 8	65. 7
400	121. 9	175. 8	90. 4	151. 9	78. 1	148. 6	76. 4	144. 8	74. 5	139. 5	71. 8	135. 8	69. 9
500	152. 4	181. 5	93. 4	158. 2	81. 4	154. 9	79. 7	151. 1	77. 7	145. 9	75. 1	142. 1	73. 1

5.3 Inflight Winds

5.3.1 Introduction

Inflight wind speed profiles are used in vehicle design studies primarily to establish structural and control system capabilities and compute performance requirements. The inflight wind speeds selected for vehicle design may not represent the same percentile value as the design surface wind speed. The selected wind speeds (inflight and surface) are determined by the desired vehicle launch capability and can differ in the percentile level since the inflight and surface wind speeds differ in degree of persistance for a given reference time period and are statistically independent.

Wind information for inflight design studies is presented in three basic forms: discrete or synthetic profiles, statistical distributions, and measured profile samples. A detailed discussion of these three types of presentations and their uses may be found in Reference 5.14. There are certain limitations to each of these wind input forms, and their utility in design studies depends upon a number of considerations such as, (1) accuracy of basic measurements, (2) complexity of input to vehicle design, (3) economy and practicality for design use, (4) ability to represent significant features of the wind profile, (5) statistical assumption versus physical representation of the wind profile, (6) ability of input to ensure control system and structural integrity of the vehicle, and (7) flexibility of use in design trade-off studies.

An accurate and adequate number of measured wind profiles are necessary for developing a valid statistical description of the wind profile. Fortunately, current records of data from some locations (Cape Kennedy in particular) fulfill these requirements, although a continuing program of data acquisition is vital to further enhance the confidence of the statistical information generated. Various methods and sensors for obtaining inflight profiles include the rawinsonde, the FPS-16 Radar/Jimsphere, and the rocketsonde. The statistical analyses performed on the inflight wind profiles provide detailed descriptions of the upper winds and an understanding of the profile characteristics such as temporal and height variations, as well as indications of the frequency and the persistence of transient meteorological systems.

The synthetic type of wind profile is the oldest method used to present inflight design wind data. The synthetic wind profile data are presented in this document since this method of presentation provides a reasonable approach for most design studies when properly used, especially during the early design periods. Also, the concept of synthetic wind profiles is generally understood and employed in most aerospace organizations for design computations. It should be understood that the synthetic wind profile includes the wind speed, wind speed change, maximum wind layer thickness, and gusts that are required to establish vehicle design values.

Generally, launch vehicles for use at various launch sites and in comprehensive space research mission and payload configurations are designed by use of synthetic wind profiles based upon scalar wind speeds without regard to specific wind directions. However, if a vehicle is restricted to a given launch site, rather narrow flight azimuths, and a specific configuration and mission, winds based upon components (head, tail, left cross or right cross) are used. For a given percentile, the magnitudes of component winds are equal to or less than those of the scalar winds. Component or directional dependent winds should not be employed in initiated design studies unless specifically authorized by the cognizant design organization.

Selection of a set of detailed wind profiles for final design verification and launch delay risk calculations requires the matching of vehicle simulation resolution and technique to frequency content of the profile. These detail wind profile data sets are currently becoming available and should be utilized to assure an understanding of the vehicle design capability relative to potential operational wind loads.

The synthetic wind profile provides a conditionalized wind shear/gust condition with respect to the given design wind speed. Therefore, in concept, it should produce a vehicle design which has a launch delay risk not greater than a specified value which is generally the value associated with the design wind speed. This statement, although generally correct, depends on changes made in the control system response characteristics, for example. In using the design verification selection of detailed wind profiles a joint condition of wind shear, gust, and speeds is given. Therefore, the resulting launch delay risk for a given vehicle design is the specified value computed. For the synthetic profile a vehicle inflight wind speed capability and maximum launch delay risk may be stated which is conditional upon the wind/gust design values. However, for the selection of detailed wind profiles only a vehicle launch risk value may be given, since the wind characteristics are treated as a joint condition. These two differences in philosophy should be understood to avoid misinterpretation of vehicle response calculation comparisons. In both cases allowance for a vehicle's non-nominal characteristics should be made prior to flight simulation through the wind profiles and establishment of vehicle design response or operational launch delay risk values. The objective is to insure that a space vehicle will accommodate the desired percentage of wind profiles or conditions in its non-nominal flight mode.

5.3.2 Wind Aloft Climatology

The development of design wind speed profiles and associated shears and gusts require use of the measured wind speed and wind direction data collected at the area of interest for some reasonably long period of time, i.e., five years of longer. The subject of wind climatology for an area, if treated in detail, would make up a voluminous document. The intent here is to give a brief treatment of selected topics that are frequently considered in space vehicle development and operations problems and provide references to more extensive information.

Considerable data summaries (monthly and seasonal) exist on wind aloft statistics for the world. However, it is necessary to interpret these data in terms of the engineering design problem and design philosophy. For example, wind requirements for performance calculations relative to aircraft fuel consumption requirements must be derived for the specific routes and design reference period. Such data are available on request.

5.3.3 Wind Component Statistics

Wind component statistics are used in mission planning to provide information on the probability of exceeding a given wind speed in the pitch or yaw planes and to bias the tilt program at a selected launch time.

Computation of the wind component statistics are made for various launch azimuths (15-degree intervals were selected at MSFC) for each month for the pitch plane (range) and yaw plane (cross range) at the Eastern Test Range and the Space and Missile Test Center (Vandenberg AFB, California).

References 5.15, 5.16, 5.17, and 5.18 contain information on the statistical distributions of wind speeds and component wind speeds for the test ranges at Cape Kennedy, Florida; El Paso, Texas; Santa Monica, California; and Wallops Island, Virginia. The Range Reference Atmosphere Documents (Ref. 5.18) provide similar information for other test ranges.

5.3.3.1 Idealized Annual Wind Component Envelopes — Windiest Monthly Reference Period Concept

To provide information on the wind distribution for an entire year, envelopes for the Space and Missile Test Center (Ref. 5.19) are most useful because the data are based upon monthly wind distributions. Thus, the data can be used to determine the worst condition expected for a selected launch azimuth during any month of the entire year. Similar data are available for the Eastern Test Range (Ref. 5.20).[10] (Also see subsection 5.3.5.2).

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10. References 5.19 and 5.20 are currently being updated and the interested user should request a copy of the new report from Aerospace Environment Division, NASA-Marshall Space Flight Center.

5.3.3.2 Upper Wind Correlations

Coefficients of correlations of wind components between altitude levels with means and standard deviations at altitude levels may be used in a statistical model to derive representative wind profiles. A method of preparing synthetic wind profiles by use of correlation coefficients between wind components is described in Reference 5.21. In addition, these correlation data are applicable to certain statistical studies of vehicle responses (Ref. 5.22).

Data on correlations of wind between altitude levels for various geographical locations are presented in References 5.23, 5.24, and 5.25. The reports give values of the interlevel and intralevel coefficients of linear correlations between wind components. Because of the occurrence of the regular increase of winds with altitude below and the decrease of winds above the 10- to 14-kilometer level, the correlation coefficients decrease with greater altitude separation of the levels being correlated. Likewise, the highest correlation coefficients between components occur in the 10- to 14-kilometer level.

5.3.3.3 Thickness of Strong Wind Layers (Ref. 5.26)

Wind speeds in the middle latitudes generally increase with altitude to a maximum between 10- and 14-kilometers. Above 14 kilometers, the wind speeds decrease with altitude, then increase at higher altitude, depending upon season and location. Frequently, these winds exceed 50 m/sec in the jet stream, a core of maximum winds over the midlatitudes in the 10- to 14-kilometer altitudes. The vertical extent of the core of maximum winds, or the sharpness of the extent of peak winds on the wind profile is important in some vehicle design studies.

Table 5.3.1 shows the design vertical thickness (based on maximum thickness) of the wind layers for wind speeds of 50, 75, and 97 m/sec for the Eastern Test Range. Similar data for the Space and Missile Test Center are given in Table 5.3.2. At both ranges, the thickness of the layer decreases with increase of wind speed; that is, the sharpness of the peak is greater with greater winds.

5.3.3.4 Exceedance Probabilities

The probability of inflight winds exceeding or not exceeding some critical wind speed for a specified time duration may be of considerable importance in mission planning, and in many cases, more information than just the occurrence of critical winds is desired. If a dual launch, with the second vehicle being launched 1 to 3 days after the first, is planned, and if

TABLE 5.3.1 DESIGN THICKNESS FOR STRONG WIND LAYERS AT THE EASTERN TEST RANGE

Quasi-Steady-State Wind Speed (±5 ms^{-1})	Maximum Thickness (km)	Altitude Range (km)
50	4	8.5 to 16.5
75	2	10.5 to 15.5
92	1	10.0 to 14.0

TABLE 5.3.2 DESIGN THICKNESS FOR STRONG WIND LAYERS AT THE SPACE AND MISSILE TEST CENTER (Vandenberg AFB, California)

Quasi-Steady-State Wind Speed (±5 ms^{-1})	Maximum Thickness (km)	Altitude Range (km)
50	4	8.0 to 16
75	2	9.5 to 14

the launch opportunity extends over a 10-day period, what is the probability that winds below (or above) critical levels will last for the entire 10 days? What is the probability of 2 or 3 consecutive days of favorable winds in the 10-day period? Suppose the winds are favorable on the scheduled launch day, but the mission is delayed for other reasons. Now, what is the probability that the winds will remain favorable for 3 or 4 more days? Answers to these questions could also be used for certain design considerations involving specific vehicles prepared for a given mission and launch window.

5.3.3.4.1 Empirical Exceedance Probabilities

To provide inflight wind information useful in mission analysis type studies, the Cape Kennedy serially complete radiosonde wind observations were subjected to statistical analyses described below. All calculations were conducted using the maximum wind speed in the 10- to 15-kilometer altitude layer.

From an analysis independent of that for exceedance probabilities, the run probabilities and conditional probabilities for the same data sample (the maximum wind speed 10 to 15 km over Cape Kennedy) were computed for specified wind speeds. Since these statistics were determined at different times and with different techniques, the notation is slightly different. The most satisfying feature is that the resulting statistics are identical, giving rise to confidence in the correctness of the computation processes, as well as providing an independent approach to the same problem. Figure 5.3.1 is a useful graphic form to display the probabilities of runs.

5.3.3.4.2 Empirical Multiple Exceedance Probabilities

The longest succession of maximum wind speed in the 10- to 15-kilometer layer with wind speed ≧ 75 m/sec occurred during the winter of 1958. This year would be referred to as a high wind year. In terms of runs, the longest runs ≧ 75 m/sec by months are given in Table 5.3.3.

The counting rule for runs is as follows: If a run begins in one month and extends into the following month, it is counted as a run for the month in which it begins.

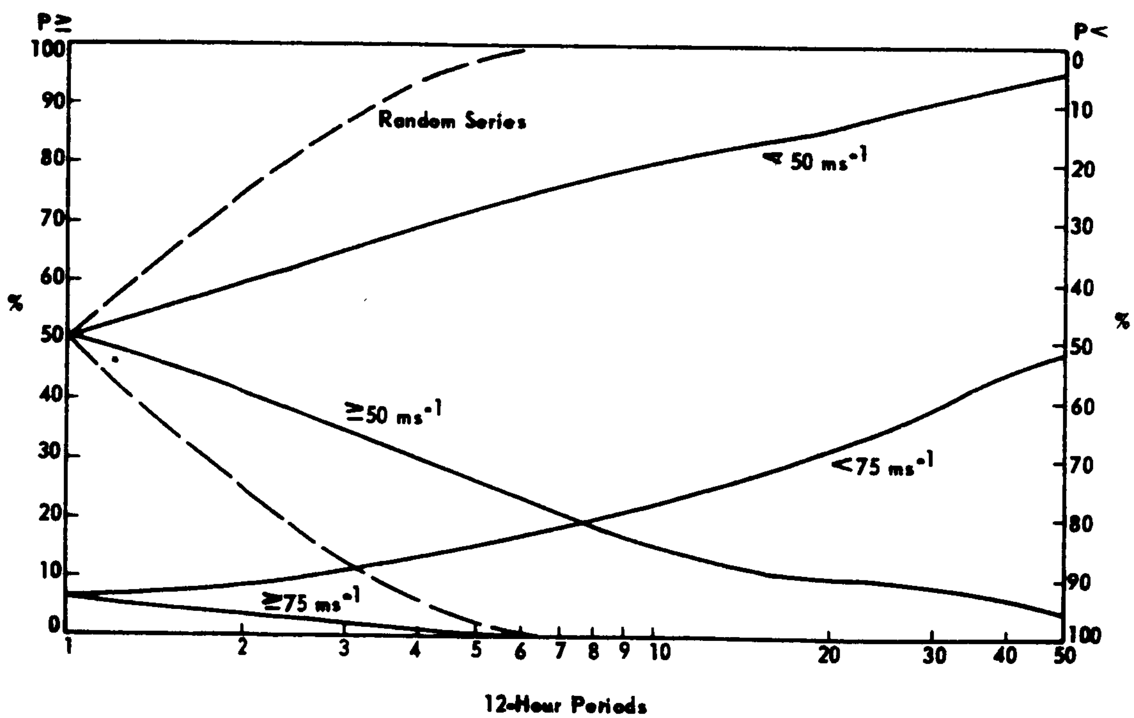


FIGURE 5.3.1 PROBABILITY OF THE MAXIMUM WIND SPEED IN THE 10- TO 15-km LAYER BEING LESS THAN, EQUAL TO, OR GREATER THAN SPECIFIED VALUES FOR k-CONSECUTIVE 12-hr PERIODS DURING JANUARY AT CAPE KENNEDY

TABLE 5.3.3 DATES OF LONGEST RUNS OF WIND SPEEDS GREATER THAN OR EQUAL TO 75 m/sec IN THE 10- TO 15-km LAYER AT CAPE KENNEDY

Maximum Length of Run in 12-hour Periods	Date	Dates and Times Inclusive
6	Jan 1958	25, 1200Z - 27, 1200Z
14	Feb 1958	10, 0000Z - 16, 1200Z
7	Mar 1958	28, 1200Z - 31, 1200Z
3	Apr 1958	15, 1200Z - 16, 1200Z
(There were no values ≥ 75 m/sec for May through Oct for any year)		
6	Nov 1956	25, 0300Z - 27, 1500Z
4	Dec 1956	29, 0300Z - 30, 1500Z

Beginning at 1200Z on January 25, 1958, the wind blew at a speed ≥ 75 m/sec for 53 12-hour periods (26.5 days) with only six exceptions: There were two single breaks; that is, twice the wind dropped below 75 m/sec, twice the wind dropped below 75 m/sec for two 12-hour periods, and twice the wind dropped below 75 m/sec for three 12-hour periods. For this particular sample period of 53, there was a 77-percent chance that the wind was ≧ 75 m/sec. Yet, for the entire sample of eight Januaries, there was a 6-percent chance that the wind speed was ≧75 m/sec in the 10- to 15-kilometer layer.

5.3.3.4.3 Current Exceedance Probability Work

Considerable exceedance probability work related to mission planning and analysis of runs has been accomplished. These data will be provided upon request to the Aerospace Environment Division, MSFC.

5.3.3.5 Design Scalar Wind Speeds (10-15 km Altitude Layer)

The distributions of design scalar wind wind speed in the 10- to 15-kilometer altitude layer over the United States are shown in Figure 5.3.2 for the 95 percentile and Figure 5.3.3 for the 99 percentile values. The line of maximum isopleths (maximum wind speeds) are shown by heavy lines with arrows. These winds occur at approximately the level of maximum dynamic pressure for most space vehicles.

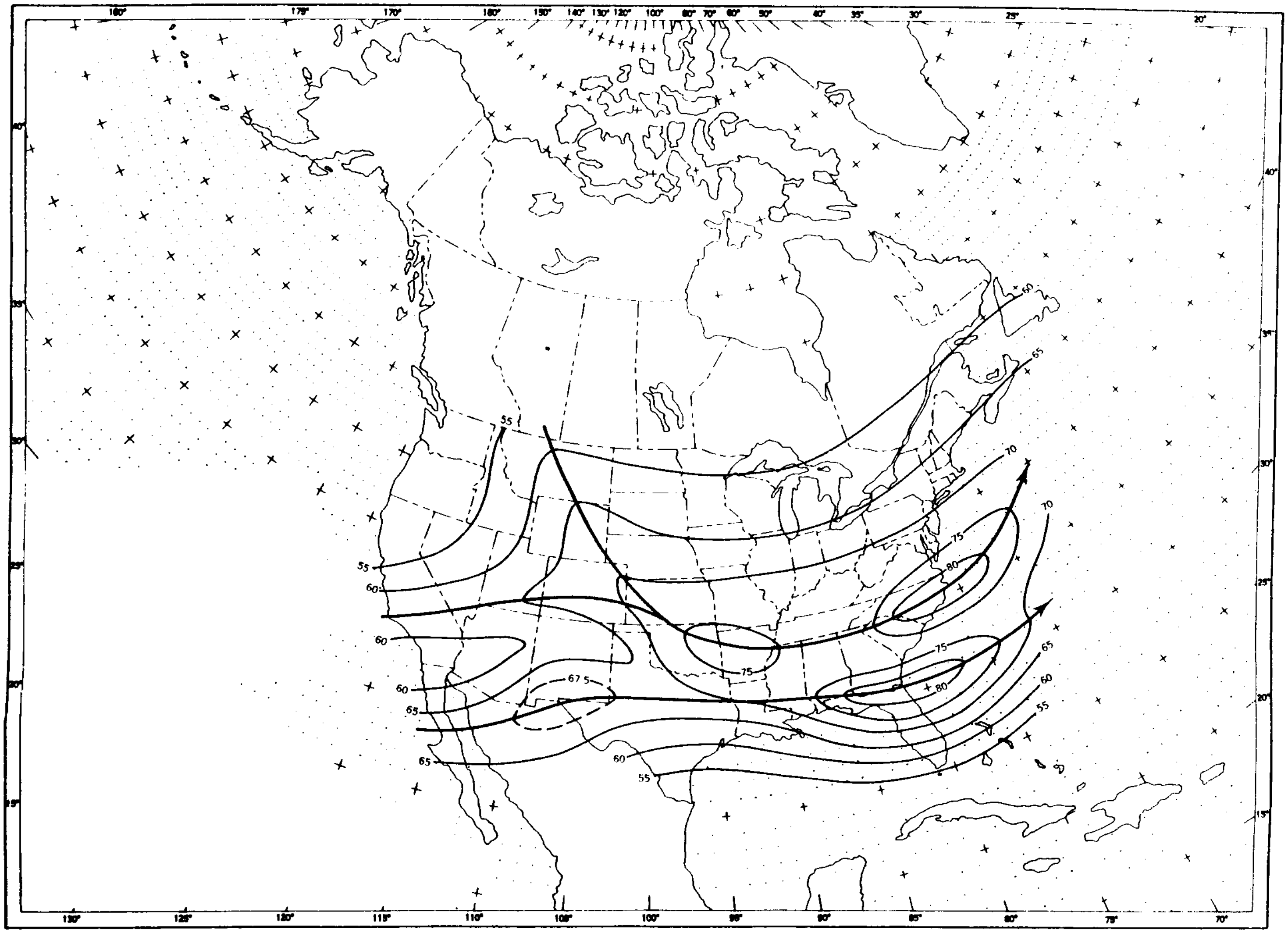


FIGURE 5. 3. 2 DESIGN SCALAR WIND SPEEDS (m/sec) 95 PERCENTILE ENVELOPE ANALYSIS PREPARED FROM WINDIEST MONTH AND MAXIMUM WINDS IN THE 10- TO 15-km LAYER

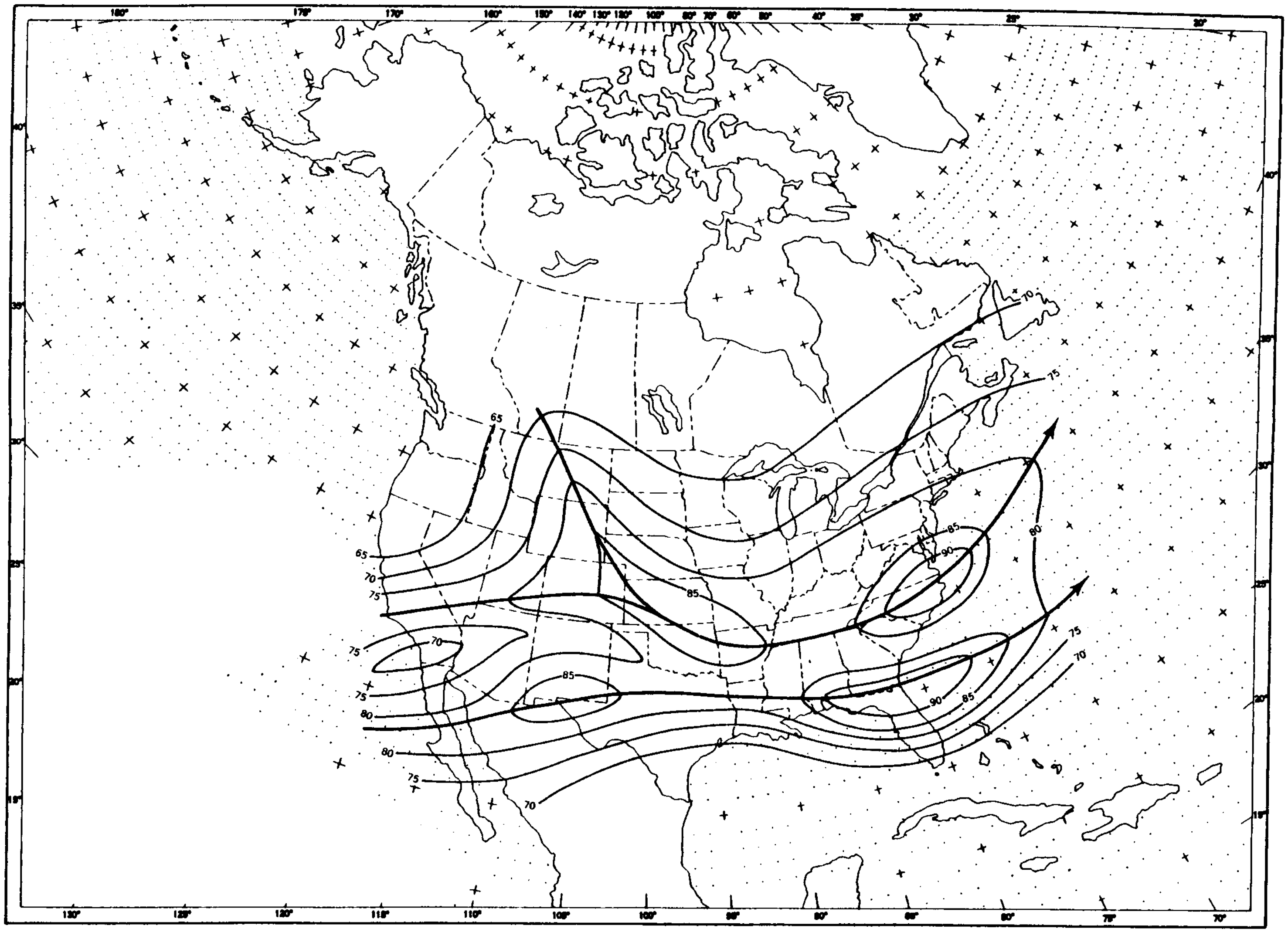


FIGURE 5. 3. 3 DESIGN SCALAR WIND SPEEDS (m/sec) 99 PERCENTILE ENVELOPE ANALYSIS PREPARED FROM WINDIEST MONTH AND MAXIMUM WINDS IN THE 10- TO 15-km LAYER

5.3.3.6 Inflight Wind Variation

Studies by Camp and Susko for Cape Kennedy (Ref. 5.27) and Camp and Fox for Santa Monica (Ref. 5.28) provide extensive information on probabilities of occurrence of various time-dependent wind changes when the month, altitude layer, and initial wind speed and direction are known. This will give the reader some insight as to probable wind speed changes with time that may be expected at various reference altitudes prior to a vehicle launch.

5.3.4 Wind Speed Profiles for Biasing Tilt Program

In attempting to maintain a desired flight path for a space vehicle through a strong wind region, the vehicle control system could introduce excessive bending moments and orbit anomalies. To reduce this problem, it is sometimes desirable to wind bias the pitch program, that is, to tilt the vehicle sufficiently to produce the desired flight path and minimize maximum dynamic pressure level loads with the expected wind profile. Since most inflight strong winds over Cape Kennedy are winter westerlies, it is generally adequate to use the monthly or seasonal pitch plane median wind speed profile for bias analysis.

Head and tail wind components and right and left cross wind components from 0- to 60-kilometer altitudes were computed for every 15 degrees of flight azimuth for the Eastern Test Range launch area and were published by NASA (Ref. 5.28A). Similar calculations are available upon request for other ranges.

It is not usually necessary to bias the vehicle in the yaw plane because of the flight azimuths normally used at Cape Kennedy. For applications where both pitch and yaw biasing are used at Cape Kennedy, monthly vector mean winds may be more efficient for wind biasing. Such statistics have been made available. [11]

5.3.5 Design Wind Speed Profile Envelopes

The wind data given are not expected to be exceeded by the given percentage of time (time as related to the observational interval of the data sample) based upon the windiest monthly reference period. To obtain the profiles, monthly frequency distributions are combined for each percentile level

11. "Monthly vector mean winds versus altitude for Cape Kennedy, Florida, for Skylab (INT-21) wind bias trajectory analysis," Office Memorandum S&E-AERO-YT-77-71, January 29, 1971, NASA, Marshall Space Flight Center, Alabama 35812.

to give the envelope values for all 12 months of data. The profiles represent horizontal wind flow referenced to the earth's surface. Vertical wind flow is negligible except as represented in the gust or turbulence considerations. The scalar wind speed envelopes are normally applied without regard to flight directions to establish the initial design requirements. Directional wind criteria for use with the synthetic wind profile techniques should be applied with care and specific knowledge of the vehicle mission and flight path, since severe wind constraints could result for other flight paths and missions.

5.3.5.1 Scalar Wind Speed Envelopes

Scalar wind speed profile envelopes are presented in Tables 5.3.4 through 5.3.8 and Figures 5.3.4 through 5.3.8. These are idealized steady-state scalar wind speed profile envelopes for five active or potential operational space vehicle launch or landing sites, i.e., Eastern Test Range, Florida; The Space and Missile Test Center (Vandenberg AFB), California; Wallops Island, Virginia; White Sands Missile Range, New Mexico; and Edwards Air Force Base, California. Table 5.3.9 and Figure 5.3.9 envelope the 95 and 99 percentile steady-state scalar wind speed profile envelopes from the same five locations. They are applicable for design criteria when initial design or operational capability has not been restricted to a specific launch site or may involve several geographical locations. However, if the specific geographical location for application has been determined as being near one of the five referenced sites then the relevant data should be applied.

This section provides design nondirectional wind data for various percentiles; therefore, the specific percentile wind speed envelope applicable to design should be specified in the appropriate space vehicle specification documentation. For engineering convenience the design wind speed profile envelopes are given as linear segments between altitude levels; therefore, the tabular values are connected, when graphed, by straight lines between the points.

5.3.5.2 Directional Wind Speed Envelopes

Directional wind speed envelopes, prepared using the windiest monthly reference period concept, may be used to estimate the winds relative to a given percentile level that may be encountered at any flight azimuth. Figure 5.3.10 was constructed by plotting the component wind speed at the appropriate percentile (extracted from empirical cumulative percentage frequencies) and the appropriate flight azimuth. The coordinate system was rotated to obtain all flight azimuths and the plotting convention was chosen

TABLE 5.3.4 SCALAR WIND SPEED PROFILE ENVELOPES (steady-state) FOR THE EASTERN TEST RANGE

Geometric Altitude (km)	Wind Speed (m/sec) for Various Percentiles				
	Percentile				
	50	75	90	95	99
1	10	14	18	21	27
10	45	58	70	75	92
14	45	58	70	75	92
20	10	16	21	25	30
23	10	16	21	25	30
50	85	100	112	120	135
60	85	100	112	120	135
75	55	70	83	90	105
80	55	70	83	90	105

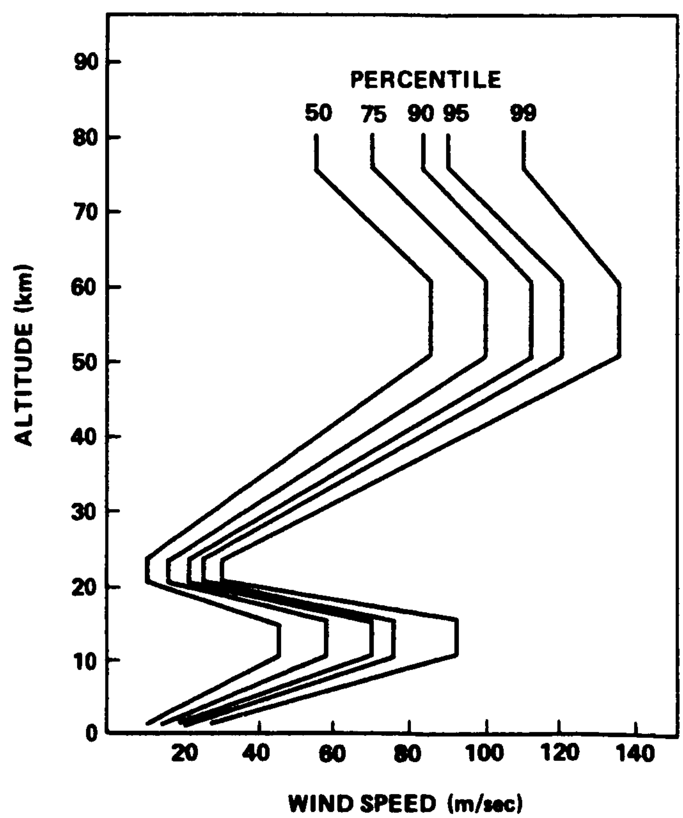


FIGURE 5.3.4 SCALAR WIND SPEED PROFILE ENVELOPES (steady-state) FOR THE EASTERN TEST RANGE

TABLE 5.3.5 SCALAR WIND SPEED PROFILE ENVELOPES (steady-state) FOR THE SPACE AND MISSILE TEST CENTER (Vandenberg AFB, California)

Geometric Altitude (km)	Wind Speed (m/sec) for Various Percentiles				
	Percentile				
	50	75	90	95	99
1	6	10	15	17	22
9	34	46	60	65	80
13	34	46	60	65	80
20	10	13	17	21	27
23	10	13	17	21	27
50	85	104	120	140	155
60	85	104	120	140	155
75	60	77	93	102	120
80	60	77	93	102	120

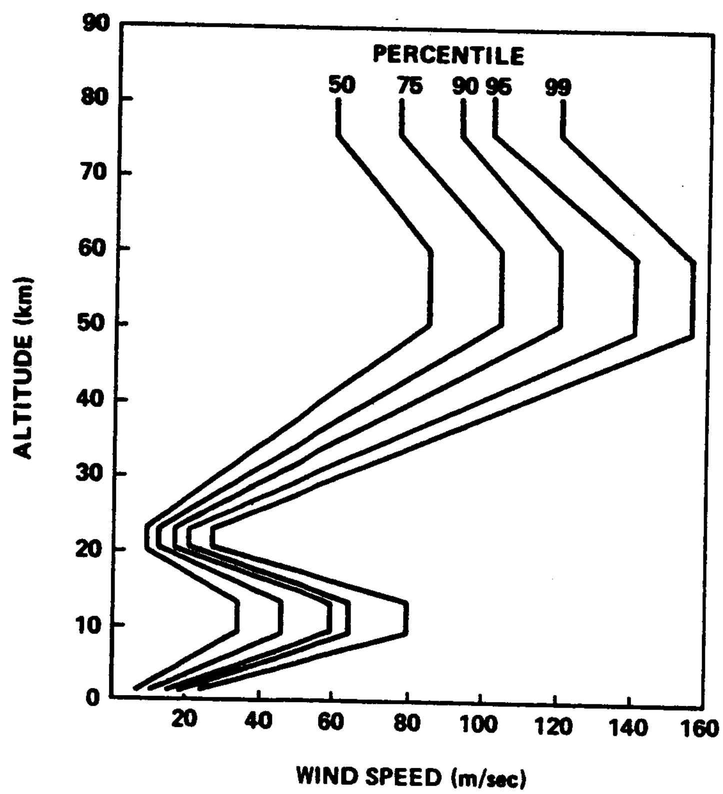


FIGURE 5.3.5 SCALAR WIND SPEED PROFILE ENVELOPES (steady-state) FOR THE SPACE AND MISSILE TEST CENTER (Vandenberg AFB, California)

TABLE 5.3.6 SCALAR WIND SPEED PROFILE ENVELOPES (steady-state) FOR WALLOPS TEST RANGE

Geometric Altitude (km)	Wind Speed (m/sec) for Various Percentiles				
	Percentile				
	50	75	90	95	99
1	11	15	20	24	30
9	50	60	71	75	92
13	50	60	71	75	92
20	15	21	27	30	36
23	15	21	27	30	36
50	102	120	140	150	170
60	102	120	140	150	170
75	85	100	113	120	135
80	85	100	113	120	135

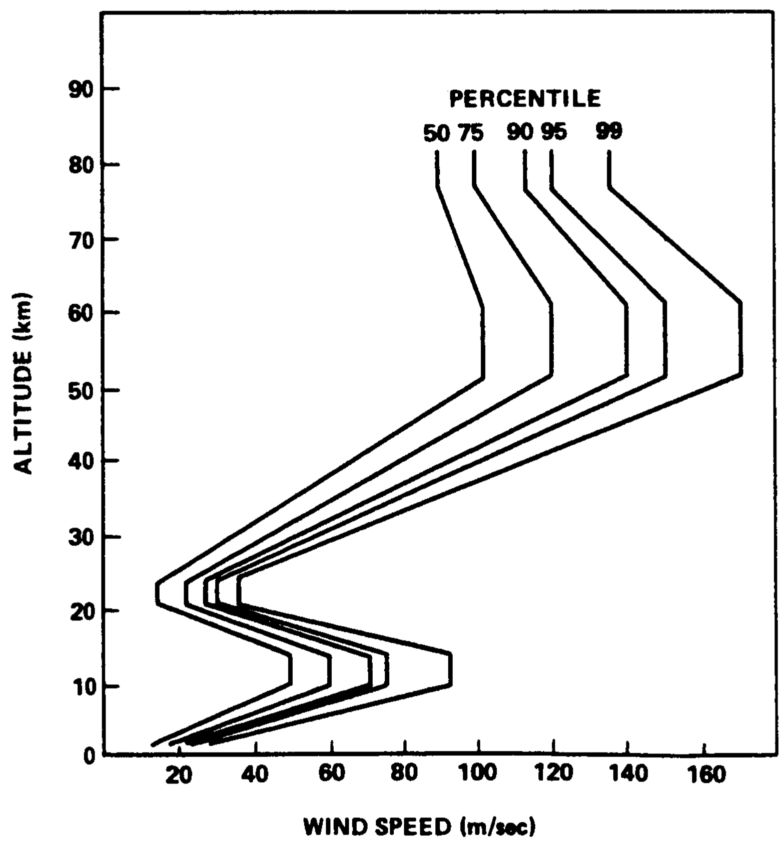


FIGURE 5.3.6 SCALAR WIND SPEED PROFILE ENVELOPES (steady-state) FOR WALLOPS TEST RANGE

TABLE 5. 3. 7 SCALAR WIND SPEED PROFILE ENVELOPES (steady-state) FOR WHITE SANDS MISSILE RANGE

Geometric Altitude (km)	Wind Speed (m/sec) for Various Percentiles				
	Percentile				
	50	75	90	95	99
2. 5	7	11	14	20	28
10	42	55	64	70	85
13	42	55	64	70	85
19	11	15	19	25	31
23	11	15	19	25	31
50	85	104	120	130	150
60	85	104	120	130	150
75	60	77	93	102	120
80	60	77	93	102	120

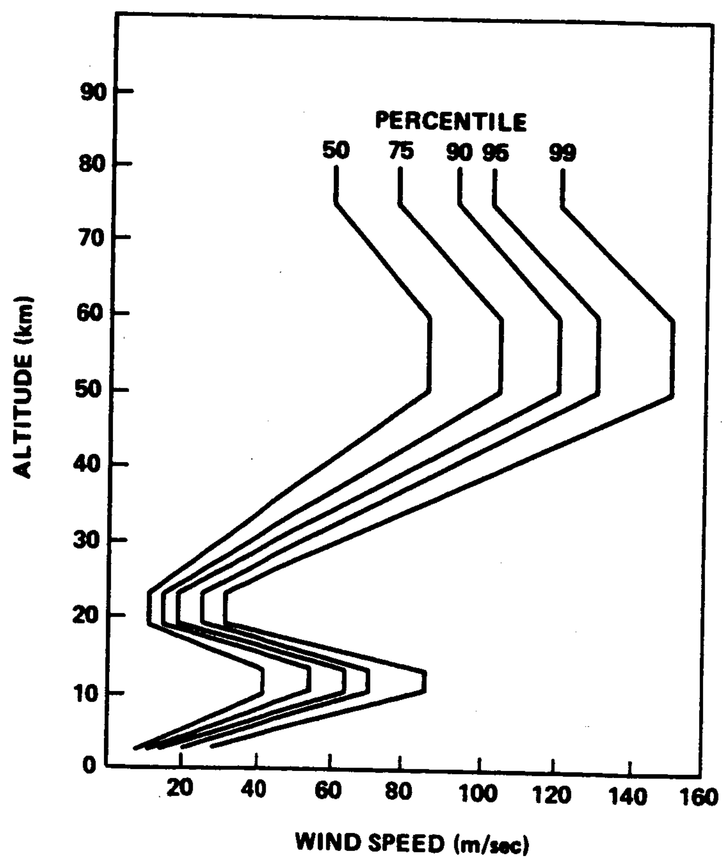


FIGURE 5. 3. 7 SCALAR WIND SPEED PROFILE ENVELOPES (steady-state) FOR WHITE SANDS MISSILE RANGE

TABLE 5.3.8 SCALAR WIND SPEED PROFILE ENVELOPES (steady-state) FOR EDWARDS AIR FORCE BASE

Geometric Altitude (km)	Wind Speed (m/sec) for Various Percentiles				
	Percentile				
	50	75	90	95	99
1	6	10	14	16	20
9	32	45	57	64	77
13	32	45	57	64	77
20	8	15	22	26	33
23	8	15	22	26	33
50	85	104	120	130	150
60	85	104	120	130	150
75	60	77	93	102	120
80	60	77	93	102	120

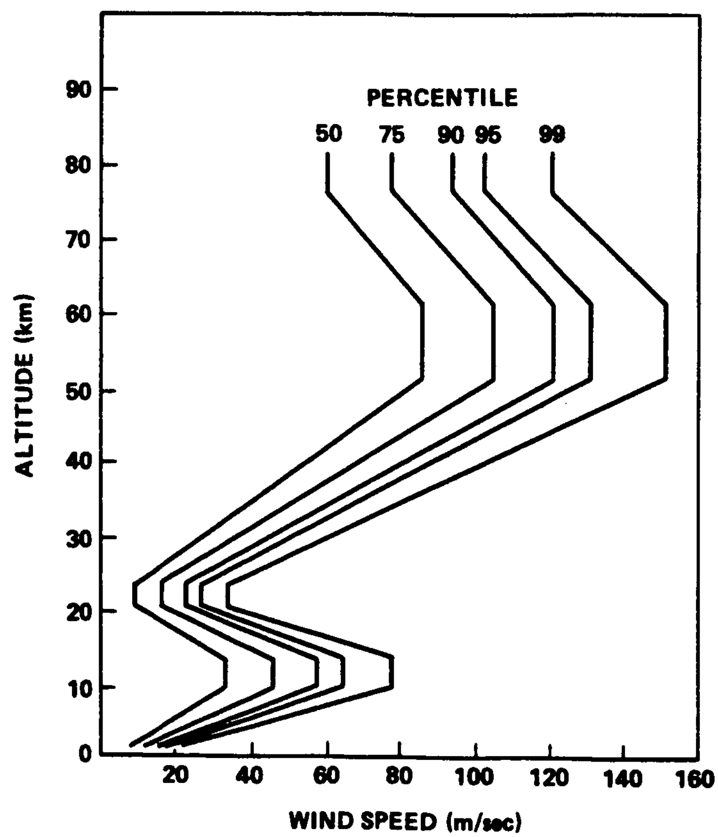


FIGURE 5.3.8 SCALAR WIND SPEED PROFILE ENVELOPES (steady-state) FOR EDWARDS AIR FORCE BASE

TABLE 5.3.9 SCALAR WIND SPEED PROFILE ENVELOPES (steady-state) ENCOMPASSING ALL FIVE LOCATIONS

Geometric Altitude (km)	Wind Speed (m/sec) for Various Percentiles	
	Percentile	
	95	99
1	21	28
10	75	92
14	75	92
20	25	40
23	25	40
50	150	190
60	150	190
75	126	150
80	126	150

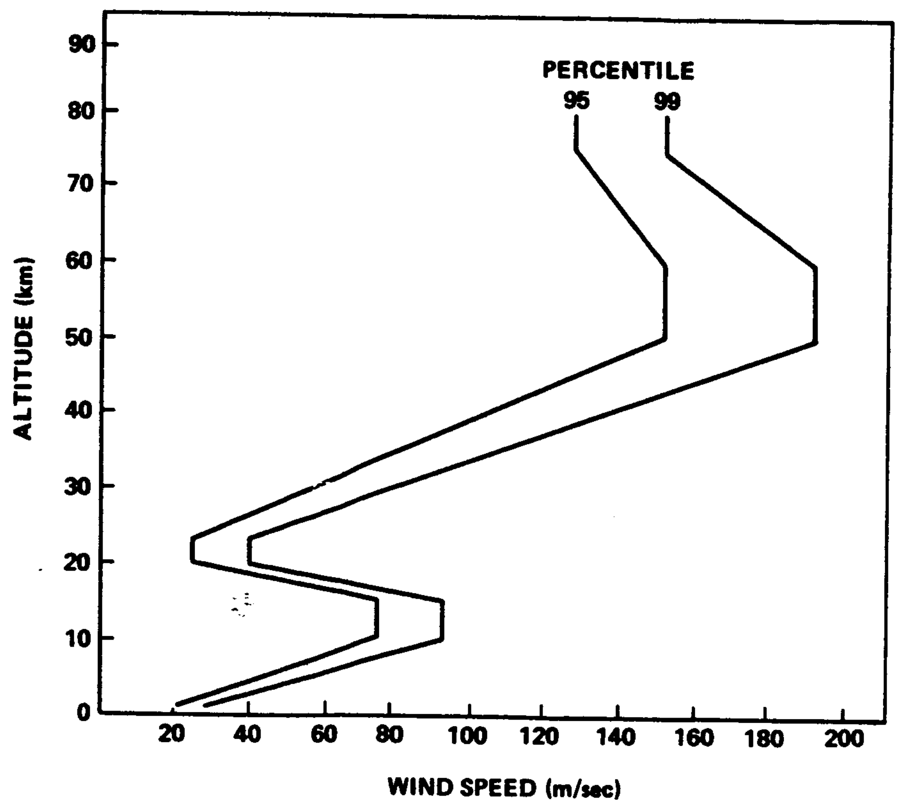


FIGURE 5.3.9 SCALAR WIND SPEED PROFILE ENVELOPES (steady-state) FOR ALL FIVE LOCATIONS

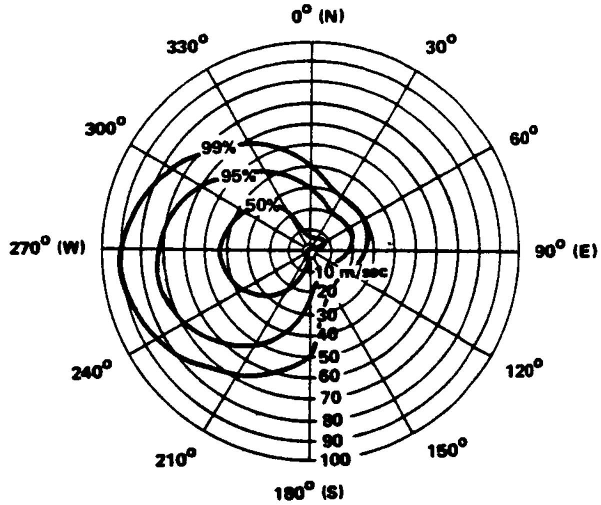
to indicate the direction from which the wind was blowing. Directional wind component values for other altitudes are available upon request to the Aerospace Environment Division, MSFC.

To illustrate the use of the envelopes, suppose an estimate of the strongest winds (99 percentile head, tail, and cross) in the 9- to 13-kilometer altitude region for several launch azimuths – perhaps 40, 180, 250, and 330 degrees – is required at Edwards AFB. For the 40-degree launch azimuth, read the headwind component along 40 degrees, the tailwind along 220 degrees, the right crosswind along 130 degrees, and the left crosswind along 310 degrees. The desired wind speeds are read from the intersection of the percentile and the proper azimuth. The appropriate wind speeds for this example are listed below:

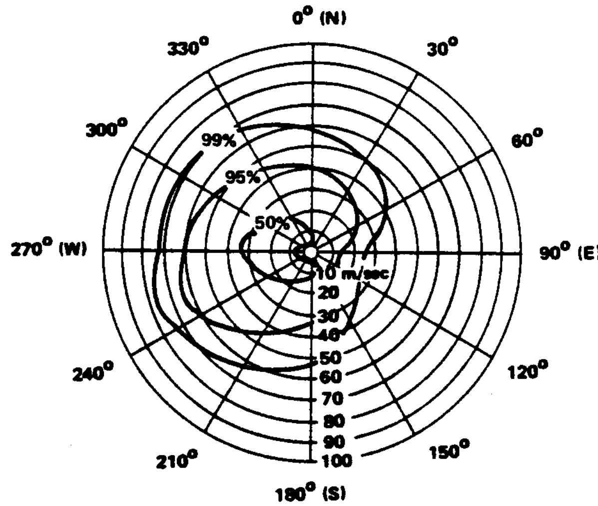
Launch Azimuth (deg)	Head Wind	Tail Wind	Right Cross	Left Cross
40	48	68	30	67
180	55	58	74	26
250	76	35	64	42
330	67	36	42	75

It is emphasized that the procedure followed in the construction of these envelopes permits no connection between the component winds. The data insure that the speed will in no month be exceeded at that probability level for a given azimuth relative to the launch azimuth selected. Design use requires a careful check of vehicle response in pitch and yaw for all planned flight azimuths.

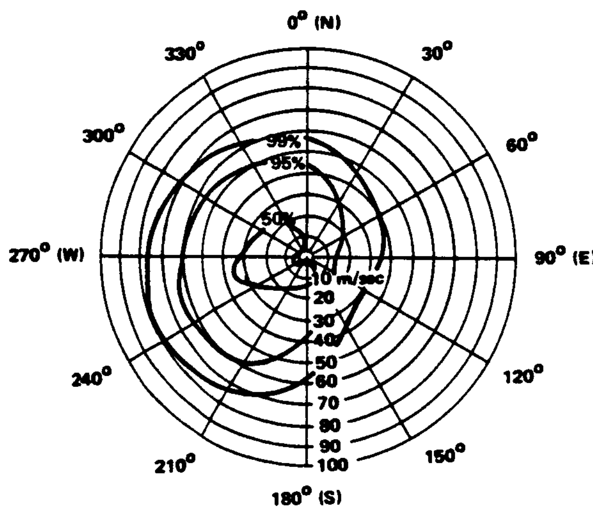
An example of directional wind profile envelopes is given in Table 5.3.10 for several flight azimuths for Cape Kennedy (Eastern Test Range), Florida, and Vandenberg AFB (SAMTEC), California. These were prepared from advance data on the upper altitude regions for which the complete results of the analysis are available upon request. If so designated by the development agency, such envelope profiles may be employed for initial design and performance studies as synthetic profiles with the appropriate values of wind shear/gust as noted in the following sections. Due to method used in constructing these directional profile envelopes, they are applied independently as head, tail, right, and left cross wind inputs for the given flight azimuth. The direction producing the largest vehicle response is used in the design analysis. It is again emphasized, however, that directional wind criteria



CAPE KENNEDY; 10-14 km ALTITUDE LAYER

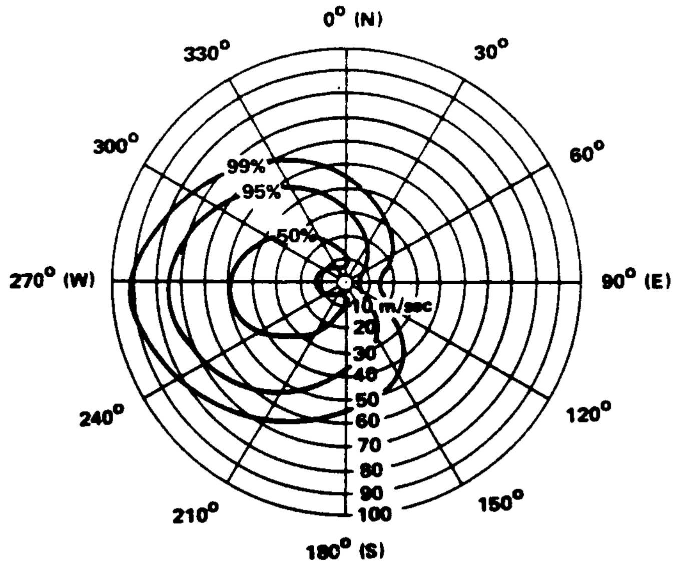


EDWARDS AFB; 9-13 km ALTITUDE LAYER

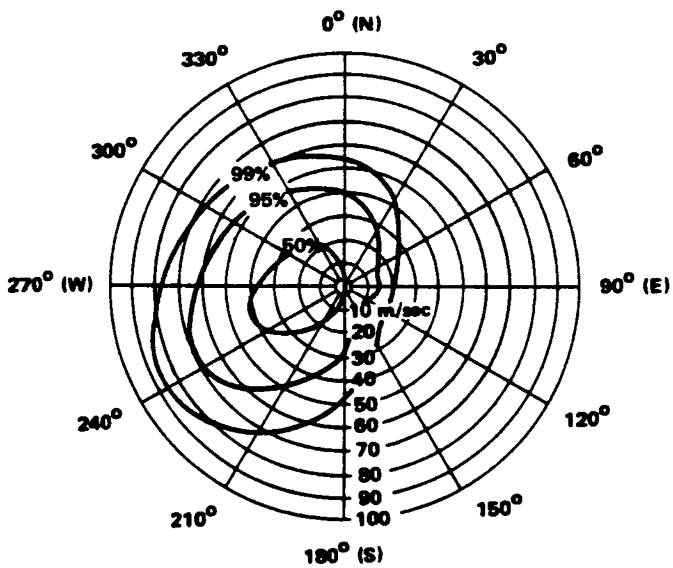


VANDENBERG, AFB; 9-10 km ALTITUDE LAYER

FIGURE 5.3.10 DIRECTIONAL WIND COMPONENT ENVELOPES (steady-state) FOR 99, 95, and 50 PERCENTILES



WALLOPS ISLAND; 9-13 km ALTITUDE LAYER



WHITE SANDS; 9-13 km ALTITUDE LAYER

FIGURE 5. 3. 10 DIRECTIONAL WIND COMPONENT ENVELOPES (steady-state) FOR 99, 95, and 50 PERCENTILES (Concluded)

TABLE 5.3.10 DIRECTIONAL WIND SPEED (m/sec) PROFILE ENVELOPES (95th percentile) FOR SELECTED FLIGHT AZIMUTHS

Altitude (km)	Cape Kennedy Flight Azimuth (α)												Vandenberg AFB Flight Azimuth (α)			
	α = 38 deg [a]				α = 90 deg [a]				α = 180 deg [a]				α = 182 deg [a]			
	Head Wind	Tail Wind	Right Cross Wind	Left Cross Wind	Head Wind	Tail Wind	Right Cross Wind	Left Cross Wind	Head Wind	Tail Wind	Right Cross Wind	Left Cross Wind	Head Wind	Tail Wind	Right Cross Wind	Left Cross Wind
1	11	16	9	14	11	20	13	9	13	9	20	11	12	14	10	7
2	12	22	9	18	12	27	15	11	15	11	27	12	16	17	16	8
3	13	27	10	23	13	33	16	14	16	14	33	13	19	21	23	9
4	14	32	10	27	14	39	18	16	18	16	39	14	23	25	29	10
5	15	37	11	32	15	45	20	18	20	18	45	15	27	28	35	11
6	16	42	11	36	16	51	21	20	21	20	51	16	31	31	41	11
10	20	63	13	54	20	75	28	29	28	29	75	20	42	42	60	14
14	20	63	13	54	20	75	28	29	28	29	75	20	42	42	60	14
20	17	18	18	15	25	25	8	7	8	7	25	25	7	10	20	16
23	17	18	18	15	25	25	8	7	8	7	25	25	7	10	20	16
50	47	95	65	97	72	120	52	30	52	30	120	72	60	28	140	88
60	47	95	65	97	72	120	52	30	52	30	120	72	60	28	140	88
75	30	70	34	50	50	90	30	20	30	20	90	50	32	25	98	25
80	30	70	34	50	50	90	30	20	30	20	90	50	32	25	98	25

a. Wind speeds given are applicable for $\alpha \pm 10°$

should be applied with care and specific knowledge of the vehicle design mission(s) configurations and flight azimuths, since severe wind constraints could result for other flight azimuths, missions, or launch sites.

5. 3. 6 Wind Speed Change (Shear) Envelopes

This section provides representative information on wind speed change (shear)[12] for scales of distance between 100 and 5000 meters. Scalar wind speed change is defined as the total magnitude (speed) change between the wind vectors at the top and bottom of a specified layer, regardless of wind direction. Wind shear is the wind speed change divided by the altitude interval. When applied to space vehicle synthetic wind profile criteria, it is frequently referred to as a wind buildup or backoff rate depending upon whether it occurs below (buildup) or above (backoff) the reference height of concern. Shear values ≥ 1000 meters thickness were computed from rawinsonde and rocketsonde observations, while the small scale shears, i. e., < 1000-meter intervals, were determined from relationships developed by Fichtl (Ref. 5. 29) using experimental results from FPS-16 Radar/Jimsphere balloon wind sensor measurements of the detail wind profile structure. Thus, a buildup wind value is the change in wind speed which a vehicle may experience while ascending vertically through a specified layer to the known altitude. Backoff magnitudes describe the change speed which may be experienced above the chosen level. Both buildup and backoff wind speed change data are presented in this section as a function of reference level wind vector magnitude and geographic location. Wind buildup or backoff may be determined for a vehicle with other than a vertical flight path by multiplying the wind speed change by the cosine of the angle between the vertical axis and the vehicle trajectory.

An envelope of the 99 percentile wind speed buildup is used currently in constructing synthetic wind profiles. For most design studies, the use of this 99 percentile scalar buildup wind shear data is warranted. The envelopes for backoff shears have application to certain design studies and should be considered where appropriate. These envelopes are not meant to imply perfect correlation between shears for the various scales of distance; however, certain correlations do exist, depending upon the scale of distance and the wind speed magnitude considered. This method of describing the wind shear for vehicle design has proven to be especially acceptable in preliminary design studies since the dynamic response of the vehicle's structure or control

12. Vector shears are not included in this document, but may be obtained from the Aerospace Environment Division upon request.

system in these various modes is essentially influenced by specific wavelengths as represented by a given wind shear. Construction of synthetic profiles for vehicle design application is described in subsection 5. 3. 8.

Wind speed change (shear) statistics for various locations differ primarily because of prevailing meteorological conditions, orographic features, and data sample size. Significant differences, especially from an engineering standpoint, are known to exist in the shear profiles for different locations. Therefore, consistent vehicle design shear data representing five active or potentially operational space vehicle launch or landing sites are presented in Tables 5. 3. 11 through 5. 3. 20; i. e. , for Eastern Test Range, Space and Missile Test Center, Wallops Island, White Sands Missile Range, and Edwards Air Force Base. Tables 5. 3. 21 and 5. 3. 22 envelope the 99 percentile shears from these five locations. They are applicable for design criteria when initial design or operational capability has not been restricted to a specific launch site or may involve several geographical locations. However, if the specific geographic location for application has been determined as being near one of the five referenced sites, then the relevent data should be applied. Reference 5. 30 further substantiates that the shear data presented in this document are representative for higher altitudes and applicable for engineering design.

5. 3. 7 Gusts - Vertically Flying Vehicles

The steady-state inflight wind speed envelopes presented in subsection 5. 3. 5 do not contain the gust (high frequency content) portion of the wind profile. The steady-state wind profile measurements have been defined as those obtained by the rawinsonde system. These measurements represent wind speeds averaged over approximately 600 meters in the vertical and, therefore, eliminate features with smaller scales. These smaller scale features are represented in the detailed profiles measured by the FPS-16 Radar/Jimsphere system.

A number of attempts have been made to represent the high frequency content of vertical wind profiles in a suitable form for use in vehicle design studies. Most of the attempts resulted in gust information that could be used for specific applications, but, to date, no universal gust representation has been formulated. Information on discrete and continuous gust representation is given below relative to vertically ascending space vehicles.

TABLE 5.3.11 BUILDUP DESIGN ENVELOPES OF 99 PERCENTILE SCALAR WIND SPEED CHANGE, 1- TO 80-km ALTITUDE REGION, EASTERN TEST RANGE

Wind Speed at Top of Altitude Layer (m/sec)	Scales of Distance (m)									
	5000	4000	3000	2000	1000	800	600	400	200	100
≥ 90	65.6	59.5	52.3	43.5	34.0	29.0	23.8	17.9	11.2	6.8
80	60.4	55.5	49.7	42.0	32.7	27.7	22.7	17.0	10.6	6.5
70	56.0	51.7	47.0	40.4	31.2	26.6	21.8	16.4	10.1	6.2
60	51.3	48.5	44.5	38.6	30.0	25.6	21.1	15.8	9.8	6.0
50	46.5	45.0	41.2	36.5	28.5	24.4	20.0	15.0	9.2	5.7
40	38.5	37.7	36.8	34.9	26.5	22.6	18.5	13.8	8.6	5.3
30	28.0	27.5	26.5	24.5	20.8	17.8	14.5	10.8	6.7	4.1
20	17.6	17.3	16.6	15.8	14.6	12.5	10.2	7.2	4.7	2.9

TABLE 5.3.12 BACKOFF DESIGN ENVELOPES OF 99 PERCENTILE SCALAR WIND SPEED CHANGE, 1- TO 80-km ALTITUDE REGION, EASTERN TEST RANGE

Wind Speed at Top of Altitude Layer (m/sec)	Scales of Distance (m)									
	5000	4000	3000	2000	1000	800	600	400	200	100
≥ 90	77.5	74.4	68.0	59.3	42.6	36.4	29.7	22.4	13.8	8.5
80	71.0	68.0	63.8	56.0	40.5	34.7	28.5	21.4	13.2	8.1
70	63.5	61.0	57.9	52.0	38.8	33.1	27.0	20.3	12.5	7.7
60	56.0	54.7	52.3	47.4	36.0	31.0	25.3	18.9	11.7	7.2
50	47.5	47.0	46.2	43.8	33.0	28.3	23.2	17.5	10.7	6.6
40	39.0	38.0	37.0	35.3	29.5	25.3	20.6	15.5	9.6	5.9
30	30.6	30.0	29.4	26.9	22.6	19.4	15.8	11.9	7.3	4.5
20	18.0	17.5	16.7	15.7	14.2	12.2	9.9	7.5	4.6	2.8

TABLE 5.3.13 BUILDUP DESIGN ENVELOPES OF 99 PERCENTILE SCALAR WIND SPEED CHANGE, 1- TO 80-km ALTITUDE REGION, SPACE AND MISSILE TEST CENTER (Vandenberg AFB)

	Scales of Distance (m)									
Wind Speed at Top of Altitude Layer (m/sec)	5000	4000	3000	2000	1000	800	600	400	200	100
≥ 90	75.8	73.1	70.5	62.9	43.0	36.8	30.0	22.5	14.0	8.6
80	70.7	69.5	67.0	58.8	40.4	34.9	28.4	21.4	13.2	8.1
70	62.2	61.6	60.4	54.4	38.2	32.6	26.7	20.1	12.3	7.6
60	55.0	54.5	53.5	48.0	35.7	30.5	24.9	18.7	11.5	7.1
50	47.4	46.8	45.9	42.5	33.4	28.5	23.4	17.6	10.8	6.7
40	35.5	35.0	33.5	31.5	27.8	23.8	19.5	14.6	8.9	5.5
30	27.5	26.8	26.0	24.5	20.5	17.5	14.3	10.8	6.6	4.1
20	18.5	17.8	17.5	16.7	15.4	13.1	10.7	8.1	5.0	3.1

TABLE 5.3.14 BACKOFF DESIGN ENVELOPES OF 99 PERCENTILE SCALAR WIND SPEED CHANGE, 1- TO 80-km ALTITUDE REGION, SPACE AND MISSILE TEST CENTER (Vandenberg AFB)

	Scales of Distance (m)									
Wind Speed at Top of Altitude Layer (m/sec)	5000	4000	3000	2000	1000	800	600	400	200	100
≥ 90	78.2	74.2	67.5	57.3	43.8	37.5	30.5	23.0	14.0	8.7
80	71.2	68.6	63.0	53.5	41.0	35.0	28.5	21.2	13.2	8.2
70	64.0	61.1	56.6	48.1	37.2	32.0	26.1	19.7	12.1	7.4
60	54.4	52.3	49.0	43.0	33.0	28.3	23.2	17.4	10.7	6.6
50	45.0	43.9	40.7	36.2	29.5	25.2	20.7	15.6	9.6	5.9
40	36.3	34.9	32.5	29.6	25.3	21.6	17.7	13.3	8.1	5.0
30	28.0	26.5	24.8	22.8	19.5	16.7	13.7	10.3	6.3	3.9
20	18.0	17.5	16.6	15.5	13.0	11.1	9.0	6.8	4.2	2.6

TABLE 5. 3. 15 BUILDUP DESIGN ENVELOPES OF 99 PERCENTILE SCALAR WIND SPEED CHANGE, 1- TO 80-km ALTITUDE REGION, WHITE SANDS MISSILE RANGE

Wind Speed at Top of Altitude Layer (m/sec)	Scales of Distances (m)									
	5000	4000	3000	2000	1000	800	600	400	200	100
≥ 90	70. 7	67. 0	61. 2	52. 4	42. 0	36. 0	29. 4	22. 1	13. 6	8. 4
80	66. 0	63. 0	57. 7	50. 0	40. 2	34. 5	28. 1	21. 2	13. 0	8. 0
70	60. 2	57. 0	53. 0	46. 5	38. 0	32. 6	26. 6	20. 0	12. 3	7. 6
60	52. 4	50. 0	46. 5	42. 3	35. 5	30. 5	24. 9	18. 7	11. 5	7. 1
50	44. 8	43. 0	40. 2	36. 5	32. 0	28. 3	23. 1	17. 4	10. 7	6. 6
40	36. 4	35. 3	33. 8	31. 0	27. 5	23. 6	19. 3	14. 5	8. 9	5. 5
30	27. 4	26. 5	25. 6	24. 3	20. 6	17. 7	14. 4	10. 8	6. 7	4. 1
20	18. 4	17. 7	17. 3	16. 5	15. 0	12. 9	10. 5	7. 9	4. 9	3. 0

TABLE 5. 3. 16 BACKOFF DESIGN ENVELOPES OF 99 PERCENTILE SCALAR WIND SPEED CHANGE, 1- TO 80-km ALTITUDE REGION, WHITE SANDS MISSILE RANGE

Wind Speed at Top of Altitude Layer (m/sec)	Scales of Distance (m)									
	5000	4000	3000	2000	1000	800	600	400	200	100
≥ 90	66. 2	62. 0	57. 0	50. 0	37. 0	31. 7	25. 9	19. 5	12. 0	7. 4
80	62. 0	58. 5	54. 0	48. 0	35. 8	30. 7	25. 1	18. 9	11. 6	7. 1
70	57. 5	54. 5	50. 7	44. 3	34. 2	29. 3	23. 9	18. 0	11. 1	6. 8
60	52. 6	49. 2	45. 5	40. 5	32. 8	28. 1	23. 0	17. 3	10. 6	6. 5
50	45. 0	42. 8	40. 1	37. 0	31. 0	26. 6	21. 7	16. 3	10. 0	6. 2
40	36. 5	35. 5	34. 8	33. 5	29. 3	25. 1	20. 5	15. 4	9. 5	5. 8
30	27. 4	27. 0	26. 4	24. 8	22. 0	19. 3	15. 8	11. 8	7. 3	4. 5
20	17. 7	17. 3	16. 7	15. 8	14. 1	12. 1	9. 9	7. 4	4. 6	2. 8

TABLE 5.3.17 BUILDUP DESIGN ENVELOPES OF 99 PERCENTILE SCALAR WIND SPEED CHANGE, 1- TO 80-km ALTITUDE REGION, WALLOPS ISLAND

Wind Speed at Top of Altitude Layer (m/sec)	Scales of Distance (m)									
	5000	4000	3000	2000	1000	800	600	400	200	100
≥ 90	71.0	66.2	60.2	50.5	37.6	32.3	26.3	19.8	12.2	7.5
80	66.5	62.5	57.5	48.8	37.0	31.7	25.9	19.5	12.0	7.4
70	61.2	58.5	53.8	46.5	35.8	30.7	25.1	18.9	11.6	7.1
60	54.4	52.5	50.0	44.2	34.5	29.6	24.2	18.2	11.2	6.9
50	45.2	43.4	42.3	38.8	33.0	28.3	23.2	17.4	10.7	6.6
40	36.1	35.6	34.5	32.3	27.6	23.7	19.3	14.5	8.9	5.5
30	27.0	26.3	25.3	24.2	20.6	17.7	14.4	10.8	6.7	4.1
20	17.7	17.3	16.8	16.4	15.2	13.0	10.6	8.0	4.9	3.0

TABLE 5.3.18 BACKOFF DESIGN ENVELOPES OF 99 PERCENTILE SCALAR WIND SPEED CHANGE, 1- TO 80-km ALTITUDE REGION, WALLOPS ISLAND

Wind Speed at Top of Altitude Layer (m/sec)	Scales of Distance (m)									
	5000	4000	3000	2000	1000	800	600	400	200	100
≥ 90	72.5	67.0	59.2	49.0	31.5	27.0	22.1	16.6	10.2	6.3
80	66.3	62.0	56.0	46.0	30.0	25.7	21.0	15.8	9.7	6.0
70	60.0	56.5	51.5	43.6	28.5	24.5	20.0	15.0	9.2	5.7
60	53.5	50.7	46.8	40.4	27.0	23.2	18.9	14.2	8.7	5.4
50	46.2	44.2	41.0	35.8	25.2	21.6	17.6	13.3	8.2	5.0
40	36.7	35.2	32.7	28.7	21.5	18.4	15.1	11.3	7.0	4.3
30	27.2	26.1	24.8	22.5	18.2	15.6	12.7	9.6	5.9	3.6
20	17.8	17.3	16.4	15.2	13.0	11.1	9.0	6.8	4.2	2.6

TABLE 5.3.19 BUILDUP DESIGN ENVELOPES OF 99 PERCENTILE SCALAR WIND SPEED CHANGE, 1- TO 80-km ALTITUDE REGION, EDWARDS AIR FORCE BASE

	Scales of Distance (m)									
Wind Speed at Top of Altitude Layer (m/sec)	5000	4000	3000	2000	1000	800	600	400	200	100
$\geq$ 90	69.0	65.0	59.5	52.0	39.5	33.9	27.7	20.8	12.8	7.9
80	64.9	61.8	56.9	50.0	38.2	32.8	26.7	20.1	12.4	7.6
70	59.0	57.0	53.0	46.8	37.0	31.7	25.9	19.5	12.0	7.4
60	51.8	50.4	47.8	43.6	35.5	30.5	24.9	18.7	11.5	7.1
50	44.8	43.6	41.3	38.2	31.8	27.5	22.4	16.9	10.4	6.4
40	36.5	35.5	34.3	32.0	26.5	23.0	18.8	14.1	8.7	5.3
30	28.0	27.3	26.3	24.5	20.8	17.8	14.6	11.0	6.7	4.2
20	18.0	17.7	17.4	16.7	15.2	13.0	10.6	8.0	4.9	3.0

TABLE 5.3.20 BACKOFF DESIGN ENVELOPES OF 99 PERCENTILE SCALAR WIND SPEED CHANGE, 1- TO 80-km ALTITUDE REGION, EDWARDS AIR FORCE BASE

	Scales of Distance (m)									
Wind Speed at Top of Altitude Layer (m/sec)	5000	4000	3000	2000	1000	800	600	400	200	100
$\geq$ 90	75.2	72.0	67.3	59.0	42.8	36.7	30.2	22.5	13.9	8.5
80	68.0	66.3	62.5	55.5	40.8	35.0	28.6	21.5	13.2	8.1
70	60.4	59.0	56.8	51.4	38.7	33.2	27.0	20.4	12.5	7.7
60	53.0	51.8	49.3	45.0	36.0	30.9	25.2	19.0	11.7	7.2
50	44.5	43.3	41.5	38.4	32.0	27.5	22.4	16.9	10.4	6.4
40	35.7	35.3	34.5	33.0	27.0	23.2	18.9	14.2	8.8	5.4
30	27.1	27.0	26.9	26.3	21.4	18.4	15.0	11.3	6.9	4.3
20	18.0	17.0	16.6	15.7	14.2	12.2	9.9	7.5	4.6	2.8

TABLE 5. 3. 21 BUILDUP DESIGN ENVELOPES OF 99 PERCENTILE SCALAR WIND SPEED CHANGE, 1- TO 80-km ALTITUDE REGION, FOR ALL FIVE LOCATIONS

Wind Speed at Top of Altitude Layer (m/sec)	Scales of Distance (m) 5000	4000	3000	2000	1000	800	600	400	200	100
≥ 90	75. 8	73. 1	70. 5	62. 9	43. 0	36. 8	30. 0	22. 5	14. 0	8. 6
80	70. 7	69. 5	67. 0	58. 8	40. 4	34. 9	28. 4	21. 4	13. 2	8. 1
70	62. 2	61. 6	60. 4	54. 4	38. 2	32. 6	26. 7	20. 1	12. 3	7. 6
60	55. 0	54. 5	53. 5	48. 0	35. 7	30. 5	24. 9	18. 7	11. 5	7. 1
50	47. 4	46. 8	45. 9	42. 5	33. 4	28. 5	23. 4	17. 6	10. 8	6. 7
40	38. 5	37. 7	36. 8	34. 9	27. 8	23. 8	19. 5	14. 6	8. 9	5. 5
30	28. 0	27. 5	26. 5	24. 5	20. 8	17. 8	14. 5	10. 8	6. 7	4. 1
20	18. 5	17. 8	17. 5	16. 7	15. 4	13. 1	10. 7	8. 1	5. 0	3. 1

TABLE 5. 3. 22 BACKOFF DESIGN ENVELOPES OF 99 PERCENTILE SCALAR WIND SPEED CHANGE, 1- TO 80-km ALTITUDE REGION, FOR ALL FIVE LOCATIONS

Wind Speed at Top of Altitude Layer (m/sec)	Scales of Distance (m) 5000	4000	3000	2000	1000	800	600	400	200	100
≥ 90	78. 2	74. 4	68. 0	59. 3	43. 8	37. 5	30. 5	23. 0	14. 0	8. 7
80	71. 2	68. 6	63. 8	56. 0	41. 0	35. 0	28. 5	21. 2	13. 2	8. 2
70	64. 0	61. 1	57. 9	52. 0	38. 9	33. 4	27. 0	20. 3	12. 5	7. 7
60	56. 0	54. 7	52. 3	47. 4	36. 0	31. 0	25. 3	18. 9	11. 7	7. 2
50	47. 5	47. 0	46. 2	43. 8	33. 0	28. 3	23. 2	17. 5	10. 7	6. 6
40	39. 0	38. 0	37. 0	35. 3	29. 5	25. 3	20. 6	15. 5	9. 6	5. 9
30	30. 6	30. 0	29. 4	26. 9	22. 6	19. 4	15. 8	11. 9	7. 3	4. 5
20	18. 0	17. 5	16. 7	15. 7	14. 2	12. 2	9. 9	7. 5	4. 6	2. 8

5. 3. 7. 1 Discrete Gusts

Discrete gusts are specified in an attempt to represent, in a physically reasonable manner, characteristics of small scale motions associated with vertical wind velocity profiles. Gust structure usually is quite complex and it is not always understood. For vehicle design studies, discrete gusts are usually idealized because of their complexity and to enhance their utilization. Examples of discrete (individual and sinusoidial type) gusts in nature are given in subsection 5. 3. 8.

Well defined, sharp edged, and repeated sinusoidal gusts are important types in terms of their influence upon space vehicles. Quasi-square-wave gusts with amplitudes of approximately 9 m/sec have been measured. These gusts are frequently referred to as embedded jets or singularities in the vertical wind profile. By definition, a gust is a wind speed in excess of the defined steady-state value; therefore, these gusts are employed on top of the steady-state wind profile values.

Figure 5. 3. 11 is a schematic representation of the design quasi-square-wave gust with wavelengths varying between 60 and 300 meters with an amplitude of 9 m/sec. The mean shear buildup rate at the leading and trailing edges of gust is 9 m/sec per 30 meters. The relationship of the gust to the idealized wind speed envelope and the wind buildup envelope is shown in Figure 5. 3. 11

Another form of discrete gusts that has been observed is approximately sinusoidal in nature, where gusts occur in succession. Figure 5. 3. 12 illustrates the estimated number of consecutive sinusoidal type gusts that may occur and their respective amplitudes for design purposes. It is extremely important when applying these gusts in vehicle studies to realize that these are pure sinusoidal representations that have never been observed in nature. The degree of purity of these sinusoidal features on the vertical wind profiles has not been established. These gusts should be superimposed symmetrically upon the steady-state profile. The data presented here on sinusoidal discrete gusts are at best preliminary and should be treated as such in design studies.

5. 3. 7. 2 Spectra

In general, the small scale motions associated with vertical detailed wind profiles are characterized by a superposition of discrete gusts and many random frequency components. Spectral methods have been employed to specify the characteristics of this superposition of small scale motions.

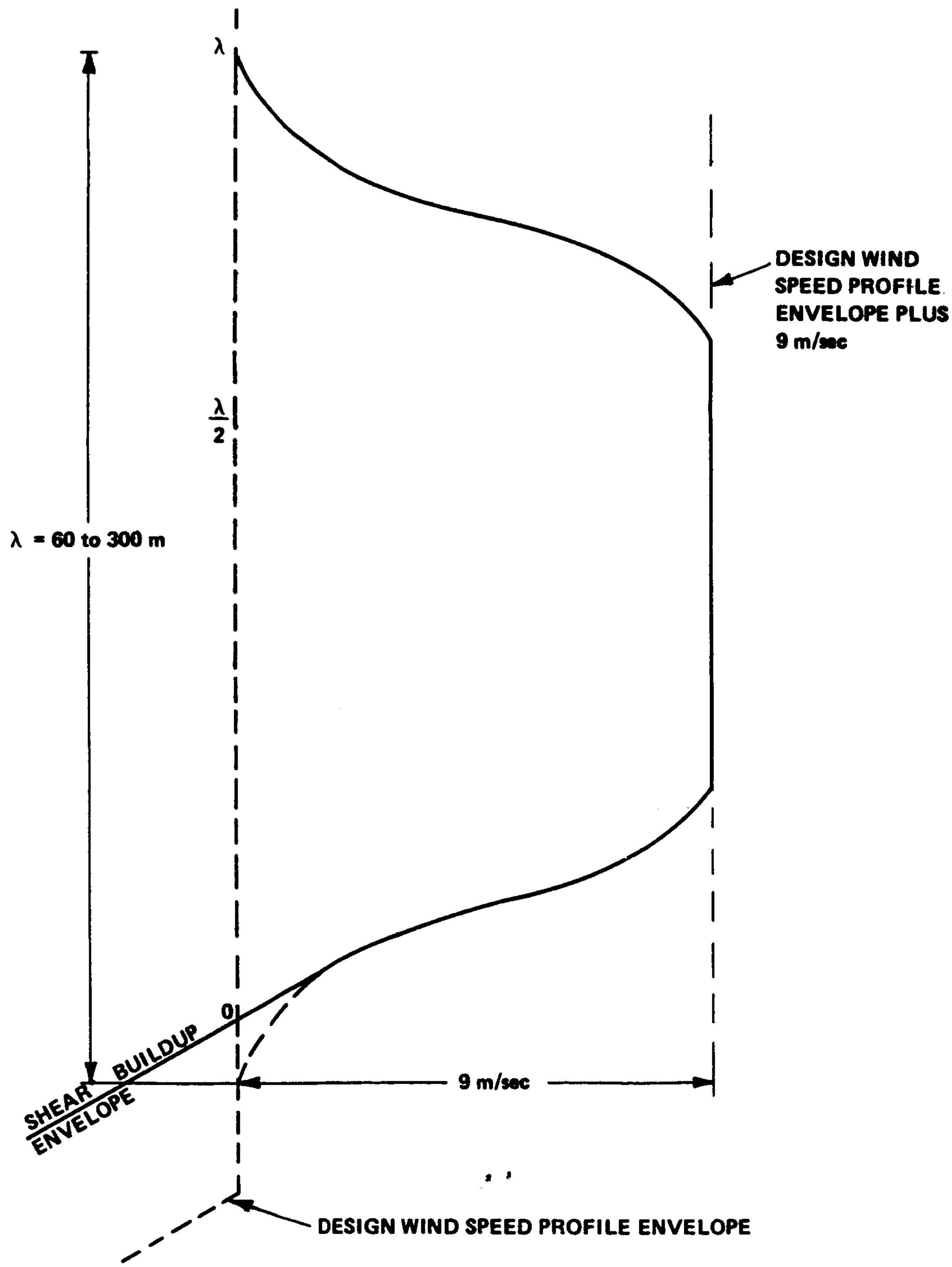


FIGURE 5.3.11 RELATIONSHIP BETWEEN DISCRETE GUST AND/OR EMBEDDED JET CHARACTERISTICS (quasi-square-wave shape) AND THE DESIGN WIND SPEED PROFILE ENVELOPE

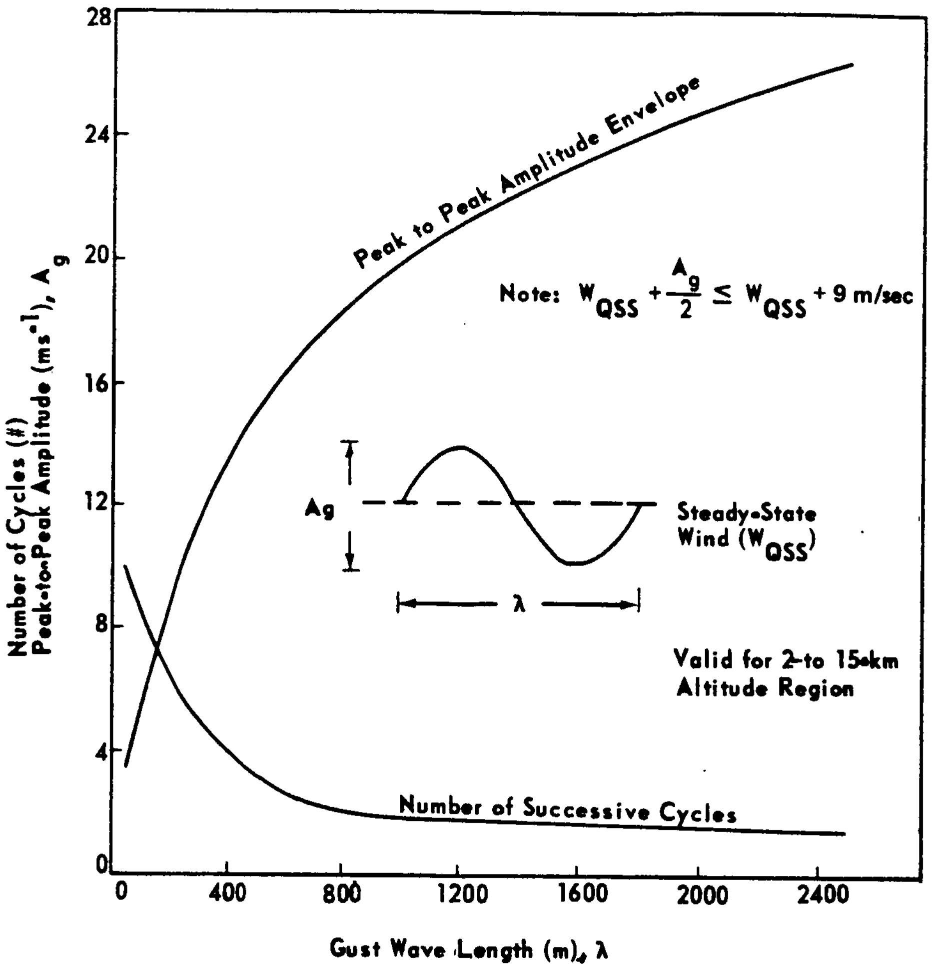


FIGURE 5.3.12 BEST ESTIMATE OF EXPECTED (≧ 99 percentile) GUST AMPLITUDE AND NUMBER OF CYCLES AS A FUNCTION OF GUST WAVELENGTHS

A digital filter was developed to separate small scale motions from the steady-state wind profile. The steady-state wind profile defined by the separation process approximates those obtained by the rawinsonde system.[13] Thus, a spectrum of small scale motions is representative of the motions

13. This definition was selected to enable use of the much larger rawinsonde data sample in association with a continuous type gust representation.

included in the FPS-16 Radar/Jimsphere measurements, which are not included in the rawinsonde measurements. Therefore, a spectrum of those motions should be added to the steady-state wind profiles to obtain a representation of the detailed wind profile. Spectra of the small scale motions for various probability levels have been determined and are presented in Figure 5.3.13. The spectra were computed from approximately 1200 detailed wind profile measurements by computing the spectra associated with each profile, then determining the probabilities of occurrence of spectral density as a function of wave number (cycles/4000 m). Thus the spectra represent envelopes of spectral density for the given probability levels. Spectra associated with each profile were computed over the altitude range between approximately 4 and 16 kilometers. It has been shown that energy (variance) of the small scale motions is not homogeneous; that is, it is not constant with altitude. The energy content over limited altitude intervals and for limited frequency bands may be much larger than that represented by the spectra in Figure 5.3.13. This should be kept in mind when interpreting the significance of vehicle responses when employing the spectra of small scale motions. Additional details on this subject are available upon request. Envelopes of spectra for detailed profiles without filtering (solid lines) are also shown in Figure 5.3.13. These spectra are well represented for wave numbers ≥ 5 cycles per 4000 meters by the equation

$$E(k) = E_0 k^{-p} \quad , \qquad (5.24)$$

where E is the spectral density at any wave number k (cycles/4000 m) between 1 and 20, $E_0 = E(1)$, and p is a constant for any particular percentile level of occurrence of the power spectrum.

Properties of all the spectra are summarized in Table 5.3.23. Data presented in this table show that the small scale motions associated with the meridional profiles (generally cross wind component in yaw plane) contain more energy than those associated with either the zonal or scalar profiles for

TABLE 5.3.23 PARAMETERS DEFINING SPECTRA OF DETAILED WIND PROFILES $\{E_0 - m^2 sec^{-2} [cycles\ (4000\ m)^{-1}]^{-1}\}$

Percentile	E_0	p
50	5.3	2.38
90	13.5	2.46
99	25.5	2.49

the 50 and 90 percentile spectra. Because of computational difficulties, the spectra do not extend to wavelengths longer than 4000 meters. However, this wavelength encompasses the significant characteristic structural and control mode frequencies for most vertically rising vehicles of interest.

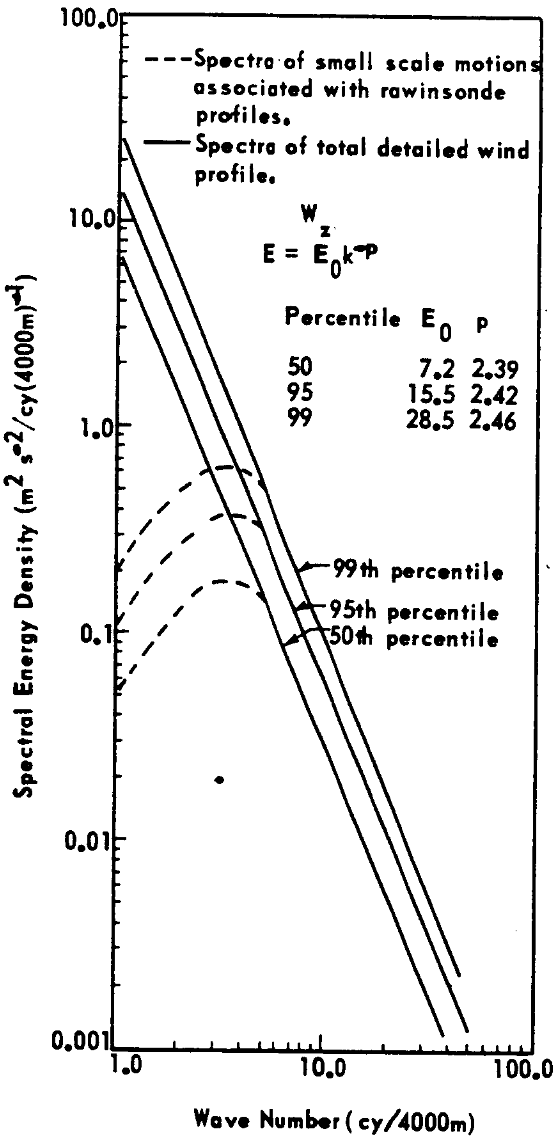


FIGURE 5. 3. 13 SPECTRA OF DETAILED WIND PROFILES

Spectra of the total wind speed profiles may be useful in control systems and other slow response parametric studies for which the spectra of small scale motions may not be adequate.

The power spectrum recommended for use in elastic body studies is given by the following expression:

$$E(\kappa) = \frac{683.4\ (4000\,\kappa)^{1.62}}{1 + 0.0067\ (4000\,\kappa)^{4.05}}\ , \tag{5.25}$$

where the spectrum $E(\kappa)$ is defined so that integration over the domain $0 \leq \kappa \leq \infty$ yields the variance of the turbulence. In this equation $E(\kappa)$ is now the power spectral density [m^2 sec^{-2}/(cycles per meter)] at wave number κ (m^{-1}). This function represents the 99 percentile scalar wind spectra for small scalar motions given by the dashed curve and its solid line extension into the high wave number region in Figure 5. 3. 13. The associated design turbulence loads are obtained by multiplying the load standard deviations by a factor of three. (Spectra for meridional and zonal components are available upon request.)

Vehicle responses obtained from application of this turbulence spectra should be added to rigid vehicle responses resulting from use of the synthetic wind speed and wind shear profile (with the 0.85 factor on shears) but without a discrete gust. See section 5. 3. 8. 2 for construction.

5. 3. 8 Synthetic Wind Speed Profiles

Two methods of constructing synthetic wind speed profiles are described herein. The first method uses design wind speed profile envelopes (subsection 5. 3. 5), wind shear (wind speed change) envelopes (subsection 5. 3. 6), and discrete gusts or spectra (subsection 5. 3. 7) without consideration of any lack of correlation between the shears and gusts. The second method takes into account the relationships between the wind shear and gust characteristics.

5. 3. 8. 1 Synthetic Wind Speed Profiles for Vertical Flight Path Considering Only Speeds and Shears

In the method that follows, correlation between the design wind speed profile envelope and wind shear envelope is considered. The method is illustrated with the 95 percentile design nondirectional (scalar) wind speed profile and the 99 percentile scalar wind speed buildup envelope (Figure 5. 3. 14) and is stated as follows:

a. Start with a speed on the design wind speed profile envelope at a selected (reference) altitude.

b. Subtract the amount of the shear (wind speed change) for each required altitude layer from the value of the wind speed profile envelope at the selected altitude. For example, in Figure 5. 3. 14, by using the selected altitude of 12 kilometers on the wind speed profile envelope for Eastern Test Range (Figure 5. 3. 4) to determine the point at 11 kilometers on the shear buildup envelope, a value of wind speed change (buildup) of 32. 7 m/sec is obtained (from Table 5. 3. 11, Eastern Test Range) for ≥ 80 m/sec wind speed and 1000 meters scale of distance. By subtracting 32. 7 m/sec from 75 m/sec, the value of the wind speed profile envelope of 42. 3 m/sec is obtained.

c. Plot values obtained for each altitude layer at the corresponding altitudes. (The value of 42. 3 m/sec, obtained in the example in b, would be plotted at 11 km.) Continue plotting values until a 5000-meter layer is reached (5000 meters below the selected altitude).

d. Draw a smooth curve through the plotted points starting at the selected altitude on the wind speed profile envelope. The lowest point is extended from the origin with a straight line tangent to the plotted shear buildup curve. This curve then becomes the shear buildup envelope.

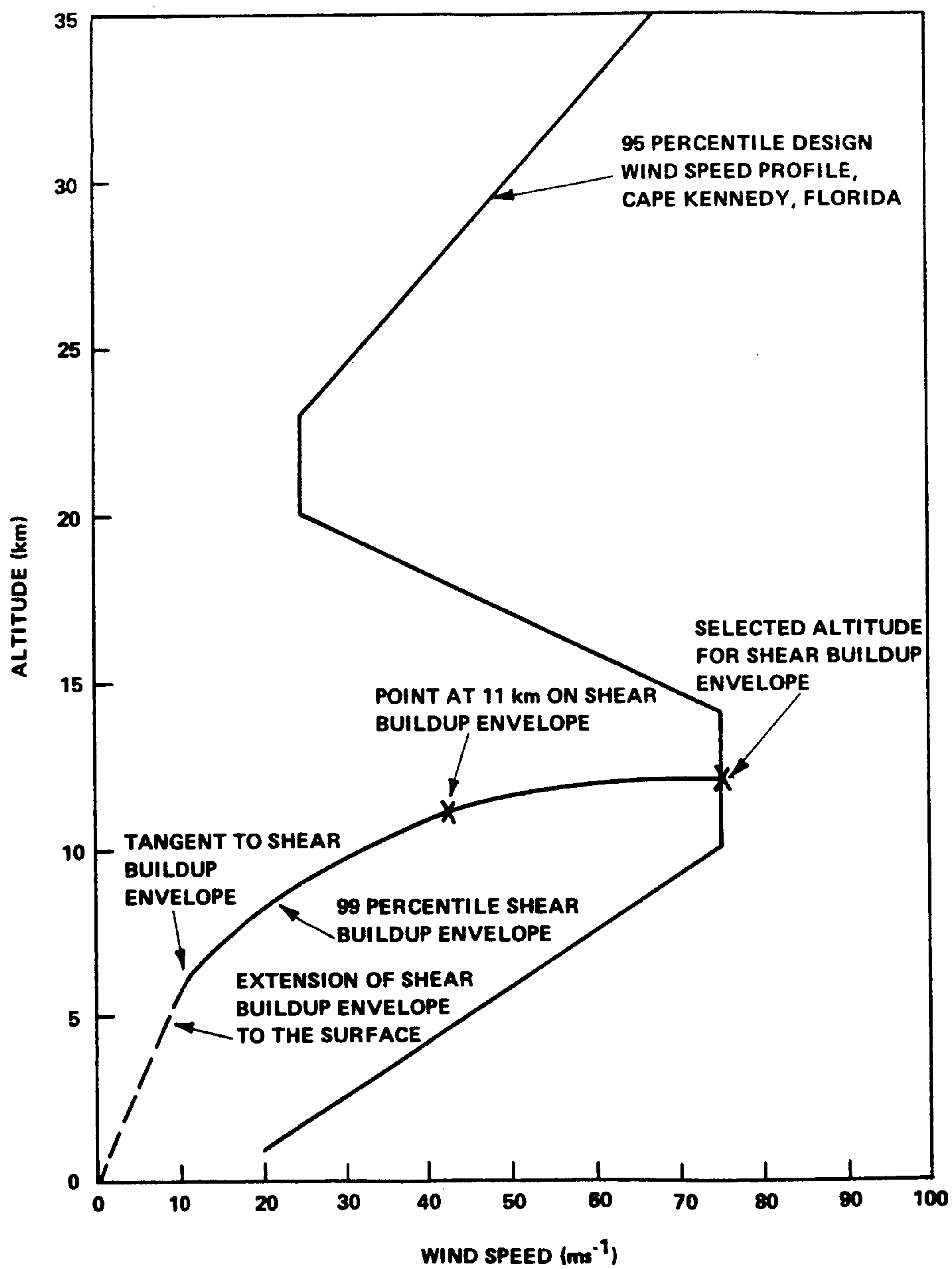


FIGURE 5.3.14 EXAMPLE OF SYNTHETIC WIND PROFILE CONSTRUCTION, WITHOUT ADDITION OF GUST

e. If a gust is desired, then superimpose the gust upon the profile (Figure 5. 3. 15) taking into account the lack of perfect correlation between the shears and gusts as noted in subsection 5. 3. 8. 2.

5.3.8.2 Synthetic Wind Speed Profiles For Vertical Flight Path Considering Relationships Between Speeds, Shears, and Gusts.

In the construction of a synthetic wind speed profile, the lack of perfect correlation between the wind shear and gust can be taken into account by multiplying the shears (wind speed changes) (subsection 5. 3. 6) and the quasi-square-wave discrete gusts (subsection 5. 3. 7) by a factor of 0. 85 before constructing the synthetic wind profile. This is equivalent, as an engineering approximation,[14] to taking the combined 99 percentile gust and shear combination rather than the separate addition of the 99 percentile values for the gusts and shears in a perfectly correlated manner.

Thus, to construct the synthetic wind speed profiles (considering relationships between shears, speeds, and gusts, using the design wind speed envelopes given in subsection 5. 3. 5), the procedure that follows is used. Figures 5. 3. 15 and 5. 3. 16 show an example using the 95 percentile design wind speed profile envelope, the 99 percentile wind speed buildup envelope, and the modified one-minus-cosine discrete gust shape.

a. Construct the shear buildup envelope in the way described in subsection 5. 3. 8. 1, except multiply the values of wind speed change used for each scale-of-distance by 0. 85. (In the example for the selected altitude of 12 km, the point at 11 km will be found by using the wind speed change of 32. 7 × 0. 85, or 27. 8 m/sec.) This value subtracted from 75 m/sec then gives a value of 47. 2 m/sec for the point plotted at 11 kilometers instead of the value of 42. 3 m/sec used when shear and gust relationships were not considered.

b. The superimposed gust is added by extending the shear buildup envelope until it becomes tangent to the one-minus-cosine shaped gust. As shown in Figure 5. 3. 15, the extension of the shear buildup envelope is made with the same slope as that of the last 100-meter layer segment before it meets the design wind speed profile. To eliminate the problem of exaggerated vehicle responses when a discontinuous function made up of straight lines is

14. This approach was used successfully in the Apollo/Saturn vehicle development program.

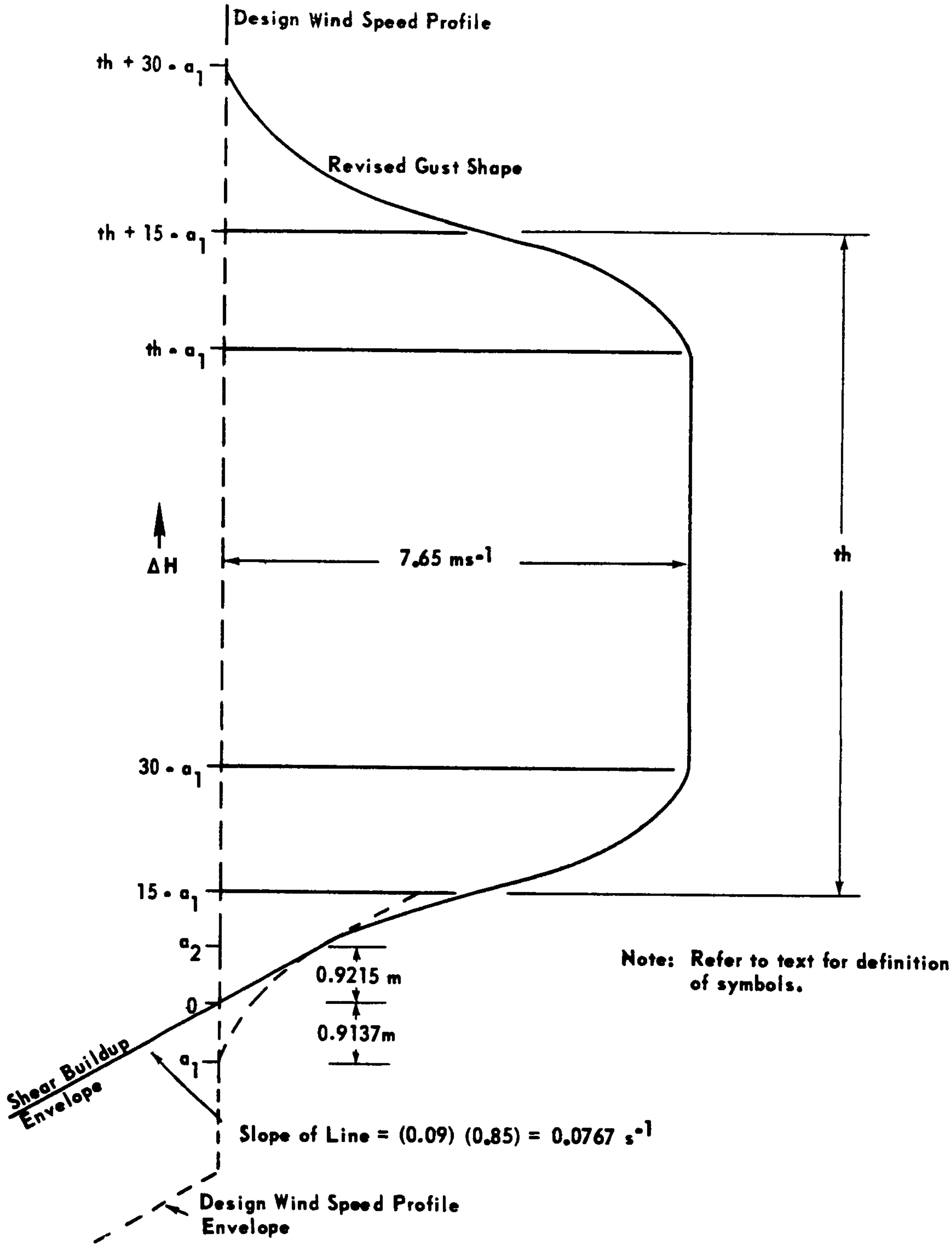


FIGURE 5.3.15 RELATIONSHIP BETWEEN REVISED GUST SHAPE, DESIGN WIND SPEED ENVELOPE, AND SPEED BUILDUP ENVELOPE

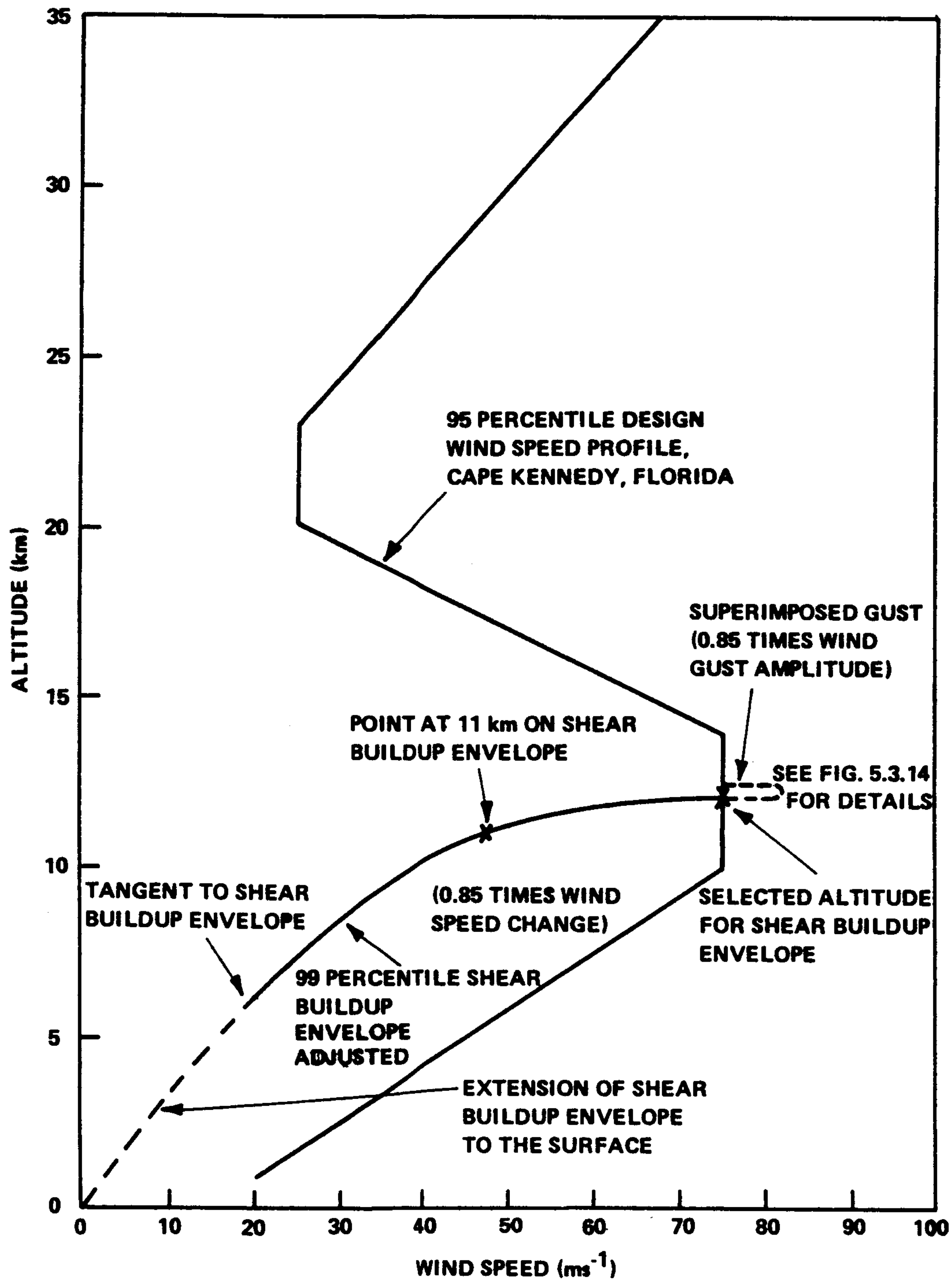


FIGURE 5.3.16 EXAMPLE OF SYNTHETIC WIND PROFILE CONSTRUCTION, WITH RELATIONSHIP OF WIND SHEARS AND GUSTS ASSUMED

applied to a vehicle, the gust should be represented by a modified one-minus-cosine shape to round the corners as shown in Figure 5. 3. 15. Details of the one-minus-cosine shaped gust are as follows:

1. The gust consists of the linear extension of the shear buildup envelope from the design wind speed envelope, the buildup to the peak gust speed on a one-minus-cosine curve (first half of curve) in 30 meters of altitude (a half-wavelength), a constant velocity plateau of from 0 to 215 meters, and a tail-off on the second half of the one-minus-cosine curve, also in 30 meters altitude. The amplitude of the gust (total wind speed increase) from the design wind speed envelope to the constant velocity plateau is equal to 0. 85 × 9 m/sec = 7. 6 m/sec. The one-minus-cosine curve has a half-wavelength of 30 meters (altitude).

2. Starting at the point where the shear buildup envelope meets the design wind speed envelope as the zero point, the 99 percentile gust (Figure 5. 3. 15) is described by the following equations:

$$0 \le \Delta H \le a_2 \qquad \Delta W_G = (0.09)\ (0.85)\ \Delta H = 0.0765\ \Delta H$$

$$a_2 \le \Delta H \le 30 - a_1 \qquad \Delta W_G = 3.825 \left\{1 - \cos\left[\frac{\pi}{30}\ (\Delta H + a_1)\right]\right\}$$

$$30 - a_1 \le \Delta H \le th - a_1 \qquad \Delta W_G = 7.65$$

$$th - a_1 \le \Delta H \le th + 30 - a_1 \qquad \Delta W_G = 3.825 \left\{1 - \cos\left[\frac{\pi}{30}(\Delta H + 30 + a_1 - th)\right]\right\}$$

$$th + 30 - a_1 \le \Delta H \qquad \Delta W_G = 0 \quad ,$$

where

ΔH = altitude difference (m)

ΔW_G = gust wind speed (m/sec)

a_1 = the shift of the one-minus-cosine buildup required to a tangential changeover from the shear buildup envelope and the gust (m)

a_2 = the tangent point of the shear buildup envelope and the gust (m)

th = the "thickness" of the gust (m)

a_1 = 0.9137 m , a_2 = 0.9215 m

The range of thickness (th) of the gust is 30 m ≤ 240 m.

c. When the gust ends at the design wind speed envelope, the synthetic wind profile may follow the design wind speed envelope or shear backoff profile. Vehicle response should be checked for flight performance through flight using the wind envelope as forcing function also.

d. If a power spectrum representation (see 5.3.7.2) is used then disregard all references to discrete gusts in the above. Use the 0.85 factor on shears and apply the spectrum as given in subsection 5.3.7.2.

5.3.8.3 Synthetic Wind Speed Profiles For Non Vertical Flight Path

The application of the synthetic wind profile for other than the vertical flight path is accomplished by multiplying the steady state wind and wind shear buildup and backoff values by the cosine of the angle between the vertical axis (earth fixed coordinate system) and the vehicle's flight path. The gust (or turbulence spectra) is applied directly to the vehicle without respect to the flight path angle. The synthetic wind profile is otherwise developed according to procedures given in section 5.3.8.2.

5.3.9 Characteristic Wind Profiles to a Height of 18 Kilometers

5.3.9.1 Features of Wind Profiles

A significant problem of space vehicles is to provide assurance of an adequate design for flight through wind profiles of various configurations. During the major design phase of a space vehicle, the descriptions of various characteristics of the wind profile are employed in determining the applicable vehicle response requirement. Since much of the vehicle is in a preliminary status of design and the desired detail data on structural dynamic modes and other characteristics are not known at this time, the use of characteristic (statistical and synthetic) representations of the wind profile are desirable. However, after the vehicle design has been finalized and tests have been conducted to establish certain dynamic capabilities and parameters, it is desirable to evaluate the total system by simulated dynamic flight through wind profiles containing adequate frequency resolution (Ref 5.31). The profiles shown in Figures 5.3.17 through 5.3.22 are actual scalar values of wind velocities measured by the FPS-16 Radar/Jimsphere wind measuring system, and they illustrate the following: (1) jet stream winds, (2) sinusoidal variation

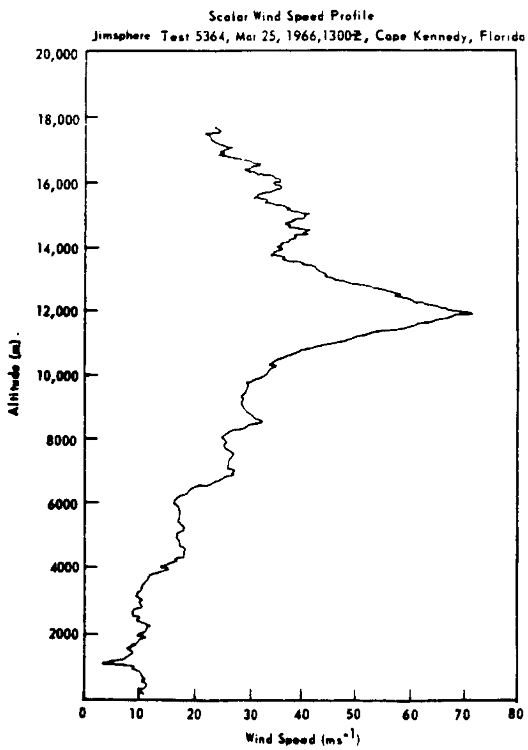


FIGURE 5. 3. 17 EXAMPLE OF JET STREAM WINDS

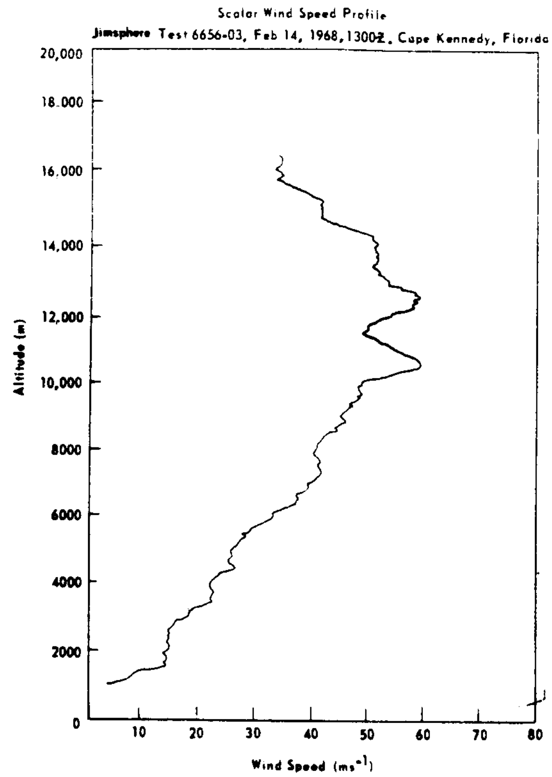


FIGURE 5. 3. 18 EXAMPLE OF SINE WAVE FLOW IN THE 10- TO 14-km ALTITUDE REGION

in wind with height, (3) high winds with broad altitude band, (4) light wind speeds, and (5) discrete gusts.

These profiles show only a few of the possible wind profiles that can occur. Jet stream winds (Figure 5. 3. 17) are quite common to the various test ranges during the winter months and can reach magnitudes in excess of 100 m/sec. These winds occur over a limited altitude range, making the wind shears very large. Figure 5. 3. 18 depicts winds having sinusoidal behavior in the 10- to 14-kilometer region. These types of winds can create excessive loads upon a vertically rising vehicle, particularly if the reduced forcing frequencies couple with the vehicle control frequencies and result in additive loads. It is not uncommon to see periodic variations occur in the vertical winds. Some variations are of more concern than others, depending upon wavelength and, of course, amplitude. Figure 5. 3. 19 is an interesting example of high wind speeds that persisted over 6 kilometers in depth. Such flow is not uncommon for the winter months. Figure 5. 3. 20 shows scalar winds of very low values. These winds were generally associated with

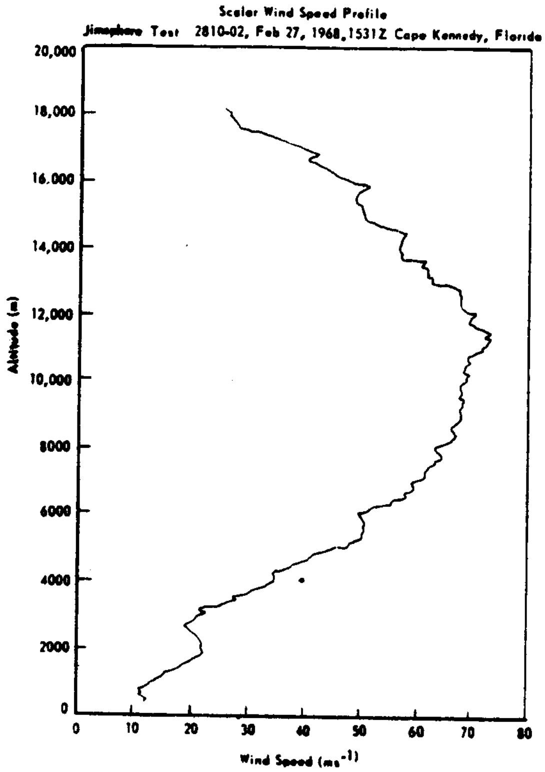


FIGURE 5. 3. 19 EXAMPLE OF HIGH WIND SPEEDS OVER A DEEP ALTITUDE LAYER

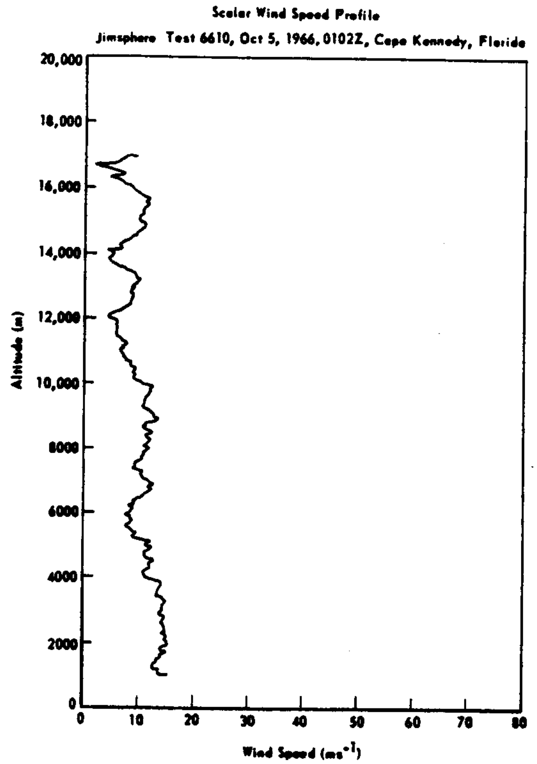


FIGURE 5. 3. 20 EXAMPLE OF LOW WIND SPEEDS

easterly flow over the entire altitude interval (surface to 16 km) at Kennedy Space Center, Florida. The last examples (Figures 5. 3. 21 and 5. 3. 22) illustrate two samples of discrete gusts.

5. 3. 10 Detail Wind Profile Representative Samples

5. 3. 10. 1 Introduction

FPS-16 Radar/Jimsphere detailed wind profile measurements have been made at Cape Kennedy since December 1964. The reduction technique used to reduce the radar data provides a mean wind velocity (direction and speed) associated with an altitude layer of about 50 meters (Ref. 5. 32). A discussion on the accuracy of these data is presented in Reference 5. 33. A magnetic tape data record containing 1800 wind profiles has been established for engineering use in aerospace vehicle design verification and launch delay risk calculations. These data sets are designated as MSFC / NASA Jimsphere Wind Data Tape for Design Verification and are available upon request to the Aerospace Environment Division, NASA-Marshall Space Flight Center, Huntsville, Alabama 35812 (Ref. 5. 34).

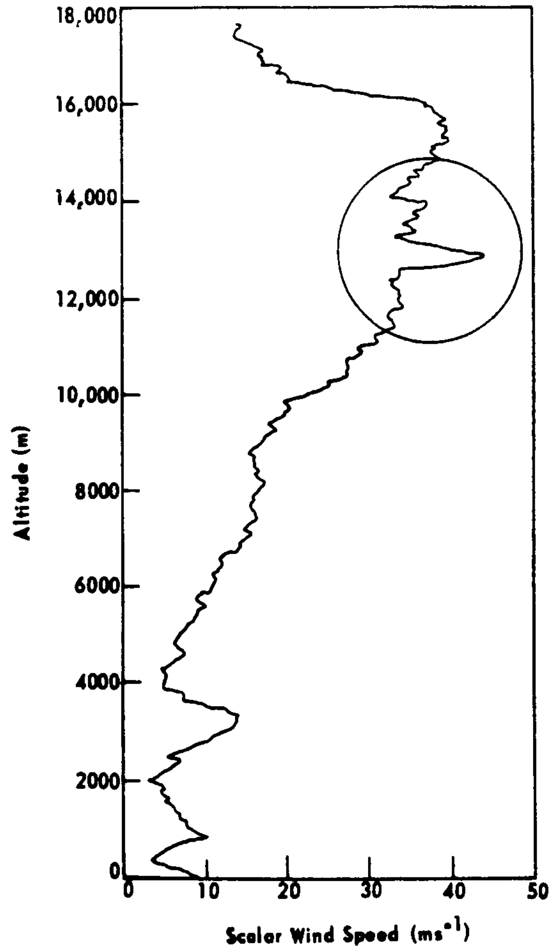


FIGURE 5.3.21 EXAMPLE OF A DISCRETE GUST OBSERVED BY A JIMSPHERE RELEASED AT 2103Z ON NOVEMBER 8, 1967, AT THE EASTERN TEST RANGE

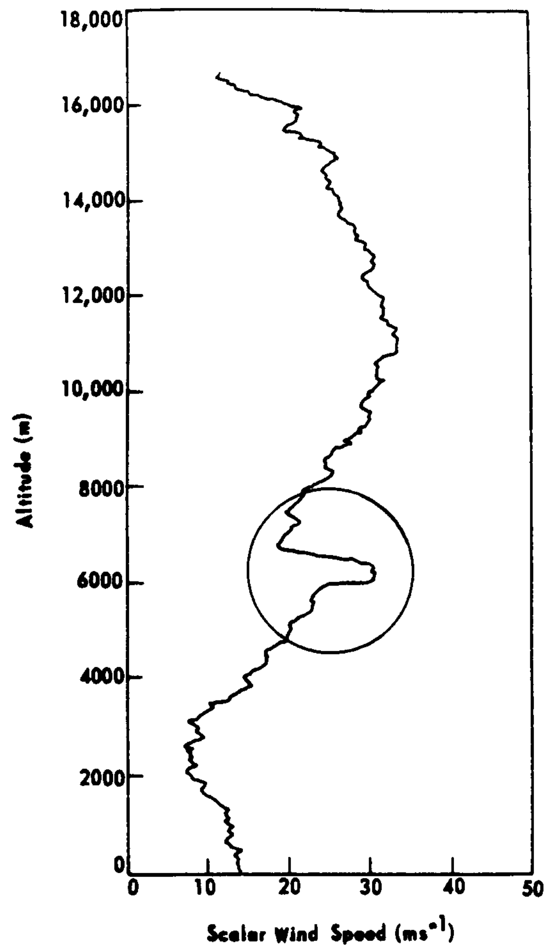


FIGURE 5.3.22 EXAMPLE OF A DISCRETE GUST OBSERVED AT 1300Z ON JANUARY 21, 1968, AT THE EASTERN TEST RANGE

5.3.10.2 Utilization of MSFC Jimsphere Wind Data for Design Verification

These records provide a representative selection of detailed wind velocity profiles for each of the twelve monthly periods for a given launch site. The data encompass a frequency content which exceeds the frequency of the first structural mode of most aerospace vehicles. Therefore, no additional allowance is required for high frequency components as is necessary for conventional rawinsonde profile data records. These data are intended for use in aerospace vehicle final design verification analysis to determine vehicle systems operational capabilities from near the earth's surface to approximately 18 kilometers altitude. Data have been interpolated for the lower few hundred meters and upper few kilometers to provide a complete profile (surface to 20 km) for computer use. Statistical comparisons of aerospace vehicle responses calculated from these wind profile records will be more easily assessed on the month-to-month basis using an equal number of profiles for each month provided by these records.

For vehicle operational capabilities analysis the vehicle simulations should be conducted with adequate representation of the vehicle's aeroelastic and dynamic characteristics to warrant utilization of detailed wind velocity profile data as a forcing function. It is considered that these wind profiles are an adequate selection for use in design verification analyses. Simulations may be conducted and statistically summarized with respect to an annual, seasonal, or monthly reference period. The monthly reference period is recommended.

Vehicle response simulations should be accomplished for the complete range of intended flight azimuths with respect to the total vector wind profile and not the scalar wind speed profiles (i. e., magnitude of the wind vector). Direction variations may be critical to the magnitude of the wind shears. All wind profiles should be utilized for each monthly period since the frequency content of wind profiles with low wind speed magnitudes may be as critical for some vehicle structural and control configurations as those for high wind speed.

The organization that uses these inflight wind data must establish a probability level of launch delay that it is willing to accept in the verification of a vehicle's design relative to the inflight wind influences. The probability level selected is the risk of launch delay and not vehicle loss if an adequate prelaunch monitorship program (Ref. 5.42) is employed.

The following steps outline recommended procedures for using the wind velocity profile data to calculate vehicle operational capability and launch delay risks:

Step 1. Calculate the vehicle response from flight simulation for each profile without wind bias using an appropriate flight simulation model and taking into consideration non-nominal vehicle performance with adequate vehicle aeroelastic and dynamic characteristics. A representative selection should be made of flight azimuths expected for the operational life of the vehicle.

Step 2. If the flight simulations reveal that the vehicle has a capability to fly through all wind profiles for a given month, and the specified flight azimuths, then the probability equal to N(the number of profiles in the month) divided by N + 1 is assigned as the vehicle launch capability relative to inflight winds. This probability value for the monthly sample size is 0. 9934, based on 150 profiles per month.

Step 3. For other probability levels the maximum response to each wind profile is taken (see Step 1) for the given flight azimuths, grouped for each monthly period, and probability distribution function is determined. From this distribution function the probability that the response will be less than any given value can be determined. Also, the probability that the response is greater than, or equal to, any given value can be determined. This latter probability (expressed in percent) is called the probability of launch delay risk for the given response. If the vehicle launch capability is such that the launch delay risk is less than or equal to a pre-established acceptable level (a suggested level is ≤ 5 percent since it provides on the average a launch delay risk of 1. 5 days during a month) for given flight azimuths in each monthly reference period, then the design shall be considered verified relative to the specified launch site.

Step 4. If the launch delay risk is significantly greater (in a statistical sense) than the preestablished acceptable level, then potential areas of design enhancement to permit the desired launch probability may be considered. Some methods are (a) structural/control systems modification and (b) wind bias trajectory.

Step 5. If conditions are not satisfied by Step 4, then operational constraints may be imposed such as restrictions on flight azimuth or acceptance of a larger launch delay risk for certain months for the specified launch site(s).

Final launch delay probability calculations for an operational vehicle may be computed in the same manner. However, in this case, the specific mission's flight azimuth(s) and month of launch should be used in the calculation. Adequate vehicle aeroelastic and dynamic representation and allowance for non-nominal vehicle characteristics should be made. The individual vehicle peak response should be ordered as stated above and the launch probability determined with respect to the desired flight azimuth.

5.3.11 Wind Profile Data Availability

5.3.11.1 Availability of FPS-16 Radar/Jimsphere Wind Velocity Profiles

There are currently over 3000 profiles from Cape Kennedy, 300 profiles from Point Mugu,[15] 350 profiles from White Sands Missile Range, 240 profiles from Green River, and 250 profiles from Wallops Island which have been reduced and edited. Additional data are being acquired. Some of these profile data have been published (Ref. 5.35). All the data are available on magnetic tapes. Master tapes have been prepared to make the data readily accessible for use in research studies. These data will be made available to aerospace, scientific, and engineering organizations upon request to the Chief, Aerospace Environment Division, Aero-Astrodynamics Laboratory, NASA-George C. Marshall Space Flight Center, Marshall Space Flight Center, Alabama 35812.

5.3.11.2 Availability of Rawinsonde Wind Velocity Profiles

Serially complete, edited, and corrected rawinsonde wind profile data are available for 14 years, two observations per day, for Cape Kennedy (Eastern Test Range), and for 9 years, four observations per day, for Santa Monica (Space and Missile Test Center), and for 5 years, two observations per day, for Vandenberg Air Force Base (Pacific Missile Range). Qualified requestors in aerospace, scientific, and engineering organizations may obtain these data, which are also on magnetic tapes, upon request to the Chief, Aerospace Environment Division, Aero-Astrodynamics Laboratory, NASA-George C. Marshall Space Flight Center, Marshall Space Flight Center, Alabama 35812. They are also available as card deck 600 from the National Climatic Center, NOAA, Asheville, North Carolina 28801.

5.3.11.3 Availability of Rocketsonde Wind Velocity Profiles

Rocketsonde wind profile data have been collected for approximately 10 years from various launch sites around the world. These data can be obtained from the World Data Center A, Asheville, North Carolina 28801.

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15. Vandenberg AFB, California, measurements were started in spring of 1971.

5.3.11.4 Availability of Smoke Trail Wind Velocity Profiles

A limited amount of wind velocity data have been obtained by the use of smoke trail techniques to determine the small scale variations of wind velocity with altitude. References 5. 36 and 5. 37 should be consulted for obtaining such data.

5.3.11.5 Utility of Data

All wind profile data records should be checked carefully by the user before employing them in any vehicle response calculations. Wherever practical, the user should become familiar with the representativeness of the data and frequency content of the profile used, as well as the measuring system and reduction schemes employed in handling the data. For those organizations that have aerospace-meteorology oriented groups or individuals on their staffs, consultations should be held with them. Otherwise, various government groups concerned with aerospace vehicle design and operation can be of assistance. Such action by the user can prevent expensive misuse and error in interpretation of the data relative to the intended application.

5.3.12 Atmospheric Turbulence Criteria for Horizontally Flying Vehicles

In this section are presented the continuous turbulence random model for the design of aerospace vehicles capable of flying horizontally and vertically through the atmosphere. In general both the continuous random model (sections 5.3.12 and 5.3.13) and the discrete model (section 5.3.14) are used to calculate vehicle responses with the procedure producing the larger response being used for design. The NASA Space Shuttle will have this mixed mode capability. This vehicle, consisting of two stages (Booster and Orbiter), will be launched vertically. After the boost phase, the Booster will fly back to a recovery site, while the Orbiter will continue to ascend into earth orbit. After the orbital mission has been completed, the Orbiter will return to earth; however, during the last part of the let-down phase the Booster and Orbiter will execute horizontal flight. Thus, the Orbiter and Booster stages will be subjected to loads resulting from atmospheric turbulence during horizontal or near horizontal flight.

To a reasonable degree of approximation, inflight atmospheric turbulence experienced by horizontally flying vehicles can be assumed to be homogeneous, stationary, Gaussian, and isotropic. Under some conditions, these assumptions might appear to be drastic, but for engineering purposes they seem to be appropriate, except for flight at low level over rough terrain. It has been found that the spectrum of turbulence first suggested by von

Karman appears to be a good analytical representation of atmospheric turbulence. The longitudinal spectrum is given by

$$\Phi_u(\Omega, L) = \sigma^2 \frac{2L}{\pi} \frac{1}{[1 + (1.339\ L\Omega)^2]^{5/6}} , \qquad (5.26)$$

where σ^2 is the variance of the turbulence, L is the scale of turbulence, and Ω is the wave number in units of radians per unit length. The spectrum is defined so that

$$\sigma^2 = \int_0^\infty \Phi_u(\Omega, L)\, d\Omega \ . \qquad (5.27)$$

The theory of isotropic turbulence predicts that the spectrum Φ_w of the lateral and vertical components of turbulence are related to the longitudinal spectrum through the differential equation

$$\Phi_w = \frac{1}{2}\left(\Phi_u - \Omega \frac{d\Phi_u}{d\Omega}\right) \ . \qquad (5.28)$$

Substitution of equation (5.26) into equation (5.28) yields

$$\Phi_w = \sigma^2 \frac{L}{\pi} \frac{1 + \frac{8}{3}(1.339\ L\Omega)^2}{[1 + (1.339\ L\Omega)^2]^{11/6}} \ . \qquad (5.29)$$

The dimensionless quantities $2\pi \Phi_u / \sigma^2 L$ and $2\pi \Phi_v / \sigma^2 L$ are depicted in Figure 5. 3. 23 as function of ΩL. As $L\Omega \rightarrow \infty$, Φ_u and Φ_w asymptotically behave like

$$\Phi_u \sim \sigma^2 \frac{2L}{\pi} \frac{(L\Omega)^{-5/3}}{(1.339)^{5/3}} \quad (L\Omega \rightarrow \infty) \qquad (5.30)$$

$$\Phi_w \sim \sigma^2 \frac{2L}{\pi} \frac{(L\Omega)^{-5/3}}{(1.339)^{5/3}} \quad (L\Omega \rightarrow \infty) \ , \qquad (5.31)$$

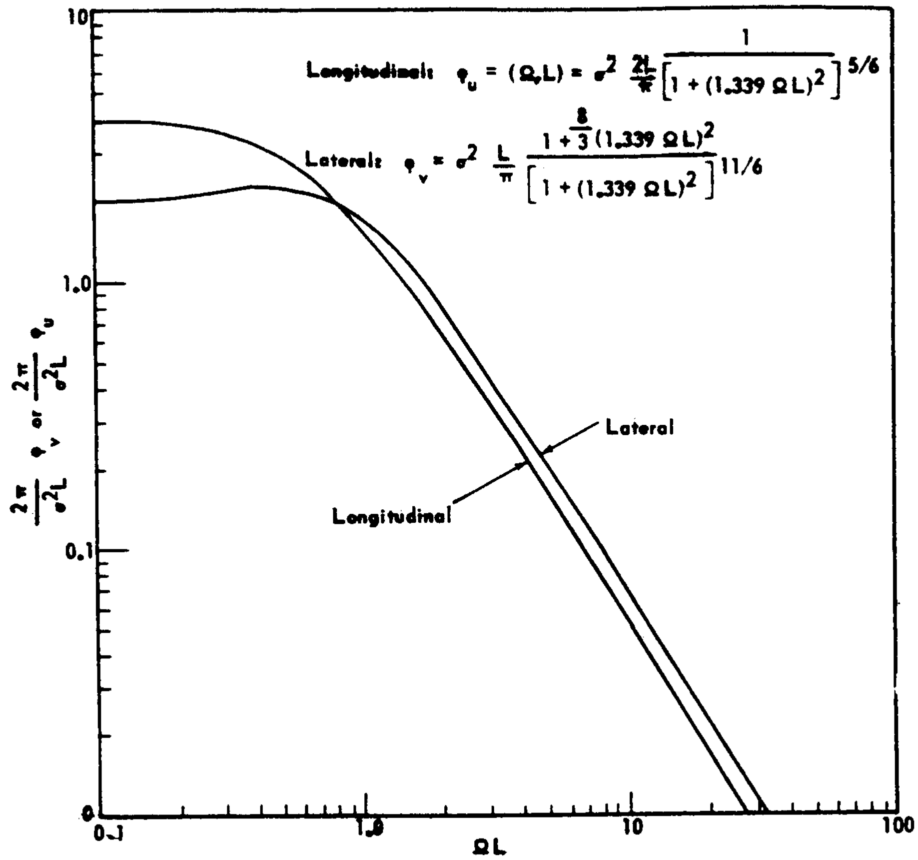

FIGURE 5. 3. 23 THE DIMENSIONLESS LONGITUDINAL AND LATERAL $\frac{2\pi\Phi_u}{\sigma^2 L}$ AND $\frac{2\pi\Phi_w}{\sigma^2 L}$ SPECTRA AS FUNCTIONS OF THE DIMENSIONLESS FREQUENCY $L\Omega$

consistent with the concept of the Kolmogorov inertial subrange. In addition, $\Phi_w/\Phi_u \rightarrow 4/3$ as $\Omega L \rightarrow \infty$. Design values of the scale of turbulence L are given in Table 5. 3. 24. Experience indicates that the scale of turbulence increases as height increases in the first 762 meters (2500 ft)[16] of the atmosphere, and typical values of L range from 183 meters (600 ft) near the surface to 610 meters (2000 ft) at approximately a 762-meter (2500-ft) altitude. Above

16. U S. customary units are used in the section in parentheses to maintain continuity with source of data – Air Force Flight Dynamics Laboratory and other documentation.

TABLE 5. 3. 24 PARAMETERS FOR THE TURBULENCE MODEL FOR HORIZONTALLY FLYING VEHICLES

Altitude		Mission Segment[a]	Turbulence Component[b]	P_1	b_1		P_1	b_1		L	
(m)	(ft)			(unitless)	(m/sec)	(ft/sec)	(unitless)	(m/sec)	(ft/sec)	(m)	(ft)
0 - 304. 8	0 - 1 000	Low Level Contour (rough terrain)	V	1. 00	0. 82	2. 7	10^{-5}	3. 25	10. 65	152. 4	500
0 - 304. 8	0 - 1 000	Low Level Contour (rough terrain)	L, L	1. 00	0. 94	3. 1	10^{-5}	4. 29	14. 06	152. 4	500
0 - 304. 8	0 - 1 000	C, C, D	V, L, L	1. 00	0. 77	2. 51	0. 005	1. 54	5. 04	152. 4	500
304. 8 - 672	1 000 - 2 500	C, C, D	V, L, L	0. 42	0. 92	3. 02	0. 0033	1. 81	5. 94	533. 4	1750
672 - 1 524	2 500 - 5 000	C, C, D	V, L, L	0. 30	1. 04	3. 42	0. 0020	2. 49	8. 17	762	2500
1 524 - 3 048	5 000 - 10 000	C, C, D	V, L, L	0. 15	1. 09	3. 59	0. 00095	2. 81	9. 22	762	2500
3 048 - 6 096	10 000 - 20 000	C, C, D	V, L, L	0. 062	1. 00	3. 27	0. 00028	3. 21	10. 52	762	2500
6 096 - 9 144	20 000 - 30 000	C, C, D	V, L, L	0. 025	0. 96	3. 15	0. 00011	3. 62	11. 88	762	2500
9 144 - 12 192	30 000 - 40 000	C, C, D	V, L, L	0. 011	0. 89	2. 93	0. 000095	3. 00	9. 84	762	2500
12 192 - 15 240	40 000 - 50 000	C, C, D	V, L, L	0. 0046	1. 00	3. 28	0. 000115	2. 69	8. 81	762	2500
15 240 - 18 288	50 000 - 60 000	C, C, D	V, L, L	0. 0020	1. 16	3. 82	0. 000078	2. 15	7. 04	762	2500
18 288 - 21 336	60 000 - 70 000	C, C, D	V, L, L	0. 00088	0. 89	2. 93	0. 000057	1. 32	4. 33	762	2500
21 336 - 24 384	70 000 - 80 000	C, C, D	V, L, L	0. 00038	0. 85	2. 80	0. 000044	0. 55	1. 80	762	2500
above 24 384	above 80 000	C, C, D	V, L, L	0. 00025	0. 76	2. 50	0	0	0	762	2500

a. Climb, cruise, and descent (C, C, D).

b. Vertical, lateral, and longitudinal (V, L, L).

the 762-meter (2500-ft) level, typical values of L are in the order of 914 to 1829 meters (3000 to 6000 ft). Thus, the scales of turbulence in Table 5.3.24 are probably low, and they would be expected to give a somewhat conservative or high number of load or stress exceedances per unit length of flight.

The power spectrum analysis approach is applicable only to stationary Gaussian continuous turbulence, but atmospheric turbulence is neither statistically stationary or Gaussian over long distances. The statistical quantities used to describe turbulence vary with altitude, wind direction, terrain roughness, atmospheric stability, and a host of other variables. Nevertheless, it appears that the observed power spectrum of the vertical velocity from 304 to 12 190 meters (1000 to 40 000 ft) above terrain is reasonably invariant. Accordingly, it is recommended that atmospheric turbulence be considered locally Gaussian and stationary and that the total flight history of a horizontally flying vehicle be considered to be composed of an ensemble of exposures to turbulence of various intensities, all using the same power spectrum shape. Thus, it is recommended that the following statistical distribution of rms gust intensities be used:

$$p(\sigma) = \frac{P_1}{b_1}\sqrt{\frac{2}{\pi}}\exp\left(-\frac{\sigma^2}{2b_1^2}\right) + \frac{P_2}{b_2}\sqrt{\frac{2}{\pi}}\exp\left(-\frac{\sigma^2}{2b_2^2}\right) \quad , \tag{5.32}$$

where b_1 and b_2 are the standard deviations of σ in nonstorm and storm turbulence. The quantities P_1 and P_2 denote the fractions of flight time or distance flown in nonstorm and storm turbulence. It should be noted that if P_0 is the fraction of flight time or distance in smooth air, then

$$P_0 + P_1 + P_2 = 1 \quad . \tag{5.33}$$

The recommended design values of P_1, P_2, b_1, and b_2 are given in Table 5.3.24. Note that over rough terrain b_2 can be extremely large in the first 304 meters (1000 ft) above the terrain and the b's for the vertical, the lateral, and the longitudinal standard deviations of the turbulence are not equal. Thus, in the first 304 meters (1000 ft) of the atmosphere above rough terrain, turbulence is significantly anisotropic and this anisotropy must be taken into account in engineering calculations.

An exceedance model of gust loads and stresses can be developed with the above information. Let y denote any load quantity that is a dependent variable in a linear system of response equations (for example, bending moment at a particular wing station). This system is forced by the longitudinal, lateral, and vertical components of turbulence, and upon producing the Fourier transform of the system, it is possible to obtain the spectrum of y. This spectrum will be proportional to the input turbulence spectra, the function of proportionality being the system transfer function. Upon integrating the spectrum of y over the domain $0 < \Omega < \infty$, we obtain the relationship

$$\sigma_y = A\sigma \quad , \tag{5.34}$$

where A is a positive constant that depends upon the system parameters and the scale of turbulence, and where σ_y is the standard deviation of y.

If the output y is considered to be Gaussian for a particular value of σ, then the expected number of fluctuations of y that exceed y* with positive slope per unit distance with reference to a zero mean is

$$N(y^*) = N_0 \exp\left(-\frac{y^{*2}}{2\sigma_y^2}\right) \quad , \tag{5.35}$$

where N_0 is the expected number of zero crossings of y unit distance with positive slope and is given by

$$N_0 = \frac{1}{2\pi\sigma_y}\left[\int_0^\infty \Omega^2 \Phi_y(\Omega)\, d\Omega\right]^{1/2} \quad . \tag{5.36}$$

In this equation, Φ_y is the spectrum of y and

$$\sigma_y = \left[\int_0^\infty \Phi_y(\Omega)\, d\Omega\right]^{1/2} \quad . \tag{5.37}$$

The standard deviation of σ_y is related to standard deviation of turbulence through equation (5.34), and σ is distributed according to equation (5.32). Accordingly, the number of fluctuations of y that exceed y* for standard deviations of turbulence in the interval σ to $\sigma + d\sigma$ is $N(y^*)\, p(\sigma) d\sigma$, so that integration over the domain $0 < \sigma < \infty$ yields

$$\frac{M(y^*)}{N_0} = P_1 \exp\left(-\frac{|y^*|}{b_1 A}\right) + P_2 \exp\left(-\frac{|y^*|}{b_2 A}\right) \quad , \qquad (5.38)$$

where $M(y^*)$ is the overall expected number of fluctuations of y that exceed y^* with positive slope. To apply this equation, the engineer needs only to calculate A and N_0 and specify the risk of failure he wishes to accept. The appropriate values of P_1, P_2, b_1, and b_2 are given in Table 5. 3. 24. Figures 5. 3. 24 and 5. 3. 25 give plots of $M(y^*)/N_0$ as a function of $|y^*|/A$ for the various altitudes for the design data given in Table 5. 3. 24. Table 5. 3. 25 provides a summary of the units of the various quantities in this model.

It should be noted that $M(y^*)$ and N_0 in equation (5. 38) have the units of inverse time (i.e., sec^{-1}) provided $M(y^*)$ and N_0 both have the same units. This amounts to transforming Ω in equation (5. 36) to a frequency (rad/sec) through a Jacobian transformation.

5. 3. 12. 1 Application of Power Spectral Model

To apply equation (5. 38), the engineer can either calculate A and N_0 and then calculate the load quantity y^* for a specified value of $M(y^*)$, or calculate A and calculate the load quantity y^* for a specified value of

TABLE 5. 3. 25 METRIC AND U. S. CUSTOMARY UNITS OF VARIOUS QUANTITIES IN THE TURBULENCE MODEL FOR HORIZONTALLY FLYING VEHICLES

Quantity	Metric Units	U. S. Customary Units
Ω	rad/m	rad/ft
Φ_u, Φ_w	$m^2/sec^2/rad/m$	$ft^2/sec^2/rad/ft$
σ^2	m^2/sec^2	ft^2/sec^2
L	m	ft
b_1, b_2	m/sec	ft/sec
P_1, P_2	dimensionless	dimensionless
σ_y/A	m/sec	ft/sec
$\|y^*\|/A$	m/sec	ft/sec
N_0, N, M	m/sec	ft/sec

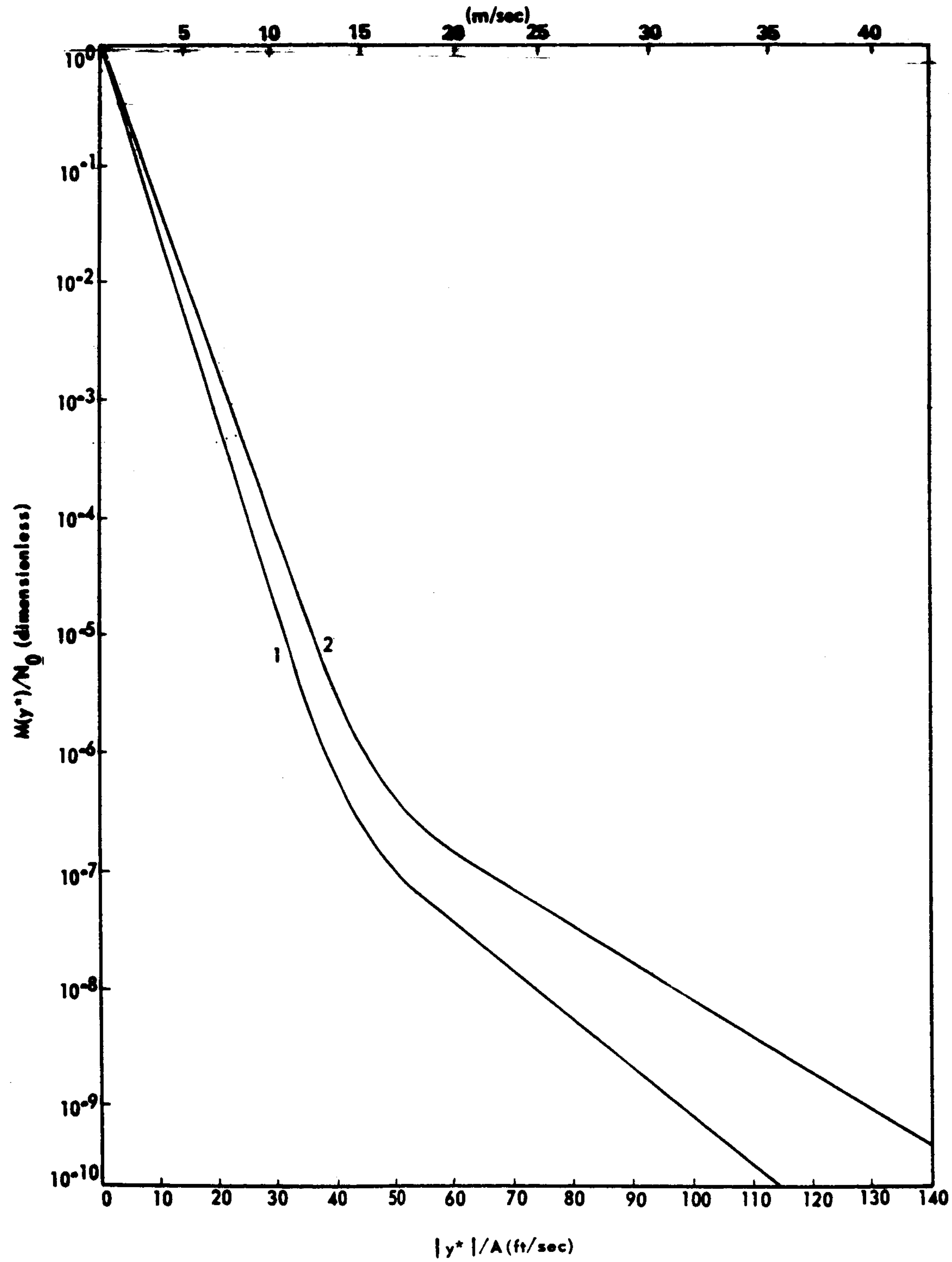

FIGURE 5. 3. 24 EXCEEDANCE CURVES FOR THE VERTICAL, LATERAL, AND LONGITUDINAL COMPONENTS OF TURBULENCE FOR THE 0- TO 1000-ft ALTITUDE RANGE

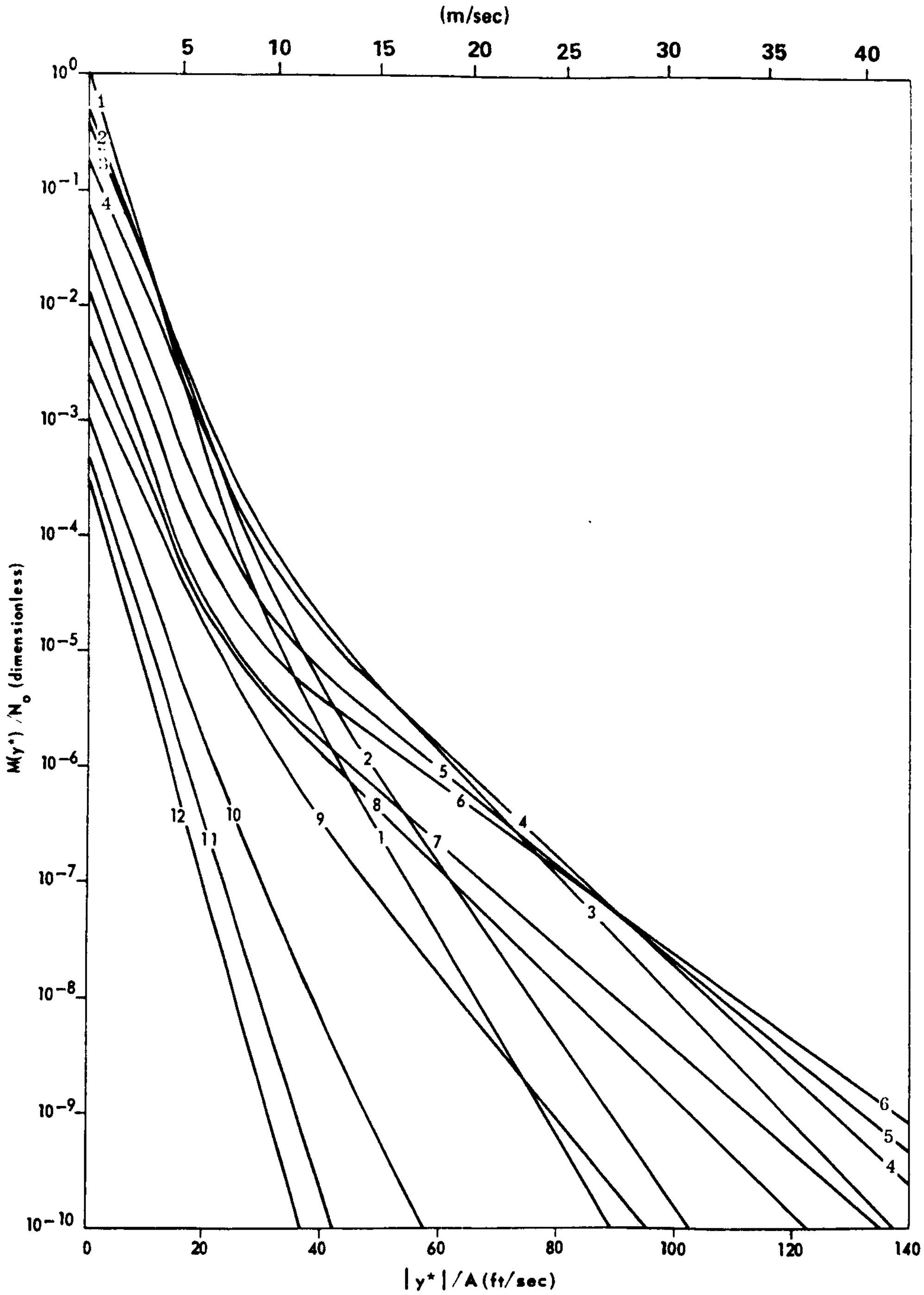

FIGURE 5. 3. 25 EXCEEDANCE CURVES FOR THE VERTICAL, LATERAL, AND LONGITUDINAL COMPONENTS OF TURBULENCE FOR VARIOUS ALTITUDE RANGES

$M(y^*)/N_0$. In a recent study performed by the Lockheed-California Company for the FAA (Ref. 5. 38), design values of $M(y^*)$ and $M(y^*)/N_0$ were calculated. These design criteria were consistent with the limit load capabilities of present day commercial aircraft. The criterion in which $M(y^*)$ is specified is suitable for a mission analysis approach to the design problem. The criterion in which $M(y^*)/N_0$ is specified is suitable for a design envelope approach to aircraft design.

In the design envelope approach, it is assumed that the airplane operates 100 percent of the time at its critical design envelope point. A new vehicle is designed on a limit load basis for a specified value of M/N_0. According to the authors of Reference 5. 38, $M/N_0 = 6 \times 10^{-9}$ is suitable for the design of commercial aircraft. To apply this criterion, all critical altitudes, weights, and weight distributions are specified and associated values of A are calculated. The limit loads are calculated for each of the specified configurations with equation (5. 38) for $M/N_0 = 6 \times 10^{-9}$.

In the mission analysis approach, a new aircraft is designed on a limit load basis according to Reference 5. 38 for $M = 2 \times 10^{-5}$ load exceedances per hour. To apply this criterion, the engineer must construct an ensemble of flight profiles which define the expected range of payloads and the variation with time of speed, altitude, gross weight, and center of gravity position. These profiles are divided into mission segments, or blocks, for analysis; and average or effective values of the pertinent parameters are defined for each segment. For each mission segment, values of A and N_0 are determined by dynamic analysis. A sufficient number of load and stress quantities are included in the dynamic analysis to assure that stress distributions throughout the structure are realistically or conservatively defined. Now the contribution to $M(y^*)$ from the ith flight segment is $t_i M_i (y^*)/T$ where t_i is the amount of time spent in the ith flight regime (mission segment), T is the total time flown by the vehicle over all mission segments, and $M_i(y^*)$ is the exceedance rate associated with the ith segment. The total exceedance rate for all mission segments, k say, is

$$M(y^*) = \sum_{i=1}^{k} \frac{t_i}{T} N_{0_i} \left(P_1 e^{-|y^*|/b_1 A} + P_2 e^{-|y^*|/b_2 A}\right) \quad , \quad (5.39)$$

where subscript i denotes the ith mission segment. The limit gust load quantity $|y^*|$ can be calculated with this formula upon setting $M(y^*) = 2 \times 10^{-5}$ exceedances per hour.

The above mentioned limit load design criteria were derived for commercial aircraft which are normally designed for 50 000-hour lifetimes. Therefore, to apply these criteria to horizontally flying aerospace vehicles which will have relatively short lifetimes would be too conservative. However, it is possible to modify these criteria so that they will reflect a shorter vehicle lifetime. The probability F_p that a load will be exceeded in a given number of flight hours T is

$$F_p = 1 - e^{-TM} \quad . \tag{5.40}$$

It it is assumed that the limit load criterion $M = 2 \times 10^{-5}$ exceedances per hour is associated with an aircraft with a lifetime T equal to 50 000 hours, this means that $F_p = 0.63$, i.e., there is a 63 percent chance that an aircraft designed for a 50 000-hour operating lifetime will exceed its limit load capability at least once during its operating lifetime. This high failure probability, based on limit loads, is not excessive in view of the fact that an aircraft will receive many inspections on a routine basis during its operating lifetime. In addition, after safety factors are applied to the design limit loads the ultimate load exceedance rate will be on the order of 10^{-8} exceedances per hour. Substitution of this load exceedance rate into equation (5.40) for $T = 50\ 000$ hours yields a failure probability, on an ultimate load basis, of $F_p = 0.0005$. This means that there will only be a 0.05 percent chance that an aircraft will exceed its ultimate load capability during its operating lifetime of 50 000 hours. Thus, a failure probability of $F_p = 0.63$ on a limit load basis is reasonable for design. Let us now assume that $F_p = 0.63$ is the limit load design failure probability so that equation (5.40) can be used to calculate design values of M associated with a specified vehicle lifetime. Thus, for example, if we expect a vehicle to fly only 100 hours, then according to equation (5.40), we have $M = 10^{-2}$ exceedances per hour. Similarly, if we expect a vehicle to be exposed to the atmosphere for 1000 hours of flight, then $M = 10^{-3}$ exceedances per hour.

The corresponding design envelope criterion can be obtained by dividing the above calculated values of M by an appropriate value of N_0. In the case of the 50 000 hours cirterion, we have $M/N_0 = 6 \times 10^{-9}$ and $M = 2 \times 10^{-5}$ exceedances per hour so that an estimate of N_0 for purposes of obtaining a design criterion is $N_0 = 0.333 \times 10^4\ \text{hr}^{-1}$. Thus, upon solving equation (5.40) for M and dividing by $N_0 = 0.333 \times 10^4\ \text{hr}^{-1}$, the design envelope criterion takes the form

$$\frac{M}{N_0} = \frac{3 \times 10^{-4}}{T} \tag{5.41}$$

where we have used $F_p = 0.63$. Thus, for a 100-hour aircraft, the design envelope criterion is $M/N_0 = 3 \times 10^{-6}$ and for a 1000-hour aircraft $M/N_0 = 3 \times 10^{-7}$.

It is recommended that both the limit load and ultimate load failure probabilities, $F_p = 0.63$ and 0.0005 respectively, be used in the gust load calculations for the horizontal flight phase in the design of aerospace vehicles like the NASA Space Shuttle. To apply the design environment the engineer would calculate the limit loads for a prescribed mission profile with equations (5.39) and (5.40) for $F_p = 0.63$ and then calculate a set of ultimate loads by applying appropriate factors of safety to the limit loads. We shall term these loads "safety factor ultimate loads." To guarantee that the ultimate load failure probability is at most $F_p = 0.0005$, a floor on the ultimate design loads should be determined by calculating a second set of loads again with equations (5.39) and (5.40), however, with $F_p = 0.0005$. If the safety factor ultimate loads are greater than or equal to the floor loads, then the ultimate load failure probability, F_p is less than or equal to 0.0005. If the safety factor ultimate loads fall below the floor loads then the floor loads should be used in the design.

It is recommended that the power spectral approach be used in place of the standard discrete gust methods. Reasonably discrete gusts undoubtedly occur in the atmosphere; however, there is accumulating evidence that the preponderance of gusts are better described in terms of continuous turbulence models. It has long been accepted that clear air turbulence at moderate intensity levels is generally continuous in nature. Thunderstorm gust velocity profiles are now available in considerable quantity, and they almost invariably display the characteristics of continuous turbulence. Also, low level turbulence is best described with power spectral methods. A power spectral method of load analysis is not necessarily more difficult to apply than a discrete gust method. The present static load plunge-only discrete gust methods can, in fact, be converted to a power spectral basis by making a few simple modifications in the definitions of the gust alleviation factor and the design discrete gust. To be sure, this simple rigid-airplane analysis does not exploit the full potentiality of the power spectral approach, but it does account more realistically for the actual mix of gust gradient distances in the atmosphere and the variation of gust intensity with gradient distance.

5. 3. 13 Turbulence Model for Flight Simulation

For simulation of turbulence in either an analog or digital fashion, the turbulence realizations are to be generated by passing a white noise process through a passive filter. The model of turbulence as given in subsection 5. 3. 12 is not particularly suited for the simulation of turbulence with white noise. This results because the von Karman spectra given by equations (5. 26) and (5. 29) are irrational. Thus, for engineering purposes, the Dryden spectra may be used for simulation of continuous random turbulence. They are given by

$$\text{Longitudinal:} \quad \Phi_u(\Omega) = \sigma^2 \frac{2L}{\pi} \frac{1}{1 + (L\Omega)^2} \qquad (5.42)$$

$$\text{Lateral and Vertical:} \quad \Phi_w(\Omega) = \sigma^2 \frac{L}{\pi} \frac{1 + 3(L\Omega)^2}{[1 + (L\Omega)^2]} \; . \qquad (5.43)$$

Since these spectra are rational, a passive filter may be generated. It should be noted that the Dryden spectra are somewhat similar to the von Karman spectra. As $\Omega L \rightarrow 0$ the Dryden spectra asymptotically approach the von Karman spectra. As $\Omega L \rightarrow \infty$ the Dryden spectra behave like $(\Omega L)^{-2}$, while the von Karman spectra behave like $(\Omega L)^{-5/3}$. Thus, the Dryden spectra depart from the von Karman spectra by a factor proportional to $(\Omega L)^{-1/3}$ as $\Omega L \rightarrow \infty$, so that at sufficiently large values of ΩL the Dryden spectra will fall below the von Karman spectra. However, this deficiency in spectral energy of the Dryden spectra with respect to the von Karman spectra is not serious from an engineering point of view. If the capability to use the von Karman spectra is already available, the user should use it in flight simulation rather than the Dryden spectra.

The spectra as given by equations (5. 42) and (5. 43) can be transformed from the wave number (Ω) domain to the frequency domain (ω, rad/sec) by noting that $\Omega = \omega/V$ and a Jacobian transformation, so that

$$\Phi_u(\omega) = \frac{L}{V} \frac{2\sigma^2}{\pi} \frac{1}{1 + (L\omega/V)^2} \qquad (5.44)$$

$$\Phi_w(\omega) = \frac{L}{V} \frac{\sigma^2}{\pi} \frac{1 + 3(L\omega/V)^2}{[1 + (L\omega/V)^2]^2} \; . \qquad (5.45)$$

The quantity V is the magnitude of the mean wind vector relative to the aerospace vehicle, $\vec{\bar{u}} - \vec{C}$. The quantities $\vec{\bar{u}}$ and $\vec{C}$ denote the velocity vectors of the mean flow of the atmosphere and the aerospace vehicle relative to the earth. The longitudinal component of turbulence is defined here to be the component of turbulence parallel to the mean wind vector relative to the aerospace vehicle $(\vec{\bar{u}} - \vec{C})$. The lateral and vertical components of turbulence are perpendicular to the relative mean wind vector and act in the lateral and vertical directions relative to the vehicle flight path.

5.3.13.1 Transfer Functions

Atmospheric turbulence can be simulated by passing white noise through filters with the following frequency response functions:

$$\text{Longitudinal:} \quad F_u(j\omega) = \frac{(2k)^{1/2}}{a + j\omega} \tag{5.46}$$

$$\text{Lateral and Vertical:} \quad F_w(j\omega) = \frac{(3k)^{1/2}\left(3^{-1/2}a + j\omega\right)}{(a + j\omega)^2}\ , \tag{5.47}$$

where

$$a = \frac{V}{L} \tag{5.48}$$

$$k = \frac{a\sigma^2}{\pi}\ . \tag{5.49}$$

To generate the three components of turbulence, three distinct uncorrelated Gaussian white noise sources should be used.

To define the rate of change of gust velocities about the pitch, yaw, and roll axes for simulation purposes, a procedure consistant with the above formulation can be found in Section 3.7.5, "Application of Turbulence Models and Analyses," of reference 5.38A. This should be checked for applicability.

5.3.13.2 Boundary Layer Turbulence Simulation

The turbulence in the atmospheric boundary layer, defined here to be the first 533.4 meters (1750) of the atmosphere, is inherently anisotropic. To simulate this turbulence realistically as possible, the differences between the various scales and intensities of turbulence should be

TABLE 5. 3. 26 VALUES OF σ AND L FOR SIMULATION OF TURBULENCE IN THE ATMOSPHERIC BOUNDARY LAYER WITH THE DRYDEN MODEL

	Altitude Interval		
	0 to 18. 3 m	18. 3 to 100 m	100 to 533. 4 m
σ_u	$2.23\, u_{*0}$	$2.23\, u_{*0} \left(\frac{z}{18.3}\right)^{-0.32}$	$1.30\, u_{*0}$
σ_v	$1.70\, u_{*0}$	$1.70\, u_{*0} \left(\frac{z}{18.3}\right)^{-0.18}$	$1.25\, u_{*0}$
σ_w	$1.25\, u_{*0}$	$1.25\, u_{*0}$	$1.25\, u_{*0}$
L_u	170 m	170 m	$170 \left(\frac{z}{100}\right)^{0.68}$ m
L_v	98 m	$98 \left(\frac{z}{18.3}\right)^{0.28}$ m	$157 \left(\frac{z}{100}\right)^{0.68}$ m
L_w	53 m	$53 \left(\frac{z}{18.3}\right)^{0.64}$ m	$157 \left(\frac{z}{100}\right)^{0.68}$ m

taken into account. To do this, the values in Table 5. 3. 26 of σ and L should be used in the simulation of turbulence in the atmospheric boundary layer with the Dryden model.

In the table, z is height above natural grade in meters, and the L's and σ's have units of meters and meters per second. The subscripts u, v, and w denote quantities associated with the longitudinal, lateral, and vertical components of turbulence. The quantity u_{*0} is the surface friction velocity and is given by

$$u_{*0} = 0.4 \frac{\bar{u}_{18.3}}{\ell n \left(\frac{18.3}{z_0}\right)} , \qquad (5.50)$$

where z_0 is the surface roughness length in meters (subsection 5. 26. 2), and $\bar{u}_{18.3}$ is the 18. 3-meter level mean flow wind speed. The mean profile which defines the mean scalar wind speed is

$$\left|\vec{\bar{u}}\right| = \bar{u}_{18.3} \left(\frac{z}{18.3}\right)^{0.22} \tag{5.51}$$

To apply this model for turbulence simulation in the atmospheric boundary layer, the engineer must specify the 18.3-meter level wind speed $\bar{u}_{18.3}$; the surface roughness length z_0; and the wind direction of the mean wind vector $\bar{u}$ (z) for each flight simulation. The mean flow wind vector lies in the horizontal plane. The specification of z_0 and $\bar{u}_{18.3}$ define u_{*0} and thus σ_u, σ_v, and σ_w. Substitution of the values of σ and L into (5.46 - 5.49) determines the transfer functions to be used in the simulation.

5.3.13.3 Turbulence Simulation in the Free Atmosphere (above 533.4 m)

To simulate turbulence in the free atmosphere (above 533.4 m) above the atmospheric boundary layer, it is recommended that equations (5.38) and (5.41) and the supporting data in Table 5.3.24 be used to specify the appropriate values of σ. The turbulence at these altitudes can be considered to be isotropic for engineering purposes so that the integral scales and intensities of turbulence are independent of direction. Past studies have shown that the integral scale of turbulence of L = 762 meters in Table 5.3.24 should be replaced with a value of L = 533.4 meters when the Dryden spectrum is being used (Ref. 5.38A). This reduction in scale tends to bring the Dryden spectrum in line (with the von Karman spectrum with L = 762 m) over the band of wave numbers of the turbulence which are of primary importance in the design of aerospace vehicles. Accordingly, it is recommended that L = 533.4 meters for altitudes above the 533.4 meter level.

To calculate the value of σ appropriate for performing a simulation, the following procedure is used to calculate the design instantaneous gust from which the design value of σ shall be obtained. The procedure consists of specifying the vehicle lifetime T; calculating the limit load design value of M/N_0 with equation (5.41); and calculating the limit load instantaneous gust velocity, $w*$ say, with equation (5.38) for A = 1. The instantaneous gust velocity $w*$ should be associated with the 99.98-percent value of gust velocity for a given realization of turbulence. In addition, the turbulence shall be assumed to be Gaussian, so that the value of σ for performing a simulation shall be obtained by dividing $w*$ by 3.5. This value of σ and L = 533.4 meters shall be used to simulate the longitudinal, lateral, and vertical components of turbulence with equations (5.46) and (5.49).

5.3.14 Discrete Gust Model - Horizontally Flying Vehicles

Often it is useful for the engineer to use discrete gusts in load and flight control system calculations of horizontally flying vehicles. The discrete gust is defined as follows:

$$V_d = 0, \quad x < 0$$

$$V_d = \frac{V_m}{2}\left(1 - \cos\frac{\pi x}{d_m}\right), \quad 0 \leq x \leq 2d_m$$

$$V_d = 0, \quad x > 2d_m,$$

where V_m is the maximum velocity of the gust which occurs at position $x = d_m$ in the gust. To apply the model, the engineer specifies several values of the gust half-width d_m, so as to cover the range of frequencies of the system to be analyzed. To calculate the gust parameter V_m one enters Figure 5.3.26 with d_m/L and reads out V_m/σ. Figure 5.3.26 is based on the Dryden spectrum of turbulence. Accordingly, the procedures outlined in subsections 5.3.13.2 and 5.3.13.3 can be used for the specification of the σ's and L's to determine the gust magnitude V_m from Figure 5.3.26. In the boundary layer, three values of V_m will occur at each altitude, one for each component of turbulence. In the free atmosphere the longitudinal, lateral, and verticle values of V_m are equal at each altitude. In general both the continuous random model (sections 5.3.12 and 5.3.13) and the discrete model (section 5.3.14) are often used to calculate vehicle responses with the procedure producing the larger response being used for design.

5.3.15 Flight Regimes For Use of Horizontal and Vertical Turbulence Models (Specta and Discrete Gusts)

Sections 5.3.7, 5.3.12, and 5.3.14 contain turbulence (spectra and discrete gusts) models for response calculations of vertically ascending and horizontally flying aerospace vehicles.

The turbulence model for the horizontally flying vehicles was derived from turbulence data gathered with airplanes. The turbulence model for the vertically ascending or descending vehicles was derived from wind profile measurements made with vertically ascending Jimsphere balloons and smoke trails. In many instances aerospace vehicles neither fly in a pure horizontal

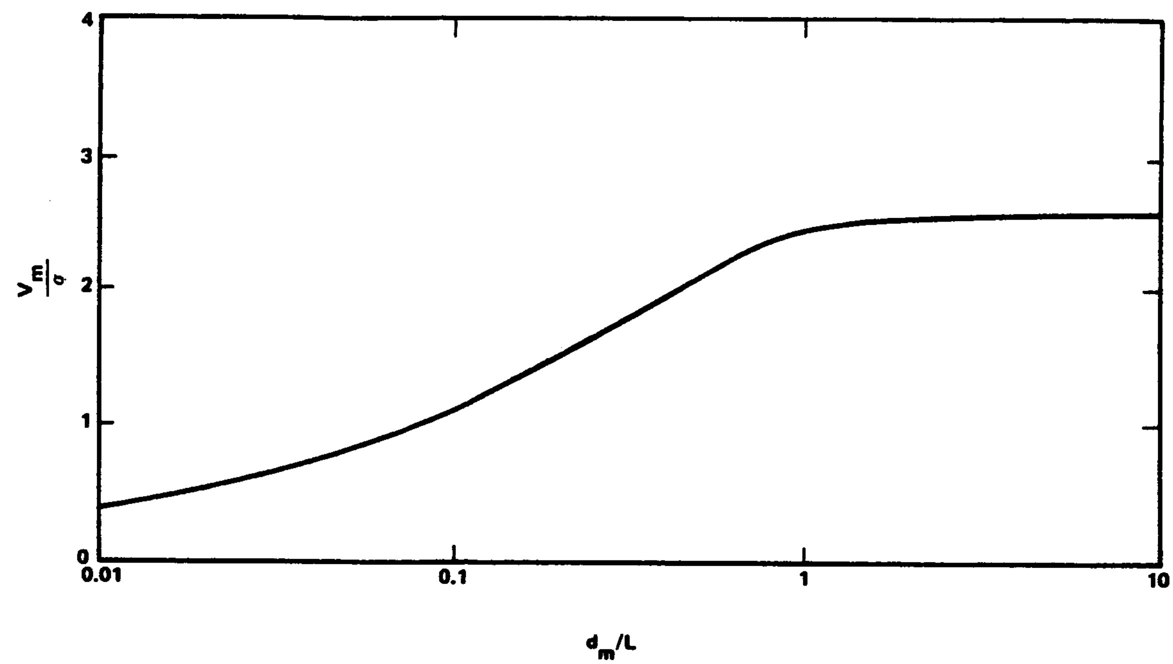

FIGURE 5. 3. 26. NONDIMENSIONAL DISCRETE GUST MAGNITUDE V_m/σ AS A FUNCTION OF NONDIMENSIONAL GUST HALF-WIDTH

flight mode nor ascend or descend in a stricly vertical flight path. At this time there does not appear to be a consistent way of combining the turbulence models for horizontal and vertical flight so as to be applicable to the design of aerospace vehicles with other than near horizontal or vertical flight paths without being unduly complicated or overly conservative. In addition, the unavailablility of a sufficient large data sample of turbulence measurements in three dimensions precludes the development of such a combined model.

Accordingly, in lieu of the availability of a combined turbulence model and for the sake of engineering simplicity the turbulence model in section 5. 3. 7 should be applied to ascending and descending aerospace vehicles when the smallest angle between the flight path and the local vertical is less than or equal to 30 degrees. Similarly, the turbulence model in Sections 5. 3. 12 and 5. 3. 14 should be applied to aerospace vehicles when the smallest angle between the flight path and the local horizontal is less than or equal to 30 degrees. In the remaining flight path region between 30 degrees from the local vertical and 30 degrees from the local horizontal, both turbulence models should be independently applied and the most adverse responses used in the design.

5. 4 Mission Analysis, Prelaunch Monitoring, and Flight Evaluation

Wind information is useful in the following three general cases of mission analysis:

a. Mission Planning. Since this activity will normally take place well in advance of the mission, the statistical attributes of the wind are used.

b. Prelaunch Operations. Although wind statistics are useful at the beginning of this period, the emphasis is placed upon forecasting and wind monitoring.

c. Postflight Evaluation. The effect of the observed winds on the flight is analyzed.

5. 4. 1 Mission Planning

From wind climatology, the optimum time (month and time of day) and place to conduct the operation can be identified (Ref. 5. 39). Missions with severe wind constraints may have such a low probability of success that the risk is unacceptable. Feasibility studies based upon wind statistics can identify these problem areas and answer questions such as: "Is the mission feasible as planned?" and "If the probable risk of mission delay or failure is unacceptably high, can it be reduced by rescheduling to a lighter wind period?"

The following examples are given to illustrate the use of some of the many wind statistics available to the mission planner.

If it is necessary to remove the wind loads damper from a large launch vehicle for a number of hours and this operation must be scheduled some days in advance, the well known diurnal ground wind variation should be considered for this problem. If, for example, 10. 3 m/sec (20 knots) were the critical wind speed, there is a 1-percent risk at 0600 EST, but a 13-percent risk at 1500 EST in July. Obviously the midday period in the summer should be avoided for this operation. Since these probability values apply to 1-hour exposure periods, it is important to recognize that the wind risk depends not only upon wind speed, but also upon exposure time. From Figure 5. 4. 1, the risk in percentage associated with 15. 4-m/sec (30-knot) wind at 10 meters in February at Cape Kennedy can be obtained for various exposure times. The upper curve shows the risk increasing from 1 percent for 1-hour exposure

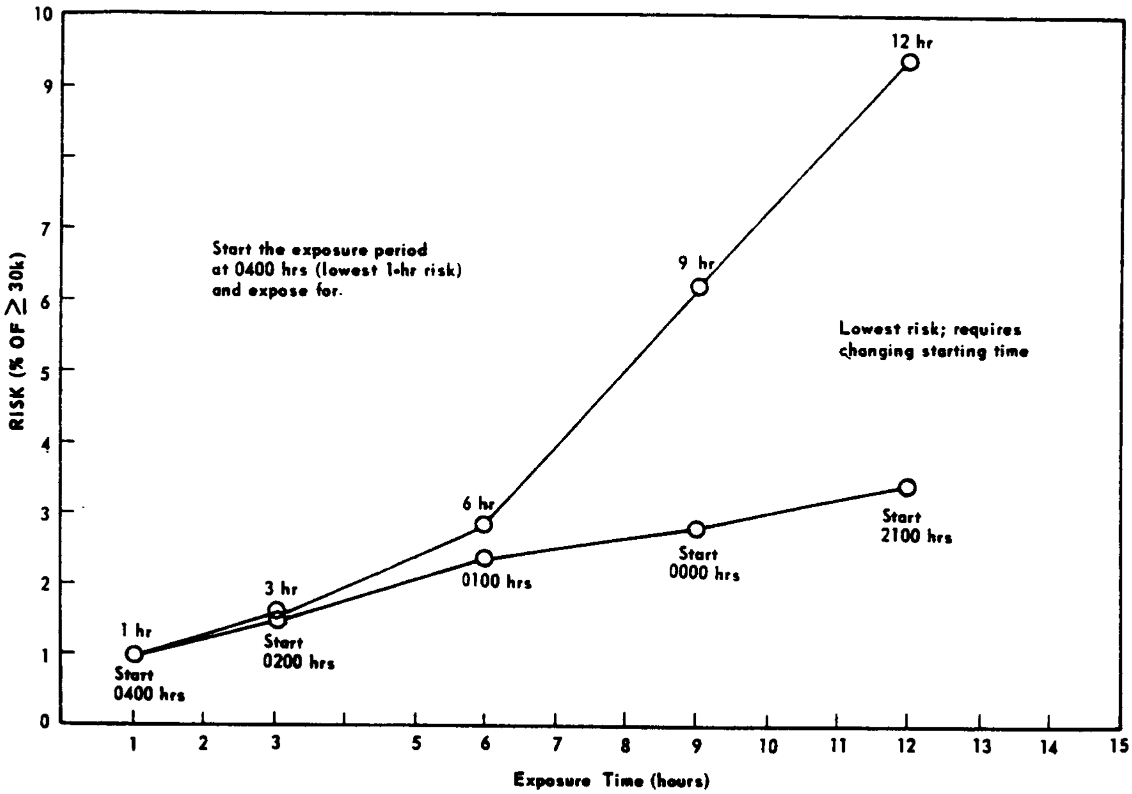

FIGURE 5. 4. 1 EXAMPLE OF WIND RISK FOR VARIOUS EXPOSURE TIMES

starting at 0400 EST to 9. 3 percent for 12-hour exposure starting at 0400 EST. In this case the exposure period extends through the high risk part of the day. The lower curve illustrates the minimum risk associated with each exposure period. The lowest risk, of course, can be realized if the starting times are changed to avoid the windy portion of the day. Although there is no space here for the tabulation, wind risk probabilities by month and starting hour for exposure periods from 1 hour to 365 days are available upon request.

When winds aloft are considered for mission planning purposes, again the first step might be to acquire general climatological information on the area of concern. From Figures 5. 4. 2 and 5. 4. 3 it is readily apparent that for Cape Kennedy most strong winds occur during winter in the 10- to 15-kilometer altitude region (this applies also to nearly all midlatitude locations). It is also true that these strong winds are usually westerly.

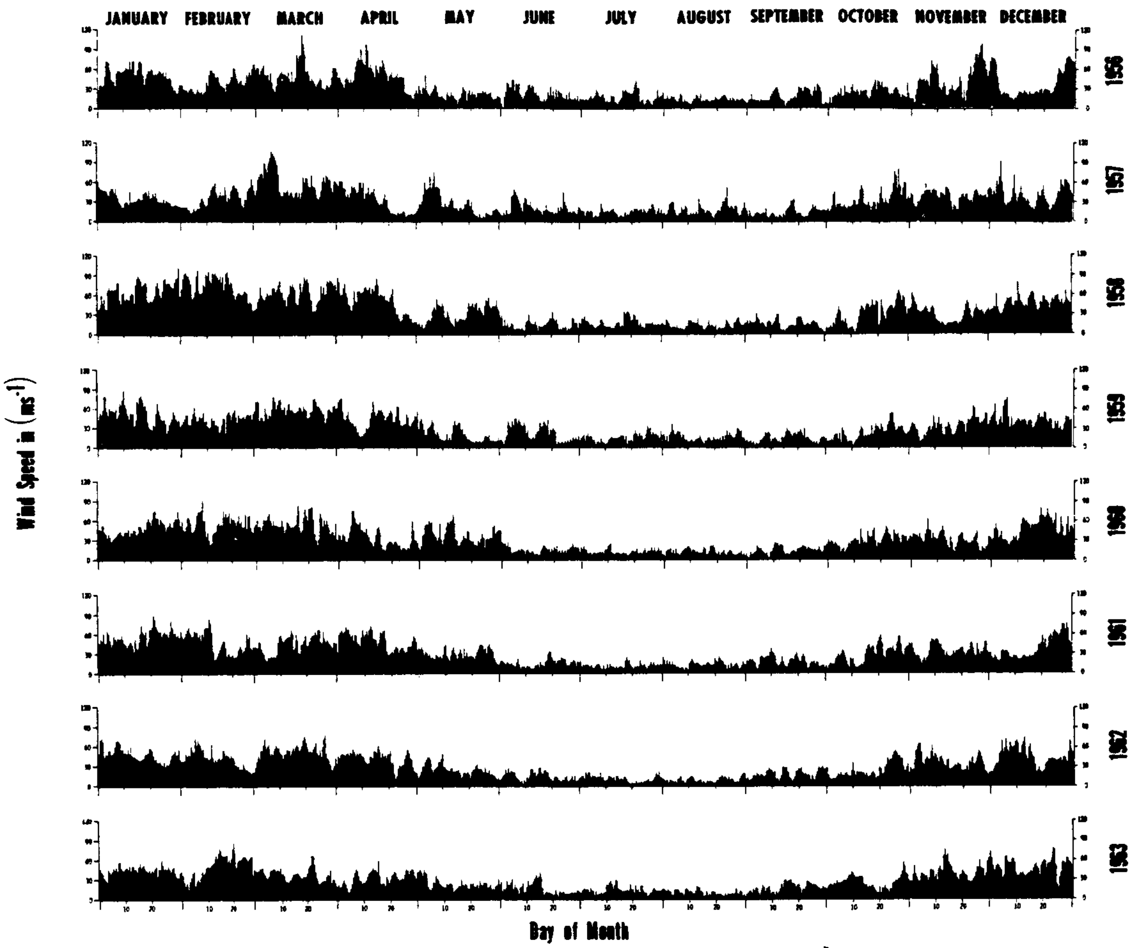

FIGURE 5. 4. 2 TWICE DAILY MAXIMUM WIND SPEED IN THE 10- TO 15-km LAYER AT CAPE KENNEDY

Next, the mission analyst might ask if a particular mission is feasible. If, for example, the flight is to take place in January and 10- to 15-kilometer altitude winds ≧ 50 m/sec are critical, the probability of favorable winds on any day in January is 0. 496. With such a low probability of success, this mission may not be feasible. But, to continue the example, if it is necessary that continuously favorable winds exist for 3 days (perhaps for a dual launch) the probability of success will decrease to 0. 256. Obviously an alternate mission schedule must be planned or else the scheduled space vehicle must be provided additional capability through redesign.

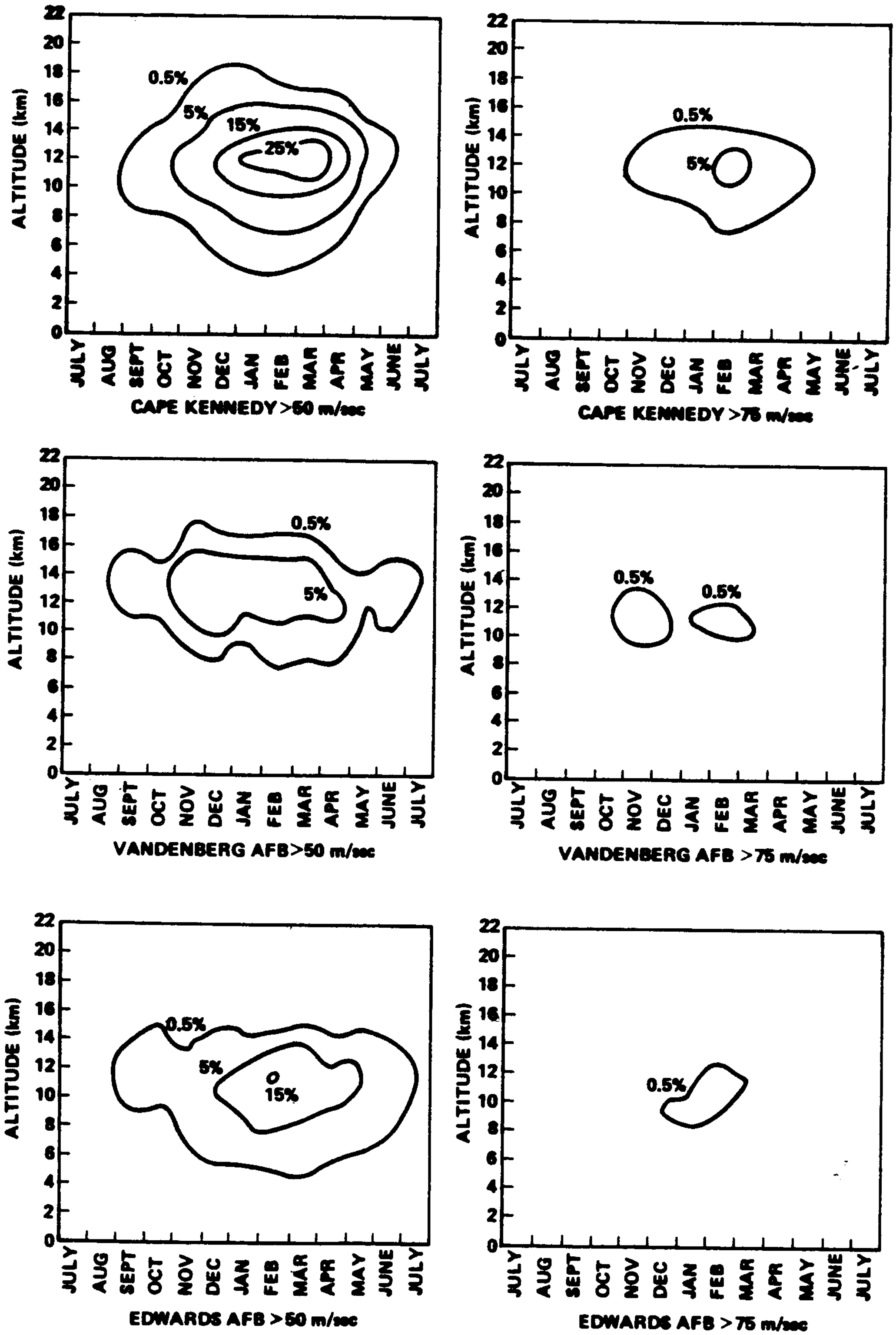

FIGURE 5. 4. 3 FREQUENCY OF SCALAR WIND SPEED EXCEEDING GIVEN WIND SPEED AS A FUNCTION OF ALTITUDE FOR STATIONS INDICATED

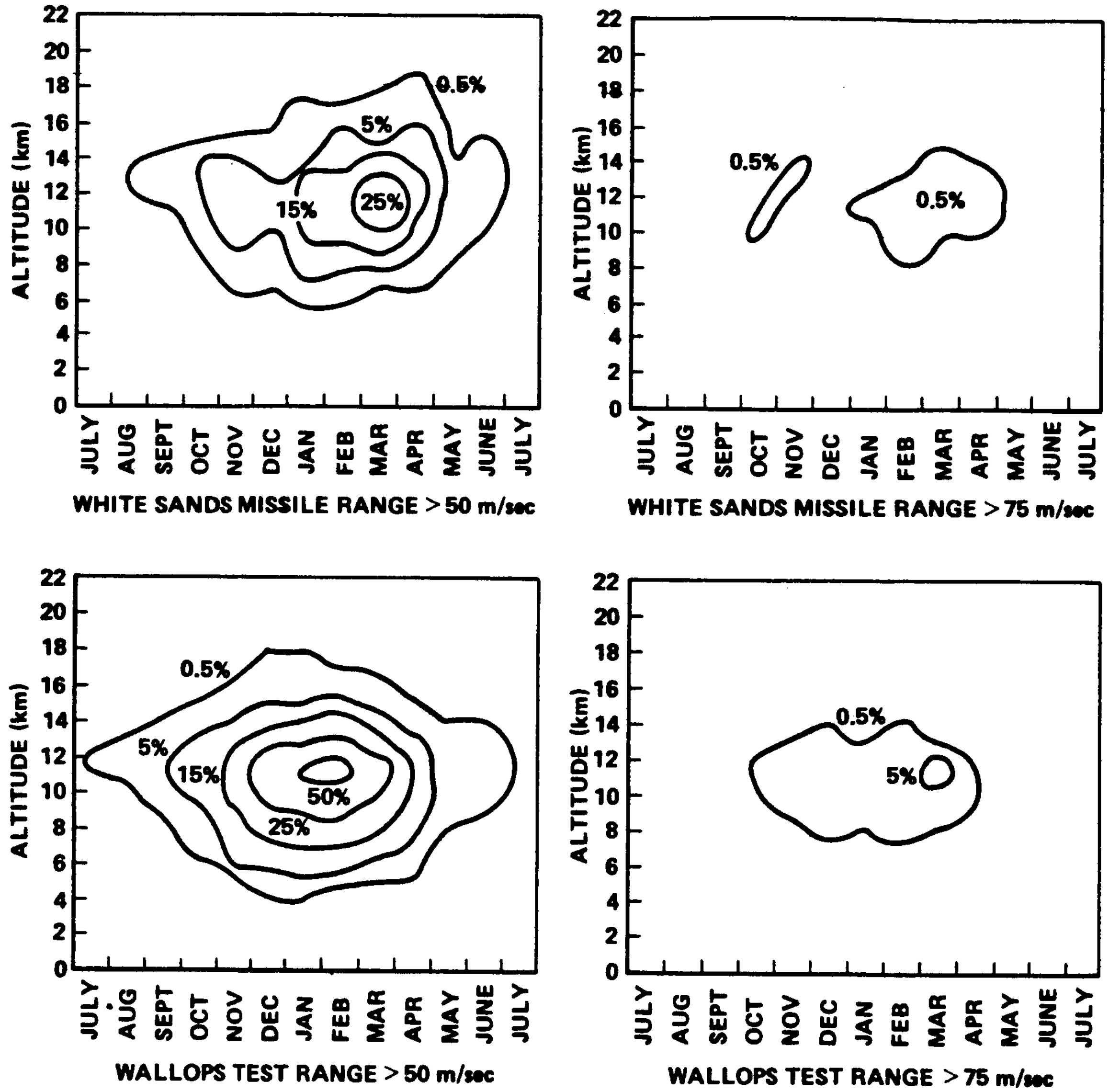

FIGURE 5. 4. 3 FREQUENCY OF SCALAR WIND SPEED EXCEEDING GIVEN WIND SPEED AS A FUNCTION OF ALTITUDE FOR STATIONS INDICATED (Concluded)

Perhaps the vehicle can remain on the pad in a state of near readiness awaiting launch for several days. In this case it would be desirable to know that the probability of occurrence of at least one favorable wind speed, for example, in a 4-day period is 0. 813. If greater flexibility of operation is desired, one might require four favorable opportunities in 4 days. This probability is 0. 550. Now, if consecutive favorable opportunities are required, for example, four consecutive successes in eight periods, the probability of success will somewhat lower (0. 431).

The mission planner might also gain some useful information from the persistence of the winds aloft. The probability of winds < 50 m/sec on any day in January is 0. 496. But if a wind speed < 50 m/sec does occur, then the probability that the next observed wind 12 hours later would be < 50 m/sec is 0. 82, a rather dramatic change. Furthermore, if the wind continues below 50 m/sec for five observations, the probability that it will remain there for one more 12-hour period is 0. 92.

As the time of the operation approaches T-4 to T-1 days, the conditional probability statements assume a more significant role. At this point, as the winds will usually be monitored, the appropriate conditional probability value can be identified and used to greater advantage.

The above is intended to illustrate the type of analysis that can be accomplished to provide objective data for program decisions. This may best be accomplished by a close working relationship between the analyst and those concerned with the decision.

5. 4. 2 Prelaunch Wind Monitoring

Inflight winds constitute the major atmospheric forcing function in space vehicle and missile design and operations (Ref 5. 40). A frequency content of the wind profile near the bending mode frequencies or wind shear with the characteristics of a step input may exceed the vehicle's structural capabilities (especially on forward stations for the small scale variations of the wind profiles). Wind profiles with high speeds and shears exert high structural loads at all stations on a large space vehicle, and when the influences of bending dynamics are high, even a profile with low speeds and high shears can create large loads (Ref. 5. 41).

Because of the possibility of launch into unknown winds, operational missile systems must accept some inflight loss risk in exchange for a rapid-launch capability. But research and development missiles, and space vehicles in particular, cost so much that the overall success of a flight outweighs the consideration of launch delays caused by excessive inflight wind loads. If the exact wind profile could be known in advance, it would be a relatively simple task to decide upon the launch date and time. However, there is little hope of accurately forecasting the detailed wind profile very much into the future.

Over the years, these situations have increasingly put emphasis on prelaunch monitoring of inflight winds. Now, finally, prelaunch and profile determination techniques essentially preclude the risk of launching a space vehicle or research and development missile into an inflight wind condition that would cause it to fail.

Recent development and operational deployment of the FPS-16 Radar/Jimsphere system (Ref. 5.42) significantly minimizes vehicle failure risks when properly integrated into a flight simulation program. The Jimsphere sensor, when tracked with the FPS-16 or other radar with equal tracking capability, provides a very accurate "all weather" detailed wind profile measurement. FPS-16 radars are available at all national test ranges.

In general, the system provides a wind profile measurement from the surface to an altitude of 17 kilometers in slightly less than 1 hour, a vertical spatial frequency resolution of 1 cycle per 100 meters, and an rms error of about 0.5 m/sec or less for wind velocities averaged over 50-meter intervals. The resolution of these data permits calculating the structural loads associated with the first bending mode and generally the second mode of missiles and space vehicles during the critical, high dynamic pressure phase of flight. This provides better than an order-of-magnitude accuracy improvement over the conventional rawinsonde wind profile measuring system (Ref. 5.43).

By employing the appropriate data transmission resources, a detailed wind profile from the FPS-16 radar can be ready for input to the vehicle's flight simulation program within a few minutes after tracking of the Jimsphere. The flight simulation program provides flexibility relative to vehicle dynamics and other parameters in order to make maximum use of the detailed wind profiles.

If very critical wind conditions exist and the mission requirement dictates a maximum effort to launch with provision for last minute termination of the operation, then a contingency plan that will provide essentially real-time wind profile and flight simulation data may be employed. This is done while the Jimsphere balloon is still in flight.

An example of the FPS-16 Radar/Jimsphere system data appears in Figure 5.4.4 — the November 8 and 9, 1967, sequence observed during prelaunch activities for the first Apollo/Saturn-V test flight, AS-501. The persistence over a period of 1 hour of some small scale features in the wind profile structure, as well as the rather distinct changes that developed in the profiles over a period of a few hours, is evident.

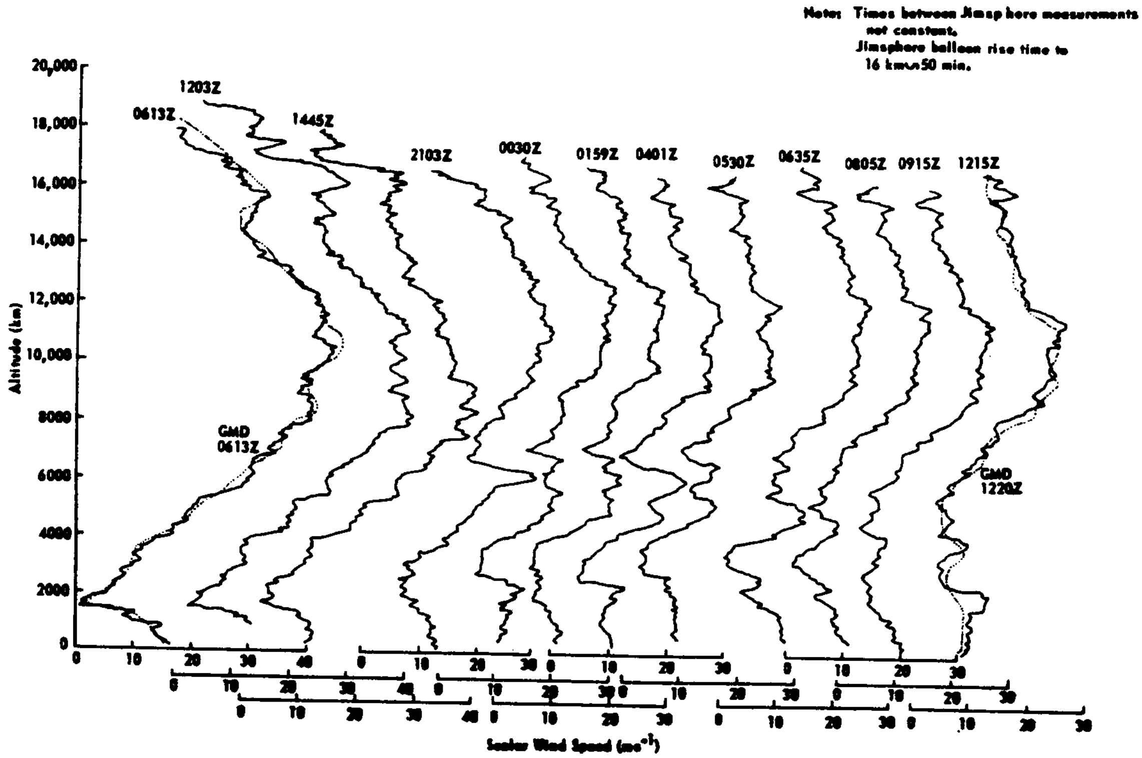

FIGURE 5. 4. 4 EXAMPLE OF THE FPS-16 RADAR/JIMSPHERE SYSTEM DATA, NOVEMBER 8-9, 1967

The FPS-16 Radar/Jimsphere system (Fig. 5. 4. 5) is routinely used in the prelaunch monitoring of NASA's Apollo/Saturn-IB and -V flights. The wind profile data are transmitted to the Manned Spacecraft Center and Marshall Space Flight Center, and the flight simulation results are sent to the launch complex at Kennedy Space Center.

An FPS-16 Radar/Jimsphere operational measurement program capability exists at all the national test ranges to obtain detailed wind profile data for use in space vehicle and missile response studies, airplane turbulence analysis, atmospheric turbulence investigations, and mesometeorological studies. Sequential measurements similar to the Saturn-V data shown here — of eight to ten Jimsphere wind profiles approximately 1 hour apart — are currently being made on at least 1 day per month for each location. Single profile measurements are also made daily at Cape Kennedy.

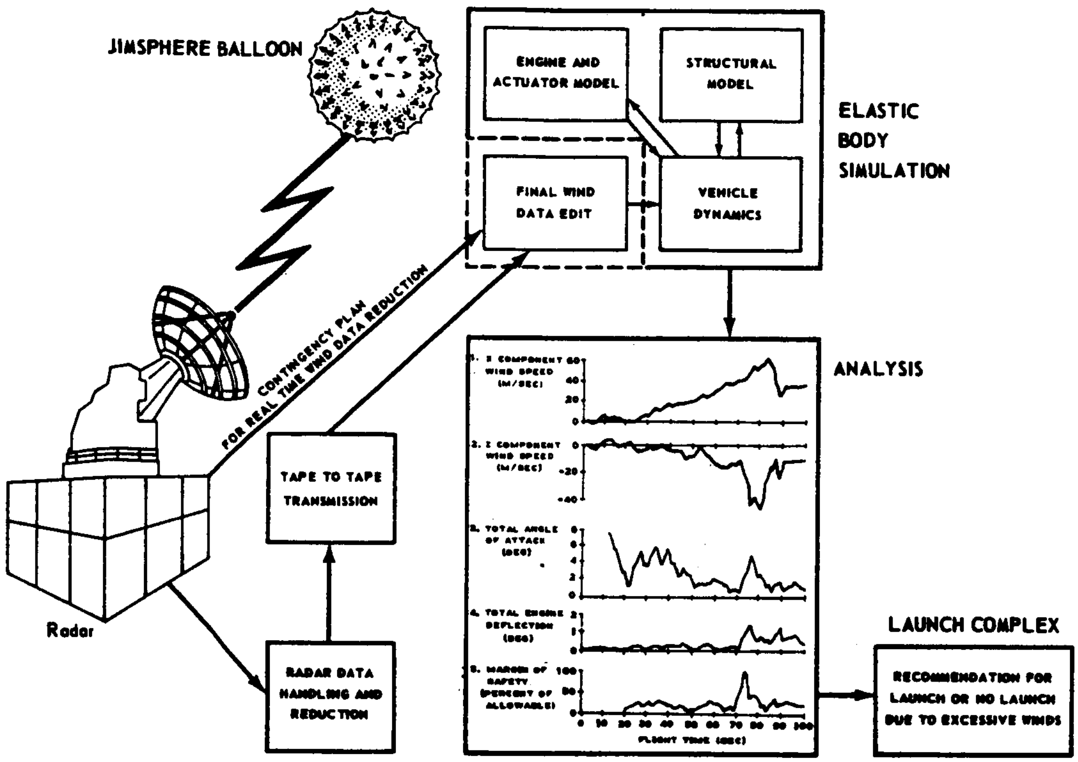

FIGURE 5. 4. 6 OPERATION OF THE FPS-16 RADAR/JIMSPHERE SYSTEM

5. 4. 3 Post-Flight Evaluation

5. 4. 3. 1 Introduction

Because of the variable effects of the atmosphere upon a large space vehicle at launch and during flight, various meteorological parameters are measured at the time of each space vehicle launch, including wind and thermodynamic data at the earth's surface and up to an altitude of at least 50 kilometers. To make the data available, meteorological tapes are prepared, presentations are made at flight evaluation meetings, memoranda of data tabulations are prepared and distributed, and a summary is written for the final vehicle flight evaluation report. Reference 5. 44 for Apollo/Saturn-503 is an example of one of the reports with an atmospheric section.

5. 4. 3. 2 Meteorological Tapes

Shortly after the launch of each space vehicle, under the cognizance of the Marshall Space Flight Center, preliminary meteorological tape is prepared by combining the FPS-16 Radar/Jimsphere wind profile data and the rawinsonde wind profile and thermodynamic data (temperature, pressure, and humidity) observed as near the vehicle launch time as feasible. This is done under the supervision of the Marshall Space Flight Center's Aerospace Environment Division. The preliminary meteorological tape is normally available within 12 hours after launch time and provides data to about 35 kilometers. The final meteorological tape is prepared with the addition of rocketsonde wind and thermodynamic data extending the data to at least 50 kilometers and is available for use about 3 days after launch.

In the two meteorological data tapes (preliminary and final), thermodynamic data above the measured data are given by Patrick Reference Atmosphere values (Ref 5. 45). To prevent unnatural jumps in the data when the two types are merged, the data are carefully examined to pick the best altitude for the merging.

The meteorological data tapes are made available to all government and contractor groups for their use in the space vehicle launch and flight evaluation. This provides a consistent set of data for all evaluation studies and ensures the best available information of the state of the atmosphere.

Twenty-one parameters of data are included in the meteorological data tape at 25-meter increments of altitude[17] in Table 5. 4. 1.

5. 4. 3. 3 Presentations at Flight Evaluation Working Group Meetings

Unless the space vehicle performance were bad or the magnitude of some atmospheric parameters were near extremes at launch or during flight, only two presentations are made at the flight evaluation meetings on the atmospheric launch environment.

The first presentation is given at the "quick look" meeting normally held on the day following launch. At this meeting, preliminary values of the surface weather conditions (temperature, pressure, dew point or relative humidity, visibility, cloudiness, and launch pad wind speed and direction) are given, and plots of the upper wind speeds, direction, and components are shown up to the highest altitude of the available data. Any unusual features of the data are discussed in detail.

At the "first general" flight evaluation meeting, the final upper wind speeds and component graphs are shown for all the data used in the meteorological data tape.

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17. Altitude increments of 25 meters were chosen to provide for maximum engineering value and for use of the available atmospheric data and do not necessarily represent the attainable frequency response of the measurements.

TABLE 5.4.1 FORMAT OF METEOROLOGICAL TAPE

First Record: Identification			
Word	Symbol	Parameter	Units
1	Y_S	Altitude (geometric) ($0=Y_S=700,000$) H=25	m
2	T	Temperature	°K
3	P	Pressure	mb
4	W	Wind Speed	m/sec
5	W_D	Wind Direction	deg
6	U/100	Relative Humidity (U is percent)	(10^{-2}) %
7	E	Water Vapor Pressure	mb
8	ρ	Density	kg/m^3
9	P'	Pressure	$newtons/cm^3$
10	$V_S=C_S$	Velocity of Sound	m/sec
11	N_o	Optical Index of Refraction	unitless
12	N_e	Electomagnetic Index of Refraction	unitless
13	W_x	Pitch Component of Wind Velocity	m/sec
14	W_x	Yaw Component of Wind Velocity	m/sec
15	W_{w-e}	Zonal Component of Wind Velocity	m/sec
16	W_{a-n}	Meridional Component of Wind Velocity	m/sec
17	ρ	Density	kg/m^3
18	μ	Coefficient of Viscosity	$newtons/m^3$
19	T	Temperature	°C
20	S_{x250}	Pitch Component Wind Shear	sec^{-1}
21	S_{z250}	Yaw Component Wind Shear	sec^{-1}

Surface wind speeds and directions are measured and recorded at several locations and heights above the launch pad, starting several hours before launch time. Detailed tabulations are made from the various measuring locations and are distributed by memoranda for flight evaluation purposes.

5.4.3.4 Atmospheric Data Section for Final Vehicle Launch Report

The results of the flight evaluation are presented in a final vehicle launch report. A section in this report gives the information on the atmospheric environment at launch time. Records are maintained on the atmospheric parameters for MSFC sponsored vehicle test flights conducted at Kennedy Space Center, Florida. Requests for summaries of these atmospheric data, or related questions on specific topics, should be directed to the Aerospace Environment Division, NASA-Marshall Space Flight Center, Alabama 35812.

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SECTION VI. ABRASION

By

Glenn E. Daniels

6.1 Introduction.

Particles carried by wind will remove paint from exposed surfaces or scratch, abrade, or erode them, and pit transparent surfaces. When the wind velocities are low or moderate, damage can occur whenever the particle hardness is equal to or greater than the exposed surface. When the speed of an object with relation to atmospheric particles is high, erosion will occur even when the particles have a hardness less than the exposed surface. A space vehicle and its associated facilities should be designed to either withstand or be protected from the conditions described for the geographic area of application.

The penetration of sand and dust into moving parts (bearings, gears, etc.) can result in abnormal wear and failure. Large sand and dust particles may be suspended in the atmosphere during periods of high winds and low humidities (under 50 percent). Particles of dust less than 0.002 mm (0.000078 in.) in diameter are common at any time near or over land surfaces except shortly after precipitation. Particles larger than 0.002 mm (0.000078 in.) will settle out rapidly unless wind or other forces are present to keep the particles suspended. Small particles in the atmosphere over the sea will consist almost entirely of salt.

Particle hardness in this section is expressed according to Mohs' hardness scale, which is based on the relative hardness of representative minerals as listed in Table 6.1 (Ref. 6.2).

TABLE 6.1 MOHS' SCALE-OF-HARDNESS FOR MINERALS

Mohs' Relative Hardness	Mineral	Mohs' Relative Hardness	Mineral
1	Talc	6	Orthoclase
2	Gypsum	7	Quartz
3	Calcite	8	Topaz
4	Fluorite	9	Corundum
5	Apatite	10	Diamond

6.2 Sand and Dust at Surface.

The presence of sand and dust can be expected in all geographical areas of interest, but will occur more frequently in the areas with lower water vapor concentration. The extreme values expected are as follows:

6.2.1 Size of Particles.

a. Sand particles will be between 0.080 mm (0.0031 in.) and 1.0 mm (0.039 in.) in diameter. At least 90 percent of the particles will be between 0.080 mm (0.0031 in.) and 0.30 mm (0.012 in.) in diameter.

b. Dust particles will be between 0.0001 mm (0.0000039 in.) and 0.080 mm (0.0031 in.) in diameter. At least 90 percent of these particles will be between 0.0001 mm (0.0000039 in.) and 0.002 mm (0.000079 in.) in diameter.

6.2.2 Hardness and Shape.

More than 50 percent of the sand and dust particles will be composed of angular quartz or harder material, with a hardness of 7 to 8.

6.2.3 Number and Distribution of Particles.

a. Sand. For a wind speed of 10 m sec^{-1} (19.4 knots) at 3 m (9.9 ft) above surface and relative humidity of 30 percent or less, there will be 0.02 g cm^{-3} (1.2 lb ft^{-3}) of sand suspended in the atmosphere during a sand storm. Under these conditions, 10 percent of the sand grains will be between 0.02 m (0.079 ft) and 1.0 m (3.3 ft) above the ground surface, with the remaining 90 percent below 0.02 m (0.079 ft), unless disturbed by a vehicle moving through the storm.

When the wind speed decreases below 10 m sec^{-1} (19.4 knots), the sand grains will be distributed over a smaller distance above the ground surface; while a steady-state wind speed below 5 m sec^{-1} (9.7 knots) will not be sufficient to set the grains of sand in motion.

As the wind speed increases above 10 m sec^{-1} (19.4 knots), the sand grains will be distributed over higher and higher distances above the ground surface.

b. Dust. For a wind speed of 10 m sec^{-1} (19.4 knots) at 3 m (9.9 ft) above surface, and relative humidity of 30 percent or less, there will be 6×10^{-9} g cm^{-3} (3.7×10^{-7} lb ft^{-3}) of dust suspended in the atmosphere. Distribution will be uniform to about 200 m (656 ft) above the ground.

6.3 Sand and Dust at Altitude.

Only small particles (less than 0.002 mm [0.000079 in.]) will be in the atmosphere above 400 m (1312 ft) in the areas of interest. During actual flight, the vehicle should pass through the region of maximum dust in such a short time that little or no abrasion can be expected.

6.4 Snow and Hail at Surface.

Snow and hail can cause abrasion at Huntsville, River Transportation, New Orleans, Wallops Test Range, and White Sands Missile Range areas. Extreme values expected with reference to abrasion are as follows:

6.4.1 Snow Particles.

Snow particles will have a hardness of 2 to 4 (Ref. 6.3) and a diameter of 1.0 mm (0.039 in.) to 5.0 mm (0.20 in.). A wind speed of 10 m sec^{-1} (19 knots) at a minimum air temperature of -17.8°C (0°F) should be considered for design calculations. At New Orleans a minimum air temperature of -9.4°C (15°F) should be used.

6.4.2 Hail Particles.

Hail particles will have a hardness of 2 to 4 and a diameter of 5.0 mm (0.20 in.) or greater. A wind speed of 10 m sec^{-1} (19 knots) at an air temperature of 10.0°C (50°F) should be considered for design calculations.

6.5 Snow and Hail at Altitude.

Snow and hail particles will have higher hardness values at higher altitudes. The approximate hardness of snow and hail particles in reference to temperature is given in Table 6.2 (See paragraph 4.4.2 remarks).

TABLE 6.2 HARDNESS OF HAIL AND SNOW FOR ALL LOCATIONS

Temperature		Relative Hardness
(°C)	(°F)	(Mohs' Scale)
0	32.0	2
-20	- 4.0	3
-40	-40.0	4
-60	-76.0	5
-80	-112.0	6

Although the flight time of a vehicle through a cloud layer will be extremely short, if the cloud layer contains a large concentration of moderate sized hailstones (25 mm [1 in.] or larger) at temperatures below - 20.0°C (-4°F), considerable damage may be expected (especially to antennas and other protrusions) because of the kinetic energy of the hailstone at impact. Tests have shown a definite relationship between the damage to aluminum aircraft wing sections and the velocity of various sized hailstones. Equal dents (sufficient to require repair) of 1 mm (0.039 in.) in 75 S-T aluminum resulted from the following impacts (Ref. 6.4):

a. A 19-mm (0.75 in.) ice sphere at 190 m sec^{-1} (369 knots).

b. A 32-mm (1.25 in.) ice sphere at 130 m sec^{-1} (253 knots).

c. A 48-mm (1.88 in.) ice sphere at 90 m sec^{-1} (175 knots).

6.6 Raindrops.

With the advent of high-speed aircraft a new phenomenon has been encountered in the erosion of paint coatings, of structural plastic components, and even of metallic parts by the impingement of raindrops on surfaces. The damage may be severe enough to affect the performance of a space vehicle. Tests conducted by the British Ministry of Aviation (Ref. 6.1) have resulted in a table of rates of erosion for various materials and coatings. These materials and coatings were tested at speeds of 220 m sec^{-1} (428 knots). Sufficient data are not available to present any specific extreme values for use in design, but results of the tests indicate that materials used should be carefully considered and weather conditions evaluated prior to launch.

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SECTION VII. ATMOSPHERIC PRESSURE (SURFACE)

By

Glenn E. Daniels

7.1 Definition

Atmospheric pressure (also called barometric pressure) is the force exerted as a consequence of gravitational attraction, by the mass of the column of air of unit cross section lying directly above the area in question. It is expressed as a force per unit area.

7.2 Pressure

The total variation of pressure from day to day is relatively small. Rapid but slightly greater variations occur as the result of the passage of frontal systems, while the passage of a hurricane can cause somewhat larger, but still not significant changes for pressure environment design of space vehicles. Surface pressure extremes for various locations and their extreme ranges are given in Table 7.1. These data use the results of a study of pressure extremes (Ref. 7.1 and Section XV).

7.3 Pressure Change

a. A gradual rise or fall in pressure of 3 mb (0.04 lb $in.^{-2}$) and then a return to original pressure can be expected over a 24-hour period.

b. A maximum pressure change (frontal passage change) of 6 mb (0.09 lb $in.^{-2}$) (rise or fall) can be expected within a 1-hour period at all localities.

7.4 Data on pressure distribution with altitude are given in Section XIV.

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TABLE 7.1 SURFACE PRESSURE EXTREMES

Area	Pressure				Elevation (from mean sea level) of Equivalent Station with Standard Atmospheric Conditions			
	Units	Maximum[a]	Mean	Minimum[a]	Units	Maximum[a]	Mean	Minimum[a]
Huntsville	$N\ m^{-2}$ mb $lb\ in.^{-2}$	102 500 1025 14.9	98 800 988 14.3	96 000 960 13.9	m ft	-92 -302	202 663	432 1417
River Transportation	$N\ m^{-2}$ mb $lb\ in.^{-2}$	104 400 1044 15.1	100 000 1000 14.5	95 000 950 13.8	m ft	-238 -781	106 348	516 1693
New Orleans, Gulf Transportation, Panama Canal Transportation, and Wallops Test Range	$N\ m^{-2}$ mb $lb\ in.^{-2}$	105 000 1050 15.2	101 325 1013.25 14.7	90 000 900 13.1	m ft	-285 -935	0 0	948 3110
Eastern Test Range	$N\ m^{-2}$ mb $lb\ in.^{-2}$	103 550 1035.5 15.0	101 750 1017.5 14.8	99 250 992.5 14.4	m ft	-185 -606	-40 -133	166 544
West Coast Transportation, SAMTEC, and Sacramento	$N\ m^{-2}$ mb $lb\ in.^{-2}$	104 800 1048 15.2	101 325 1013.25 14.7	93 800 938 13.6	m ft	-265 -882	0 0	617 2024
White Sands Missile Range	$N\ m^{-2}$ mb $lb\ in.^{-2}$	90 700 907 13.2	88 000 880 12.8	82 800 828 12.0	m ft	886 2907	1216 3989	1614 5295
Edwards Air Force Base	$N\ m^{-2}$ mb $lb\ in.^{-2}$	95 000 950 13.8	93 500 935 13.6	92 000 920 13.3	m ft	664 2180	706 2316	747 2452

a. Based on period of available records.

b. During hurricane conditions.

SECTION VIII. ATMOSPHERIC DENSITY (SURFACE)

By

Glenn E. Daniels

8.1 Definition.

Density is the ratio of the mass of a substance to its volume. (It also is defined as the reciprocal of specific volume.) Density is usually expressed in grams or kilograms per cubic centimeter or cubic meter.

8.2 Atmospheric Density

The variation of the density of the atmosphere at the surface from the average for any one station, and between the areas of interest, is small and should have no important effect on preflight operations. Table 8.1 gives the median density at the surface for the five test ranges.

TABLE 8.1 MEDIAN SURFACE* DENSITIES

Area	Surface Altitude (m)	Source of Data	Density (kg m^{-3})	Density (lb ft^{-3})
Eastern Test Range	5	(Ref. 8.1)	1.1835	7.388×10^{-2}
Vandenberg AFB	61	(Ref. 8.2)	1.2267	7.658×10^{-2}
White Sands Missile Range	1219	(Ref. 8.3)	1.049	6.549×10^{-2}
Wallops Test Range	2	(Ref. 8.4)	1.2320	7.691×10^{-2}
Edwards AFB	706	(Ref. 8.5)	1.1244	7.020×10^{-2}

8.3 Data on density distribution with altitude are given in Section XIV.

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* At station elevation above mean sea level.

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SECTION IX. ATMOSPHERIC ELECTRICITY

By

Glenn E. Daniels

9.1 Introduction

Atmospheric electricity must be considered in the design, transportation, and operation of aerospace vehicles. The effect of the atmosphere as an insulator and conductor of high voltage electricity, at various atmospheric pressures, must also be considered. Aerospace vehicles not adequately protected can be damaged by (1) a direct lightning stroke to the vehicle while on the ground or after launch, (2) current induced in the vehicle from the transport of charge by nearby lightning, and (3) a large buildup of the atmospheric potential gradient near the ground as a result of charged clouds nearby. Also, high voltage systems aboard the vehicle which are not properly designed can arc or break down at low atmospheric pressures.

The vehicle can be protected by (1) insuring that all metallic sections are connected electrically bonded so that the current flow from a lightning stroke is conducted over the skin without any gaps where sparking would occur or current would be carried inside [MIL-B-5087B (ASG), October 15, 1964, and later amendments (Ref. 9.1) give requirements for electrical bonding]; (2) protecting objects on the ground, such as buildings, by a system of lightning rods and wires over the outside to carry the lightning stroke to the ground; (3) providing a zone of protection (as shown in Reference 9.2 for the lightning protection plan for Saturn Launch Complex 39); (4) providing protection devices in critical circuits (Ref. 5.3); (5) using systems which have no single failure mode [the Saturn V launch vehicle uses triple redundant circuitry on the auto-abort system, which requires two out of the three signals to be correct before abort is initiated (Ref. 9.4) ; (6) appropriate shielding of units sensitive to electromagnetic radiation; and (7) for horizontally flying vehicles, avoidance of potentially hazardous thunderstorm areas by proper flight planning and flight operations. Reference 9.4A has an excellent discussion on areas in thunderstorms that are potentially dangerous for lightning discharges.

If lightning should strike a vehicle ready for test or flight, or a large metallic object nearby such as the test stand or gantry, sufficient system checks should be made to insure that all electronic components and subsystems of the vehicle are functional.

9.2 Thunderstorm Electricity

On a day without clouds, the potential gradient in the atmosphere near the surface of the earth is relatively low (< 300 V/m), but when clouds build up, the potential gradient near the surface of the earth will increase. If the clouds become large enough to have water droplets of sufficient size to produce rain, the atmospheric potential gradient may be sufficient to result in a lightning discharge which would require gradients of greater than 500 000 V/m.

9.2.1 Potential Gradient

The earth-ionospheric system can be considered as a large capacitor: the earth's surface as one plate, the ionosphere the other plate, and the atmosphere the dielectric. The earth is negatively charged.

9.2.1.1 Fair-Weather[1] Potential Gradients

The fair-weather electrical field intensity (the negative of the electrical gradient) measured near the ground is on the order of 100 to 300 V/m and is negative; i.e., the earth is negatively charged and the atmosphere above the earth is positively charged. The fair-weather value of 100 to 300 V/m will vary somewhat in time at a specific location and will also be somewhat different at various locations. These variations in fair weather will be caused by the amount of particulate matter in the atmosphere (dust, salt particles, etc.), atmospheric humidity, and instrument location and exposure (Ref. 9.5). The fair-weather potential gradient decreases with altitude, reaching a value near zero at 10 kilometers. This fair-weather potential gradient over a 100-meter high vehicle could result in a 10 000-volt, or greater, potential difference between the air near the ground and the air around the vehicle top.

9.2.1.2 Potential Gradients With Clouds

When clouds develop, the potential gradient at the ground increases. Because of the increased potential gradient on days when scattered cumulus type clouds occur, severe shock may result from charges carried down metal cables connected to captive balloons. Similar induced charges on home television antenas have been great enough to explode fine wire coils in antenna circuits in television sets. Damage to equipment connected to wires and antennas can be reduced or prevented with lightning arresters with air gaps

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1. The term "fair-weather" is used to mean without clouds. "Fine-weather" is also used in speaking about atmospheric electricity.

close enough to discharge the current before the voltage reaches values high enough to damage the equipment.

9.2.1.3 Potential Gradients During Thunderstorms

If the cloud development reaches the cumulonimbus state, lightning discharges result when the potential gradient at some location reaches a value equal to the critical breakdown value of air. Laboratory data indicate this value to be as much as 10^6 V/m at standard sea-level atmospheric pressure. Electrical fields measured at the surface of the earth are much less than 10^6 V/m during lightning discharges because of several effects: (1) Most clouds have centers of both polarities which tend to neutralize values measured at the surface. (2) Each charge in the atmosphere and its image within the earth comprise an electrical dipole, and the intensity of the electrical field decreases with the cube of the distance to the dipole. (3) The atmospheric electric field measured over land at the surface is limited by discharge currents arising from grounded points, such as grass, trees, and other structures, which ionize the air around the points, thus producing screen space charges. For these reasons, the measured electrical field at the surface is never more than about 15×10^3 V/m. The potential gradient values indicated by measuring equipment at the surface will show high values when the charged cloud is directly overhead. As the distance to the charged center of the cloud becomes greater, the readings of the measuring equipment become lower, reaching zero at some distance from the cloud, and then change to the opposite sign at greater distances from the cloud (Refs. 9.1 and 9.5).

9.2.1.4 Corona Discharge

As the atmospheric potential gradient increases, the air surrounding exposed sharp points becomes ionized by corona discharge. The induced charge from a nearby lightning stroke may aid such a discharge. The corona discharge may be quite severe when lightning storms or large cumulus cloud developments are within about 16 kilometers (10 mi) of the launch pad.

9.2.2 Characteristics of Lightning Discharges

The lightning discharge to ground which appears to the eye as a single flash is usually made up of three or four strokes. These strokes are preceeded by a leader stroke of lesser intensity. A summary of the characteristics of various types of lightning discharges are given in Table 9.1. (Refs. 9.6 and 9.7).

9.2.2.1 Lightning Characteristics for Design

Based on the latest information (Table 9.1), the following is a summary of lightning characteristics that should be considered in design:

1. On the launch pad or during ground transportation:

a. An average peak current of 20 000 amperes can be expected. The peak current flow is often reached 6 microseconds after start of stroke, with a fall to one-half the peak value in 24 microseconds. A total flash charge of 5 coulombs is transmitted to the earth with 90 percent of the current flow, after the initiation of the first stroke. Additional strokes will have about the same currents, with the peaks of the currents at 10-millisecond intervals.

b. The maximum peak current will not be greater than 100 000 amperes in 98 percent of the strokes. This peak current flow is reached in 10 microseconds after start of the stroke, and the current then falls to one-half the peak value in 20 microseconds. A total stroke charge of 20 coulombs is transmitted to the earth, with 95 percent of the current flow, after the initiation of the first stroke, at less than 5000 amperes.

2. Inflight triggered lightning:

The space vehicle while in flight should be capable of withstanding an electrical discharge from triggered lightning. The characteristic of such a discharge is expected to be an average peak current of about 20 000 amperes. The peak current flow is reached in 6 microseconds after the start of the stroke, with a fall to one-half the peak value in 24 microseconds. After the current drops to 185 amperes, it will remain close to that level for at least 175 milliseconds (17 500 μsec) before falling to zero. There will be only one stroke in the discharge called a long-continuing-current discharge (Refs. 9.1, 9.4, 9.6, 9.7, and 9.8).

9.2.2.2 Surges From a Lightning Discharge

If an electrical line, antenna, or other metallic object is struck by a lightning discharge there will be a surge of current through the object. If the object is grounded and is of sufficient size, then characteristic currents equal to the current in the lightning discharge (subsection 9.2.2) will be conducted through the object to ground. If the object is not grounded then the current flow will be less in relation to the resistance of the object and the

TABLE 9.1 CHARACTERISTICS OF LIGHTNING DISCHARGES

Type of Lightning	Average Peak Current per Stroke (A)	Maximum Rate of Rise of Current (A/μsec)	Average Amount of Charge Transferred		Average Total Duration of Stroke (msec)	Average Number of Strokes (unitless)	Average Time Between Strokes (msec)	Remarks
			Per Stroke (C)	Total (C)				
Intercloud lightning	100 - 2000	100-500	1-5	1-5	300	1		
Discrete lightning strokes to ground								
Leader	100		1-5	5	20	1		
Return stroke	20 000	10 000	5	4-20	0.3	3 to 4	40	Peak current exceeding 100,000 A have been measured about 2 percent of the time.
Long continuing current lightning strokes to ground								
Leader	100		1-5	5	20	1		
Return stroke	20 000	10 000	12-40	12-40	200	1		Average current value of 185 A for long periods (175 msec).

ground. Metallic objects whose cross sections are too small to carry the current from a lightning stroke may be melted or vaporized.

9.2.2.3 Ground Current

When lightning strikes an object the current will flow through a path to the true earth ground. The voltage drop along this path may be great enough over short distances to be dangerous to personnel and equipment (Ref. 9.2). Cattle and humans have been electrocuted from the current flow through the ground and the voltage potential between their feet while standing under a tree struck by lightning.

9.2.2.4 Radio Interference

When an electrical charge produces a spark between two points, electromagnetic radiation is emitted. This discharge is not limited to a narrow band of frequencies but covers most of the electromagnetic radiation spectrum with various intensities. Most static heard in radio reception is related to electrical discharges, with lightning strokes contributing a large percentage of the interference. This interference from lightning strokes is propagated through the atmosphere in accordance with laws valid for ordinary radio transmission and may travel great distances. With the transmission of interference from lightning strokes over great distances, certain frequencies remain prominent, with those near 30 kilohertz being the major frequencies. Interference with telemetering and guidance needs to be considered only when thunderstorms are occurring within 100 kilometers (60 mi) of the space vehicle launch site. Thunderstorm locations can be obtained from meteorologists providing operational support for the vehicle launch.

9.2.3 Frequency of Occurrence of Thunderstorms

According to standard United States weather observing a thunderstorm is reported whenever thunder is heard at the station. It is reported along with other atmospheric phenomena on the standard weather observer's form WBAN-10 when thunder is heard and ends 15 minutes after thunder is last heard. This type of reporting of thunderstorms may contain a report of one or more thunderstorms during a period. For this reason, these types of observations will be referred to as "thunderstorm events," i.e., a period during which one or more thunderstorms is reported (heard). Because of the method of reporting thunderstorms, most analyses of thunderstorm data are based on the number of days per year in which thunder is heard one or more times on a day, i.e., "thunderstorm days." A detailed study on frequencies of thunderstorms occurring in the Cape Kennedy area have been made (Ref. 9.9).

9.2.3.1 Thunderstorm Days per Year (Isoceraunic Level)[2]

The frequency of occurrence of thunderstorm days is an approximate guide to the probability of lightning strokes to earth in a given area. The number of thunderstorm days per year is called the "isoceraunic level." A direct lightning stroke is possible at all locations of interest, but the frequency of such an occurrence varies between the locations (Table 9.2 and Refs. 9.2, 9.3, and 9.10).

9.2.3.2 Thunderstorm Occurrence per Day

In a study made using the WBAN-10 data, which reports a thunderstorm when thunder is heard (Ref. 9.9), the frequencies were computed on the number of days which had 0, 1, 2, . . . , thunderstorms reported, i.e., none or more "thunderstorm events." Tables 9.3 and 9.4 (Ref. 9.9) give this information.

9.2.3.3 Thunderstorm Hits

There were sufficient data for the summer months (June-August) at Cape Kennedy to make an analysis of the frequency of occurrence of thunderstorm hits as:

1. A thunderstorm actually reported overhead.

2. A thunderstorm first reported in a sector and last reported in the opposite sector, if it is assumed that thunderstorms move in straight lines over small areas. Tables 9.5 and 9.6 (Ref. 9.3) list this information.

9.2.3.4 Hourly Distribution of Thunderstorms

Figure 9.1 presents the empirical probability that a thunderstorm will occur in the Cape Kennedy area at each hour of the day during each month. The highest frequency of thunderstorms (24 percent) is at 1600 EST in July. A thunderstorm is reported by standard observational practice if thunder is heard, which it can be over a radius of approximately 25 kilometers. Thus, the statistics presented in Figure 9.1 are not necessarily the probability that a thunderstorm will "hit," for example, a vehicle on the launch pad, or occur at a given location on Cape Kennedy.

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2. Also spelled isokeraunic.

TABLE 9.2 FREQUENCY-OF-OCCURRENCE OF "THUNDERSTORM DAYS" (ISOCERAUNIC LEVEL)

Location	Mean Number of Days Per Year of Thunderstorms	Monthly Distribution (% of Annual No. Days)											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Huntsville	70	1 0.70	3 2.10	6 4.20	8 5.60	11 7.70	19 13.30	22 15.40	18 12.60	9 6.30	1 0.70	1 0.70	1 0.70
River Transportation and New Orleans	75	3 2.25	3 2.25	5 3.75	5 3.75	8 6.0	16 12.0	21 15.75	20 15.0	10 7.5	3 2.25	3 2.25	3 2.25
Gulf Transportation	90	1 0.90	1 0.90	4 3.60	2 1.80	9 8.10	18 16.20	24 21.60	23 20.70	12 10.80	4 3.60	1 0.90	1 0.90
Eastern Test Range	70.09	0.77 0.54	1.94 1.36	4.28 3.00	4.02 2.82	9.73 6.82	18.55 13.00	21.27 14.91	20.23 14.18	13.22 9.27	3.89 2.73	1.18 0.82	0.92 0.64
Panama Canal Transportation	100	1 1.0	1 1.0	4 4.0	2 2.0	9 9.0	18 18.0	24 24.0	23 23.0	12 12.0	4 4.0	1 1.0	1 1.0
West Coast Transportation	6	9 0.54	11 0.66	19 1.14	13 0.78	7 0.42	4 0.24	3 0.18	7 0.42	8 0.48	8 0.48	3 0.24	8 0.48
Vandenberg AFB, California	2	5 0.1	15 0.3	15 0.3	5 0.1	2 0.04	1.5 0.03	10 0.2	10 0.2	25 0.5	1.5 0.03	5 0.1	5 0.1
Sacramento	4	6 0.24	16 0.64	12 0.48	15 0.60	9 0.54	6 0.24	3 0.12	3 0.12	10 0.40	12 0.48	5 0.20	3 0.12
Wallops Test Range[a]	40.6	0.5 0.2	1.2 0.5	5.2 2.1	8.4 3.4	12.6 5.1	17.2 7.0	21.7 8.8	20.4 8.3	7.9 3.2	3.2 1.3	1.0 0.4	0.7 0.3
White Sands Missile Range[b]	38.1	0.8 0.3	0.1 0.05	1.8 0.7	4.7 1.8	7.6 2.9	15.2 5.8	30.5 11.6	23.9 9.1	8.7 3.3	5.2 2.0	0.5 0.2	1.0 0.4
Edwards AFB, California	4.3	2.3 0.1	2.3 0.1	2.3 0.1	7.0 0.3	4.7 0.2	2.3 0.1	23.3 1.0	25.6 1.1	20.9 0.9	7.0 0.3	2.3 0.1	0 0

a. Data from Norfolk, Virginia

b. Data from Holloman AFB, New Mexico

TABLE 9.3 FREQUENCIES OF THE OBSERVED NUMBER OF DAYS THAT EXPERIENCED x THUNDERSTORM EVENTS AT CAPE KENNEDY FOR THE 11-YEAR PERIOD OF RECORD JANUARY 1957 THROUGH DECEMBER 1967

x	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Spr.	Sum.	Fall
0	335	295	308	299	266	187	177	185	228	311	321	334	873	549	860
1	4	9	20	18	43	77	80	89	54	17	6	3	81	246	77
2	2	4	9	10	25	40	47	30	33	9	3	2	44	117	45
3		2	3	3	3	17	26	24	12	4		2	9	67	16
4			1		3	6	9	10	3				4	25	3
5					0	2	2	3					0	7	
6					1	1							1	1	
n	341	310	341	330	341	330	341	341	330	341	330	341	1012	1012	1001

TABLE 9.4 RELATIVE FREQUENCY OF DAYS THAT EXPERIENCED AT LEAST ONE THUNDERSTORM EVENT AT CAPE KENNEDY

Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Spr.	Sum.	Fall
0.018	0.048	0.097	0.094	0.220	0.433	0.481	0.457	0.309	0.088	0.027	0.021	0.137	0.458	0.141

TABLE 9.5 FREQUENCIES OF THE OBSERVED NUMBER OF DAYS THAT EXPERIENCED x THUNDERSTORM HITS AT CAPE KENNEDY FOR THE 11-YEAR PERIOD OF RECORD JANUARY 1957 THROUGH DECEMBER 1967

x	June	July	August	Summer
0	293	305	300	898
1	27	24	30	81
2	5	6	7	18
3	3	3	2	8
4 or more	2	3	2	7
Total	330	341	341	1012

TABLE 9.6 RELATIVE FREQUENCY OF DAYS THAT EXPERIENCED AT LEAST ONE THUNDERSTORM HIT AT CAPE KENNEDY

June	July	August	Summer
0.112	0.106	0.121	0.113

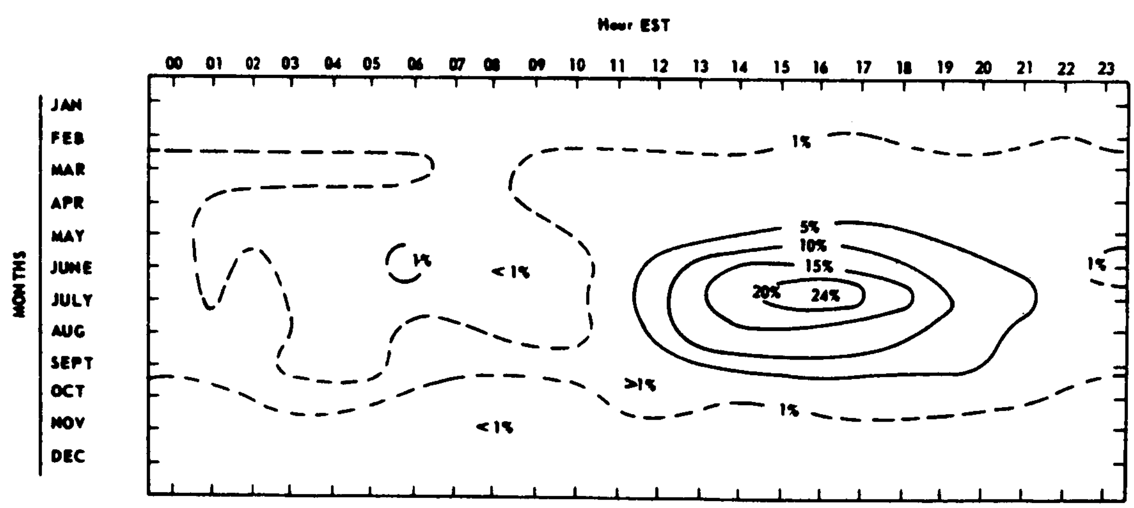

FIGURE 9.1 PROBABILITY (%) OF OCCURRENCE OF THUNDERSTORMS BY MONTHS VERSUS TIME OF DAY IN THE CAPE KENNEDY AREA

9.2.4 Frequency of Lightning Strokes to Earth

Although reliable representative data concerning the number of thunderstorms actually passing over Cape Kennedy (or the launch site) are available, the data have not been directly related to the number of lightning strokes to the launch pad. But in another study (Ref. 9.2) it was determined that if the isoceraunic level is multiplied by 0.23 an estimate of the stroke frequency to the earth per square mile can be obtained. For the 0.32-square kilometer (0.2-mi^2) launch area of the Launch Complex 39 at Kennedy Space Center there are an estimated four strokes per year or nearly one stroke for the month of August. The probable number of strokes per year to buildings of different heights increases with height, as shown in Table 9.7 (Ref. 9.2).

TABLE 9.7 ESTIMATE OF THE NUMBER OF LIGHTNING STROKES PER YEAR FOR VARIOUS HEIGHTS FOR CAPE KENNEDY

Height		Number of Lightning Strokes per Year
(m)	(ft)	
30.5	100	0.4
61.0	200	1.1
91.4	300	2.3
121.9	400	3.5
152.4	500	4.4
182.9	600	5.3
213.4	700	5.8

9.3 Static Electricity

A static electric charge may accumulate on an object from its motion through an atmosphere containing raindrops, ice particles, or dust. A stationary object, if not grounded, can also accumulate a charge from wind-borne particles (often as nuclei too small to be visible) or rain or snow particles striking the object. This charge can build up until the local electric field at the point of sharpest curvature exceeds the breakdown field. The quantity of maximum charge will depend on the size and shape of the object (especially if sharp points are on the object). Methods of calculating this charge are given in Reference 9.6.

If a charge builds up on an ungrounded vehicle on a launch pad, any discharges which occur could ignite explosive gases or fuels, interfere with radio communications or telemetry data, or cause severe shocks to persons. Static electric charges occur more frequently during periods of low humidity and can be expected at all geographical areas.

9.4 Electrical Breakdown of the Atmosphere

The atmosphere of the earth at normal sea-level pressure (101 325 N/m^2) is an excellent insulator, having a resistance greater than 10^{16} ohms for a column one square centimeter in cross section and one meter long. When there is a charge in the atmosphere, ionization takes place, thus increasing the conductivity of the air. This charge can be from either cloud buildups or electrical equipment. If the voltage is increased sufficiently, the ionization will be high enough for a spark discharge to occur.

The breakdown voltage (voltage required for a spark to jump a gap) for direct current is a function of atmospheric pressure. The breakdown voltage decreases with altitude until a minimum is reached of 327 V/mm at an atmosphere pressure of 760 N/m^2 (7.6 mb), representing an altitude of 33.3 kilometer. Above and below this altitude, the breakdown voltage increases rapidly (Ref. 9.11), being several thousand volts per millimeter at normal atmospheric pressure (Figure 9.2).

The breakdown voltage is also a function of frequency of an alternating current. With an increase of frequency the breakdown voltage decreases. A more complete discussion can be found in NASA SP-208 (Ref. 9.12).

Several measures can be taken to prevent arcing of high voltage in equipment:

1. Have equipment voltages off at the time the space vehicle is going through the critical atmospheric pressures. Any high-voltage capacitors should have bleeding resistors to prevent high-voltage charges remaining in the capacitors.

2. Eliminate all sharp points and allow sufficient space between high-voltage circuits.

3. Seal high-voltage circuits in containers at normal sea-level pressures.

4. Have materials available to protect, with proper use, against high-voltage arcing by potting circuits.

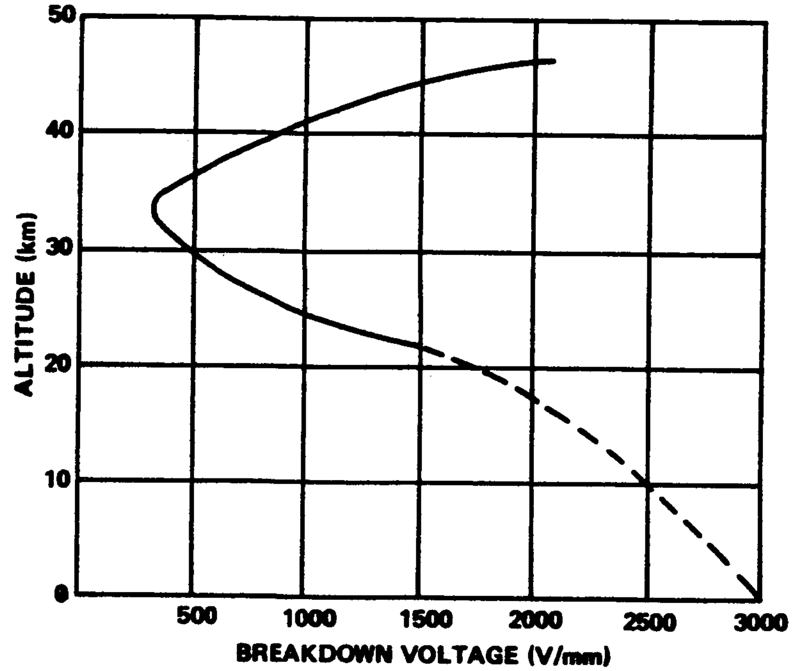

FIGURE 9.2 BREAKDOWN VOLTAGE VERSUS ALTITUDE

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SECTION X. ATMOSPHERIC CORROSION

By

Glenn E. Daniels

10.1 Introduction.

The atmosphere near the ocean will cause corrosion of exposed metals. Wind moving over breaking sea waves will pick up small droplets of salt water. These droplets are small enough to remain suspended in the air. Some will evaporate and leave tiny particles of salt in the air. When these droplets and particles accumulate on surfaces and dry, a film of salt remains on the surface. The efficiency of an optical surface coated with this salt film will be considerably reduced over periods of time. When the relative humidity is near saturation, or when light rain or drizzle occurs, the salt on the surface will absorb water and form a highly conductive solution. Corrosion by electrolytic action can result when two dissimilar metals are involved, and corrosion of a single metal can occur when the solution can react chemically. This solution can provide a conductive electrical path and short electrical equipment.

10.2 Corrosion.

The amount of corrosion is a function of several factors. Among the most important factors are (Ref. 10.1):

a. The distance of the exposed site from the ocean.

b. The length of time the humidity is high — the longer a material is wet, the more the corrosion.

c. Air temperature.

d. The corrosion rate varies with elevation above sea level.

e. Corrosion is dependent on exposure direction, shelter around or near the material, and the direction and magnitude of the prevailing winds.

10.2.1 Laboratory Salt Spray Tests.

Methods have been devised to simulate the effects of salt spray in the laboratory. The following procedures have been taken from MIL-STD-810, Method 509 (Ref. 10.2), (Federal Test Method Standard No. 151; Method 811 has slight differences):

a. A salt solution is formed under the following conditions:

(1) Five percent sodium chloride in distilled water.

(2) pH between 6.5 and 7.2 and specific gravity from 1.027 to 1.041 when measured at a temperature between 33.3° and 36.1° C (92° and 97° F).

b. An air temperature of 35.0° C (95° F) is maintained in the test chamber.

c. The salt solution is atomized and applied so that 0.5 to 3.0 milliliters (0.015 to 0.10 fluid ounces) of solution will collect over an 80-square-centimeter (12.4 square in.) horizontal area in 1 hour.

d. The time of exposure of the test will vary with the material being evaluated.

Increasing the salt concentration will not accelerate the test.

Acceptance of the laboratory tests as an exact representation of the corrosion which will occur at a specific site may result in erroneous conclusions.

In any area where corrosion by the atmosphere can be an important factor, on-the-spot tests are needed. A test such as "Sample's wire-on-bolt test" (Ref. 10.3) should be conducted on the site, with tests made at various heights above the ground.

Protection from salt spray corrosion will be required in the following areas:

(1) New Orleans

(2) Gulf Transportation

(3) Eastern Test Range

(4) Panama Canal Transportation

(5) Space and Missile Test Center

(6) West Coast Transportation

(7) Sacramento

(8) Wallops Test Range

10.3 Obscuration of Optical Surfaces.

The accumulation of salt on exposed surfaces is greatest during onshore winds when many waves are breaking and forming white caps. Extremes expected are as follows (Ref. 10.4):

a. Particle size: Range from 0.1 to 20 microns, with 98 percent of the total mass greater than 0.8 microns.

b. Distribution is uniform above 3048 meters (10 000 ft), but below cloud levels.

c. Fallout of salt particles at Eastern Test Range:

(1) Maximum: 5.0×10^{-7} g cm^{-2} day^{-1}, to produce a coating on an exposed surface of 100 microns day^{-1}. This extreme occurs during precipitation.

(2) Minimum: 2.5×10^{-8} g cm^{-2} day^{-1}, to produce a coating on an exposed surface averaging 5 microns day^{-1}. This fallout occurs continuously during periods of no precipitation, and is independent of wind direction. This coating will not usually be of uniform thickness, but be spots of salt particles unevenly distributed over the optical surface.

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SECTION XI. FUNGI AND BACTERIA

By

Glenn E. Daniels

Fungi (including mold) and bacteria have the highest rate of growth at temperatures between 20.0° C (68° F) and 37.7° C (100° F) and relative humidities between 75 and 95 percent (Refs. 11.1 and 11.2). Fungi and bacteria secrete enzymes and acids during their growth. These secretions can destroy most organic substances and many of their derivatives. Typical materials which will support growth of fungi and bacteria and are damaged by them if not properly protected are cotton, wood, linen, leather, paper, cork, hair, felt, lens-coating material, paints, and metals. The four groups of fungi used in the fungus-resistance tests for equipment are as follows:

Group	Organism	American Type Culture Collection Number
I	Chaetomuim globosum	6205
	Myrothecium verrucaria	9095
II	Memenialla echinata	9597
	Aspergillus niger	6275
III	Aspergillus flavus	10836
	Aspergillus terreus	10690
IV	Penicillium citrinum	9849
	Penicillium ochrochloron	9112

A suspension of mixed spores made from one species of fungus from each group is sprayed on the equipment being tested in a test chamber. The equipment is then left for 28 days in the test chamber at a temperature of 30° ± 2° C (86° ± 3.6° F) and relative humidity of 95 ± 5 percent.

Equipment is usually protected from fungi and bacteria by incorporating a fungicide-bactericide in the material, by a fungicide-bactericide spray, or by reducing the relative humidity to a degree where growth will not take place. A unique method used in the Canal Zone to protect delicate, expensive bearings in equipment was to maintain a pressure (with dry air or nitrogen) slightly above the outside atmosphere (few millibars) within the working parts of the equipment, thus preventing fungi from entering equipment.

Proper fungus- and bacteria-proofing measures are required at the following areas:

(1) River Transportation

(2) New Orleans

(3) Gulf Transportation

(4) Panama Canal Transportation

(5) Eastern Test Range

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SECTION XII. ATMOSPHERIC OXIDANTS

By

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12.1 Introduction.

Air pollution at the earth's surface has received considerable publicity in recent years because the pollutants reduce visibility, cause damage to crops, irritate the eyes, and have an objectional odor. The ingredients which cause the air pollution are a mixture of oxides of organic matter (mostly nitrogen oxides and hydrocarbons) and ozone. In the Los Angeles area, the mixing of the organic oxides, ozone, and water droplets forms the well known smog. Ozone, although considered one of the rare atmospheric gases, needs consideration in design because of its chemical reaction (oxidation) with organic materials, especially rubber, which becomes hard and brittle under tension in a few minutes time. The presence in smog of strong oxidizing agents closely resembling ozone in their action on organic compounds leads one to believe that ozone exists in smog in greater quantities than in the normal atmosphere.

12.2 Ozone.

Ozone, in high concentrations, is explosive and poisonous. One hundred (100) parts per hundred million (phm) of ozone is toxic to man sufficient to cause death. The use of the atmosphere at high altitudes for breathing by pressurizing, requires removal of the ozone. Ozone may be formed in high concentrations by short wavelength ultraviolet light (below 2537Å), or by the arcing or discharge of electrical currents. A motor or generator with arcing brushes is an excellent source of ozone. The natural ozone concentration at the earth's surface is normally less than 3 parts per hundred million (phm), except during periods of intense smog, where it may exceed 5 phm. Ozone concentration increases with altitude, with the maximum concentration of 1100 parts per hundred million being at about 30 km (98,000 ft).

Maximum expected values of natural atmospheric ozone, for purposes of design studies, are as follows: (a) surface, at all areas, a maximum concentration of 3 phm except during smog, when the maximum will be 6 phm, and (b) maximum concentration, with altitude, is given in Table 12.1 (Ref. 12.1).

TABLE 12.1 DISTRIBUTION OF MAXIMUM DESIGN VALUES OF OZONE CONCENTRATION WITH ALTITUDE FOR ALL LOCATIONS

Geometric Altitude (km)	(ft)	Ozone (parts per hundred million)	Ozone Concentration (cm/km)
SRF*	SRF*	6	0.006
9.1	30,000	30	0.010
15.2	50,000	200	0.030
21.3	70,000	700	0.040
27.4	90,000	1100	0.024
33.5	110,000	1100	0.009
39.6	130,000	600	0.002
45.7	150,000	400	0.0005

*SRF - Surface

12.3 Atmospheric Oxidants.

At the surface, a maximum of 60 parts per hundred million of oxidants composed of nitrogen oxides, hydrocarbons, sulphur dioxide, sulphur trioxides, peroxides, and ozone can be expected for 72 hours when smog occurs. The effect of these oxidants on rubber cracking and in some chemical reactions will be equivalent to 22 parts per hundred million of ozone, but not necessarily equivalent to this concentration of ozone in other reactions (Ref. 12.2).

REFERENCES

12.1 Ditaranto, R. A.; and Lamb, J. J.: "Preliminary Investigation of Hyper-Environments and Methods of Simulation, Part I, Natural and Induced Environments Above 75,000 ft." WADC Technical Report 57-456, Part I, ASTIA Doc. No. AD-142002, 1957.

12.2 Haagen-Smit, A. J.: "Chemistry and Physiology of Los Angeles Smog." Industrial and Engineering Chemistry, vol. 44, no. 6, June 1952, pp. 1342-1346.

SECTION XIII. ATMOSPHERIC COMPOSITION

By

Glenn E. Daniels

13.1 Composition.

The earth's atmosphere is made up of a number of gases in different relative amounts. Near sea level and up to about 90 km, the amount of these atmospheric gases in clean, relatively dry air is practically constant. Four of these gases, nitrogen, oxygen, argon, and carbon dioxide, make up 99.99 percent by volume of the atmosphere. Two gases, ozone and water vapor, change in relative amounts, but the total amount of these two is very small compared to the amount of the other gases.

The atmospheric composition shown in Table 13.1 can be considered valid up to 90 km geometric altitude. Above 90 km, mainly because of molecular dissociation and diffusive separation, the composition changes from that shown in Table 13.1. Reference is made to the Space Environment Criteria Guidelines document (Ref. 13.2) for additional information on composition above 90 km.

13.2 Molecular Weight.

The atmospheric composition shown in Table 13.1 gives a molecular weight of 28.9644 for dry air (Ref. 13.1). This value of molecular weight can be used as constant up to 90 km, and is equivalent to the value 28.966 on the basis of a molecular weight of 16 for oxygen.

The molecular weight of the atmosphere with relation to height is shown in Table 13.2.

TABLE 13.1 NORMAL ATMOSPHERIC COMPOSITION FOR CLEAN, DRY AIR AT ALL LOCATIONS (VALID TO 90 KILOMETERS GEOMETRIC ALTITUDE)

Gas	Percent by Volume	Percent by Weight*
Nitrogen (N_2)	78.084	75.520
Oxygen (O_2)	20.9476	23.142
Argon (Ar)	0.934	1.288
Carbon dioxide (CO_2)	0.0314	0.048
Neon (Ne)	1.818×10^{-3}	1.27×10^{-3}
Helium (He)	5.24×10^{-4}	7.24×10^{-5}
Krypton (Kr)	1.14×10^{-4}	3.30×10^{-4}
Xenon (Xe)	8.7×10^{-6}	3.9×10^{-5}
Hydrogen (H_2)	5×10^{-5}	3×10^{-6}
Methane (CH_4)	2×10^{-4}	1×10^{-4}
Nitrous Oxide (N_2O)	5×10^{-5}	8×10^{-5}
Ozone (O_3) summer	0 to 7×10^{-6}	0 to 1.1×10^{-5}
winter	0 to 2×10^{-6}	0 to 3×10^{-6}
Sulfur dioxide (SO_2)	0 to 1×10^{-4}	0 to 2×10^{-4}
Nitrogen dioxide (NO_2)	0 to 2×10^{-6}	0 to 3×10^{-6}
Ammonia (NH_3)	0 to trace	0 to trace
Carbon monoxide (CO)	0 to trace	0 to trace
Iodine (I_2)	0 to 1×10^{-6}	0 to 9×10^{-6}

*On basis of Carbon 12 isotope scale for which $C^{12} = 12.000$, as adopted by the International Union of Pure and Applied Chemistry meeting, Montreal, in 1961.

TABLE 13.2 MOLECULAR WEIGHT OF THE ATMOSPHERE FOR ALL LOCATIONS

Geometric Altitude (km)	(ft)	Molecular Weight
SRF* to 90	SRF* to 295,000	28.9644 28.9644

*SRF - Surface

REFERENCES

13.1 "U. S. Standard Atmosphere, 1962." United States Government Printing Office, Washington 25, D.C., 1962.

13.2 Weidner, Don K., Editor: "Space Environment Criteria Guidelines for Use in Space Vehicle Development (1969 Revision)." TM X-53957, Second Edition August 26, 1970. NASA-Marshall Space Flight Center, Huntsville, Alabama.

SECTION XIV. INFLIGHT THERMODYNAMIC PROPERTIES

By

Orvel E. Smith, S. Clark Brown, Glenn E. Daniels, and Dale L. Johnson

14.1 Introduction

This section presents the inflight thermodynamic parameters (temperature, pressure, and density) of the atmosphere. Mean and extreme values of the thermodynamic parameters given here can be used in application of many aerospace problems, such as (1) research planning and engineering design of remote earth sensing systems; (2) vehicle design and development; and (3) vehicle trajectory analysis, dealing with vehicle thrust, dynamic pressure, aerodynamic drag, aerodynamic heating, vibration, structural and guidance limitations, and reentry lifting body analysis. Atmospheric density plays a very important role in most of the above problems. The first part of this section gives median and extreme values of these thermodynamic variables with respect to altitude. An approach is presented for temperature, pressure, and density as independent variables, with a method to obtain simultaneous values of these variables at discrete altitude levels. A subsection on reentry is presented, giving atmospheric models to be used for reentry heating, trajectory, etc., analysis. Various parts of Section XIV have been updated since the last revision of this document (Ref. 14.1).

Standard day is a term used by some engineers to mean the U. S. Standard Atmosphere, 1962 (Ref. 14.2). This term means a Standard Atmosphere Day and at sea level is a pressure of 1013.25 mb, a temperature of 288.15° K, and a density of 1.2250 kg m^{-3}.

14.2 Temperature

14.2.1 Air Temperature at Altitude

Median and extreme air temperatures for the following test ranges were compiled from radiosonde frequency distributions of temperature for the different ranges from 0 through 30 kilometers altitude. Meteorological rocketsonde mean and extreme temperatures for the different ranges were used above 30 kilometers altitude.

a. Eastern Test Range air temperature values with altitude are given in Table 14. 1 (Ref. 14. 3). (Radiosonde period of record was May 1950 to April 1960; rocketsonde period of record was April 1960 to January 1969.)

b. Space and Missile Test Center air temperature values with altitude are given in Table 14. 2. (Radiosonde period of record was July 1959 to June 1964; rocketsonde period of record was May 1959 to October 1967.)

c. Wallops Test Range air temperature values with altitude are given in Table 14. 3. (Radiosonde period of record was January 1951 to October 1960; rocketsonde period of record was January 1960 to January 1968.)

d. White Sands Missile Range air temperature values with altitude are given in Table 14. 4. (Radiosonde period of record was November 1951 to January 1960; rocketsonde period of record was July 1957 to January 1968.)

e. Edwards Air Force Base air temperature values with altitude are given in Table 14. 5. (Radiosonde period of record was January 1956 to March 1967; rocketsonde period of record was May 1959 to October 1967.)

14. 2. 2 Compartment Extreme Cold Temperature

Extreme cold temperatures during aircraft flight, when compartments are not heated, are given in Table 14. 6.

14. 3 Atmospheric Pressure

14. 3. 1 Definition

Atmospheric pressure (also called barometric pressure) is the force exerted, as a consequence of gravitational attraction, by the mass of the column of air of unit cross section lying directly above the area in question. It is expressed as force per unit area.

14. 3. 2 Pressure at Altitude

Atmospheric pressure extremes for all locations are given in Table 14. 7. These data were taken from the radiosonde pressure frequency distributions for the four test ranges. Rocketsonde pressure means and extremes were used above 25 kilometers altitude.

TABLE 14.1 EASTERN TEST RANGE AIR TEMPERATURES AT VARIOUS ALTITUDES

Geometric Altitude (km)	Minimum (°C)	Minimum (°F)	Median (°C)	Median (°F)	Maximum (°C)	Maximum (°F)
SRF (0.005 MSL)	-2.2	28	23.9	75	37.2	99
1	-8.9	16	17.2	63	27.8	82
2	-10.0	14	12.2	54	21.1	70
3	-11.1	12	7.2	45	16.1	61
4	-13.9	7	2.2	36	11.1	52
5	-20.0	-4	-3.9	25	5.0	41
6	-26.1	-15	-10.0	14	-1.1	30
7	-33.9	-29	-17.2	1	-7.2	19
8	-41.1	-42	-25.0	-13	-13.9	7
9	-50.0	-58	-32.2	-26	-21.1	-6
10	-56.1	-69	-40.0	-40	-30.0	-22
16.2	-80.0	-112	-70.0	-94	-57.8	-72
20	-76.1	-105	-62.8	-81	-47.8	-54
30	-58.9	-74	-42.2	-44	-30.0	-22
35	-47.4	-53	-30.6	-23	-14.6	6
40	-36.7	-34	-17.4	1	1.9	35
45	-23.0	-9	-5.2	23	12.8	55
50	-18.2	-1	-2.2	28	22.0	72
55	-34.4	-30	-6.0	21	18.9	66
60	-28.5	-19	-10.2	14	17.0	63
			a			

a. For higher altitudes see References 14.3, 14.4, 14.5, and 14.6(1).

TABLE 14.2 SPACE AND MISSILE TEST CENTER (Vandenberg AFB, California) AIR TEMPERATURES AT VARIOUS ALTITUDES

Geometric Altitude (km)	Minimum (°C)	Minimum (°F)	Median (°C)	Median (°F)	Maximum (°C)	Maximum (°F)
SRF (0.06 MSL)	-2.2	28	12.6	55	41.7	107
1	-3.6	26	13.5	56	33.4	92
2	-7.0	19	10.1	50	28.0	82
3	-15.2	5	4.7	41	17.6	64
4	-22.6	-9	-0.9	30	12.1	54
5	-29.7	-22	-7.2	19	3.3	38
6	-35.6	-32	-14.4	6	-2.7	27
7	-43.3	-46	-21.9	-7	-9.9	14
8	-47.4	-53	-29.8	-22	-15.9	3
9	-51.3	-60	-36.9	-34	-26.8	-16
10	-57.0	-71	-44.6	-48	-31.2	-24
16.3	-76.0	-105	-64.1	-83	-51.0	-60
20	-74.9	-103	-59.5	-75	-49.0	-56
30	-63.7	-83	-42.5	-45	-29.4	-21
40	-42.2	-44	-18.0	0	17.8	64
45	-30.5	-23	-5.2	23	27.6	82
50	-18.2	-1	-1.6	29	28.0	82
55	-21.8	-7	-3.6	26	31.6	89
60	-25.1	-13	-6.0	21	35.7	96
			a			

a. For higher altitudes see References 14.4, 14.5, 14.6(6), and 14.2.

TABLE 14.3 WALLOPS TEST RANGE AIR TEMPERATURES AT VARIOUS ALTITUDES

Geometric Altitude (km)	Minimum (° C)	Minimum (° F)	Median (° C)	Median (° F)	Maximum (° C)	Maximum (° F)
SRF (0.002 MSL)	-11.7	11	12.8	55	39.4	103
1	-21.1	-6	10.0	50	31.1	88
2	-26.1	-15	5.0	41	22.8	73
3	-30.0	-22	1.1	34	15.0	59
4	-33.9	-29	-3.9	25	7.8	46
5	-40.0	-40	-10.0	14	2.8	37
6	-43.9	-47	-17.2	1	-1.1	30
7	-47.8	-54	-23.9	-11	-7.8	18
8	-50.6	-59	-32.2	-26	-15.0	5
9	-56.1	-69	-38.9	-38	-21.1	-6
10	-61.1	-78	-45.0	-49	-27.2	-17
16.5	-77.8	-108	-62.2	-80	-47.2	-53
20	-71.1	-96	-57.2	-71	-46.1	-51
30	-65.0	-85	-43.9	-47	-27.2	-17
40	-35.7	-32	-18.2	-1	5.8	42
45	-27.7	-18	-5.2	23	14.8	59
50	-24.9	-13	-0.8	31	21.8	71
55	-22.6	-9	-1.7	29	35.0	95
			a			

a. For higher altitudes see References 14.4, 14.5, 14.6(8), and 14.2.

TABLE 14.4 WHITE SANDS MISSILE RANGE AIR TEMPERATURES AT VARIOUS ALTITUDES

Geometric Altitude (km)	Minimum (° C)	Minimum (° F)	Median (° C)	Median (° F)	Maximum (° C)	Maximum (° F)
SRF (1.2 MSL)	-11.7	11	16.1	61	42.8	109
2	-11.7	11	12.8	55	31.1	88
3	-18.9	-2	6.1	43	22.2	72
4	-23.9	-11	0.0	32	12.8	55
5	-31.1	-24	-7.2	19	6.1	43
6	-36.1	-33	-13.9	7	0.0	32
7	-42.2	-44	-20.0	-4	-7.2	19
8	-48.9	-56	-30.0	-22	-13.9	7
9	-55.0	-67	-37.2	-35	-21.1	-6
10	-60.0	-76	-42.8	-45	-27.2	-17
16.5	-80.0	-112	-67.2	-89	-47.8	-54
20	-77.8	-108	-60.0	-76	-52.2	-62
30	-58.9	-74	-42.8	-45	-26.1	-15
35	-52.2	-62	-32.3	-26	-7.8	18
40	-41.8	-43	-18.5	-1	5.0	41
45	-30.5	-23	-5.5	22	19.6	67
50	-29.1	-20	-2.0	28	25.9	79
55	-28.7	-20	-4.5	24	30.2	86
60	-35.8	-32	-10.0	14	28.0	82
65	-36.5	-34	-12.6	9	31.3	88
			a			

a. For higher altitudes see References 14.4, 14.5, 14.6(2), and 14.2,

TABLE 14.5 EDWARDS AFB AIR TEMPERATURES AT VARIOUS ALTITUDES

Geometric Altitude (km)	Minimum (°C)	Minimum (°F)	Median (°C)	Median (°F)	Maximum (°C)	Maximum (°F)
SRF (0.7 MSL)	-5.0	23	13.5	56	40.0	104
1	-6.0	21	15.4	60	35.3	96
2	-12.9	9	11.1	52	26.2	79
3	-16.9	2	4.9	41	19.0	66
4	-23.4	-10	-1.2	30	10.7	51
5	-29.7	-21	-8.0	18	5.2	41
6	-35.2	-31	-15.3	4	-2.9	27
7	-42.0	-44	-22.4	-8	-12.1	10
8	-48.9	-56	-30.1	-22	-17.4	1
9	-55.0	-67	-38.0	-36	-24.2	-12
10	-58.8	-74	-45.2	-49	-30.8	-23
17.8	-78.0	-108	-64.4	-84	-53.0	-63
20	-73.5	-100	-61.1	-78	-49.6	-57
25	-73.2	-100	-52.9	-63	-40.4	-41
30	-66.1	-87	-45.8	-50	-29.1	-20
40	-42.2	-44	-18.0	0	17.8	64
45	-30.5	-23	-5.2	23	27.6	82
50	-18.2	-1	-1.6	29	28.0	82
55	-21.8	-7	-3.6	26	31.6	89
60	-25.1	-13	-6.0	21	35.7	96
			a			

a. For higher altitudes see References 14.4, 14.5, 14.6(6), and 14.2.

TABLE 14.6 COMPARTMENT DESIGN COLD TEMPERATURE EXTREMES FOR ALL LOCATIONS

Maximum Flight Altitude (Geometric) of Aircraft Used for Transport		Compartment Cold Temperature Extreme	
(m)	(ft)	(°C)	(°F)
4 550	15 000	-35.0	-31
6 100	20 000	-45.0	-49
7 600	25 000	-53.3	-64
9 150	30 000	-65.0	-85
15 200	50 000	-86.1	-123

14.4 Atmospheric Density

14.4.1 Definition

Density (ρ) is the ratio of the mass of a substance to its volume. (It is also defined as the reciprocal of specific volume.) Density is usually expressed in grams or kilograms per cubic centimeter or cubic meter.

14.4.2 Atmospheric Density at Altitude

The density of the atmosphere decreases rapidly with height, decreasing to one-half that of the surface of 7 kilometers altitude. Density is also variable at a fixed altitude, with the greatest relative variability occurring at about 70 kilometers altitude in the high northern latitudes (60° N) for altitude ranges up to 90 kilometers. Other altitudes of maximum density variability occur around 16 kilometers and 0 kilometers. Altitudes of minimum variability (isopycnic levels) occur around 8, 24, and 90 kilometers altitude.

Density varies with latitude in the northern hemisphere, with the mean annual density near the surface increasing to the north. In the region around 8 kilometers, the density variation with latitude and season is small (isopycnic level). Above 8 kilometers to about 28 kilometers, the mean annual density decreases toward the north. Mean-monthly densities between 30 and 90 kilometers increase toward the north in July and toward the south in January.

Considerable data are now available on the mean density and its variability below 30 kilometers at the various test ranges from the data collected for preparation of the IRIG Range Reference Atmospheres (Ref. 14.6). Additional information on the seasonal variability of density below 30 kilometers is presented in an article by J. W. Smith (Ref. 14.7).

Above 30 kilometers, the data are less plentiful and the accuracy of the temperature measurements (used to compute densities) becomes poorer with altitude.

The median density and extreme minimum and maximum values for the Eastern Test Range are given in Table 14.8. These extreme density values do approach the $\pm 3\sigma$ (corresponding to the normal distribution) density values.

The maximum, minimum, and median densities for 2 kilometers and above (Table 14.8) can be used for all locations with an adjustment of the surface median density by using the values given in Table 8.1, Section VIII, at station altitude.

The units for density (kg m^{-3}) are consistent units with those given in the Patrick Reference Atmosphere, 1963 Revision (PRA-63), included in Table 14.11 of this document. Density deviations were found as follows:

$$\% \text{ Deviation } \Delta\rho = \frac{\rho_{\text{max or min}} - \rho_{\text{PRA-63}}}{\rho_{\text{PRA-63}}} \times 100 \quad ,$$

TABLE 14.7 ATMOSPHERIC PRESSURE-HEIGHT EXTREMES FOR ALL LOCATIONS

Geometric Altitude (above mean sea level)		Pressure					
		Maximum		Median		Minimum	
(km)	(ft)	(mb)	(lb in.$^{-2}$)	(mb)	(lb in.$^{-2}$)	(mb)	(lb in.$^{-2}$)
0	0	(Use values in Table 7.1 for surface pressure for each station)					
3	9 800	730	10.6	714	10.4	680	9.86
6	19 700	510	7.40	490	7.11	457	6.63
10	32 800	295	4.28	283	4.10	251	3.64
15	49 200	135	1.96	129	1.87	116	1.68
20	65 600	60	8.7×10^{-1}	56	8.1×10^{-1}	51	7.4×10^{-1}
25	82 000	30	4.4×10^{-1}	28	4.1×10^{-1}	22	3.2×10^{-1}
30	98 400	14.5	2.1×10^{-1}	12.2	1.8×10^{-1}	10.4	1.5×10^{-1}
35	114 800	7.4	1.1×10^{-1}	6.0	8.7×10^{-2}	4.9	7.1×10^{-2}
40	131 200	3.8	5.5×10^{-2}	3.0	4.4×10^{-2}	2.4	3.5×10^{-2}
45	147 600	2.0	2.9×10^{-2}	1.6	2.3×10^{-2}	1.2	1.7×10^{-2}
50	164 000	1.2	1.7×10^{-2}	8.5×10^{-1}	1.2×10^{-2}	6.1×10^{-1}	8.8×10^{-3}
55	180 400	6.0×10^{-1}	8.7×10^{-3}	4.6×10^{-1}	6.7×10^{-3}	3.1×10^{-1}	4.5×10^{-3}
60	196 800	3.2×10^{-1}	4.6×10^{-3}	2.4×10^{-1}	3.5×10^{-3}	1.6×10^{-1}	2.3×10^{-3}
65	213 300	1.7×10^{-1}	2.5×10^{-3}	1.3×10^{-1}	1.9×10^{-3}	8.3×10^{-2}	1.2×10^{-3}
70a	229 700	8.5×10^{-2}	1.2×10^{-3}	5.5×10^{-2}	8.0×10^{-4}	4.1×10^{-2}	5.9×10^{-4}
				b			

a. Median values from Reference 14.2, maximum and minimum values estimated.

b. For higher altitudes see References 14.4, 14.5, 14.6, and 14.2.

TABLE 14.8 DENSITY HEIGHT MAXIMUM (≈ +3 SIGMA), MINIMUMS (≈ -3 SIGMA) AND MEDIANS FOR EASTERN TEST RANGE

Altitude[a]		Density							
		Maximum			Median[b]		Minimum		
(km)	(ft)	(kg m^{-3})	(lb ft^{-3})	(% Deviation)	(kg m^{-3})	(lb ft^{-3})	(% Deviation)	(kg m^{-3})	(lb ft^{-3})
0	0	1.326	8.278×10^{-2}	12.0	1.1835	7.388×10^{-2}	-3.6	1.141	7.123×10^{-2}
2	6 600	1.047	6.536×10^{-2}	6.1	9.7903×10^{-1}	6.112×10^{-2}	-3.0	9.497×10^{-1}	5.929×10^{-2}
4	13 100	8.287×10^{-1}	5.174×10^{-2}	3.7	7.9916×10^{-1}	4.989×10^{-2}	-2.1	7.824×10^{-1}	4.885×10^{-2}
6	19 700	6.706×10^{-1}	4.187×10^{-2}	3.2	6.4983×10^{-1}	4.057×10^{-2}	-2.2	6.355×10^{-1}	3.967×10^{-2}
8	26 200	5.428×10^{-1}	3.389×10^{-2}	3.1	5.2652×10^{-1}	3.287×10^{-2}	-4.0	5.055×10^{-1}	3.156×10^{-2}
10	32 800	4.352×10^{-1}	2.717×10^{-2}	3.0	4.2255×10^{-1}	2.638×10^{-2}	-6.8	3.938×10^{-1}	2.458×10^{-2}
15	49 200	2.345×10^{-1}	1.464×10^{-2}	7.0	2.1920×10^{-1}	1.368×10^{-2}	-9.7	1.979×10^{-1}	1.235×10^{-2}
20	65 600	1.002×10^{-1}	6.255×10^{-3}	7.5	9.3194×10^{-2}	5.818×10^{-3}	-6.1	8.751×10^{-2}	5.463×10^{-3}
25	82 000	4.274×10^{-2}	2.668×10^{-3}	5.9	4.0358×10^{-2}	2.520×10^{-3}	-6.1	3.790×10^{-2}	2.366×10^{-3}
30	98 400	1.976×10^{-2}	1.234×10^{-3}	7.8	1.8334×10^{-2}	1.145×10^{-3}	-7.3	1.700×10^{-2}	1.061×10^{-3}
35	115 000	9.427×10^{-3}	5.885×10^{-4}	10.3	8.5464×10^{-3}	5.336×10^{-4}	-10.6	7.640×10^{-3}	4.770×10^{-4}
40	131 200	4.637×10^{-3}	2.895×10^{-4}	12.5	4.1220×10^{-3}	2.573×10^{-4}	-14.8	3.512×10^{-3}	2.193×10^{-4}
50	164 000	1.275×10^{-3}	7.960×10^{-5}	16.3	1.0966×10^{-3}	6.846×10^{-5}	-21.3	8.630×10^{-4}	5.388×10^{-5}
60	196 800	3.946×10^{-4}	2.463×10^{-5}	19.4	3.3049×10^{-4}	2.063×10^{-5}	-25.4	2.465×10^{-4}	1.539×10^{-5}
70	229 700	1.100×10^{-4}	6.867×10^{-6}	23.6	8.8998×10^{-5}	5.556×10^{-6}	-25.1	6.666×10^{-5}	4.162×10^{-6}
80	262 500	2.342×10^{-5}	1.462×10^{-6}	19.0	1.9677×10^{-5}	1.228×10^{-6}	-18.9	1.596×10^{-5}	9.964×10^{-7}
90	295 000	3.684×10^{-6}	2.300×10^{-7}	10.9	3.3216×10^{-6}	2.074×10^{-7}	-11.8	2.930×10^{-6}	1.829×10^{-7}

a. Geometric altitude above mean sea level.

b. Median values from Reference 14.3.

where

$$\Delta\rho = \text{deviation of density from PRA-63}$$

$$\rho_{PRA\ 63} = \text{PRA-63 density} = \text{median density}$$

$$\rho_{max\ or\ min} = \text{given maximum or minimum densities.}$$

14.5 Simultaneous Values of Temperature, Pressure, and Density at Discrete Altitude Levels

14.5.1 Introduction

This subsection presents simultaneous values for temperature, pressure, and density as guidelines for aerospace vehicle design considerations. The necessary assumptions and the lack of sufficient statistical data sample restrict the precision by which these data can presently be presented; therefore, the analysis is limited to Cape Kennedy.[1]

14.5.2 Method of Determining Simultaneous Value

An aerospace vehicle design problem that often arises in considering natural environmental data is stated by way of the following question: "How should the extremes (maxima and minima) of temperature, pressure, and density be combined (a) at discrete altitude levels? (b) versus altitude?" It would seem simple to work with only three variables with respect to altitude that are connected by two physical equations, which are (1) the equation of state and (2) the hydrostatic equation. However, it is these facts that make rigorous statistical treatment of sample data impossible, and the only recourse is to make empirical comparisons of results derived by independent methods. The following discussion will be addressed to the first question: "How should extremes of three variables be combined?" Or, stated in another way: "Given an extreme density, what values of temperature and pressure should be used simultaneously with the extreme density?"

The differentiation of the equation of state yields

$$\frac{d\rho}{\rho} = \frac{dP}{P} - \frac{dT}{T} \quad . \tag{14.1}$$

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1. Similar analysis for Vandenberg AFB (Space and Missile Test Center), California, is currently being completed and will be made available upon request.

Equation (14.1) holds only if the departures $d\rho$, dP, and dT are small relative to their respective quantities. There is also a problem of how to treat the ± deviations. What is needed is the correlation coefficients between these variables. From basic statistical principles (Ref. 14.8) a satisfactory set of three equations can be derived to relate these three variables to each other. These equations are

$$\left(\frac{\sigma_T}{\bar{T}}\right) = \left(\frac{\sigma_P}{\bar{P}}\right) r(PT) - \left(\frac{\sigma_\rho}{\bar{\rho}}\right) r(\rho T) \tag{14.2}$$

$$\left(\frac{\sigma_P}{\bar{P}}\right) = \left(\frac{\sigma_\rho}{\bar{\rho}}\right) r(P\rho) + \left(\frac{\sigma_T}{\bar{T}}\right) r(PT) \tag{14.3}$$

$$\left(\frac{\sigma_\rho}{\bar{\rho}}\right) = \left(\frac{\sigma_P}{\bar{P}}\right) r(P\rho) - \left(\frac{\sigma_T}{\bar{T}}\right) r(\rho T) \quad , \tag{14.4}$$

where

r( ) = correlation coefficients between thermodynamic quantities denoted in parenthesis

σ = standard deviation of the thermodynamic quantity denoted by subscript.

As written, equations (14.2), (14.3), and (14.4) represent population parameters, and the underlying assumption is that the sample distribution is normal (Gaussian). From private communications with Dr. Buell,[2] it was learned that in deriving these equations, second and higher order terms have been neglected. An application of these equations was made to derive the correlation coefficients using the available statistics for Cape Kennedy. In the development of the pole-to-pole cross sections for Reference 14.9, the means and standard deviations of temperature, pressure, and density were computed for several stations, including Cape Kennedy. From these statistics the sample estimates for

$$\frac{\sigma_T}{\bar{T}}, \quad \frac{\sigma_P}{\bar{P}}, \quad \frac{\sigma_\rho}{\bar{\rho}}$$

were computed. These parameters are called coefficients of variation (CV). Using the sample coefficients of variations as known quantities gives a

2. Dr. C. Eugene Buell, Kaman Sciences Corporation, Colorado Springs, Colorado.

simultaneous solution of equations (14.2), (14.3), and (14.4) to yield the desired correlation coefficients, namely,

$$r(P\rho) = \frac{\left(\frac{\sigma_\rho}{\bar{\rho}}\right)^2 - \left(\frac{\sigma_T}{\bar{T}}\right) + \left(\frac{\sigma_P}{\bar{P}}\right)^2}{2\left[\left(\frac{\sigma_\rho}{\bar{\rho}}\right)\left(\frac{\sigma_P}{\bar{P}}\right)\right]} \tag{14.5a}$$

$$r(PT) = \frac{\left(\frac{\sigma_T}{\bar{T}}\right)^2 + \left(\frac{\sigma_P}{\bar{P}}\right)^2 - \left(\frac{\sigma_\rho}{\bar{\rho}}\right)^2}{2\left[\left(\frac{\sigma_T}{\bar{T}}\right)\left(\frac{\sigma_P}{\bar{P}}\right)\right]} \tag{14.5b}$$

$$r(\rho T) = \frac{\left(\frac{\sigma_P}{\bar{P}}\right)^2 - \left(\frac{\sigma_\rho}{\bar{\rho}}\right)^2 - \left(\frac{\sigma_T}{\bar{T}}\right)^2}{2\left[\left(\frac{\sigma_T}{\bar{T}}\right)\left(\frac{\sigma_\rho}{\bar{\rho}}\right)\right]} \tag{14.5c}$$

From equations (14.5) the correlation coefficients were computed for seasonal data samples at 1-kilometer intervals from 0 to 27 kilometers altitude for Cape Kennedy and were compared with the correlation coefficients that were derived by the standard statistical method for Cape Kennedy. The maximum differences in the correlation coefficients for the two different methods occurred at 0 kilometer altitude for r(PT) and r(Pρ). These differences were less than 0.08. At altitudes above 1 kilometer, the derived correlation coefficients are almost identical to those computed by the standard statistical method.

The values for the coefficient of variations and the derived correlation coefficients r(Pρ), r(PT), and r(ρT) are illustrated in Figures 14.1 and 14.2, respectively, and are given in Table 14.9. The density variability is a minimum at the isopycnic levels near 8 and 90 kilometers altitude. The correlation coefficient between pressure and density is also a minimum at the isopycnic levels. Because of the meager data sample for statistical analysis at altitudes above 30 kilometers, the coefficients of variation had to be adjusted by making several trial computations to yield correlation coefficients that were consistent with statistical theory. That is, the correlation coefficients must lie between ± 1. Even though no claim for accuracy can be made about the

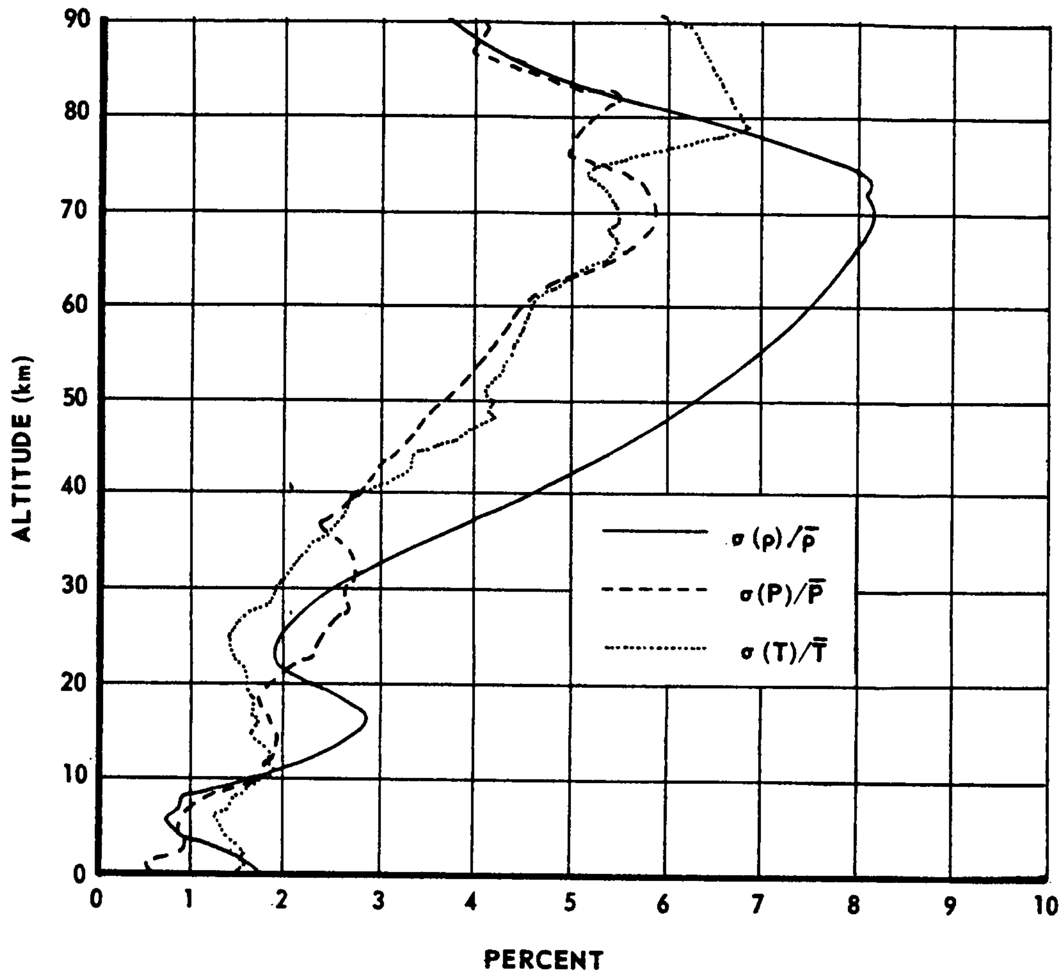

FIGURE 14.1 COEFFICIENT OF VARIATION OF DENSITY, PRESSURE, AND TEMPERATURE AT CAPE KENNEDY

resulting data, for the first time deviations for temperature, pressure, and density from 0 to 90 kilometers altitude are consistent in terms of a statistical method, and a procedure exists whereby departures from the mean values of these quantities can be combined. As an example, suppose one desires to know what temperature and pressure should be used simultaneously with a maximum density at a discrete altitude. The solution would be to let the mean density plus three standard deviations represent the maximum density. From the foregoing equations it is seen that

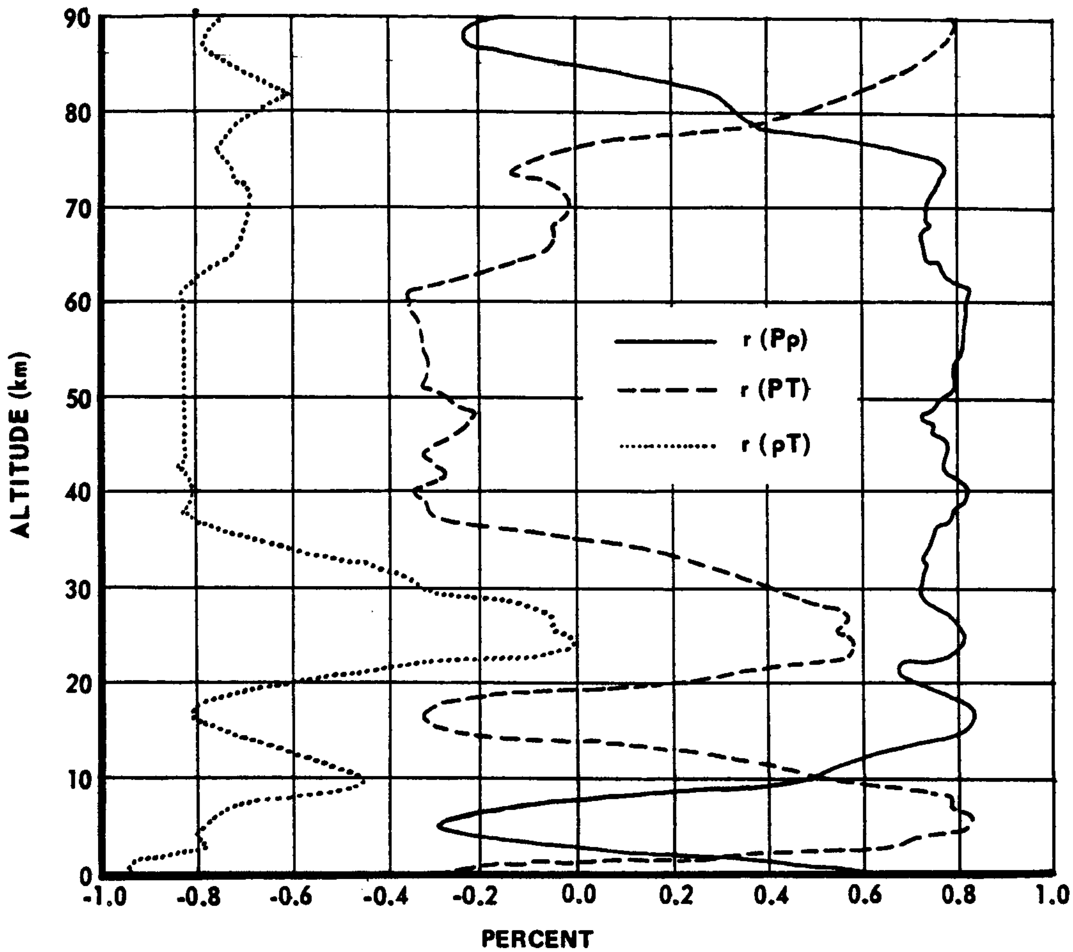

FIGURE 14.2 DISCRETE ALTITUDE LEVEL CORRELATION COEFFICIENTS BETWEEN PRESSURE-DENSITY, r(Pρ); PRESSURE-TEMPERATURE, r(PT); AND DENSITY-TEMPERATURE, r(ρT) AT CAPE KENNEDY

$$\text{maximum } \rho = (\bar{\rho} + 3\sigma_\rho) = \bar{\rho}\left(1 + 3\,\frac{\sigma_\rho}{\bar{\rho}}\right)$$

$$= \bar{\rho}\left\{1 + 3\left[\underbrace{\left(\frac{\sigma_P}{\bar{P}}\right) r(P\rho)}_{(A)} - \underbrace{\left(\frac{\sigma_T}{\bar{T}}\right) r(\rho T)}_{(B)}\right]\right\} . \quad (14.6)$$

TABLE 14.9 COEFFICIENTS OF VARIATION AND DISCRETE ALTITUDE LEVEL CORRELATION COEFFICIENTS BETWEEN PRESSURE - DENSITY r(Pρ); PRESSURE - TEMPERATURE r(PT); AND DENSITY - TEMPERATURE r(ρT), CAPE KENNEDY, ANNUAL

ALTITUDE	COEFFICIENTS OF VARIATION (CV)			CORRELATION COEFFICIENTS (r)		
(km)	$\sigma(\rho)/\bar{\rho}$ (percent)	$\sigma(P)/\bar{P}$ (percent)	$\sigma(T)/\bar{T}$ (percent)	r(Pρ) (unitless)	r(PT) (unitless)	r(ρT) (unitless)
0	1.8000	.6000	1.5000	.6250	-0.3500	-0.9500
1	1.7000	.5500	1.6000	.3382	-0.0156	-0.9462
2	1.5000	.8000	1.5900	.1508	.3609	-0.8675
3	1.1800	.9800	1.5700	-0.0485	.6606	-0.7818
4	.9700	.8500	1.4000	-0.1799	.7318	-0.8021
5	.8000	.8700	1.3400	-0.2864	.8203	-0.7830
6	.7400	.8400	1.2600	-0.2690	.8246	-0.7666
7	.8800	.9800	1.4200	-0.1633	.7913	-0.7324
8	.9000	1.1300	1.4700	-0.0364	.7910	-0.6402
9	1.1800	1.4700	1.6200	.2678	.7124	-0.4854
10	1.6300	1.7500	1.7200	.4840	.5588	-0.4553
11	1.8800	1.8000	1.7800	.5328	.4485	-0.5174
12	2.1500	1.8700	1.8500	.5841	.3320	-0.5717
13	2.3800	1.9000	1.8500	.6470	.1946	-0.6220
14	2.6200	1.9200	1.7700	.7373	-0.0066	-0.6804
15	2.7800	1.8800	1.6700	.8107	-0.2238	-0.7520
16	2.8800	1.8400	1.7100	.8262	-0.3154	-0.7953
17	2.8800	1.8000	1.7000	.8338	-0.3537	-0.8113
18	2.7500	1.7500	1.7000	.8036	-0.2706	-0.7904
19	2.5000	1.7800	1.6700	.7449	-0.0492	-0.7031
20	2.2700	1.8500	1.6500	.6969	.1625	-0.5944
21	2.0800	1.9500	1.6200	.6786	.3325	-0.4672
22	1.9800	2.1200	1.5700	.7087	.4565	-0.3041
23	1.9200	2.3200	1.4800	.7721	.5659	-0.0870
24	1.9500	2.4000	1.4300	.8032	.5831	-0.0157
25	2.000	2.4300	1.4200	.8116	.5682	-0.0196
26	2.0800	2.5000	1.5000	.8006	.5565	-0.0523
27	2.1500	2.6000	1.5800	.7948	.5640	-0.0528
28	2.2300	2 6700	1.7500	.7591	.5584	-0.1161
29	2.3700	2.6300	1.8700	.7249	.4877	-0.2479
30	2.5200	2.6300	1.9200	.7228	.4211	-0.3224
31	2.7000	2.7000	2.000	.7257	.3704	-0.3704
32	2.8800	2.7500	2.0800	.7279	.3142	-0.4222
33	3.0700	2.7300	2.1700	.7260	.2310	-0.5014
34	3.2700	2.6800	2.2300	.7361	.1223	-0.5817
35	3.4800	2.6000	2.3200	.7454	.0027	-0.6647
36	3.7000	2.5000	2.4300	.7587	-0.1263	-0.7421
37	3.9200	2.3700	2.5500	.7793	-0.2686	-0.8129
38	4.1200	2.4600	2.6300	.7947	-0.3096	-0.8222
39	4.3300	2.6400	2.6900	.8084	-0.3199	-0.8163
40	4.5500	2.7900	2.7680	.8220	-0.3442	-0.8176
41	4.7500	2.8600	3.0200	.7958	-0.3046	-0.8192
42	4.9300	2.9200	3.2600	.7712	-0.2706	-0.8215
43	5.1300	3.0000	3.3400	.7850	-0.3075	-0.8309
44	5.3200	3.1800	3.3500	.8037	-0.3270	-0.8252
45	5.5000	3.2400	3.6000	.7797	-0.2912	-0.8261
46	5.6700	3.3200	3.8300	.7571	-0.2539	-0.8242
47	5.8300	3.4100	3.9800	.7489	-0.2402	-0.8232
48	5.9800	3.4800	4.1900	.7284	-0.2090	-0.8223
49	6.1300	3.5900	4.1400	.7572	-0.2540	-0.8241
50	6.2700	3.6900	4.1900	.7644	-0.2633	-0.8232
51	6.4200	3.8200	4.0800	.7984	-0.3201	-0.8260
52	6.5500	3.9100	4.1800	.7950	-0.3103	-0.8234
53	6.7000	4.0100	4.2700	.7953	-0.3089	-0.8222
54	6.8000	4.0700	4.3100	.7990	-0.3164	-0.8232
55	6.9200	4.1400	4.3700	.8016	-0.3220	-0.8241
56	7.0300	4.2100	4.4200	.8043	-0.3267	-0.8244
57	7.1500	4.2800	4.4700	.8081	-0.3351	-0.8258
58	7.2700	4.3600	4.5100	.8127	-0.3434	-0.8263
59	7.3700	4.4200	4.5400	.8172	-0.3530	-0.8277
60	7.4700	4.4800	4.5900	.8188	-0.3565	-0.8283

TABLE 14. 9 COEFFICIENTS OF VARIATION AND DISCRETE ALTITUDE LEVEL CORRELATION COEFFICIENTS BETWEEN PRESSURE - DENSITY r(Pρ); PRESSURE - TEMPERATURE r(PT); AND DENSITY - TEMPERATURE r(ρT), CAPE KENNEDY, ANNUAL (Concluded)

ALTITUDE	COEFFICIENTS OF VARIATION (CV)			CORRELATION COEFFICIENTS (r)		
(km)	$\sigma(\rho)/\rho$ (percent)	$\sigma(P)/P$ (percent)	$\sigma(T)/T$ (percent)	$r(P\rho)$ (unitless)	$r(PT)$ (unitless)	$r(\rho T)$ (unitless)
61	7. 5700	4. 5400	4. 6300	. 8217	-0. 3629	-0. 8293
62	7. 6500	4. 7000	4. 8600	. 7926	-0. 2805	-0. 8076
63	7. 7500	4. 9000	5. 0000	. 7778	-0. 2256	-0. 7878
64	7. 8300	5. 1500	5. 1500	. 7602	-0. 1558	-0. 7602
65	7. 9000	5. 3800	5. 3800	. 7342	-0. 0781	-0. 7342
66	7. 9800	5. 5700	5. 4400	. 7324	-0. 0505	-0. 7170
67	8. 0300	5. 6600	5. 4700	. 7326	-0. 0408	-0. 7099
68	8. 0700	5. 7700	5. 4000	. 7437	-0. 0429	-0. 6998
69	8. 1000	5. 8200	5. 5100	. 7331	-0. 0215	-0. 6957
70	8. 1200	5. 8700	5. 4900	. 7369	-0. 0208	-0. 6911
71	8. 1200	5. 8900	5. 4700	. 7392	-0. 0205	-0. 6885
72	8. 0700	5. 7900	5. 3800	. 7459	-0. 0426	-0. 6973
73	8. 1200	5. 6500	5. 2900	. 7615	-0. 1008	-0. 7216
74	8. 0700	5. 5000	5. 1700	. 7733	-0. 1432	-0. 7383
75	7. 9000	5. 2900	5. 4100	. 7313	-0. 0901	-0. 7452
76	7. 6800	4. 9900	5. 6500	. 6779	-0. 0383	-0. 7606
77	7. 3800	5. 0100	6. 1600	. 5628	. 1390	-0. 7403
78	7. 0500	5. 0400	6. 5200	. 4587	. 2771	-0. 7267
79	6. 6800	5. 1100	6. 8400	. 3508	. 4045	-0. 7145
80	6. 3200	5. 2700	6. 7800	. 3265	. 4730	-0. 6784
81	5. 9500	5. 3600	6. 7200	. 2975	. 5342	-0. 6482
82	5. 5800	5. 5200	6. 6600	. 2800	. 5942	-0. 6057
83	5. 2500	5. 1300	6. 6100	. 1891	. 6259	-0. 6475
84	4. 9200	4. 7800	6. 5600	. 0855	. 6645	-0. 6877
85	4. 6300	4. 4700	6. 5100	-0. 0232	. 7032	-0. 7272
86	4. 4000	4. 1900	6. 4500	-0. 1271	. 7363	-0. 7647
87	4. 2000	3. 9600	6. 4000	-0. 2296	. 7694	-0. 7983
88	4. 0200	4. 0500	6. 3400	-0. 2344	. 7874	-0. 7838
89	3. 8800	4. 1400	6. 2800	-0. 2255	. 7986	-0. 7665
90	3. 7800	4. 0400	5. 9600	-0. 1608	. 7798	-0. 7432

The associated values for pressure and temperature are the last two terms, (A) and (B), multiplied by $\bar{P}$ and $\bar{T}$, respectively, and then this result is added to $\bar{P}$ and $\bar{T}$, respectively. The appropriate values of r and CV may be obtained from Table 14. 9.

In general, the three extreme ρ, P, and T equations of interest are

$$\text{extreme } \rho = \left(\bar{\rho} \pm M\sigma_{\rho}\right) = \bar{\rho}\left[1 \pm M\left(\frac{\sigma_{\rho}}{\bar{\rho}}\right)\right]$$

$$= \bar{\rho}\left\{1 \pm M\left[\left(\frac{\sigma_P}{\bar{P}}\right) r(P\rho) - \left(\frac{\sigma_T}{\bar{T}}\right) r(\rho T)\right]\right\} \qquad (14.7a)$$

$$\text{extreme P} = \left(\bar{P} \pm M\sigma_P\right) = \bar{P}\left[1 \pm M\left(\frac{\sigma_P}{\bar{P}}\right)\right]$$

$$= \bar{P}\left\{1 \pm M\left[\left(\frac{\sigma_\rho}{\bar{\rho}}\right) r(P\rho) + \left(\frac{\sigma_T}{\bar{T}}\right) r(PT)\right]\right\} \qquad (14.7b)$$

$$\text{extreme T} = \left(\bar{T} \pm M\sigma_T\right) = \bar{T}\left[1 \pm M\left(\frac{\sigma_T}{\bar{T}}\right)\right]$$

$$= \bar{T}\left\{1 \pm M\left[\left(\frac{\sigma_P}{\bar{P}}\right) r(PT) - \left(\frac{\sigma_\rho}{\bar{\rho}}\right) r(\rho T)\right]\right\}, \qquad (14.7c)$$

where M denotes the multiplication factor to give the desired deviation. The values of M for the normal distribution and the associated percentile levels are as follows:

	M		Percentile
mean	-3	standard deviations	0.135
mean	-2	standard deviations	2.275
mean	-1	standard deviations	15.866
mean	±0	standard deviations = median	50.000
mean	+1	standard deviations	84.134
mean	+2	standard deviations	97.725
mean	+3	standard deviations	99.865

The two associated atmospheric parameters that deal with a third extreme parameter are listed, in more detail, in the following chart.

	For Extreme Density	For Extreme Temperature	For Extreme Pressure
$P_{assoc.}$ =	$\bar{P}\left[1 \pm \left\{M\left(\frac{\sigma_P}{\bar{P}}\right) r(P\rho)\right\}\right]$	$\bar{P}\left[1 \pm \left\{M\left(\frac{\sigma_P}{\bar{P}}\right) r(PT)\right\}\right]$	
$T_{assoc.}$ =	$\bar{T}\left[1 \pm \left\{M\left(\frac{\sigma_T}{\bar{T}}\right) r(\rho T)\right\}\right]$		$\bar{T}\left[1 \pm \left\{M\left(\frac{\sigma_T}{\bar{T}}\right) r(PT)\right\}\right]$
$\rho_{assoc.}$ =		$\bar{\rho}\left[1 \pm \left\{M\left(\frac{\sigma_\rho}{\bar{\rho}}\right) r(\rho T)\right\}\right]$	$\bar{\rho}\left[1 \pm \left\{M\left(\frac{\sigma_\rho}{\bar{\rho}}\right) r(P\rho)\right\}\right]$

Use + sign when extreme parameter is maximum.
Use - sign when extreme parameter is minimum.

It must be emphasized that this procedure is to be used at discrete altitudes only. Whenever extreme profiles of pressure, temperature, and density are required for engineering application, the use of these correlated variables at discrete altitudes is not satisfactory. Subsection 14.6 deals directly with this problem, since a profile of extreme pressure, temperature, or density from 0 to 90 kilometers altitude is unrealistic in the real atmosphere.

14.6 Extreme Density Profiles for Cape Kennedy[3]

Given in this section are the two extreme density profiles that correspond to the summer (hot) and winter (cold) extreme atmospheres for Cape Kennedy, Florida (Table 14.10). These two extreme density profiles should be used in the design (aerodynamic heating during ascent, engine performance, etc.) of vehicles to be launched from Cape Kennedy, Florida. For those aerospace vehicles with ferrying capability, design calculations should use these extreme profiles (Table 14.10) in conjunction with the hot or cold day design ambient air temperatures over runways from paragraph 15.4.1 of Section XV. The extreme atmosphere producing the maximum vehicle design requirement should be utilized to determine the design.

The envelopes of deviations of density in Table 14.8 imply that a typical individual extreme density profile may be represented by a similarly shaped profile, that is, deviations of density either all negative or all positive from sea level to 90 kilometers altitude. However, examination of many individual density profiles shows that when large positive deviations of density occur at the surface, correspondingly large negative deviations will occur near 15 kilometers altitude and above. Such a situation occurs during the winter season (cold atmosphere). The reverse is also true — density profiles with large negative deviations at lower levels will have correspondingly large positive deviations at higher levels. This situation occurs in the summer season (hot atmosphere) (Figure 14.3).

The two extreme density profiles of Figure 14.3 are shown as percent deviations from the Patrick Reference Atmosphere, 1963 density profile. The two profiles obey the hydrostatic equation and the ideal gas law. The extreme density profiles shown here to 30 kilometers altitude were derived from a study of actual extreme density profiles that were observed

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3. Similar profiles for Vandenberg AFB (Space and Missile Test Center), California, are currently being prepared and will be made available upon request.

in the atmosphere. The results shown above 30 kilometers are somewhat speculative because of the limited data from this region of the atmosphere. Isopycnic levels (levels of minimum density variation) are noted at approximately 8 and 86 kilometers. Another level of minimum density variability is seen at 24 kilometers, and levels of maximum variability occur at 0, 15, and 68 kilometers altitude.

Figure 14.4 compares the temperature[4] profiles of the hot-and-cold atmospheres with the Patrick Reference Atmosphere, 1963 temperature profile. Figures 14.5 and 14.6 show the relative deviations (%) of temperatures[4] and pressures, respectively, that are associated with the two extreme density profiles of Figure 14.3. Table 14.10 gives the numerical data used to prepare Figures 14.3 through 14.6.

The envelopes given in Figures 14.5 and 14.6 are ±3 standard deviation limits from the mean (with the ±3 standard deviation being derived from s = 1/6 of the range). Since atmospheric parameters are not normally distributed, any profile that goes outside such a theoretical envelope does not necessarily mean the profile is in error (Figure 14.6).

14.7 Reference Atmospheres

In design and preflight analysis of space vehicles, special nominal atmospheres are used to represent the mean or median thermodynamic conditions with respect to altitude. For general worldwide design, the U. S. Standard Atmosphere, 1962 (US 62) (Ref. 14.2) is used, but more specific atmospheres are needed at each launch area. A group of Range Reference Atmospheres (Ref. 14.6) have been prepared to represent the thermodynamic medians in the first 30 kilometers at various launch areas.

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4. Temperatures below 10 kilometers altitude are virtual temperature, that is, temperature corrected for atmospheric moisture.

$$T_v = T(1 + 0.61\ w),$$

where

T_v = virtual temperature (° K)

T = kinetic temperature (° K)

w = mixing ratio (g/kg).

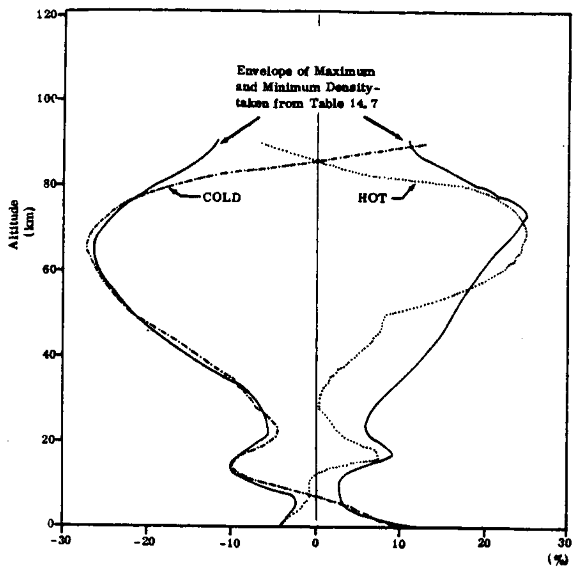

FIGURE 14.3 RELATIVE DEVIATIONS (%) OF EXTREME DENSITY PROFILES WITH RESPECT TO PRA-63

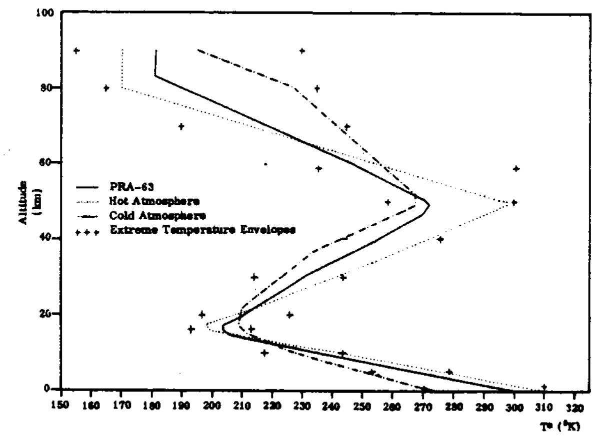

FIGURE 14.4 VIRTUAL TEMPERATURE PROFILES OF THE HOT, COLD, AND PRA-63

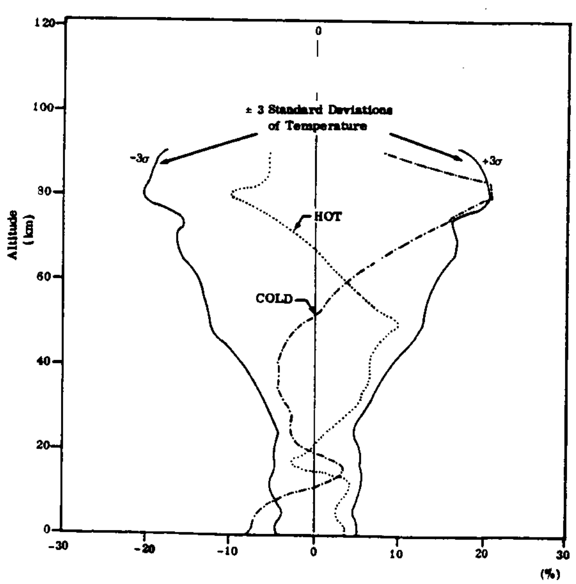

FIGURE 14.5 RELATIVE DEVIATIONS (%) OF TEMPERATURE, ASSOCIATED WITH EXTREME DENSITY, WITH WITH RESPECT TO PRA-63

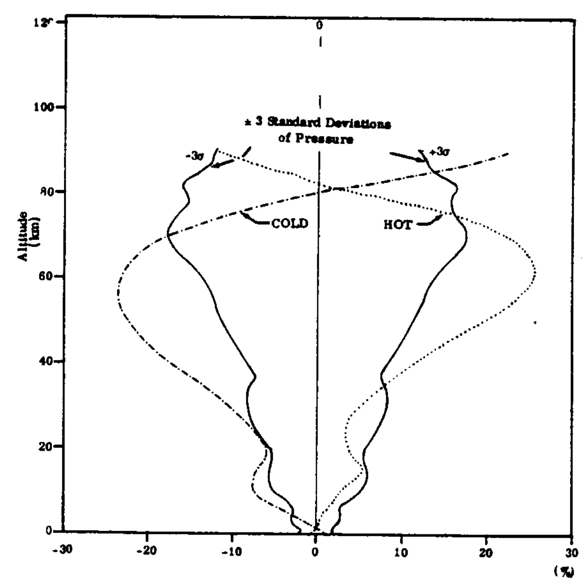

FIGURE 14.6 RELATIVE DEVIATIONS (%) OF PRESSURE, ASSOCIATED WITH EXTREME DENSITY, WITH RESPECT TO PRA-63

The Patrick Reference Atmosphere (PRA-63) is a more extensive reference atmosphere presenting data to 700 kilometers for the Eastern Test Range. Because of the utility of this atmosphere, Table 14. 11 is included in this section from reference 14. 3. The computer subroutine used to prepare these values is available in the subroutine files of the MSFC Computation Laboratory as Computer Subroutine PRA-63. Criteria for orbital studies are in reference 14. 5.

A reference atmosphere is also available for SAMTEC (Vandenberg AFB) (Ref. 14. 10). This provides a nominal annual atmosphere model to 700 kilometers and has been designated as Computer Subroutine VRA-71.

In Table 14. 11, the values are given in standard computer printout, where the two-digit numbers that are at the end of the tabular value (number preceded by E) indicate the power of 10 by which the respective principal value must be multiplied. For example, a tabular value indicated as 2. 9937265E 02 is 299. 37265 or 1. 5464054E-05 is 0. 000015464054.

14. 8 Reentry (90 Kilometers to Surface)

The atmospheric models to be used for all reentry analyses are the US 62 (Ref. 14. 2) and the U. S. Standard Atmosphere Supplements, 1966 (Ref. 14. 4), as expanded in the following paragraphs. Primary consideration is given to atmospheric density since it is the most significant parameter in reentry analyses.

For all analyses, the supplemental atmospheres should be used according to the latitude ranges shown in Figure 14. 7.

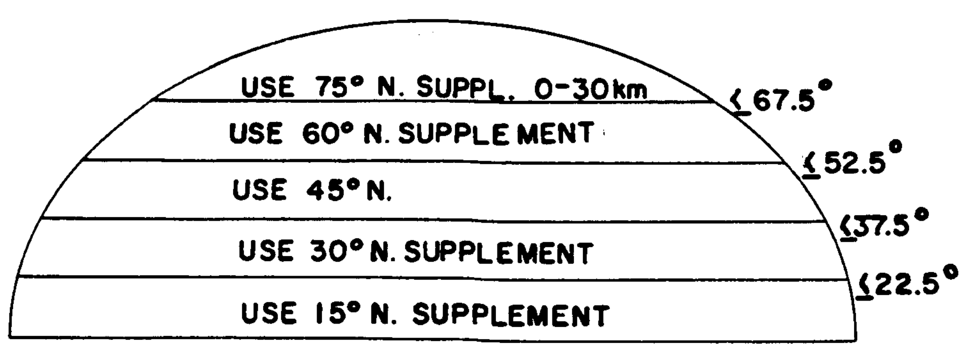

FIGURE 14. 7 LATITUDE RANGE OF SUPPLEMENTAL ATMOSPHERES (applicable to both N and S hemispheres).

TABLE 14.10 THERMODYNAMIC QUANTITIES ASSOCIATED WITH EXTREME DENSITY – CAPE KENNEDY

Extreme Winter (Cold) Density Profile

Geometric Altitude Z(m)	Geopotential Altitude H(m)	Virtual Temperature T(°K)	Pressure P(mb)	Density D(g m^{-3})	Rel Dev (T) with Respect to PRA-63 RD(T)%	Rel Dev (P) with Respect to PRA-63 RD(P)%	Rel Dev (D) with Respect to PRA-63 RD(D)%
0	0	2.7500000E 02	1.0270000E 03	1.3009947E 03	-8.14	.98	9.32
1000	998.5	2.7100000E 02	9.0590112E 02	1.1609426E 03	-7.87	-0.01	8.30
2000	1996.6	2.6500000E 02	7.9735186E 02	1.0481946E 03	-7.51	-0.98	7.16
3000	2994.5	2.6000000E 02	7.0004226E 02	9.3796951E 02	-7.46	-1.95	5.95
4000	3992.0	2.5500000E 02	6.1359700E 02	8.3752635E 02	-7.38	-2.92	4.80
5000	4989.2	2.5000000E 02	5.3547144E 02	7.4616369E 02	-7.16	-3.89	3.31
6000	5986.1	2.4525000E 02	4.6640063E 02	6.6250834E 02	-6.66	-4.82	1.96
7000	6982.7	2.4030000E 02	4.0522513E 02	5.8746284E 02	-6.03	-5.69	.36
8000	7979.0	2.3600000E 02	3.5180800E 02	5.1822344E 02	-4.57	-6.46	-1.58
9000	8975.0	2.3175000E 02	3.0335225E 02	4.5600047E 02	-3.73	-7.09	-3.49
10000	9970.5	2.2750000E 02	2.6141403E 02	4.0029973E 02	-2.42	-7.55	-5.27
11000	10965.9	2.2400000E 02	2.2469941E 02	3.4945538E 02	-0.74	-7.81	-7.15
12000	11961.0	2.2050000E 02	1.9268144E 02	3.0441713E 02	.77	-7.85	-8.59
13000	12955.7	2.1750000E 02	1.6484941E 02	2.6403770E 02	2.16	-7.70	-9.68
14000	13950.1	2.1430000E 02	1.4072197E 02	2.2075866E 02	2.55	-7.41	-10.95
15000	14944.2	2.1150000E 02	1.1985034E 02	1.9742207E 02	3.26	-7.04	-9.94
16000	15937.0	2.0950000E 02	1.0190148E 02	1.6944715E 02	3.18	-6.61	-9.47
17000	16931.4	2.0850000E 02	8.6534095E 01	1.4458359E 02	2.78	-6.20	-8.75
18000	17924.5	2.0825000E 02	7.3448205E 01	1.2286664E 02	1.44	-5.95	-7.19
19000	18917.4	2.0510000E 02	6.2341195E 01	1.0416141E 02	.34	-5.91	-6.13
20000	19909.9	2.0900000E 02	5.2029306E 01	8.8224349E 01	-0.14	-6.01	-5.33
21000	20902.1	2.0993000E 02	4.4963079E 01	7.4624530E 01	-1.41	-6.23	-4.87
22000	21894.0	2.1080000E 02	3.8222480E 01	6.3166358E 01	-2.12	-6.54	-4.57
23000	22885.6	2.1220000E 02	3.2521030E 01	5.3389622E 01	-2.52	-6.95	-4.69
24000	23876.9	2.1380000E 02	2.7699474E 01	4.5176033E 01	-2.83	-7.42	-4.85
25000	24867.8	2.1520000E 02	2.3619253E 01	3.8235053E 01	-2.94	-7.94	-5.26
26000	25858.5	2.1680000E 02	2.0163849E 01	3.2400510E 01	-2.97	-8.50	-5.76
27000	26848.8	2.1850000E 02	1.7234608E 01	2.7478169E 01	-2.88	-9.09	-6.38
28000	27838.9	2.2000000E 02	1.4747791E 01	2.3352069E 01	-2.84	-9.67	-7.03
29000	28828.6	2.2165000E 02	1.2633834E 01	1.9856616E 01	-3.04	-10.22	-7.40
30000	29818.0	2.2350000E 02	1.0836084E 01	1.6890086E 01	-3.16	-10.79	-7.88
31000	30807.1	2.2475000E 02	9.3039903E 00	1.4421397E 01	-3.55	-11.39	-8.13
32000	31795.9	2.2640000E 02	7.9983598E 00	1.2384209E 01	-3.79	-12.04	-8.57
33000	32784.4	2.2800000E 02	6.8799596E 00	1.0512084E 01	-4.17	-12.71	-9.01
34000	33772.6	2.2970000E 02	5.9258440E 00	8.9872554E 00	-4.32	-13.40	-9.40
35000	34760.4	2.3125000E 02	5.1094228E 00	7.6971138E 00	-4.65	-14.13	-9.94
36000	35748.0	2.3383928E 02	4.4112936E 00	6.5718296E 00	-4.57	-14.85	-10.77
37000	36735.2	2.3642857E 02	3.8147285E 00	5.6208316E 00	-4.51	-15.56	-11.57
38000	37722.1	2.3901785E 02	3.3040516E 00	4.8156430E 00	-4.45	-16.24	-12.34
39000	38708.8	2.4160714E 02	2.8661799E 00	4.1326772E 00	-4.41	-16.91	-13.08
40000	39695.1	2.4419642E 02	2.4901084E 00	3.5523582E 00	-4.35	-17.57	-13.82
41000	40681.1	2.4678571E 02	2.1665931E 00	3.0584061E 00	-4.28	-18.22	-14.55
42000	41666.8	2.4937500E 02	1.8878493E 00	2.6372555E 00	-4.19	-18.85	-15.30
43000	42652.2	2.5196428E 02	1.6473091E 00	2.2775014E 00	-4.06	-19.46	-16.05
44000	43637.3	2.5455357E 02	1.4394217E 00	1.9699112E 00	-3.88	-20.05	-16.83
45000	44622.0	2.5714285E 02	1.2594808E 00	1.7063074E 00	-3.63	-20.62	-17.63
46000	45606.5	2.5973214E 02	1.1035217E 00	1.4801066E 00	-3.29	-21.15	-18.46
47000	46590.7	2.6232142E 02	9.6813821E-01	1.2857052E 00	-2.87	-21.63	-19.32
48000	47574.5	2.6491071E 02	8.5045663E-01	1.1183827E 00	-2.31	-22.05	-20.21
49000	48558.0	2.6750000E 02	7.4802214E-01	9.7415592E-01	-1.81	-22.38	-21.11
50000	49541.3	2.6750000E 02	6.5833498E-01	8.5735552E-01	-1.15	-22.71	-21.81
51000	50524.2	2.6750000E 02	5.7940122E-01	7.5455939E-01	-0.59	-22.99	-22.53
52000	51506.8	2.6750000E 02	5.0993155E-01	6.6408841E-01	.07	-23.20	-23.25
53000	52489.1	2.6607142E 02	4.4863705E-01	5.8740182E-01	.28	-23.36	-23.57
54000	53471.1	2.6464285E 02	3.9443926E-01	5.1922760E-01	.50	-23.49	-23.93
55000	54452.8	2.6321428E 02	3.4654601E-01	4.5865935E-01	.54	-23.59	-24.31
56000	55434.3	2.6178571E 02	3.0425490E-01	4.0488304E-01	1.27	-23.65	-24.64
57000	56415.5	2.6035714E 02	2.6693421E-01	3.5716800E-01	1.85	-23.68	-25.00
58000	57396.1	2.5892857E 02	2.3402273E-01	3.1485883E-01	2.40	-23.65	-25.44
59000	58376.6	2.5750000E 02	2.0581974E-01	2.7736794E-01	2.59	-23.57	-25.79
60000	59356.7	2.5607142E 02	1.7947906E-01	2.4416889E-01	3.63	-23.44	-26.12
61000	60336.6	2.5464285E 02	1.5700319E-01	2.1479030E-01	4.31	-23.24	-26.41
62000	61316.1	2.5321428E 02	1.3723857E-01	1.8881034E-01	5.02	-22.98	-26.66
63000	62295.4	2.5178571E 02	1.1987080E-01	1.6585177E-01	5.76	-22.65	-26.86
64000	63274.3	2.5035714E 02	1.0462037E-01	1.4557744E-01	6.53	-22.24	-27.02
65000	64253.0	2.4892857E 02	9.1239091E-02	1.2768021E-01	7.32	-21.75	-27.09
66000	65231.3	2.4750000E 02	7.9506608E-02	1.1190929E-01	8.13	-21.18	-27.11
67000	66209.3	2.4607142E 02	6.9227735E-02	9.8009240E-02	8.55	-20.57	-27.05
68000	67187.0	2.4464285E 02	6.0229135E-02	8.5765356E-02	9.79	-19.76	-26.91
69000	68164.5	2.4321428E 02	5.2357508E-02	7.4994201E-02	10.62	-18.90	-26.69
70000	69141.6	2.4178571E 02	4.5477121E-02	6.5523960E-02	11.47	-17.93	-26.38
71000	70118.4	2.4035714E 02	3.9467933E-02	5.7203836E-02	12.31	-16.85	-25.97
72000	71094.9	2.3892857E 02	3.4223851E-02	4.9899772E-02	13.16	-15.65	-25.47
73000	72071.1	2.3750000E 02	2.9651106E-02	4.3492690E-02	14.01	-14.35	-24.88
74000	73047.0	2.3607142E 02	2.5667298E-02	3.7876850E-02	14.87	-12.87	-24.15
75000	74022.6	2.3464285E 02	2.2199159E-02	3.2958467E-02	15.73	-11.27	-23.33
76000	74997.9	2.3321428E 02	1.9182649E-02	2.8654395E-02	16.59	-9.52	-22.40
77000	75972.8	2.3178571E 02	1.6561106E-02	2.4890989E-02	17.48	-7.60	-21.35
78000	76947.5	2.3035714E 02	1.4284949E-02	2.1603037E-02	18.38	-5.52	-20.19
79000	77921.9	2.2892857E 02	1.2310254E-02	1.8732897E-02	19.20	-3.26	-18.91
80000	78896.0	2.2750000E 02	1.0598658E-02	1.6229580E-02	20.27	-0.80	-17.52
81000	79869.7	2.2425000E 02	9.1100835E-03	1.4153365E-02	20.31	1.80	-15.39
82000	80843.2	2.2100000E 02	7.8146779E-03	1.2318465E-02	20.29	4.48	-13.22
83000	81816.4	2.1775000E 02	6.6879608E-03	1.0699261E-02	20.53	7.25	-11.02
84000	82789.2	2.1450000E 02	5.7097916E-03	9.2752244E-03	18.74	10.06	-7.31
85000	83761.8	2.1125000E 02	4.8615947E-03	8.0197194E-03	16.94	12.67	-3.65
86000	84734.0	2.0800000E 02	4.1317612E-03	6.9200572E-03	15.14	15.04	-0.06
87000	85706.0	2.0475000E 02	3.5013688E-03	5.9573279E-03	13.34	17.16	3.37
88000	86677.6	2.0150000E 02	2.9593041E-03	5.1162570E-03	11.54	19.00	6.68
89000	87649.0	1.9825000E 02	2.4943291E-03	4.3831696E-03	9.74	20.52	9.82
90000	88620.1	1.9500000E 02	2.0964004E-03	3.7453638E-03	7.94	21.72	12.76

Extreme Summer (Hot) Density Profile

Geometric Altitude Z(m)	Virtual Temperature T(°K)	Pressure P(mb)	Density D(g m^{-3})	Rel Dev (T) with Respect to PRA-63 RD(T)%	Rel Dev (P) with Respect to PRA-63 RD(P)%	Rel Dev (D) with Respect to PRA-63 RD(D)%
0	3.0900000E 02	1.0180000E 03	1.1353717E 03	3.74	-0.07	-4.87
1000	3.0313636E 02	9.0349767E 02	1.0382743E 03	3.66	-0.28	-3.81
2000	2.9637272E 02	8.0614180E 02	9.4754474E 02	3.43	.12	-3.21
3000	2.8969090E 02	7.1741016E 02	8.6264474E 02	3.07	.48	-2.52
4000	2.8284545E 02	6.3668800E 02	7.8417924E 02	2.74	.82	-1.87
5000	2.7600181E 02	5.6341854E 02	7.1303708E 02	2.31	1.15	-1.37
6000	2.6931818E 02	4.9707115E 02	6.4256927E 02	2.20	1.42	-1.26
7000	2.6255454E 02	4.3714132E 02	5.8001606E 02	2.67	1.74	-0.91
8000	2.5579090E 02	3.8315087E 02	5.2181077E 02	3.10	2.39	-0.89
9000	2.4902727E 02	3.3464936E 02	4.6815365E 02	3.44	2.69	-0.92
10000	2.4224363E 02	2.9114943E 02	4.1872126E 02	3.51	2.98	-0.91
11000	2.3550000E 02	2.5238222E 02	3.7334291E 02	4.25	3.55	-0.81
12000	2.2820000E 02	2.1779961E 02	3.3249358E 02	4.29	4.16	-0.16
13000	2.2099000E 02	1.8727194E 02	2.9496024E 02	3.74	4.73	.91
14000	2.1360000E 02	1.5983481E 02	2.6087060E 02	2.61	5.16	2.50
15000	2.0630000E 02	1.3582879E 02	2.2936619E 02	.72	5.35	4.64
16000	1.9900000E 02	1.1475358E 02	2.0088600E 02	-1.59	5.16	7.32
17000	1.9800000E 02	9.6609149E 01	1.6997770E 02	-2.29	4.72	7.27
18000	2.0000000E 02	8.1180523E 01	1.4173082E 02	-2.38	4.17	7.05
19000	2.0166667E 02	6.8712724E 01	1.1872412E 02	-1.74	3.70	5.66
20000	2.0833333E 02	5.8222283E 01	9.7357174E 01	-0.60	3.39	4.47
21000	2.1250000E 02	4.9490132E 01	8.1142824E 01	-0.19	3.23	3.44
22000	2.1566667E 02	4.2195155E 01	6.8158038E 01	.14	3.17	2.97
23000	2.1883333E 02	3.6054892E 01	5.7396911E 01	.53	3.16	2.51
24000	2.2200000E 02	3.0873853E 01	4.8449254E 01	1.10	3.21	2.05
25000	2.2166667E 02	2.6502290E 01	4.1003141E 01	1.55	3.29	1.68
26000	2.2833333E 02	2.2795346E 01	3.4778035E 01	2.19	3.44	1.15
27000	2.3150000E 02	1.9644691E 01	2.9563559E 01	2.70	3.65	.73
28000	2.3400000E 02	1.6960045E 01	2.5190201E 01	3.05	3.93	.20
29000	2.3783333E 02	1.4684043E 01	2.1505523E 01	4.04	4.35	.30
30000	2.4100000E 02	1.2731282E 01	1.8403190E 01	4.42	4.82	.38
31000	2.4416667E 02	1.1058761E 01	1.5776216E 01	4.70	5.32	.52
32000	2.4733333E 02	9.6234101E 00	1.3554523E 01	5.11	5.86	.72
33000	2.5050000E 02	8.3891024E 00	1.1666743E 01	5.49	6.44	.99
34000	2.5366667E 02	7.3256847E 00	1.0060213E 01	5.87	7.06	1.32
35000	2.5683333E 02	6.4089725E 00	8.6930130E 00	5.90	7.70	1.70
36000	2.5900000E 02	5.6164979E 00	7.5542781E 00	6.11	8.37	2.14
37000	2.6200000E 02	4.9287171E 00	6.5287534E 00	6.18	9.06	2.71
38000	2.6574952E 02	4.3293596E 00	5.6748819E 00	6.24	9.75	3.30
39000	2.6865345E 02	3.8097436E 00	4.9401346E 00	6.25	10.44	3.90
40000	2.7153872E 02	3.3570734E 00	4.3069259E 00	6.26	11.13	4.49
41000	2.7442317E 02	2.9634318E 00	3.7601128E 00	6.43	11.83	5.09
42000	2.7730769E 02	2.6171869E 00	3.2873141E 00	6.54	12.50	5.60
43000	2.8019230E 02	2.3152137E 00	2.8785427E 00	6.69	13.20	6.10
44000	2.8307692E 02	2.0507224E 00	2.5237146E 00	6.89	13.90	6.56
45000	2.8596153E 02	1.8188823E 00	2.2159771E 00	7.17	14.61	6.96
46000	2.8884615E 02	1.6148427E 00	1.9476079E 00	7.54	15.34	7.30
47000	2.9173076E 02	1.4359444E 00	1.7146247E 00	8.02	16.21	7.57
48000	2.9461538E 02	1.2776326E 00	1.5107350E 00	8.66	17.10	7.79
49000	2.9750000E 02	1.1380821E 00	1.3330981E 00	9.42	18.11	7.96
50000	2.9750000E 02	1.0140791E 00	1.1884696E 00	9.64	19.14	8.38
51000	2.9325000E 02	9.0462588E-01	1.0723468E 00	8.58	20.16	10.76
52000	2.8900000E 02	8.0392083E-01	9.6903579E-01	8.12	21.08	12.50
53000	2.8475000E 02	7.1369494E-01	8.7310210E-01	7.22	21.92	13.60
54000	2.8050000E 02	6.3239658E-01	7.8540930E-01	6.28	22.67	15.07
55000	2.7625000E 02	5.5935719E-01	7.0538261E-01	5.54	23.33	16.42
56000	2.7200000E 02	4.9381144E-01	6.3245617E-01	5.22	23.91	17.65
57000	2.6775000E 02	4.3591531E-01	5.6609455E-01	4.75	24.41	18.77
58000	2.6350000E 02	3.8257634E-01	5.0579851E-01	4.41	24.82	19.78
59000	2.5925000E 02	3.3579035E-01	4.5109791E-01	3.89	25.14	20.69
60000	2.5500000E 02	2.9383033E-01	4.0152913E-01	3.40	25.34	21.50
61000	2.5075000E 02	2.5678401E-01	3.5679071E-01	2.71	25.54	22.22
62000	2.4650000E 02	2.2381415E-01	3.1530711E-01	2.44	25.61	22.86
63000	2.4225000E 02	1.9461224E-01	2.7986115E-01	1.76	25.56	23.41
64000	2.3800000E 02	1.6889190E-01	2.4750446E-01	1.08	25.46	23.88
65000	2.3375000E 02	1.4630980E-01	2.1808491E-01	.38	25.25	24.28
66000	2.2950000E 02	1.2651174E-01	1.9127857E-01	.27	24.93	24.59
67000	2.2525000E 02	1.0920793E-01	1.6787471E-01	-0.47	24.50	24.83
68000	2.2100000E 02	9.4098311E-02	1.4663518E-01	-0.62	23.95	24.94
69000	2.1675000E 02	8.0938100E-02	1.2782014E-01	-1.41	23.28	25.03
70000	2.1250000E 02	6.7677445E-02	1.1127675E-01	-2.03	22.49	25.03
71000	2.0825000E 02	5.7624138E-02	9.6365456E-02	-2.69	21.59	24.92
72000	2.0400000E 02	4.8806497E-02	8.3486401E-02	-3.26	20.49	24.71
73000	1.9975000E 02	4.1270059E-02	7.1979594E-02	-4.11	19.26	24.37
74000	1.9550000E 02	3.4723579E-02	6.1875040E-02	-4.87	17.87	23.91
75000	1.9125000E 02	2.9109982E-02	5.3031386E-02	-5.67	16.31	23.31
76000	1.8700000E 02	2.4294072E-02	4.5251293E-02	-6.51	14.58	22.55
77000	1.8275000E 02	2.0191751E-02	3.8485577E-02	-7.38	12.65	21.62
78000	1.7850000E 02	1.6711850E-02	3.2615969E-02	-8.27	10.53	20.50
79000	1.7425000E 02	1.3760778E-02	2.7520972E-02	-9.19	8.22	19.18
80000	1.7000000E 02	1.1269865E-02	2.3125414E-02	-10.13	5.67	17.57
81000	1.7000000E 02	9.2340672E-03	1.8923344E-02	-8.29	3.18	13.12
82000	1.7000000E 02	7.5531083E-03	1.5478116E-02	-7.23	.79	9.21
83000	1.7000000E 02	6.1780218E-03	1.2661347E-02	-5.69	-0.92	5.29
84000	1.7000000E 02	5.0532660E-03	1.0356201E-02	-5.90	-2.59	3.51
85000	1.7000000E 02	4.1332395E-03	8.4695945E-03	-5.90	-4.26	1.76
86000	1.7000000E 02	3.3807201E-03	6.9278918E-03	-5.90	-5.87	.03
87000	1.7000000E 02	2.7652240E-03	5.6665541E-03	-5.90	-7.47	-1.67
88000	1.7000000E 02	2.2617800E-03	4.6348850E-03	-5.90	-9.05	-3.35
89000	1.7000000E 02	1.8499599E-03	3.7910522E-03	-5.90	-10.61	-5.01
90000	1.7000000E 02	1.5131813E-03	3.1008431E-03	-5.90	-12.15	-6.65

TABLE 14.11 CAPE KENNEDY REFERENCE ATMOSPHERE VERSUS GEOMETRIC ALTITUDE (ANNUAL)

GEOMETRIC ALTITUDE	PRESSURE	KINETIC TEMPERATURE	VIRTUAL TEMPERATURE	DENSITY	KINEMATIC VISCOSITY	COEFFICIENT OF VISCOSITY	SPEED OF SOUND
meters	newtons cm⁻²	degrees K	degrees K	kg m⁻³	m² sec⁻¹	newton-sec m⁻²	m sec⁻¹
0.	1.0170147E 01	2.9667877E 02	2.9937265E 02	1.1835467E 00	1.5464054E-05	1.8302431E-05	3.4685752E 02
250.	9.8829373E 00	2.9503576E 02	2.9749989E 02	1.1573534E 00	1.5746406E-05	1.8224157E-05	3.4577071E 02
500.	9.6022651E 00	2.9348321E 02	2.9573026E 02	1.1312045E 00	1.6044844E-05	1.8149999E-05	3.4474100E 02
750.	9.3280864E 00	2.9200674E 02	2.9404920E 02	1.1051739E 00	1.6358708E-05	1.8079299E-05	3.4375977E 02
1000.	9.0603418E 00	2.9059301E 02	2.9244316E 02	1.0793462E 00	1.6687362E-05	1.8011441E-05	3.4281772E 02
1250.	8.7989596E 00	2.8922965E 02	2.9089953E 02	1.0537666E 00	1.7030194E-05	1.7945850E-05	3.4191375E 02
1500.	8.5438573E 00	2.8790525E 02	2.8940665E 02	1.0284922E 00	1.7386608E-05	1.7881991E-05	3.4103527E 02
1750.	8.2949430E 00	2.8660932E 02	2.8795373E 02	1.0035670E 00	1.7756031E-05	1.7819367E-05	3.4017814E 02
2000.	8.0521168E 00	2.8533228E 02	2.8653088E 02	9.7902801E-01	1.8137912E-05	1.7757524E-05	3.3933664E 02
2250.	7.8152728E 00	2.8406543E 02	2.8512905E 02	9.5490568E-01	1.8531717E-05	1.7696042E-05	3.3850555E 02
2500.	7.5843002E 00	2.8280087E 02	2.8374002E 02	9.3122447E-01	1.8936939E-05	1.7634541E-05	3.3768001E 02
2750.	7.3590840E 00	2.8153156E 02	2.8235634E 02	9.0800345E-01	1.9353094E-05	1.7572676E-05	3.3685564E 02
3000.	7.1395065E 00	2.8025121E 02	2.8097134E 02	8.8525681E-01	1.9779728E-05	1.7510139E-05	3.3602846E 02
3250.	6.9254477E 00	2.7895429E 02	2.7957909E 02	8.6299447E-01	2.0216413E-05	1.7446653E-05	3.3519489E 02
3500.	6.7167869E 00	2.7763601E 02	2.7817435E 02	8.4122243E-01	2.0662760E-05	1.7381977E-05	3.3435175E 02
3750.	6.5134029E 00	2.7629224E 02	2.7675260E 02	8.1994327E-01	2.1118413E-05	1.7315901E-05	3.3349622E 02
4000.	6.3151745E 00	2.7491954E 02	2.7530995E 02	7.9915662E-01	2.1583059E-05	1.7248245E-05	3.3262585E 02
4250.	6.1219816E 00	2.7351511E 02	2.7384314E 02	7.7885945E-01	2.2056429E-05	1.7178858E-05	3.3173858E 02
4500.	5.9337050E 00	2.7207674E 02	2.7234951E 02	7.5904647E-01	2.2538305E-05	1.7107621E-05	3.3083264E 02
4750.	5.7502279E 00	2.7060280E 02	2.7082700E 02	7.3971052E-01	2.3028518E-05	1.7034437E-05	3.2990662E 02
5000.	5.5714348E 00	2.6909222E 02	2.6927405E 02	7.2084275E-01	2.3526960E-05	1.6959239E-05	3.2895940E 02
5250.	5.3972132E 00	2.6754444E 02	2.6768968E 02	7.0243297E-01	2.4033585E-05	1.6881983E-05	3.2799020E 02
5500.	5.2274531E 00	2.6595939E 02	2.6607333E 02	6.8446986E-01	2.4548412E-05	1.6802648E-05	3.2699847E 02
5750.	5.0620471E 00	2.6433747E 02	2.6442497E 02	6.6694129E-01	2.5071532E-05	1.6721240E-05	3.2598400E 02
6000.	4.9008912E 00	2.6267950E 02	2.6274496E 02	6.4983435E-01	2.5603110E-05	1.6637781E-05	3.2494679E 02
6250.	4.7438843E 00	2.6098670E 02	2.6103412E 02	6.3313566E-01	2.6143393E-05	1.6552315E-05	3.2388713E 02
6500.	4.5909286E 00	2.5926069E 02	2.5929361E 02	6.1683158E-01	2.6692708E-05	1.6464906E-05	3.2280552E 02
6750.	4.4419296E 00	2.5750339E 02	2.5752496E 02	6.0090817E-01	2.7251477E-05	1.6375635E-05	3.2170270E 02
7000.	4.2967959E 00	2.5571708E 02	2.5573002E 02	5.8535153E-01	2.7820208E-05	1.6284601E-05	3.2057962E 02
7250.	4.1554397E 00	2.5390429E 02	2.5391096E 02	5.7014776E-01	2.8399511E-05	1.6191918E-05	3.1943741E 02
7500.	4.0177761E 00	2.5206783E 02	2.5207021E 02	5.5528319E-01	2.8990096E-05	1.6097713E-05	3.1827741E 02
7750.	3.8837237E 00	2.5021074E 02	2.5021046E 02	5.4074435E-01	2.9592781E-05	1.6002129E-05	3.1710112E 02
8000.	3.7532040E 00	2.4833622E 02	2.4833459E 02	5.2651817E-01	3.0208491E-05	1.5905319E-05	3.1591021E 02
8250.	3.6261415E 00	2.4644770E 02	2.4644571E 02	5.1259196E-01	3.0838268E-05	1.5807448E-05	3.1470648E 02
8500.	3.5024639E 00	2.4454868E 02	2.4454707E 02	4.9895351E-01	3.1483272E-05	1.5708689E-05	3.1349187E 02
8750.	3.3821013E 00	2.4264284E 02	2.4264207E 02	4.8559116E-01	3.2144787E-05	1.5609225E-05	3.1226845E 02
9000.	3.2649869E 00	2.4073389E 02	2.4073420E 02	4.7249382E-01	3.2824226E-05	1.5509244E-05	3.1103836E 02
9250.	3.1510561E 00	2.3882562E 02	2.3882706E 02	4.5965099E-01	3.3523131E-05	1.5408941E-05	3.0980386E 02
9500.	3.0402469E 00	2.3692182E 02	2.3692429E 02	4.4705284E-01	3.4243187E-05	1.5308514E-05	3.0856726E 02
9750.	2.9324993E 00	2.3502631E 02	2.3502955E 02	4.3469020E-01	3.4986216E-05	1.5208165E-05	3.0733094E 02
10000.	2.8277555E 00	2.3314283E 02	2.3314652E 02	4.2255460E-01	3.5754185E-05	1.5108096E-05	3.0609732E 02
10250.	2.7259597E 00	2.3127509E 02	2.3127885E 02	4.1063824E-01	3.6549218E-05	1.5008507E-05	3.0486882E 02
10500.	2.6270579E 00	2.2942670E 02	2.2943012E 02	3.9893405E-01	3.7373593E-05	1.4909599E-05	3.0364789E 02
10750.	2.5309974E 00	2.2760114E 02	2.2760385E 02	3.8743564E-01	3.8229747E-05	1.4811567E-05	3.0243695E 02
11000.	2.4373144E 00	2.2567654E 02	2.2567654E 02	3.7638429E-01	3.9076662E-05	1.4707842E-05	3.0115374E 02
11250.	2.3466644E 00	2.2389290E 02	2.2389290E 02	3.6528888E-01	3.9999485E-05	1.4611367E-05	2.9996129E 02
11500.	2.2587459E 00	2.2215274E 02	2.2215274E 02	3.5436502E-01	4.0966008E-05	1.4516921E-05	2.9879332E 02
11750.	2.1735153E 00	2.2046105E 02	2.2046105E 02	3.4360979E-01	4.1980165E-05	1.4424796E-05	2.9765349E 02
12000.	2.0909281E 00	2.1882266E 02	2.1882266E 02	3.3302120E-01	4.3046155E-05	1.4335282E-05	2.9654540E 02
12250.	2.0109393E 00	2.1724226E 02	2.1724226E 02	3.2259810E-01	4.4168460E-05	1.4248661E-05	2.9547260E 02
12500.	1.9335036E 00	2.1572436E 02	2.1572436E 02	3.1234019E-01	4.5351869E-05	1.4165211E-05	2.9443853E 02
12750.	1.8585748E 00	2.1427329E 02	2.1427329E 02	3.0224786E-01	4.6601486E-05	1.4085200E-05	2.9344659E 02
13000.	1.7861068E 00	2.1289318E 02	2.1289318E 02	2.9232218E-01	4.7922760E-05	1.4008886E-05	2.9250004E 02
13250.	1.7160527E 00	2.1158795E 02	2.1158795E 02	2.8256482E-01	4.9321493E-05	1.3936519E-05	2.9160202E 02
13500.	1.6483655E 00	2.1036130E 02	2.1036130E 02	2.7297794E-01	5.0803867E-05	1.3868335E-05	2.9075553E 02
13750.	1.5829980E 00	2.0921670E 02	2.0921670E 02	2.6356414E-01	5.2376472E-05	1.3804560E-05	2.8996343E 02
14000.	1.5199026E 00	2.0815732E 02	2.0815732E 02	2.5432637E-01	5.4046313E-05	1.3745403E-05	2.8922838E 02
14250.	1.4590316E 00	2.0718613E 02	2.0718613E 02	2.4526789E-01	5.5820832E-05	1.3691058E-05	2.8855287E 02
14500.	1.4003371E 00	2.0630579E 02	2.0630579E 02	2.3639213E-01	5.7707945E-05	1.3641704E-05	2.8793917E 02
14750.	1.3437711E 00	2.0551865E 02	2.0551865E 02	2.2770271E-01	5.9716027E-05	1.3597501E-05	2.8738935E 02
15000.	1.2892856E 00	2.0482679E 02	2.0482679E 02	2.1920326E-01	6.1853961E-05	1.3558590E-05	2.8690521E 02
15250.	1.2368322E 00	2.0423197E 02	2.0423197E 02	2.1089744E-01	6.4131138E-05	1.3525093E-05	2.8648832E 02
15500.	1.1863629E 00	2.0373557E 02	2.0373557E 02	2.0278882E-01	6.6557450E-05	1.3497107E-05	2.8613994E 02
15750.	1.1378295E 00	2.0333869E 02	2.0333869E 02	1.9488087E-01	6.9143324E-05	1.3474711E-05	2.8586110E 02
16000.	1.0911841E 00	2.0304201E 02	2.0304201E 02	1.8717685E-01	7.1899693E-05	1.3457958E-05	2.8565248E 02
16250.	1.0463788E 00	2.0284589E 02	2.0284589E 02	1.7967978E-01	7.4838014E-05	1.3446878E-05	2.8551449E 02
16500.	1.0033656E 00	2.0275027E 02	2.0275027E 02	1.7239240E-01	7.7970223E-05	1.3441474E-05	2.8544719E 02
16750.	9.6209732E-01	2.0275470E 02	2.0275470E 02	1.6531714E-01	8.1308715E-05	1.3441724E-05	2.8545030E 02
17000.	9.2252642E-01	2.0285831E 02	2.0285831E 02	1.5845601E-01	8.4866322E-05	1.3447579E-05	2.8552323E 02
17250.	8.8460606E-01	2.0305981E 02	2.0305981E 02	1.5181071E-01	8.8656214E-05	1.3458963E-05	2.8566500E 02
17500.	8.4828967E-01	2.0335748E 02	2.0335748E 02	1.4538244E-01	9.2691882E-05	1.3475772E-05	2.8587431E 02
17750.	8.1353120E-01	2.0374913E 02	2.0374913E 02	1.3917203E-01	9.6986954E-05	1.3497872E-05	2.8614946E 02

PRECEDING PAGE BLANK NOT FILMED

TABLE 14. 11 (Continued)

GEOMETRIC ALTITUDE (meters)	PRESSURE RATIO (unitless)	DENSITY RATIO (unitless)	VISCOSITY RATIO (unitless)	MOLECULAR WEIGHT (unitless)	PRESSURE DIFFERENCE (newtons cm⁻²)
-0.	9.9999996E-01	9.9999995E-01	1.0000000E 00	2.8964400E 01	2.3841858E-07
250.	9.7175951E-01	9.7786878E-01	9.9572337E-01		2.8720987E-01
500.	9.4416186E-01	9.5577506E-01	9.9167156E-01		5.6788206E-01
750.	9.1720269E-01	9.3378559E-01	9.8780868E-01		8.4206080E-01
1000.	8.9087617E-01	9.1195906E-01	9.8410108E-01		1.1098053E 00
1250.	8.6517525E-01	8.9034644E-01	9.8051734E-01		1.3711876E 00
1500.	8.4009180E-01	8.6899160E-01	9.7702823E-01		1.6262898E 00
1750.	8.1561680E-01	8.4793186E-01	9.7360662E-01		1.8752042E 00
2000.	7.9174043E-01	8.2719843E-01	9.7022765E-01		2.1180304E 00
2250.	7.6845227E-01	8.0681703E-01	9.6686846E-01		2.3548744E 00
2500.	7.4574143E-01	7.8680835E-01	9.6350816E-01		2.5858470E 00
2750.	7.2359660E-01	7.6718850E-01	9.6012805E-01		2.8110632E 00
3000.	7.0200620E-01	7.4796946E-01	9.5671116E-01		3.0306407E 00
3250.	6.8095845E-01	7.2915960E-01	9.5324244E-01		3.2446995E 00
3500.	6.6044146E-01	7.1076401E-01	9.4970870E-01		3.4533603E 00
3750.	6.4044333E-01	6.9278488E-01	9.4609845E-01		3.6567443E 00
4000.	6.2095212E-01	6.7522185E-01	9.4240189E-01		3.8549727E 00
4250.	6.0195604E-01	6.5807240E-01	9.3861079E-01		4.0481656E 00
4500.	5.8344336E-01	6.4133206E-01	9.3471855E-01		4.2364422E 00
4750.	5.6540262E-01	6.2499476E-01	9.3071997E-01		4.4199193E 00
5000.	5.4782243E-01	6.0905305E-01	9.2661133E-01		4.5987124E 00
5250.	5.3069175E-01	5.9349830E-01	9.2239023E-01		4.7729340E 00
5500.	5.1399974E-01	5.7832093E-01	9.1805561E-01		4.9426941E 00
5750.	4.9773586E-01	5.6351072E-01	9.1360767E-01		5.1081001E 00
6000.	4.8188989E-01	5.4905677E-01	9.0904764E-01		5.2692560E 00
6250.	4.6645187E-01	5.3494775E-01	9.0437800E-01		5.4262629E 00
6500.	4.5141221E-01	5.2117212E-01	8.9960216E-01		5.5792186E 00
6750.	4.3676159E-01	5.0771816E-01	8.9472464E-01		5.7282175E 00
7000.	4.2249102E-01	4.9457407E-01	8.8975078E-01		5.8733513E 00
7250.	4.0859190E-01	4.8172814E-01	8.8468679E-01		6.0147074E 00
7500.	3.9505585E-01	4.6916878E-01	8.7953967E-01		6.1523710E 00
7750.	3.8187487E-01	4.5688466E-01	8.7431720E-01		6.2864235E 00
8000.	3.6904126E-01	4.4486470E-01	8.6902775E-01		6.4169432E 00
8250.	3.5654760E-01	4.3309820E-01	8.6368030E-01		6.5440056E 00
8500.	3.4438674E-01	4.2157483E-01	8.5828435E-01		6.6676832E 00
8750.	3.3255185E-01	4.1028473E-01	8.5284985E-01		6.7880459E 00
9000.	3.2103635E-01	3.9921856E-01	8.4738715E-01	MOLECULAR WEIGHT CONSTANT TO 90,000 METERS	6.9051602E 00
9250.	3.0983387E-01	3.8836742E-01	8.4190682E-01		7.0190911E 00
9500.	2.9893833E-01	3.7772301E-01	8.3641976E-01		7.1299003E 00
9750.	2.8834384E-01	3.6727760E-01	8.3093694E-01		7.2376479E 00
10000.	2.7804469E-01	3.5702401E-01	8.2546939E-01		7.3423917E 00
10250.	2.6803542E-01	3.4695566E-01	8.2002810E-01		7.4441875E 00
10500.	2.5831070E-01	3.3706658E-01	8.1462401E-01		7.5430893E 00
10750.	2.4886536E-01	3.2735136E-01	8.0926777E-01		7.6391498E 00
11000.	2.3965380E-01	3.1801388E-01	8.0360048E-01		7.7328327E 00
11250.	2.3074045E-01	3.0863917E-01	7.9832937E-01		7.8234828E 00
11500.	2.2209570E-01	2.9940940E-01	7.9316903E-01		7.9114012E 00
11750.	2.1371522E-01	2.9032211E-01	7.8813556E-01		7.9966319E 00
12000.	2.0559467E-01	2.8137562E-01	7.8324474E-01		8.0792190E 00
12250.	1.9772962E-01	2.7256896E-01	7.7851201E-01		8.1592078E 00
12500.	1.9011559E-01	2.6390186E-01	7.7395250E-01		8.2366436E 00
12750.	1.8274807E-01	2.5537467E-01	7.6958085E-01		8.3115723E 00
13000.	1.7562250E-01	2.4698829E-01	7.6541126E-01		8.3840404E 00
13250.	1.6873430E-01	2.3874412E-01	7.6145730E-01		8.4540944E 00
13500.	1.6207882E-01	2.3064399E-01	7.5773191E-01		8.5217816E 00
13750.	1.5565143E-01	2.2269010E-01	7.5424739E-01		8.5871491E 00
14000.	1.4944745E-01	2.1488494E-01	7.5101517E-01		8.6502445E 00
14250.	1.4346219E-01	2.0723127E-01	7.4804591E-01		8.7111155E 00
14500.	1.3769094E-01	1.9973198E-01	7.4534935E-01		8.7698100E 00
14750.	1.3212898E-01	1.9239013E-01	7.4293422E-01		8.8263760E 00
15000.	1.2677157E-01	1.8520879E-01	7.4080821E-01		8.8808615E 00
15250.	1.2161399E-01	1.7819105E-01	7.3897798E-01		8.9333149E 00
15500.	1.1665149E-01	1.7133994E-01	7.3744892E-01		8.9837842E 00
15750.	1.1187936E-01	1.6465836E-01	7.3622527E-01		9.0323176E 00
16000.	1.0729285E-01	1.5814910E-01	7.3530992E-01		9.0789630E 00
16250.	1.0288728E-01	1.5181469E-01	7.3470452E-01		9.1237683E 00
16500.	9.8657924E-02	1.4565745E-01	7.3440926E-01		9.1667815E 00
16750.	9.4600136E-02	1.3967943E-01	7.3442291E-01		9.2080498E 00
17000.	9.0709249E-02	1.3388234E-01	7.3474283E-01		9.2476207E 00
17250.	8.6980654E-02	1.2826761E-01	7.3536484E-01		9.2855411E 00
17500.	8.3409772E-02	1.2283625E-01	7.3628323E-01		9.3218575E 00
17750.	7.9992077E-02	1.1758896E-01	7.3749069E-01	2.8964400E 01	9.3566159E 00

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE	KINETIC TEMPERATURE	VIRTUAL TEMPERATURE	DENSITY	KINEMATIC VISCOSITY	COEFFICIENT OF VISCOSITY	SPEED OF SOUND
meters	newtons cm^{-2}	degrees K	degrees K	kg m^{-3}	m^2 sec^{-1}	newton-sec m^{-2}	m sec^{-1}
18000.	7.8097365E-01	2.0530313E 02	2.0530313E 02	1.3239218E-01	1.0261471E-04	1.3585386E-05	2.8723862E 02
18250.	7.4940996E-01	2.0591008E 02	2.0591008E 02	1.2665197E-01	1.0753477E-04	1.3619491E-05	2.8766290E 02
18500.	7.1920003E-01	2.0652754E 02	2.0652754E 02	1.2117497E-01	1.1268123E-04	1.3654144E-05	2.8809388E 02
18750.	6.9028297E-01	2.0715365E 02	2.0715365E 02	1.1594899E-01	1.1806259E-04	1.3689238E-05	2.8853025E 02
19000.	6.6260092E-01	2.0778667E 02	2.0778667E 02	1.1096236E-01	1.2368766E-04	1.3724675E-05	2.8897076E 02
19250.	6.3603868E-01	2.0842488E 02	2.0842488E 02	1.0620395E-01	1.2956538E-04	1.3760356E-05	2.8941420E 02
19500.	6.1072356E-01	2.0906669E 02	2.0906669E 02	1.0166309E-01	1.3570500E-04	1.3796191E-05	2.8985945E 02
19750.	5.8642544E-01	2.0971051E 02	2.0971051E 02	9.7329618E-02	1.4211596E-04	1.3832092E-05	2.9030542E 02
20000.	5.6315652E-01	2.1035486E 02	2.1035486E 02	9.3193799E-02	1.4880793E-04	1.3867977E-05	2.9075108E 02
20250.	5.4087104E-01	2.1099834E 02	2.1099834E 02	8.9246359E-02	1.5579085E-04	1.3903766E-05	2.9119544E 02
20500.	5.1952558E-01	2.1163959E 02	2.1163959E 02	8.5478435E-02	1.6307487E-04	1.3939385E-05	2.9163759E 02
20750.	4.9907848E-01	2.1227735E 02	2.1227735E 02	8.1881557E-02	1.7067049E-04	1.3974765E-05	2.9207668E 02
21000.	4.7949016E-01	2.1291042E 02	2.1291042E 02	7.8447674E-02	1.7858834E-04	1.4009840E-05	2.9251188E 02
21250.	4.6072266E-01	2.1353768E 02	2.1353768E 02	7.5169075E-02	1.8683947E-04	1.4044550E-05	2.9294246E 02
21500.	4.4273989E-01	2.1415808E 02	2.1415808E 02	7.2038414E-02	1.9543514E-04	1.4078838E-05	2.9336769E 02
21750.	4.2550730E-01	2.1477067E 02	2.1477067E 02	6.9048699E-02	2.0438693E-04	1.4112651E-05	2.9378698E 02
22000.	4.0899191E-01	2.1537455E 02	2.1537455E 02	6.6193250E-02	2.1370675E-04	1.4145944E-05	2.9419972E 02
22250.	3.9316222E-01	2.1596891E 02	2.1596891E 02	6.3465692E-02	2.2340689E-04	1.4178673E-05	2.9460538E 02
22500.	3.7798811E-01	2.1655302E 02	2.1655302E 02	6.0859976E-02	2.3349993E-04	1.4210800E-05	2.9500350E 02
22750.	3.6344091E-01	2.1712624E 02	2.1712624E 02	5.8370312E-02	2.4399890E-04	1.4242292E-05	2.9539368E 02
23000.	3.4949304E-01	2.1768800E 02	2.1768800E 02	5.5991186E-02	2.5491726E-04	1.4273120E-05	2.9577557E 02
23250.	3.3611832E-01	2.1823781E 02	2.1823781E 02	5.3717368E-02	2.6626877E-04	1.4303258E-05	2.9614885E 02
23500.	3.2329168E-01	2.1877527E 02	2.1877527E 02	5.1543851E-02	2.7806785E-04	1.4332688E-05	2.9651329E 02
23750.	3.1098904E-01	2.1930008E 02	2.1930008E 02	4.9465870E-02	2.9032938E-04	1.4361396E-05	2.9686872E 02
24000.	2.9918759E-01	2.1981200E 02	2.1981200E 02	4.7478898E-02	3.0306874E-04	1.4389370E-05	2.9721502E 02
24250.	2.8786539E-01	2.2031091E 02	2.2031091E 02	4.5578615E-02	3.1630195E-04	1.4416605E-05	2.9755212E 02
24500.	2.7700151E-01	2.2079671E 02	2.2079671E 02	4.3760915E-02	3.3004564E-04	1.4443099E-05	2.9788000E 02
24750.	2.6657591E-01	2.2126948E 02	2.2126948E 02	4.2021881E-02	3.4431725E-04	1.4468859E-05	2.9819874E 02
25000.	2.5656950E-01	2.2172934E 02	2.2172934E 02	4.0357794E-02	3.5913489E-04	1.4493892E-05	2.9850846E 02
25250.	2.4696393E-01	2.2217648E 02	2.2217648E 02	3.8765104E-02	3.7451754E-04	1.4518211E-05	2.9880929E 02
25500.	2.3774181E-01	2.2261124E 02	2.2261124E 02	3.7240437E-02	3.9048512E-04	1.4541836E-05	2.9910150E 02
25750.	2.2888635E-01	2.2303400E 02	2.2303400E 02	3.5780583E-02	4.0705849E-04	1.4564790E-05	2.9938538E 02
26000.	2.2038159E-01	2.2344526E 02	2.2344526E 02	3.4382489E-02	4.2425962E-04	1.4587102E-05	2.9966127E 02
26250.	2.1221229E-01	2.2384560E 02	2.2384560E 02	3.3043241E-02	4.4211172E-04	1.4608804E-05	2.9992961E 02
26500.	2.0436382E-01	2.2423573E 02	2.2423573E 02	3.1760075E-02	4.6063921E-04	1.4629936E-05	3.0019086E 02
26750.	1.9682221E-01	2.2461640E 02	2.2461640E 02	3.0530360E-02	4.7986792E-04	1.4650541E-05	3.0044556E 02
27000.	1.8957414E-01	2.2498853E 02	2.2498853E 02	2.9351587E-02	4.9982535E-04	1.4670667E-05	3.0069433E 02
27250.	1.8260686E-01	2.2535303E 02	2.2535303E 02	2.8221373E-02	5.2054052E-04	1.4690368E-05	3.0093780E 02
27500.	1.7590816E-01	2.2571105E 02	2.2571105E 02	2.7137454E-02	5.4204438E-04	1.4709705E-05	3.0117677E 02
27750.	1.6946640E-01	2.2606372E 02	2.2606372E 02	2.6097671E-02	5.6436988E-04	1.4728740E-05	3.0141197E 02
28000.	1.6327363E-01	2.2643885E 02	2.2643885E 02	2.5119029E-02	5.8716331E-04	1.4748972E-05	3.0166194E 02
28250.	1.5729220E-01	2.2697720E 02	2.2697720E 02	2.4141415E-02	6.1214233E-04	1.4777982E-05	3.0202032E 02
28500.	1.5154519E-01	2.2751673E 02	2.2751673E 02	2.3204199E-02	6.3811838E-04	1.4807026E-05	3.0237907E 02
28750.	1.4602270E-01	2.2805774E 02	2.2805774E 02	2.2305569E-02	6.6513066E-04	1.4836119E-05	3.0273836E 02
29000.	1.4071528E-01	2.2860044E 02	2.2860044E 02	2.1443810E-02	6.9321970E-04	1.4865272E-05	3.0309836E 02
29250.	1.3561394E-01	2.2914508E 02	2.2914508E 02	2.0617288E-02	7.2242759E-04	1.4894498E-05	3.0345920E 02
29500.	1.3071014E-01	2.2969187E 02	2.2969187E 02	1.9824461E-02	7.5279778E-04	1.4923810E-05	3.0382105E 02
29750.	1.2599566E-01	2.3024104E 02	2.3024104E 02	1.9063850E-02	7.8437554E-04	1.4953217E-05	3.0418403E 02
30000.	1.2146273E-01	2.3079274E 02	2.3079274E 02	1.8334060E-02	8.1720744E-04	1.4982730E-05	3.0454826E 02
30250.	1.1710385E-01	2.3134718E 02	2.3134718E 02	1.7633751E-02	8.5134225E-04	1.5012357E-05	3.0491385E 02
30500.	1.1291193E-01	2.3190450E 02	2.3190450E 02	1.6961662E-02	8.8682977E-04	1.5042107E-05	3.0528090E 02
30750.	1.0888012E-01	2.3246485E 02	2.3246485E 02	1.6316577E-02	9.2372233E-04	1.5071986E-05	3.0564950E 02
31000.	1.0500195E-01	2.3302838E 02	2.3302838E 02	1.5697349E-02	9.6207348E-04	1.5102004E-05	3.0601975E 02
31250.	1.0127118E-01	2.3359519E 02	2.3359519E 02	1.5102878E-02	1.0019389E-03	1.5132162E-05	3.0639170E 02
31500.	9.7681869E-02	2.3416537E 02	2.3416537E 02	1.4532122E-02	1.0433760E-03	1.5162468E-05	3.0676541E 02
31750.	9.4228337E-02	2.3473904E 02	2.3473904E 02	1.3984082E-02	1.0864443E-03	1.5192926E-05	3.0714094E 02
32000.	9.0905080E-02	2.3531626E 02	2.3531626E 02	1.3457797E-02	1.1312058E-03	1.5223539E-05	3.0751834E 02
32250.	8.7706975E-02	2.3589708E 02	2.3589708E 02	1.2952372E-02	1.1777232E-03	1.5254309E-05	3.0789762E 02
32500.	8.4628981E-02	2.3648155E 02	2.3648155E 02	1.2466932E-02	1.2260625E-03	1.5285238E-05	3.0827881E 02
32750.	8.1666349E-02	2.3706971E 02	2.3706971E 02	1.2000652E-02	1.2762913E-03	1.5316328E-05	3.0866194E 02
33000.	7.8814489E-02	2.3766155E 02	2.3766155E 02	1.1552737E-02	1.3284798E-03	1.5347578E-05	3.0904698E 02
33250.	7.6068993E-02	2.3825710E 02	2.3825710E 02	1.1122427E-02	1.3827008E-03	1.5378989E-05	3.0943396E 02
33500.	7.3425727E-02	2.3885632E 02	2.3885632E 02	1.0709009E-02	1.4390274E-03	1.5410557E-05	3.0982283E 02
33750.	7.0880660E-02	2.3945918E 02	2.3945918E 02	1.0311789E-02	1.4975367E-03	1.5442282E-05	3.1021357E 02
34000.	6.8429914E-02	2.4006563E 02	2.4006563E 02	9.9301028E-03	1.5583081E-03	1.5474160E-05	3.1060615E 02
34250.	6.6069812E-02	2.4067563E 02	2.4067563E 02	9.5633199E-03	1.6214230E-03	1.5506187E-05	3.1100052E 02
34500.	6.3796784E-02	2.4128910E 02	2.4128910E 02	9.2108314E-03	1.6869660E-03	1.5538359E-05	3.1139663E 02
34750.	6.1607495E-02	2.4190593E 02	2.4190593E 02	8.8720665E-03	1.7550219E-03	1.5570671E-05	3.1179440E 02
35000.	5.9498639E-02	2.4252600E 02	2.4252600E 02	8.5464640E-03	1.8256808E-03	1.5603116E-05	3.1219375E 02
35250.	5.7467108E-02	2.4314924E 02	2.4314924E 02	8.2334940E-03	1.8990343E-03	1.5635687E-05	3.1259463E 02
35500.	5.5509918E-02	2.4377545E 02	2.4377545E 02	7.9326513E-03	1.9751753E-03	1.5668377E-05	3.1299690E 02
35750.	5.3624192E-02	2.4440454E 02	2.4440454E 02	7.6434468E-03	2.0542013E-03	1.5701179E-05	3.1340050E 02

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE RATIO	DENSITY RATIO	VISCOSITY RATIO	MOLECULAR WEIGHT	PRESSURE DIFFERENCE
meters	unitless	unitless	unitless	unitless	newtons cm^{-2}
18000.	7.6790792E-02	1.1186054E-01	7.4227225E-01	2.8964400E 01	9.3891735E 00
18250.	7.3687228E-02	1.0701054E-01	7.4413570E-01		9.4207371E 00
18500.	7.0716777E-02	1.0238292E-01	7.4602904E-01		9.4509470E 00
18750.	6.7873449E-02	9.7967392E-02	7.4794650E-01		9.4798641E 00
19000.	6.5151556E-02	9.3754101E-02	7.4988266E-01		9.5075462E 00
19250.	6.2545671E-02	8.9733634E-02	7.5183217E-01		9.5340484E 00
19500.	6.0050611E-02	8.5896982E-02	7.5379012E-01		9.5594236E 00
19750.	5.7661451E-02	8.2235550E-02	7.5575168E-01		9.5837216E 00
20000.	5.5373487E-02	7.8741122E-02	7.5771233E-01		9.6069906E 00
20250.	5.3182223E-02	7.5405859E-02	7.5966776E-01		9.6292760E 00
20500.	5.1083388E-02	7.2222272E-02	7.6161389E-01		9.6506215E 00
20750.	4.9072887E-02	6.9183205E-02	7.6354699E-01		9.6710687E 00
21000.	4.7146826E-02	6.6281855E-02	7.6546340E-01		9.6906570E 00
21250.	4.5301473E-02	6.3511708E-02	7.6735986E-01		9.7094245E 00
21500.	4.3533282E-02	6.0866556E-02	7.6923324E-01		9.7274072E 00
21750.	4.1838853E-02	5.8340492E-02	7.7108074E-01		9.7446399E 00
22000.	4.0214945E-02	5.5927871E-02	7.7289979E-01		9.7611552E 00
22250.	3.8658459E-02	5.3623306E-02	7.7468801E-01		9.7769849E 00
22500.	3.7166434E-02	5.1421692E-02	7.7644337E-01		9.7921590E 00
22750.	3.5736052E-02	4.9318130E-02	7.7816400E-01		9.8067062E 00
23000.	3.4364600E-02	4.7307963E-02	7.7984835E-01		9.8206540E 00
23250.	3.3049504E-02	4.5386774E-02	7.8149503E-01		9.8340288E 00
23500.	3.1788299E-02	4.3550330E-02	7.8310302E-01		9.8468554E 00
23750.	3.0578617E-02	4.1794606E-02	7.8467152E-01		9.8591580E 00
24000.	2.9418216E-02	4.0115778E-02	7.8619996E-01		9.8709595E 00
24250.	2.8304938E-02	3.8510194E-02	7.8768802E-01		9.8822818E 00
24500.	2.7236725E-02	3.6974387E-02	7.8913562E-01		9.8931456E 00
24750.	2.6211607E-02	3.5505046E-02	7.9054306E-01		9.9035712E 00
25000.	2.5227707E-02	3.4099028E-02	7.9191080E-01		9.9135777E 00
25250.	2.4283220E-02	3.2753335E-02	7.9323955E-01		9.9231832E 00
25500.	2.3376438E-02	3.1465117E-02	7.9453037E-01		9.9324054E 00
25750.	2.2505707E-02	3.0231660E-02	7.9578452E-01		9.9412608E 00
26000.	2.1669459E-02	2.9050386E-02	7.9700357E-01		9.9497656E 00
26250.	2.0866196E-02	2.7918830E-02	7.9818932E-01		9.9579349E 00
26500.	2.0094480E-02	2.6834661E-02	7.9934393E-01		9.9657834E 00
26750.	1.9352936E-02	2.5795652E-02	8.0046970E-01		9.9733249E 00
27000.	1.8640255E-02	2.4799686E-02	8.0156938E-01	MOLECULAR WEIGHT CONSTANT TO 90,000 METERS	9.9805729E 00
27250.	1.7955183E-02	2.3844747E-02	8.0264578E-01		9.9875402E 00
27500.	1.7296520E-02	2.2928925E-02	8.0370228E-01		9.9942390E 00
27750.	1.6664121E-02	2.2050393E-02	8.0474230E-01		1.0000681E 01
28000.	1.6054205E-02	2.1223521E-02	8.0584776E-01		1.0006873E 01
28250.	1.5466069E-02	2.0397517E-02	8.0743278E-01		1.0012855E 01
28500.	1.4900983E-02	1.9605646E-02	8.0901966E-01		1.0018602E 01
28750.	1.4357973E-02	1.8846378E-02	8.1060922E-01		1.0024124E 01
29000.	1.3836110E-02	1.8118262E-02	8.1220207E-01		1.0029432E 01
29250.	1.3334511E-02	1.7419919E-02	8.1379894E-01		1.0034533E 01
29500.	1.2852335E-02	1.6750045E-02	8.1540048E-01		1.0039437E 01
29750.	1.2388774E-02	1.6107391E-02	8.1700722E-01		1.0044151E 01
30000.	1.1943065E-02	1.5490778E-02	8.1861973E-01		1.0048684E 01
30250.	1.1514469E-02	1.4899074E-02	8.2023848E-01		1.0053043E 01
30500.	1.1102290E-02	1.4331214E-02	8.2186393E-01		1.0057235E 01
30750.	1.0705855E-02	1.3786170E-02	8.2349647E-01		1.0061267E 01
31000.	1.0324527E-02	1.3262973E-02	8.2513652E-01		1.0065145E 01
31250.	9.9576907E-03	1.2760694E-02	8.2678432E-01		1.0068876E 01
31500.	9.6047645E-03	1.2278452E-02	8.2844017E-01		1.0072465E 01
31750.	9.2651891E-03	1.1815403E-02	8.3010430E-01		1.0075919E 01
32000.	8.9384232E-03	1.1370735E-02	8.3177692E-01		1.0079242E 01
32250.	8.6239631E-03	1.0943693E-02	8.3345811E-01		1.0082440E 01
32500.	8.3213134E-03	1.0533536E-02	8.3514802E-01		1.0085518E 01
32750.	8.0300065E-03	1.0139567E-02	8.3684671E-01		1.0088481E 01
33000.	7.7495918E-03	9.7611161E-03	8.3855411E-01		1.0091332E 01
33250.	7.4796354E-03	9.3975394E-03	8.4027032E-01		1.0094078E 01
33500.	7.2197310E-03	9.0482346E-03	8.4199516E-01		1.0096721E 01
33750.	6.9694821E-03	8.7126163E-03	8.4372852E-01		1.0099266E 01
34000.	6.7285077E-03	8.3901230E-03	8.4547024E-01		1.0101717E 01
34250.	6.4964459E-03	8.0802215E-03	8.4722012E-01		1.0104077E 01
34500.	6.2729460E-03	7.7823977E-03	8.4897795E-01		1.0106350E 01
34750.	6.0576797E-03	7.4961690E-03	8.5074338E-01		1.0108539E 01
35000.	5.8503222E-03	7.2210616E-03	8.5251606E-01		1.0110648E 01
35250.	5.6505679E-03	6.9566277E-03	8.5429571E-01		1.0112680E 01
35500.	5.4581233E-03	6.7024403E-03	8.5608178E-01		1.0114637E 01
35750.	5.2727056E-03	6.4580862E-03	8.5787399E-01	2.8964400E 01	1.0116523E 01

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE	KINETIC TEMPERATURE	VIRTUAL TEMPERATURE	DENSITY	KINEMATIC VISCOSITY	COEFFICIENT OF VISCOSITY	SPEED OF SOUND
meters	newtons cm⁻²	degrees K	degrees K	kg m⁻³	m² sec⁻¹	newton-sec m⁻²	m sec⁻¹
36000.	5.1807184E-02	2.4503628E 02	2.4503628E 02	7.3654170E-03	2.1362103E-03	1.5734080E-05	3.1380529E 02
36250.	5.0056203E-02	2.4567052E 02	2.4567052E 02	7.0981081E-03	2.2213063E-03	1.5767073E-05	3.1421114E 02
36500.	4.8368751E-02	2.4630706E 02	2.4630706E 02	6.8410974E-03	2.3095922E-03	1.5800146E-05	3.1461734E 02
36750.	4.6742370E-02	2.4694566E 02	2.4694566E 02	6.5939717E-03	2.4011762E-03	1.5833288E-05	3.1502553E 02
37000.	4.5174757E-02	2.4758610E 02	2.4758610E 02	6.3563430E-03	2.4961657E-03	1.5866486E-05	3.1543376E 02
37250.	4.3663611E-02	2.4822817E 02	2.4822817E 02	6.1278247E-03	2.5946774E-03	1.5899729E-05	3.1584251E 02
37500.	4.2206814E-02	2.4887154E 02	2.4887154E 02	5.9080626E-03	2.6968231E-03	1.5933000E-05	3.1625156E 02
37750.	4.0802266E-02	2.4951598E 02	2.4951598E 02	5.6967042E-03	2.8027235E-03	1.5966287E-05	3.1666075E 02
38000.	3.9447995E-02	2.5016116E 02	2.5016116E 02	5.4934199E-03	2.9124978E-03	1.5999574E-05	3.1706989E 02
38250.	3.8142081E-02	2.5080680E 02	2.5080680E 02	5.2978887E-03	3.0262704E-03	1.6032844E-05	3.1747878E 02
38500.	3.6882693E-02	2.5145256E 02	2.5145256E 02	5.1098048E-03	3.1441673E-03	1.6066081E-05	3.1788723E 02
38750.	3.5668057E-02	2.5209809E 02	2.5209809E 02	4.9288731E-03	3.2663182E-03	1.6099268E-05	3.1829501E 02
39000.	3.4496486E-02	2.5274305E 02	2.5274305E 02	4.7548124E-03	3.3928543E-03	1.6132386E-05	3.1870190E 02
39250.	3.3366343E-02	2.5338705E 02	2.5338705E 02	4.5873508E-03	3.5239111E-03	1.6165417E-05	3.1910768E 02
39500.	3.2276080E-02	2.5402967E 02	2.5402967E 02	4.4262311E-03	3.6596231E-03	1.6198338E-05	3.1951207E 02
39750.	3.1224165E-02	2.5467056E 02	2.5467056E 02	4.2711993E-03	3.8001346E-03	1.6231132E-05	3.1991487E 02
40000.	3.0209180E-02	2.5530928E 02	2.5530928E 02	4.1220200E-03	3.9455843E-03	1.6263778E-05	3.2031579E 02
40250.	2.9229723E-02	2.5594537E 02	2.5594537E 02	3.9784617E-03	4.0961187E-03	1.6296252E-05	3.2071457E 02
40500.	2.8284457E-02	2.5657837E 02	2.5657837E 02	3.8403036E-03	4.2518854E-03	1.6328531E-05	3.2111092E 02
40750.	2.7372115E-02	2.5720782E 02	2.5720782E 02	3.7073359E-03	4.4130322E-03	1.6360593E-05	3.2150456E 02
41000.	2.6491424E-02	2.5783324E 02	2.5783324E 02	3.5793500E-03	4.5797177E-03	1.6392412E-05	3.2189520E 02
41250.	2.5641234E-02	2.5845410E 02	2.5845410E 02	3.4561553E-03	4.7520915E-03	1.6423966E-05	3.2228253E 02
41500.	2.4820392E-02	2.5906989E 02	2.5906989E 02	3.3375628E-03	4.9303122E-03	1.6455227E-05	3.2266623E 02
41750.	2.4027806E-02	2.5968005E 02	2.5968005E 02	3.2233931E-03	5.1145384E-03	1.6486168E-05	3.2304598E 02
42000.	2.3262411E-02	2.6028407E 02	2.6028407E 02	3.1134715E-03	5.3049350E-03	1.6516764E-05	3.2342147E 02
42250.	2.2523202E-02	2.6088134E 02	2.6088134E 02	3.0076332E-03	5.5016637E-03	1.6546987E-05	3.2379233E 02
42500.	2.1809203E-02	2.6147127E 02	2.6147127E 02	2.9057187E-03	5.7048901E-03	1.6576806E-05	3.2415822E 02
42750.	2.1119469E-02	2.6205329E 02	2.6205329E 02	2.8075735E-03	5.9147853E-03	1.6606195E-05	3.2451880E 02
43000.	2.0453115E-02	2.6262673E 02	2.6262673E 02	2.7130530E-03	6.1315131E-03	1.6635121E-05	3.2487367E 02
43250.	1.9809245E-02	2.6319098E 02	2.6319098E 02	2.6220120E-03	6.3552547E-03	1.6663554E-05	3.2522247E 02
43500.	1.9187063E-02	2.6374536E 02	2.6374536E 02	2.5343198E-03	6.5861708E-03	1.6691463E-05	3.2556482E 02
43750.	1.8585732E-02	2.6428923E 02	2.6428923E 07	2.4498413E-03	6.8244486E-03	1.6718816E-05	3.2590032E 02
44000.	1.8004513E-02	2.6482185E 02	2.6482185E 02	2.3684559E-03	7.0702506E-03	1.6745577E-05	3.2622854E 02
44250.	1.7442635E-02	2.6534256E 02	2.6534256E 02	2.2900392E-03	7.3237678E-03	1.6771716E-05	3.2654911E 02
44500.	1.6899401E-02	2.6585060E 02	2.6585060E 02	2.2144782E-03	7.5851708E-03	1.6797196E-05	3.2686158E 02
44750.	1.6374120E-02	2.6634524E 02	2.6634524E 02	2.1416613E-03	7.8546414E-03	1.6821981E-05	3.2716551E 02
45000.	1.5866134E-02	2.6682574E 02	2.6682574E 02	2.0714819E-03	8.1323606E-03	1.6846038E-05	3.2746049E 02
45250.	1.5374807E-02	2.6729129E 02	2.6729129E 02	2.0038380E-03	8.4185084E-03	1.6869327E-05	3.2774604E 02
45500.	1.4899529E-02	2.6774109E 02	2.6774109E 02	1.9386315E-03	8.7132648E-03	1.6891810E-05	3.2802169E 02
45750.	1.4439711E-02	2.6817436E 02	2.6817436E 02	1.8757674E-03	9.0168161E-03	1.6913450E-05	3.2828699E 02
46000.	1.3994781E-02	2.6859025E 02	2.6859025E 02	1.8151546E-03	9.3293467E-03	1.6934206E-05	3.2854145E 02
46250.	1.3564215E-02	2.6898792E 02	2.6898792E 02	1.7567082E-03	9.6510271E-03	1.6954039E-05	3.2878458E 02
46500.	1.3147466E-02	2.6936653E 02	2.6936653E 02	1.7003416E-03	9.9820579E-03	1.6972909E-05	3.2901589E 02
46750.	1.2744066E-02	2.6972512E 02	2.6972512E 02	1.6459792E-03	1.0322590E-02	1.6990770E-05	3.2923481E 02
47000.	1.2353487E-02	2.7006288E 02	2.7006288E 02	1.5935380E-03	1.0672843E-02	1.7007582E-05	3.2944089E 02
47250.	1.1975290E-02	2.7037884E 02	2.7037884E 02	1.5429473E-03	1.1032976E-02	1.7023301E-05	3.2963355E 02
47500.	1.1609022E-02	2.7067210E 02	2.7067210E 02	1.4941352E-03	1.1403173E-02	1.7037882E-05	3.2981226E 02
47750.	1.1254254E-02	2.7094166E 02	2.7094166E 02	1.4470338E-03	1.1783607E-02	1.7051279E-05	3.2997645E 02
48000.	1.0910568E-02	2.7118660E 02	2.7118660E 02	1.4015768E-03	1.2174463E-02	1.7063446E-05	3.3012557E 02
48250.	1.0577570E-02	2.7140590E 02	2.7140590E 02	1.3577018E-03	1.2575910E-02	1.7074335E-05	3.3025902E 02
48500.	1.0254871E-02	2.7159857E 02	2.7159857E 02	1.3153475E-03	1.2988126E-02	1.7083899E-05	3.3037623E 02
48750.	9.9421220E-03	2.7176355E 02	2.7176355E 02	1.2744583E-03	1.3411255E-02	1.7092086E-05	3.3047655E 02
49000.	9.6365027E-03	2.7187674E 02	2.7187674E 02	1.2347674E-03	1.3846901E-02	1.7097701E-05	3.3054537E 02
49250.	9.3444532E-03	2.7158682E 02	2.7158682E 02	1.1986240E-03	1.4252440E-02	1.7083316E-05	3.3036908E 02
49500.	9.0608503E-03	2.7127908E 02	2.7127908E 02	1.1635643E-03	1.4668753E-02	1.7068039E-05	3.3018185E 02
49750.	8.7854533E-03	2.7095394E 02	2.7095394E 02	1.1295526E-03	1.5096144E-02	1.7051889E-05	3.2998393E 02
50000.	8.5180215E-03	2.7061178E 02	2.7061178E 02	1.0965534E-03	1.5534932E-02	1.7034883E-05	3.2977550E 02
50250.	8.2583286E-03	2.7025298E 02	2.7025298E 02	1.0645337E-03	1.5985440E-02	1.7017040E-05	3.2955681E 02
50500.	8.0061513E-03	2.6987793E 02	2.6987793E 02	1.0334612E-03	1.6448006E-02	1.6998377E-05	3.2932805E 02
50750.	7.7612761E-03	2.6948699E 02	2.6948699E 02	1.0033052E-03	1.6922975E-02	1.6978910E-05	3.2908944E 02
51000.	7.5234920E-03	2.6908057E 02	2.6908057E 02	9.7403572E-04	1.7410715E-02	1.6958658E-05	3.2884119E 02
51250.	7.2925984E-03	2.6865905E 02	2.6865905E 02	9.4562420E-04	1.7911596E-02	1.6937638E-05	3.2858353E 02
51500.	7.0683973E-03	2.6822277E 02	2.6822277E 02	9.1804309E-04	1.8426005E-02	1.6915866E-05	3.2831662E 02
51750.	6.8506990E-03	2.6777211E 02	2.6777211E 02	8.9126593E-04	1.8954342E-02	1.6893359E-05	3.2804069E 02
52000.	6.6393197E-03	2.6730745E 02	2.6730745E 02	8.6526723E-04	1.9497023E-02	1.6870136E-05	3.2775595E 02
52250.	6.4340792E-03	2.6682914E 02	2.6682914E 02	8.4002243E-04	2.0054474E-02	1.6846209E-05	3.2746258E 02
52500.	6.2348041E-03	2.6633759E 02	2.6633759E 02	8.1550777E-04	2.0627146E-02	1.6821598E-05	3.2716081E 02
52750.	6.0413253E-03	2.6583313E 02	2.6583313E 02	7.9170040E-04	2.1215500E-02	1.6796320E-05	3.2685084E 02
53000.	5.8534791E-03	2.6531610E 02	2.6531610E 02	7.6857846E-04	2.1820008E-02	1.6770388E-05	3.2653283E 02
53250.	5.6711066E-03	2.6478688E 02	2.6478688E 02	7.4612072E-04	2.2441168E-02	1.6743821E-05	3.2620700E 02
53500.	5.4940539E-03	2.6424584E 02	2.6424584E 02	7.2430671E-04	2.3079496E-02	1.6716634E-05	3.2587356E 02
53750.	5.3221716E-03	2.6369328E 02	2.6369328E 02	7.0311693E-04	2.3735514E-02	1.6688842E-05	3.2553267E 02

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE RATIO	DENSITY RATIO	VISCOSITY RATIO	MOLECULAR WEIGHT	PRESSURE DIFFERENCE
meters	unitless	unitless	unitless	unitless	newtons cm^{-2}
36000.	5.0940446E-03	6.2231737E-03	8.5967164E-01	2.8964400E 01	1.0118340E 01
36250.	4.9218759E-03	5.9973196E-03	8.6147428E-01		1.0120091E 01
36500.	4.7559539E-03	5.7801666E-03	8.6328131E-01		1.0121778E 01
36750.	4.5960367E-03	5.5713656E-03	8.6509210E-01		1.0123405E 01
37000.	4.4418980E-03	5.3705889E-03	8.6690596E-01		1.0124972E 01
37250.	4.2933116E-03	5.1775097E-03	8.6872227E-01		1.0126483E 01
37500.	4.1500691E-03	4.9918287E-03	8.7054015E-01		1.0127940E 01
37750.	4.0119641E-03	4.8132482E-03	8.7235887E-01		1.0129345E 01
38000.	3.8788028E-03	4.6414896E-03	8.7417755E-01		1.0130699E 01
38250.	3.7503962E-03	4.4762817E-03	8.7599536E-01		1.0132005E 01
38500.	3.6265643E-03	4.3173663E-03	8.7781137E-01		1.0133264E 01
38750.	3.5071328E-03	4.1644938E-03	8.7962462E-01		1.0134479E 01
39000.	3.3919357E-03	4.0174268E-03	8.8143409E-01		1.0135650E 01
39250.	3.2808122E-03	3.8759355E-03	8.8323880E-01		1.0136781E 01
39500.	3.1736099E-03	3.7398026E-03	8.8503755E-01		1.0137871E 01
39750.	3.0701783E-03	3.6088134E-03	8.8682938E-01		1.0138923E 01
40000.	2.9703779E-03	3.4827691E-03	8.8861302E-01		1.0139938E 01
40250.	2.8740708E-03	3.3614740E-03	8.9038732E-01		1.0140917E 01
40500.	2.7811256E-03	3.2447418E-03	8.9215099E-01		1.0141862E 01
40750.	2.6914178E-03	3.1323950E-03	8.9390275E-01		1.0142775E 01
41000.	2.6048221E-03	3.0242574E-03	8.9564131E-01		1.0143656E 01
41250.	2.5212255E-03	2.9201680E-03	8.9736534E-01		1.0144506E 01
41500.	2.4405145E-03	2.8199670E-03	8.9907334E-01		1.0145327E 01
41750.	2.3625819E-03	2.7235030E-03	9.0076388E-01		1.0146119E 01
42000.	2.2873230E-03	2.6306283E-03	9.0243558E-01		1.0146885E 01
42250.	2.2146388E-03	2.5412036E-03	9.0408686E-01		1.0147624E 01
42500.	2.1444333E-03	2.4550942E-03	9.0571612E-01		1.0148338E 01
42750.	2.0766138E-03	2.3721695E-03	9.0732185E-01		1.0149028E 01
43000.	2.0110933E-03	2.2923075E-03	9.0890229E-01		1.0149694E 01
43250.	1.9477835E-03	2.2153852E-03	9.1045582E-01		1.0150338E 01
43500.	1.8866062E-03	2.1412925E-03	9.1198069E-01		1.0150960E 01
43750.	1.8274791E-03	2.0699151E-03	9.1347519E-01		1.0151561E 01
44000.	1.7703296E-03	2.0011512E-03	9.1493738E-01	MOLECULAR WEIGHT CONSTANT TO 90,000 METERS	1.0152142E 01
44250.	1.7150819E-03	1.9348955E-03	9.1636553E-01		1.0152704E 01
44500.	1.6616672E-03	1.8710526E-03	9.1775768E-01		1.0153248E 01
44750.	1.6100180E-03	1.8095282E-03	9.1911191E-01		1.0153773E 01
45000.	1.5600692E-03	1.7502324E-03	9.2042631E-01		1.0154281E 01
45250.	1.5117585E-03	1.6930789E-03	9.2169876E-01		1.0154772E 01
45500.	1.4650259E-03	1.6379848E-03	9.2292717E-01		1.0155247E 01
45750.	1.4198133E-03	1.5848697E-03	9.2410953E-01		1.0155707E 01
46000.	1.3760647E-03	1.5336569E-03	9.2524362E-01		1.0156152E 01
46250.	1.3337285E-03	1.4842745E-03	9.2632723E-01		1.0156583E 01
46500.	1.2927508E-03	1.4366493E-03	9.2735821E-01		1.0157000E 01
46750.	1.2530856E-03	1.3907175E-03	9.2833408E-01		1.0157403E 01
47000.	1.2146813E-03	1.3464090E-03	9.2925265E-01		1.0157793E 01
47250.	1.1774943E-03	1.3036640E-03	9.3011150E-01		1.0158172E 01
47500.	1.1414802E-03	1.2624218E-03	9.3090819E-01		1.0158538E 01
47750.	1.1065970E-03	1.2226250E-03	9.3164015E-01		1.0158893E 01
48000.	1.0728034E-03	1.1842175E-03	9.3230493E-01		1.0159236E 01
48250.	1.0400607E-03	1.1471467E-03	9.3289990E-01		1.0159569E 01
48500.	1.0083307E-03	1.1113608E-03	9.3342245E-01		1.0159892E 01
48750.	9.7757896E-04	1.0768128E-03	9.3386976E-01		1.0160205E 01
49000.	9.4752835E-04	1.0432772E-03	9.3417658E-01		1.0160511E 01
49250.	9.1881199E-04	1.0127390E-03	9.3339058E-01		1.0160803E 01
49500.	8.9092617E-04	9.8311651E-04	9.3255587E-01		1.0161086E 01
49750.	8.6384722E-04	9.5437936E-04	9.3167348E-01		1.0161362E 01
50000.	8.3755145E-04	9.2649775E-04	9.3074435E-01		1.0161629E 01
50250.	8.1201663E-04	8.9944376E-04	9.2976943E-01		1.0161889E 01
50500.	7.8722080E-04	8.7319003E-04	9.2874972E-01		1.0162141E 01
50750.	7.6314294E-04	8.4771069E-04	9.2768611E-01		1.0162386E 01
51000.	7.3976235E-04	8.2298036E-04	9.2657958E-01		1.0162624E 01
51250.	7.1705927E-04	7.9897496E-04	9.2543113E-01		1.0162854E 01
51500.	6.9501426E-04	7.7567118E-04	9.2424155E-01		1.0163079E 01
51750.	6.7360863E-04	7.5304667E-04	9.2301184E-01		1.0163296E 01
52000.	6.5282434E-04	7.3107990E-04	9.2174293E-01		1.0163508E 01
52250.	6.3264366E-04	7.0975011E-04	9.2043562E-01		1.0163713E 01
52500.	6.1304954E-04	6.8903723E-04	9.1909096E-01		1.0163912E 01
52750.	5.9402534E-04	6.6892195E-04	9.1770983E-01		1.0164106E 01
53000.	5.7555500E-04	6.4938582E-04	9.1629300E-01		1.0164293E 01
53250.	5.5762286E-04	6.3041086E-04	9.1484141E-01		1.0164476E 01
53500.	5.4021380E-04	6.1197981E-04	9.1335599E-01		1.0164653E 01
53750.	5.2331313E-04	5.9407618E-04	9.1183751E-01	2.8964400E 01	1.0164825E 01

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE	KINETIC TEMPERATURE	VIRTUAL TEMPERATURE	DENSITY	KINEMATIC VISCOSITY	COEFFICIENT OF VISCOSITY	SPEED OF SOUND
meters	newtons cm^{-2}	degrees K	degrees K	kg m^{-3}	m^2 sec^{-1}	newton-sec m^{-2}	m sec^{-1}
54000.	5.1553130E-03	2.6312956E 02	2.6312956E 02	6.8253221E-04	2.4409778E-02	1.6660460E-05	3.2518452E 02
54250.	4.9933376E-03	2.6255506E 02	2.6255506E 02	6.6253418E-04	2.5102866E-02	1.6631507E-05	3.2482934E 02
54500.	4.8361087E-03	2.6197010E 02	2.6197010E 02	6.4310530E-04	2.5815361E-02	1.6601996E-05	3.2446728E 02
54750.	4.6834927E-03	2.6137502E 02	2.6137502E 02	6.2422839E-04	2.6547884E-02	1.6571943E-05	3.2409855E 02
55000.	4.5353597E-03	2.6077015E 02	2.6077015E 02	6.0588697E-04	2.7301070E-02	1.6541363E-05	3.2372332E 02
55250.	4.3915860E-03	2.6015581E 02	2.6015581E 02	5.8806537E-04	2.8075569E-02	1.6510270E-05	3.2334178E 02
55500.	4.2520469E-03	2.5953237E 02	2.5953237E 02	5.7074792E-04	2.8872090E-02	1.6478682E-05	3.2295411E 02
55750.	4.1166255E-03	2.5890011E 02	2.5890011E 02	5.5391979E-04	2.9691323E-02	1.6446611E-05	3.2256049E 02
56000.	3.9852059E-03	2.5825934E 02	2.5825934E 02	5.3756684E-04	3.0534011E-02	1.6414072E-05	3.2216108E 02
56250.	3.8576765E-03	2.5761043E 02	2.5761043E 02	5.2167510E-04	3.1400924E-02	1.6381081E-05	3.2175609E 02
56500.	3.7339278E-03	2.5695369E 02	2.5695369E 02	5.0623109E-04	3.2292865E-02	1.6347652E-05	3.2134569E 02
56750.	3.6138545E-03	2.5628940E 02	2.5628940E 02	4.9122195E-04	3.3210649E-02	1.6313800E-05	3.2093004E 02
57000.	3.4973535E-03	2.5561786E 02	2.5561786E 02	4.7663518E-04	3.4155129E-02	1.6279536E-05	3.2050931E 02
57250.	3.3843247E-03	2.5493941E 02	2.5493941E 02	4.6245854E-04	3.5127209E-02	1.6244878E-05	3.2008368E 02
57500.	3.2746712E-03	2.5425435E 02	2.5425435E 02	4.4868036E-04	3.6127810E-02	1.6209839E-05	3.1965334E 02
57750.	3.1682985E-03	2.5356290E 02	2.5356290E 02	4.3528944E-04	3.7157872E-02	1.6174430E-05	3.1921839E 02
58000.	3.0651143E-03	2.5286545E 02	2.5286545E 02	4.2227457E-04	3.8218422E-02	1.6138668E-05	3.1877907E 02
58250.	2.9650293E-03	2.5216226E 02	2.5216226E 02	4.0962520E-04	3.9310484E-02	1.6102565E-05	3.1833552E 02
58500.	2.8679566E-03	2.5145360E 02	2.5145360E 02	3.9733101E-04	4.0435140E-02	1.6066135E-05	3.1788789E 02
58750.	2.7738122E-03	2.5073975E 02	2.5073975E 02	3.8538216E-04	4.1593494E-02	1.6029391E-05	3.1743634E 02
59000.	2.6825136E-03	2.5002101E 02	2.5002101E 02	3.7376892E-04	4.2786719E-02	1.5992346E-05	3.1698105E 02
59250.	2.5939802E-03	2.4929760E 02	2.4929760E 02	3.6248189E-04	4.4016023E-02	1.5955011E-05	3.1652214E 02
59500.	2.5081352E-03	2.4856981E 02	2.4856981E 02	3.5151213E-04	4.5282651E-02	1.5917401E-05	3.1605979E 02
59750.	2.4249023E-03	2.4783793E 02	2.4783793E 02	3.4085073E-04	4.6587926E-02	1.5879529E-05	3.1559415E 02
60000.	2.3442082E-03	2.4710222E 02	2.4710222E 02	3.3048920E-04	4.7933204E-02	1.5841407E-05	3.1512538E 02
60250.	2.2659808E-03	2.4636295E 02	2.4636295E 02	3.2041923E-04	4.9319911E-02	1.5803048E-05	3.1465363E 02
60500.	2.1901511E-03	2.4562030E 02	2.4562030E 02	3.1063299E-04	5.0749477E-02	1.5764462E-05	3.1417902E 02
60750.	2.1166509E-03	2.4487455E 02	2.4487455E 02	3.0112260E-04	5.2223448E-02	1.5725661E-05	3.1370170E 02
61000.	2.0454141E-03	2.4412598E 02	2.4412598E 02	2.9188045E-04	5.3743437E-02	1.5686659E-05	3.1322185E 02
61250.	1.9763771E-03	2.4337476E 02	2.4337476E 02	2.8289940E-04	5.5311054E-02	1.5647464E-05	3.1273955E 02
61500.	1.9094769E-03	2.4262118E 02	2.4262118E 02	2.7417222E-04	5.6928059E-02	1.5608093E-05	3.1225500E 02
61750.	1.8446531E-03	2.4186543E 02	2.4186543E 02	2.6569211E-04	5.8596209E-02	1.5568551E-05	3.1176829E 02
62000.	1.7818466E-03	2.4110778E 02	2.4110778E 02	2.5745233E-04	6.0317397E-02	1.5528854E-05	3.1127960E 02
62250.	1.7209993E-03	2.4034843E 02	2.4034843E 02	2.4944634E-04	6.2093563E-02	1.5489012E-05	3.1078904E 02
62500.	1.6620553E-03	2.3958754E 02	2.3958754E 02	2.4166791E-04	6.3926700E-02	1.5449032E-05	3.1029671E 02
62750.	1.6049612E-03	2.3882540E 02	2.3882540E 02	2.3411097E-04	6.5818912E-02	1.5408929E-05	3.0980278E 02
63000.	1.5496626E-03	2.3806212E 02	2.3806212E 02	2.2676949E-04	6.7772384E-02	1.5368709E-05	3.0930732E 02
63250.	1.4961084E-03	2.3729799E 02	2.3729799E 02	2.1963763E-04	6.9789435E-02	1.5328386E-05	3.0881052E 02
63500.	1.4442482E-03	2.3653317E 02	2.3653317E 02	2.1270982E-04	7.1872414E-02	1.5287968E-05	3.0831246E 02
63750.	1.3940340E-03	2.3576784E 02	2.3576784E 02	2.0598070E-04	7.4023755E-02	1.5247465E-05	3.0781327E 02
64000.	1.3454170E-03	2.3500217E 02	2.3500217E 02	1.9944483E-04	7.6246075E-02	1.5206885E-05	3.0731304E 02
64250.	1.2983516E-03	2.3423638E 02	2.3423638E 02	1.9309709E-04	7.8542044E-02	1.5166240E-05	3.0681192E 02
64500.	1.2527926E-03	2.3347064E 02	2.3347064E 02	1.8693243E-04	8.0914468E-02	1.5125538E-05	3.0631001E 02
64750.	1.2086961E-03	2.3270509E 02	2.3270509E 02	1.8094601E-04	8.3366234E-02	1.5084787E-05	3.0580740E 02
65000.	1.1660196E-03	2.3193981E 02	2.3193981E 02	1.7513312E-04	8.5900316E-02	1.5043991E-05	3.0530415E 02
65250.	1.1247208E-03	2.3117513E 02	2.3117513E 02	1.6948893E-04	8.8520038E-02	1.5003167E-05	3.0480046E 02
65500.	1.0847607E-03	2.3041111E 02	2.3041111E 02	1.6400922E-04	9.1228521E-02	1.4962319E-05	3.0429636E 02
65750.	1.0460989E-03	2.2964788E 02	2.2964788E 02	1.5868945E-04	9.4029269E-02	1.4921453E-05	3.0379196E 02
66000.	1.0086976E-03	2.2888563E 02	2.2888563E 02	1.5352539E-04	9.6925850E-02	1.4880579E-05	3.0328736E 02
66250.	9.7251890E-04	2.2812446E 02	2.2812446E 02	1.4851282E-04	9.9922040E-02	1.4839704E-05	3.0278264E 02
66500.	9.3752730E-04	2.2736447E 02	2.2736447E 02	1.4364783E-04	1.0302162E-01	1.4798833E-05	3.0227787E 02
66750.	9.0368733E-04	2.2660580E 02	2.2660580E 02	1.3892644E-04	1.0622867E-01	1.4757972E-05	3.0177313E 02
67000.	8.7096431E-04	2.2584865E 02	2.2584865E 02	1.3434472E-04	1.0954754E-01	1.4717133E-05	3.0126856E 02
67250.	8.3932542E-04	2.2509302E 02	2.2509302E 02	1.2989908E-04	1.1298245E-01	1.4676317E-05	3.0076415E 02
67500.	8.0873778E-04	2.2433905E 02	2.2433905E 02	1.2558582E-04	1.1653808E-01	1.4635530E-05	3.0026000E 02
67750.	7.7916990E-04	2.2358690E 02	2.2358690E 02	1.2140136E-04	1.2021926E-01	1.4594782E-05	2.9975623E 02
68000.	7.5059128E-04	2.2283655E 02	2.2283655E 02	1.1734236E-04	1.2403084E-01	1.4554073E-05	2.9925283E 02
68250.	7.2297136E-04	2.2208819E 02	2.2208819E 02	1.1340531E-04	1.2797823E-01	1.4513411E-05	2.9874991E 02
68500.	6.9628181E-04	2.2134183E 02	2.2134183E 02	1.0958706E-04	1.3206667E-01	1.4472799E-05	2.9824749E 02
68750.	6.7049399E-04	2.2059755E 02	2.2059755E 02	1.0588440E-04	1.3630186E-01	1.4432241E-05	2.9774563E 02
69000.	6.4558010E-04	2.1985545E 02	2.1985545E 02	1.0229411E-04	1.4068984E-01	1.4391743E-05	2.9724439E 02
69250.	6.2151386E-04	2.1911562E 02	2.1911562E 02	9.8813258E-05	1.4523667E-01	1.4351309E-05	2.9674385E 02
69500.	5.9826908E-04	2.1837805E 02	2.1837805E 02	9.5438879E-05	1.4994875E-01	1.4310941E-05	2.9624399E 02
69750.	5.7582031E-04	2.1764278E 02	2.1764278E 02	9.2168063E-05	1.5483280E-01	1.4270640E-05	2.9574485E 02
70000.	5.5414297E-04	2.1690992E 02	2.1690992E 02	8.8997983E-05	1.5989589E-01	1.4230412E-05	2.9524650E 02
70250.	5.3321321E-04	2.1617939E 02	2.1617939E 02	8.5925955E-05	1.6514514E-01	1.4190254E-05	2.9474890E 02
70500.	5.1300769E-04	2.1545138E 02	2.1545138E 02	8.2949228E-05	1.7058841E-01	1.4150177E-05	2.9425218E 02
70750.	4.9350380E-04	2.1472581E 02	2.1472581E 02	8.0065238E-05	1.7623349E-01	1.4110177E-05	2.9375629E 02
71000.	4.7467952E-04	2.1400271E 02	2.1400271E 02	7.7271433E-05	1.8208870E-01	1.4070255E-05	2.9326126E 02
71250.	4.5651352E-04	2.1328214E 02	2.1328214E 02	7.4565325E-05	1.8816272E-01	1.4030415E-05	2.9276712E 02
71500.	4.3898500E-04	2.1256401E 02	2.1256401E 02	7.1944517E-05	1.9446448E-01	1.3990653E-05	2.9227382E 02
71750.	4.2207370E-04	2.1184835E 02	2.1184835E 02	6.9406629E-05	2.0100344E-01	1.3950971E-05	2.9178139E 02

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE RATIO	DENSITY RATIO	VISCOSITY RATIO	MOLECULAR WEIGHT	PRESSURE DIFFERENCE
meters	unitless	unitless	unitless	unitless	newtons cm^{-2}
54000.	5.0690643E-04	5.7668378E-04	9.1028678E-01	2.8964400E 01	1.0164992E 01
54250.	4.9097988E-04	5.5978708E-04	9.0870485E-01		1.0165154E 01
54500.	4.7552003E-04	5.4337127E-04	9.0709243E-01		1.0165311E 01
54750.	4.6051375E-04	5.2742183E-04	9.0545042E-01		1.0165464E 01
55000.	4.4594829E-04	5.1192483E-04	9.0377960E-01		1.0165612E 01
55250.	4.3181145E-04	4.9686704E-04	9.0208077E-01		1.0165755E 01
55500.	4.1809098E-04	4.8223513E-04	9.0035490E-01		1.0165895E 01
55750.	4.0477541E-04	4.6801682E-04	8.9860260E-01		1.0166030E 01
56000.	3.9185332E-04	4.5419992E-04	8.9682474E-01		1.0166162E 01
56250.	3.7931373E-04	4.4077271E-04	8.9502219E-01		1.0166289E 01
56500.	3.6714590E-04	4.2772378E-04	8.9319574E-01		1.0166413E 01
56750.	3.5533945E-04	4.1504229E-04	8.9134611E-01		1.0166533E 01
57000.	3.4388426E-04	4.0271766E-04	8.8947403E-01		1.0166650E 01
57250.	3.3277048E-04	3.9073956E-04	8.8758039E-01		1.0166763E 01
57500.	3.2198857E-04	3.7909814E-04	8.8566595E-01		1.0166872E 01
57750.	3.1152927E-04	3.6778390E-04	8.8373126E-01		1.0166979E 01
58000.	3.0138347E-04	3.5678740E-04	8.8177731E-01		1.0167082E 01
58250.	2.9154242E-04	3.4609972E-04	8.7980474E-01		1.0167182E 01
58500.	2.8199755E-04	3.3571214E-04	8.7781430E-01		1.0167279E 01
58750.	2.7274061E-04	3.2561634E-04	8.7580669E-01		1.0167373E 01
59000.	2.6376350E-04	3.1580411E-04	8.7378265E-01		1.0167464E 01
59250.	2.5505827E-04	3.0626749E-04	8.7174278E-01		1.0167553E 01
59500.	2.4661739E-04	2.9699894E-04	8.6968786E-01		1.0167639E 01
59750.	2.3843336E-04	2.8799093E-04	8.6761861E-01		1.0167722E 01
60000.	2.3049894E-04	2.7923629E-04	8.6553571E-01		1.0167803E 01
60250.	2.2280707E-04	2.7072799E-04	8.6343989E-01		1.0167881E 01
60500.	2.1535097E-04	2.6245942E-04	8.6133162E-01		1.0167957E 01
60750.	2.0812393E-04	2.5442392E-04	8.5921162E-01		1.0168030E 01
61000.	2.0111943E-04	2.4661506E-04	8.5708065E-01		1.0168101E 01
61250.	1.9433122E-04	2.3902681E-04	8.5493916E-01		1.0168171E 01
61500.	1.8775312E-04	2.3165306E-04	8.5278798E-01		1.0168238E 01
61750.	1.8137920E-04	2.2448806E-04	8.5062753E-01		1.0168302E 01
62000.	1.7520362E-04	2.1752612E-04	8.4845861E-01	MOLECULAR WEIGHT CONSTANT TO 90,000 METERS	1.0168365E 01
62250.	1.6922068E-04	2.1076172E-04	8.4628174E-01		1.0168426E 01
62500.	1.6342490E-04	2.0418957E-04	8.4409732E-01		1.0168485E 01
62750.	1.5781101E-04	1.9780458E-04	8.4190620E-01		1.0168542E 01
63000.	1.5237367E-04	1.9160163E-04	8.3970866E-01		1.0168597E 01
63250.	1.4710784E-04	1.8557580E-04	8.3750552E-01		1.0168651E 01
63500.	1.4200859E-04	1.7972236E-04	8.3529718E-01		1.0168703E 01
63750.	1.3707117E-04	1.7403681E-04	8.3308420E-01		1.0168753E 01
64000.	1.3229081E-04	1.6851453E-04	8.3086702E-01		1.0168802E 01
64250.	1.2766301E-04	1.6315121E-04	8.2864624E-01		1.0168849E 01
64500.	1.2318333E-04	1.5794259E-04	8.2642241E-01		1.0168894E 01
64750.	1.1884746E-04	1.5288455E-04	8.2419587E-01		1.0168938E 01
65000.	1.1465120E-04	1.4797314E-04	8.2196686E-01		1.0168981E 01
65250.	1.1059041E-04	1.4320426E-04	8.1973635E-01		1.0169022E 01
65500.	1.0666126E-04	1.3857435E-04	8.1750449E-01		1.0169062E 01
65750.	1.0285976E-04	1.3407958E-04	8.1527168E-01		1.0169101E 01
66000.	9.9182203E-05	1.2971638E-04	8.1303844E-01		1.0169138E 01
66250.	9.5624859E-05	1.2548116E-04	8.1080512E-01		1.0169174E 01
66500.	9.2184241E-05	1.2137064E-04	8.0857201E-01		1.0169210E 01
66750.	8.8856859E-05	1.1738146E-04	8.0633949E-01		1.0169243E 01
67000.	8.5639302E-05	1.1351028E-04	8.0410815E-01		1.0169276E 01
67250.	8.2528344E-05	1.0975408E-04	8.0187805E-01		1.0169308E 01
67500.	7.9520754E-05	1.0610972E-04	7.9964957E-01		1.0169338E 01
67750.	7.6613433E-05	1.0257420E-04	7.9742320E-01		1.0169368E 01
68000.	7.3803384E-05	9.9144681E-05	7.9519892E-01		1.0169396E 01
68250.	7.1087601E-05	9.5818192E-05	7.9297726E-01		1.0169424E 01
68500.	6.8463297E-05	9.2592089E-05	7.9075834E-01		1.0169451E 01
68750.	6.5927658E-05	8.9463636E-05	7.8854234E-01		1.0169477E 01
69000.	6.3477950E-05	8.6430142E-05	7.8632962E-01		1.0169501E 01
69250.	6.1111588E-05	8.3489105E-05	7.8412042E-01		1.0169525E 01
69500.	5.8826000E-05	8.0638031E-05	7.8191479E-01		1.0169549E 01
69750.	5.6618680E-05	7.7874460E-05	7.7971284E-01		1.0169571E 01
70000.	5.4487212E-05	7.5196002E-05	7.7751489E-01		1.0169593E 01
70250.	5.2429252E-05	7.2600390E-05	7.7532077E-01		1.0169614E 01
70500.	5.0442504E-05	7.0085300E-05	7.7313105E-01		1.0169634E 01
70750.	4.8524745E-05	6.7648565E-05	7.7094553E-01		1.0169654E 01
71000.	4.6673810E-05	6.5288028E-05	7.6876431E-01		1.0169672E 01
71250.	4.4887602E-05	6.3001588E-05	7.6658753E-01		1.0169691E 01
71500.	4.3164076E-05	6.0787221E-05	7.6441507E-01		1.0169708E 01
71750.	4.1501238E-05	5.8642914E-05	7.6224694E-01	2.8964400E 01	1.0169725E 01

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE	KINETIC TEMPERATURE	VIRTUAL TEMPERATURE	DENSITY	KINEMATIC VISCOSITY	COEFFICIENT OF VISCOSITY	SPEED OF SOUND
meters	newtons cm⁻²	degrees K	degrees K	kg m⁻³	m² sec⁻¹	newton-sec m⁻²	m sec⁻¹
72000.	4.0576003E-04	2.1113518E 02	2.1113518E 02	6.6949356E-05	2.0778947E-01	1.3911371E-05	2.9128985E 02
72250.	3.9002491E-04	2.1042441E 02	2.1042441E 02	6.4570475E-05	2.1483266E-01	1.3871847E-05	2.9079913E 02
72500.	3.7484991E-04	2.0971612E 02	2.0971612E 02	6.2267774E-05	2.2214388E-01	1.3832405E-05	2.9030931E 02
72750.	3.6021682E-04	2.0901017E 02	2.0901017E 02	6.0039119E-05	2.2973417E-01	1.3793037E-05	2.8982028E 02
73000.	3.4610846E-04	2.0830656E 02	2.0830656E 02	5.7882463E-05	2.3761504E-01	1.3753744E-05	2.8933204E 02
73250.	3.3250751E-04	2.0760531E 02	2.0760531E 02	5.5795702E-05	2.4579899E-01	1.3714527E-05	2.8884462E 02
73500.	3.1939768E-04	2.0690623E 02	2.0690623E 02	5.3776921E-05	2.5429823E-01	1.3675376E-05	2.8835789E 02
73750.	3.0676280E-04	2.0620942E 02	2.0620942E 02	5.1824119E-05	2.6312645E-01	1.3636297E-05	2.8787192E 02
74000.	2.9458748E-04	2.0551462E 02	2.0551462E 02	4.9935490E-05	2.7229680E-01	1.3597275E-05	2.8738653E 02
74250.	2.8285647E-04	2.0482191E 02	2.0482191E 02	4.8109125E-05	2.8182420E-01	1.3558316E-05	2.8690179E 02
74500.	2.7155515E-04	2.0413113E 02	2.0413113E 02	4.6343256E-05	2.9172336E-01	1.3519410E-05	2.8641758E 02
74750.	2.6066926E-04	2.0344220E 02	2.0344220E 02	4.4636129E-05	3.0200992E-01	1.3480554E-05	2.8593385E 02
75000.	2.5018505E-04	2.0275499E 02	2.0275499E 02	4.2986051E-05	3.1270005E-01	1.3441740E-05	2.8545051E 02
75250.	2.4008915E-04	2.0206947E 02	2.0206947E 02	4.1391349E-05	3.2381085E-01	1.3402968E-05	2.8496755E 02
75500.	2.3036834E-04	2.0138545E 02	2.0138545E 02	3.9850378E-05	3.3536007E-01	1.3364226E-05	2.8448482E 02
75750.	2.2101015E-04	2.0070282E 02	2.0070282E 02	3.8361580E-05	3.4736598E-01	1.3325508E-05	2.8400225E 02
76000.	2.1200230E-04	2.0002147E 02	2.0002147E 02	3.6923403E-05	3.5984789E-01	1.3286809E-05	2.8351977E 02
76250.	2.0333298E-04	1.9934132E 02	1.9934132E 02	3.5534339E-05	3.7282595E-01	1.3248124E-05	2.8303733E 02
76500.	1.9499040E-04	1.9866205E 02	1.9866205E 02	3.4192910E-05	3.8632084E-01	1.3209434E-05	2.8255468E 02
76750.	1.8696371E-04	1.9798364E 02	1.9798364E 02	3.2897717E-05	4.0035419E-01	1.3170739E-05	2.8207183E 02
77000.	1.7924187E-04	1.9730592E 02	1.9730592E 02	3.1647331E-05	4.1494902E-01	1.3132029E-05	2.8158863E 02
77250.	1.7181453E-04	1.9662865E 02	1.9662865E 02	3.0440435E-05	4.3012822E-01	1.3093290E-05	2.8110492E 02
77500.	1.6467127E-04	1.9595169E 02	1.9595169E 02	2.9275652E-05	4.4591716E-01	1.3054515E-05	2.8062060E 02
77750.	1.5780237E-04	1.9527487E 02	1.9527487E 02	2.8151717E-05	4.6234101E-01	1.3015694E-05	2.8013555E 02
78000.	1.5119831E-04	1.9459798E 02	1.9459798E 02	2.7067389E-05	4.7942609E-01	1.2976813E-05	2.7964961E 02
78250.	1.4484968E-04	1.9392081E 02	1.9392081E 02	2.6021414E-05	4.9720054E-01	1.2937861E-05	2.7916261E 02
78500.	1.3874759E-04	1.9324316E 02	1.9324316E 02	2.5012613E-05	5.1569290E-01	1.2898827E-05	2.7867443E 02
78750.	1.3288332E-04	1.9256477E 02	1.9256477E 02	2.4039828E-05	5.3493286E-01	1.2859694E-05	2.7818485E 02
79000.	1.2724843E-04	1.9188547E 02	1.9188547E 02	2.3101922E-05	5.5495180E-01	1.2820453E-05	2.7769374E 02
79250.	1.2183471E-04	1.9120492E 02	1.9120492E 02	2.2197789E-05	5.7578186E-01	1.2781084E-05	2.7720097E 02
79500.	1.1663428E-04	1.9052299E 02	1.9052299E 02	2.1326351E-05	5.9745705E-01	1.2741579E-05	2.7670611E 02
79750.	1.1163954E-04	1.8983932E 02	1.8983932E 02	2.0486587E-05	6.2001130E-01	1.2701915E-05	2.7620920E 02
80000.	1.0684305E-04	1.8915372E 02	1.8915372E 02	1.9677466E-05	6.4348133E-01	1.2662082E-05	2.7570998E 02
80250.	1.0223758E-04	1.8846591E 02	1.8846591E 02	1.8897985E-05	6.6790522E-01	1.2622063E-05	2.7520826E 02
80500.	9.7816271E-05	1.8777551E 02	1.8777551E 02	1.8147211E-05	6.9332055E-01	1.2581835E-05	2.7470371E 02
80750.	9.3572375E-05	1.8708234E 02	1.8708234E 02	1.7424191E-05	7.1976859E-01	1.2541385E-05	2.7419621E 02
81000.	8.9499401E-05	1.8638606E 02	1.8638606E 02	1.6728017E-05	7.4729094E-01	1.2500695E-05	2.7368549E 02
81250.	8.5591011E-05	1.8568642E 02	1.8568642E 02	1.6057790E-05	7.7593164E-01	1.2459747E-05	2.7317133E 02
81500.	8.1841182E-05	1.8498297E 02	1.8498297E 02	1.5412671E-05	8.0573418E-01	1.2418516E-05	2.7265341E 02
81750.	7.8244016E-05	1.8427542E 02	1.8427542E 02	1.4791815E-05	8.3674524E-01	1.2376981E-05	2.7213146E 02
82000.	7.4793850E-05	1.8356358E 02	1.8356358E 02	1.4194402E-05	8.6901376E-01	1.2335131E-05	2.7160535E 02
82250.	7.1485156E-05	1.8284694E 02	1.8284694E 02	1.3619650E-05	9.0258818E-01	1.2292935E-05	2.7107464E 02
82500.	6.8312650E-05	1.8212515E 02	1.8212515E 02	1.3066791E-05	9.3751932E-01	1.2250370E-05	2.7053908E 02
82750.	6.5271214E-05	1.8139796E 02	1.8139796E 02	1.2535078E-05	9.7386069E-01	1.2207420E-05	2.6999844E 02
83000.	6.2355810E-05	1.8066486E 02	1.8066486E 02	1.2023779E-05	1.0116662E 00	1.2164052E-05	2.6945229E 02
83250.	5.9552895E-05	1.8065000E 02	1.8065000E 02	1.1484251E-05	1.0591176E 00	1.2163172E-05	2.6944122E 02
83500.	5.6875955E-05	1.8065000E 02	1.8065000E 02	1.0968027E-05	1.1089663E 00	1.2163172E-05	2.6944122E 02
83750.	5.4319540E-05	1.8065000E 02	1.8065000E 02	1.0475044E-05	1.1611571E 00	1.2163172E-05	2.6944122E 02
84000.	5.1878215E-05	1.8065000E 02	1.8065000E 02	1.0004256E-05	1.2157997E 00	1.2163172E-05	2.6944122E 02
84250.	4.9546789E-05	1.8065000E 02	1.8065000E 02	9.5546614E-06	1.2730092E 00	1.2163172E-05	2.6944122E 02
84500.	4.7320307E-05	1.8065000E 02	1.8065000E 02	9.1253040E-06	1.3329060E 00	1.2163172E-05	2.6944122E 02
84750.	4.5194038E-05	1.8065000E 02	1.8065000E 02	8.7152717E-06	1.3956160E 00	1.2163172E-05	2.6944122E 02
85000.	4.3163465E-05	1.8065000E 02	1.8065000E 02	8.3236936E-06	1.4612710E 00	1.2163172E-05	2.6944122E 02
85250.	4.1224272E-05	1.8065000E 02	1.8065000E 02	7.9497374E-06	1.5300093E 00	1.2163172E-05	2.6944122E 02
85500.	3.9372342E-05	1.8065000E 02	1.8065000E 02	7.5926090E-06	1.6019753E 00	1.2163172E-05	2.6944122E 02
85750.	3.7603741E-05	1.8065000E 02	1.8065000E 02	7.2515500E-06	1.6773203E 00	1.2163172E-05	2.6944122E 02
86000.	3.5914714E-05	1.8065000E 02	1.8065000E 02	6.9258360E-06	1.7562028E 00	1.2163172E-05	2.6944122E 02
86250.	3.4301675E-05	1.8065000E 02	1.8065000E 02	6.6147756E-06	1.8387883E 00	1.2163172E-05	2.6944122E 02
86500.	3.2761198E-05	1.8065000E 02	1.8065000E 02	6.3177083E-06	1.9252507E 00	1.2163172E-05	2.6944122E 02
86750.	3.1290016E-05	1.8065000E 02	1.8065000E 02	6.0340037E-06	2.0157714E 00	1.2163172E-05	2.6944122E 02
87000.	2.9885006E-05	1.8065000E 02	1.8065000E 02	5.7630599E-06	2.1105407E 00	1.2163172E-05	2.6944122E 02
87250.	2.8543187E-05	1.8065000E 02	1.8065000E 02	5.5043019E-06	2.2097574E 00	1.2163172E-05	2.6944122E 02
87500.	2.7261712E-05	1.8065000E 02	1.8065000E 02	5.2571808E-06	2.3136302E 00	1.2163172E-05	2.6944122E 02
87750.	2.6037863E-05	1.8065000E 02	1.8065000E 02	5.0211724E-06	2.4223769E 00	1.2163172E-05	2.6944122E 02
88000.	2.4869045E-05	1.8065000E 02	1.8065000E 02	4.7957760E-06	2.5362261E 00	1.2163172E-05	2.6944122E 02
88250.	2.3752779E-05	1.8065000E 02	1.8065000E 02	4.5805140E-06	2.6554165E 00	1.2163172E-05	2.6944122E 02
88500.	2.2686698E-05	1.8065000E 02	1.8065000E 02	4.3749296E-06	2.7801984E 00	1.2163172E-05	2.6944122E 02
88750.	2.1668542E-05	1.8065000E 02	1.8065000E 02	4.1785873E-06	2.9108335E 00	1.2163172E-05	2.6944122E 02
89000.	2.0696155E-05	1.8065000E 02	1.8065000E 02	3.9910710E-06	3.0475960E 00	1.2163172E-05	2.6944122E 02
89250.	1.9767475E-05	1.8065000E 02	1.8065000E 02	3.8119832E-06	3.1907728E 00	1.2163172E-05	2.6944122E 02
89500.	1.8880533E-05	1.8065000E 02	1.8065000E 02	3.6409443E-06	3.3406642E 00	1.2163172E-05	2.6944122E 02
89750.	1.8033452E-05	1.8065000E 02	1.8065000E 02	3.4775922E-06	3.4975844E 00	1.2163172E-05	2.6944122E 02

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE RATIO	DENSITY RATIO	VISCOSITY RATIO	MOLECULAR WEIGHT	PRESSURE DIFFERENCE
meters	unitless	unitless	unitless	unitless	newtons cm⁻²
72000.	3.9897164E-05	5.6566718E-05	7.6008329E-01	2.8964400E 01	1.0169741E 01
72250.	3.8349976E-05	5.4556759E-05	7.5792378E-01	MOLECULAR WEIGHT CONSTANT TO 90,000 METERS	1.0169757E 01
72500.	3.6857865E-05	5.2611166E-05	7.5576879E-01		1.0169772E 01
72750.	3.5419037E-05	5.0728135E-05	7.5361782E-01		1.0169787E 01
73000.	3.4031804E-05	4.8905938E-05	7.5147093E-01		1.0169801E 01
73250.	3.2694463E-05	4.7142795E-05	7.4932821E-01		1.0169815E 01
73500.	3.1405413E-05	4.5437091E-05	7.4718909E-01		1.0169828E 01
73750.	3.0163064E-05	4.3787133E-05	7.4505390E-01		1.0169840E 01
74000.	2.8965901E-05	4.2191396E-05	7.4292182E-01		1.0169852E 01
74250.	2.7812427E-05	4.0648267E-05	7.4079321E-01		1.0169864E 01
74500.	2.6701201E-05	3.9156253E-05	7.3866751E-01		1.0169875E 01
74750.	2.5630825E-05	3.7713871E-05	7.3654450E-01		1.0169886E 01
75000.	2.4599944E-05	3.6319690E-05	7.3442382E-01		1.0169897E 01
75250.	2.3607244E-05	3.4972298E-05	7.3230540E-01		1.0169907E 01
75500.	2.2651426E-05	3.3670304E-05	7.3018862E-01		1.0169917E 01
75750.	2.1731263E-05	3.2412392E-05	7.2807317E-01		1.0169926E 01
76000.	2.0845549E-05	3.1197249E-05	7.2595872E-01		1.0169935E 01
76250.	1.9993120E-05	3.0023604E-05	7.2384508E-01		1.0169944E 01
76500.	1.9172819E-05	2.8890207E-05	7.2173114E-01		1.0169952E 01
76750.	1.8383580E-05	2.7795874E-05	7.1961697E-01		1.0169960E 01
77000.	1.7624314E-05	2.6739401E-05	7.1750195E-01		1.0169968E 01
77250.	1.6894006E-05	2.5719673E-05	7.1538536E-01		1.0169975E 01
77500.	1.6191631E-05	2.4735526E-05	7.1326679E-01		1.0169982E 01
77750.	1.5516232E-05	2.3785894E-05	7.1114566E-01		1.0169989E 01
78000.	1.4866875E-05	2.2869726E-05	7.0902130E-01		1.0169996E 01
78250.	1.4242634E-05	2.1985962E-05	7.0689307E-01		1.0170002E 01
78500.	1.3642633E-05	2.1133608E-05	7.0476035E-01		1.0170008E 01
78750.	1.3066017E-05	2.0311685E-05	7.0262225E-01		1.0170014E 01
79000.	1.2511956E-05	1.9519231E-05	7.0047820E-01		1.0170020E 01
79250.	1.1979641E-05	1.8755312E-05	6.9832718E-01		1.0170025E 01
79500.	1.1468298E-05	1.8019019E-05	6.9616869E-01		1.0170030E 01
79750.	1.0977180E-05	1.7309487E-05	6.9400159E-01		1.0170035E 01
80000.	1.0505556E-05	1.6625846E-05	6.9182519E-01		1.0170040E 01
80250.	1.0052714E-05	1.5967249E-05	6.8963866E-01		1.0170045E 01
80500.	9.6179799E-06	1.5332906E-05	6.8744068E-01		1.0170049E 01
80750.	9.2006903E-06	1.4722013E-05	6.8523062E-01		1.0170054E 01
81000.	8.8002070E-06	1.4133803E-05	6.8300741E-01		1.0170058E 01
81250.	8.4159068E-06	1.3567517E-05	6.8077012E-01		1.0170061E 01
81500.	8.0471972E-06	1.3022443E-05	6.7851731E-01		1.0170065E 01
81750.	7.6934987E-06	1.2497872E-05	6.7624797E-01		1.0170069E 01
82000.	7.3542544E-06	1.1993107E-05	6.7396140E-01		1.0170072E 01
82250.	7.0289205E-06	1.1507488E-05	6.7165588E-01		1.0170076E 01
82500.	6.7169775E-06	1.1040368E-05	6.6933023E-01		1.0170079E 01
82750.	6.4179222E-06	1.0591113E-05	6.6698355E-01		1.0170082E 01
83000.	6.1312594E-06	1.0159108E-05	6.6461403E-01		1.0170085E 01
83250.	5.8556570E-06	9.7032506E-06	6.6456598E-01		1.0170088E 01
83500.	5.5924417E-06	9.2670836E-06	6.6456598E-01		1.0170090E 01
83750.	5.3410771E-06	8.8505540E-06	6.6456598E-01		1.0170093E 01
84000.	5.1010289E-06	8.4527768E-06	6.6456598E-01		1.0170095E 01
84250.	4.8717868E-06	8.0729058E-06	6.6456598E-01		1.0170098E 01
84500.	4.6528635E-06	7.7101340E-06	6.6456598E-01		1.0170100E 01
84750.	4.4437939E-06	7.3636903E-06	6.6456598E-01		1.0170102E 01
85000.	4.2441337E-06	7.0328389E-06	6.6456598E-01		1.0170104E 01
85250.	4.0534588E-06	6.7168766E-06	6.6456598E-01		1.0170106E 01
85500.	3.8713640E-06	6.4151324E-06	6.6456598E-01		1.0170108E 01
85750.	3.6974628E-06	6.1269654E-06	6.6456598E-01		1.0170109E 01
86000.	3.5313858E-06	5.8517637E-06	6.6456598E-01		1.0170111E 01
86250.	3.3727806E-06	5.5889432E-06	6.6456598E-01		1.0170113E 01
86500.	3.2213101E-06	5.3379458E-06	6.6456598E-01		1.0170114E 01
86750.	3.0766532E-06	5.0982386E-06	6.6456598E-01		1.0170116E 01
87000.	2.9385028E-06	4.8693133E-06	6.6456598E-01		1.0170117E 01
87250.	2.8065657E-06	4.6506840E-06	6.6456598E-01		1.0170119E 01
87500.	2.6805622E-06	4.4418869E-06	6.6456598E-01		1.0170120E 01
87750.	2.5602248E-06	4.2424792E-06	6.6456598E-01		1.0170121E 01
88000.	2.4452984E-06	4.0520377E-06	6.6456598E-01		1.0170122E 01
88250.	2.3355393E-06	3.8701589E-06	6.6456598E-01		1.0170123E 01
88500.	2.2307148E-06	3.6964570E-06	6.6456598E-01		1.0170124E 01
88750.	2.1306026E-06	3.5305638E-06	6.6456598E-01		1.0170125E 01
89000.	2.0349907E-06	3.3721274E-06	6.6456598E-01		1.0170126E 01
89250.	1.9436763E-06	3.2208134E-06	6.6456598E-01		1.0170127E 01
89500.	1.8564660E-06	3.0762995E-06	6.6456598E-01		1.0170128E 01
89750.	1.7731751E-06	2.9382804E-06	6.6456598E-01	2.8964400E 01	1.0170129E 01

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE	KINETIC TEMPERATURE	MOLECULAR TEMPERATURE	DENSITY	COEFFICIENT OF VISCOSITY	SPEED OF SOUND
meters	newtons cm^{-2}	degrees K	degrees K	kg m^{-3}	newton-sec m^{-2}	m sec^{-1}
90000.	1.7224435E-05	1.8065000E 02	1.8065000E 02	3.3215805E-06	1.2163172E-05	2.6944122E 02
91000.	1.4357534E-05	1.8359648E 02	1.8365000E 02	2.7234957E-06	1.2340215E-05	2.7166927E 02
92000.	1.2003841E-05	1.8654122E 02	1.8665000E 02	2.2404228E-06	1.2516126E-05	2.7387919E 02
93000.	1.0065252E-05	1.8948421E 02	1.8965000E 02	1.8488836E-06	1.2690921E-05	2.7607143E 02
94000.	8.4635721E-06	1.9242545E 02	1.9265000E 02	1.5304616E-06	1.2864614E-05	2.7824640E 02
95000.	7.1362419E-06	1.9536494E 02	1.9565000E 02	1.2706545E-06	1.3037217E-05	2.8040450E 02
96000.	6.0330423E-06	1.9830268E 02	1.9865000E 02	1.0579997E-06	1.3208747E-05	2.8254611E 02
97000.	5.1135173E-06	2.0123868E 02	2.0165000E 02	8.8340379E-07	1.3379216E-05	2.8467161E 02
98000.	4.3449711E-06	2.0417293E 02	2.0465000E 02	7.3962724E-07	1.3548638E-05	2.8678136E 02
99000.	3.7008921E-06	2.0710543E 02	2.0765000E 02	6.2088653E-07	1.3717028E-05	2.8887571E 02
100000.	3.1597170E-06	2.1003618E 02	2.1065000E 02	5.2254595E-07	1.3884397E-05	2.9095497E 02
101000.	2.7057645E-06	2.1478336E 02	2.1565000E 02	4.3709746E-07	1.4161117E-05	2.9438778E 02
102000.	2.3253935E-06	2.1951949E 02	2.2065000E 02	3.6713880E-07	1.4435101E-05	2.9778102E 02
103000.	2.0053844E-06	2.2424457E 02	2.2565000E 02	3.0959935E-07	1.4706408E-05	3.0113603E 02
104000.	1.7351148E-06	2.2895861E 02	2.3065000E 02	2.6206711E-07	1.4975097E-05	3.0445407E 02
105000.	1.5060075E-06	2.3366159E 02	2.3565000E 02	2.2263706E-07	1.5241223E-05	3.0773633E 02
106000.	1.3111039E-06	2.3835353E 02	2.4065000E 02	1.8979684E-07	1.5504842E-05	3.1098395E 02
107000.	1.1447335E-06	2.4303442E 02	2.4565000E 02	1.6233993E-07	1.5766006E-05	3.1419801E 02
108000.	1.0022554E-06	2.4770427E 02	2.5065000E 02	1.3929915E-07	1.6024767E-05	3.1737952E 02
109000.	8.7985634E-07	2.5236306E 02	2.5565000E 02	1.1989573E-07	1.6281177E-05	3.2052946E 02
110000.	7.7438980E-07	2.5701081E 02	2.6065000E 02	1.0349983E-07	1.6535285E-05	3.2364874E 02
111000.	6.8403258E-07	2.6641332E 02	2.7065000E 02	8.8045367E-08	1.7036783E-05	3.2979880E 02
112000.	6.0696757E-07	2.7578200E 02	2.8065000E 02	7.5342182E-08	1.7529632E-05	3.3583625E 02
113000.	5.4086384E-07	2.8511684E 02	2.9065000E 02	6.4826916E-08	1.8014180E-05	3.4176707E 02
114000.	4.8386073E-07	2.9441785E 02	3.0065000E 02	5.6065657E-08	1.8490756E-05	3.4759671E 02
115000.	4.3446125E-07	3.0368503E 02	3.1065000E 02	4.8721141E-08	1.8959675E-05	3.5333018E 02
116000.	3.9145232E-07	3.1291837E 02	3.2065000E 02	4.2529020E-08	1.9421230E-05	3.5897208E 02
117000.	3.5384426E-07	3.2211787E 02	3.3065000E 02	3.7280470E-08	1.9875702E-05	3.6452667E 02
118000.	3.2082435E-07	3.3128354E 02	3.4065000E 02	3.2809278E-08	2.0323355E-05	3.6999789E 02
119000.	2.9172118E-07	3.4041538E 02	3.5065000E 02	2.8982235E-08	2.0764441E-05	3.7538938E 02
120000.	2.6597710E-07	3.4951338E 02	3.6065000E 02	2.5691890E-08	2.1199197E-05	3.8070451E 02
121000.	2.4341101E-07	3.6839206E 02	3.8065000E 02	2.2276765E-08	2.2050607E-05	3.9111815E 02
122000.	2.2377934E-07	3.8721781E 02	4.0065000E 02	1.9457748E-08	2.2879253E-05	4.0126162E 02
123000.	2.0658100E-07	4.0599062E 02	4.2065000E 02	1.7108315E-08	2.3686639E-05	4.1115493E 02
124000.	1.9141913E-07	4.2471051E 02	4.4065000E 02	1.5133149E-08	2.4474125E-05	4.2081570E 02
125000.	1.7797572E-07	4.4337744E 02	4.6065000E 02	1.3459454E-08	2.5242944E-05	4.3025962E 02
126000.	1.6599345E-07	4.6199146E 02	4.8065000E 02	1.2030946E-08	2.5994216E-05	4.3950065E 02
127000.	1.5526215E-07	4.8055254E 02	5.0065000E 02	1.0803615E-08	2.6728963E-05	4.4855134E 02
128000.	1.4560872E-07	4.9906068E 02	5.2065000E 02	9.7426983E-09	2.7448117E-05	4.5742298E 02
129000.	1.3688945E-07	5.1751589E 02	5.4065000E 02	8.8204658E-09	2.8152533E-05	4.6612582E 02
130000.	1.2898417E-07	5.3591816E 02	5.6065000E 02	8.0146089E-09	2.8842997E-05	4.7466910E 02
131000.	1.2179175E-07	5.5426750E 02	5.8065000E 02	7.3070349E-09	2.9520227E-05	4.8306132E 02
132000.	1.1522650E-07	5.7256391E 02	6.0065000E 02	6.6829568E-09	3.0184890E-05	4.9131021E 02
133000.	1.0921551E-07	5.9080738E 02	6.2065000E 02	6.1302094E-09	3.0837601E-05	4.9942288E 02
134000.	1.0369626E-07	6.0899793E 02	6.4065000E 02	5.6387136E-09	3.1478926E-05	5.0740585E 02
135000.	9.8615005E-08	6.2713553E 02	6.6065000E 02	5.2000715E-09	3.2109396E-05	5.1526515E 02
136000.	9.3925204E-08	6.4522020E 02	6.8065000E 02	4.8072428E-09	3.2729499E-05	5.2300637E 02
137000.	8.9586500E-08	6.6325194E 02	7.0065000E 02	4.4542972E-09	3.3339691E-05	5.3063467E 02
138000.	8.5563661E-08	6.8123074E 02	7.2065000E 02	4.1362113E-09	3.3940400E-05	5.3815483E 02
139000.	8.1825829E-08	6.9915662E 02	7.4065000E 02	3.8487096E-09	3.4532020E-05	5.4557136E 02
140000.	7.8345911E-08	7.1702955E 02	7.6065000E 02	3.5881386E-09	3.5114925E-05	5.5288841E 02
141000.	7.5100009E-08	7.3484955E 02	7.8065000E 02	3.3513623E-09	3.5689461E-05	5.6010988E 02
142000.	7.2066944E-08	7.5261663E 02	8.0065000E 02	3.1356758E-09	3.6255956E-05	5.6723942E 02
143000.	6.9227957E-08	7.7033076E 02	8.2064999E 02	2.9387408E-09	3.6814717E-05	5.7428046E 02
144000.	6.6566336E-08	7.8799196E 02	8.4065000E 02	2.7585267E-09	3.7366033E-05	5.8123620E 02
145000.	6.4067172E-08	8.0560023E 02	8.6064999E 02	2.5932640E-09	3.7910175E-05	5.8810970E 02
146000.	6.1717079E-08	8.2315556E 02	8.8065000E 02	2.4414047E-09	3.8447399E-05	5.9490377E 02
147000.	5.9504086E-08	8.4065795E 02	9.0065000E 02	2.3015928E-09	3.8977947E-05	6.0162112E 02
148000.	5.7417393E-08	8.5810742E 02	9.2064999E 02	2.1726345E-09	3.9502050E-05	6.0826430E 02
149000.	5.5447274E-08	8.7550395E 02	9.4065000E 02	2.0534772E-09	4.0019922E-05	6.1483570E 02
150000.	5.3584943E-08	8.9284424E 02	9.6064999E 02	1.9431903E-09	4.0531768E-05	6.2133762E 02
151000.	5.1813260E-08	9.0590969E 02	9.7565000E 02	1.8500549E-09	4.0911817E-05	6.2616974E 02
152000.	5.0126367E-08	9.1894822E 02	9.9065000E 02	1.7627216E-09	4.1288666E-05	6.3096486E 02
153000.	4.8519017E-08	9.3195982E 02	1.0056500E 03	1.6807491E-09	4.1662388E-05	6.3572381E 02
154000.	4.6986357E-08	9.4494449E 02	1.0206500E 03	1.6037353E-09	4.2033057E-05	6.4044740E 02
155000.	4.5523880E-08	9.5790220E 02	1.0356500E 03	1.5313132E-09	4.2400743E-05	6.4513641E 02
156000.	4.4127423E-08	9.7083302E 02	1.0506500E 03	1.4631480E-09	4.2765514E-05	6.4979159E 02
157000.	4.2793123E-08	9.8373690E 02	1.0656500E 03	1.3989338E-09	4.3127434E-05	6.5441364E 02
158000.	4.1517377E-08	9.9661385E 02	1.0806500E 03	1.3383898E-09	4.3486565E-05	6.5900328E 02
159000.	4.0296878E-08	1.0094639E 03	1.0956500E 03	1.2812601E-09	4.3842970E-05	6.6356118E 02

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE RATIO	DENSITY RATIO	VISCOSITY RATIO	MOLECULAR WEIGHT	PRESSURE DIFFERENCE
meters	unitless	unitless	unitless	unitless	newtons cm^{-2}
90000.	1.6936269E-06	2.8064633E-06	6.6456598E-01	2.8964400E 01	1.0170130E 01
91000.	1.4117332E-06	2.3011306E-06	6.7423916E-01	2.8955960E 01	1.0170133E 01
92000.	1.1803016E-06	1.8929737E-06	6.8385054E-01	2.8947520E 01	1.0170135E 01
93000.	9.8968600E-07	1.5621551E-06	6.9340090E-01	2.8939080E 01	1.0170137E 01
94000.	8.3219761E-07	1.2931146E-06	7.0289101E-01	2.8930640E 01	1.0170139E 01
95000.	7.0168521E-07	1.0735989E-06	7.1232166E-01	2.8922200E 01	1.0170140E 01
96000.	5.9321091E-07	8.9392306E-07	7.2169362E-01	2.8913760E 01	1.0170141E 01
97000.	5.0279678E-07	7.4640381E-07	7.3100764E-01	2.8905320E 01	1.0170142E 01
98000.	4.2722794E-07	6.2492440E-07	7.4026446E-01	2.8896880E 01	1.0170143E 01
99000.	3.6389759E-07	5.2459823E-07	7.4946484E-01	2.8888440E 01	1.0170143E 01
100000.	3.1068547E-07	4.4150850E-07	7.5860950E-01	2.8880000E 01	1.0170144E 01
101000.	2.6604969E-07	3.6931154E-07	7.7372877E-01	2.8848000E 01	1.0170144E 01
102000.	2.2864895E-07	3.1020220E-07	7.8869860E-01	2.8816000E 01	1.0170145E 01
103000.	1.9718342E-07	2.6158608E-07	8.0352218E-01	2.8784000E 01	1.0170145E 01
104000.	1.7060862E-07	2.2142523E-07	8.1820267E-01	2.8752000E 01	1.0170145E 01
105000.	1.4808119E-07	1.8811007E-07	8.3274316E-01	2.8720000E 01	1.0170145E 01
106000.	1.2891690E-07	1.6036277E-07	8.4714662E-01	2.8688000E 01	1.0170146E 01
107000.	1.1255820E-07	1.3716394E-07	8.6141597E-01	2.8656000E 01	1.0170146E 01
108000.	9.8548763E-08	1.1769636E-07	8.7555408E-01	2.8624000E 01	1.0170146E 01
109000.	8.6513629E-08	1.0130207E-07	8.8956368E-01	2.8592000E 01	1.0170146E 01
110000.	7.6143421E-08	8.7448876E-08	9.0344751E-01	2.8560000E 01	1.0170146E 01
111000.	6.7258868E-08	7.4391119E-08	9.3084816E-01	2.8511000E 01	1.0170146E 01
112000.	5.9681296E-08	6.3657969E-08	9.5777620E-01	2.8462000E 01	1.0170146E 01
113000.	5.3181515E-08	5.4773431E-08	9.8425070E-01	2.8413000E 01	1.0170147E 01
114000.	4.7576571E-08	4.7370886E-08	1.0102897E 00	2.8364000E 01	1.0170147E 01
115000.	4.2719269E-08	4.1165371E-08	1.0359102E 00	2.8315000E 01	1.0170147E 01
116000.	3.8490330E-08	3.5933537E-08	1.0611285E 00	2.8266000E 01	1.0170147E 01
117000.	3.4792442E-08	3.1498941E-08	1.0859597E 00	2.8216999E 01	1.0170147E 01
118000.	3.1545694E-08	2.7721151E-08	1.1104184E 00	2.8167999E 01	1.0170147E 01
119000.	2.8684067E-08	2.4487613E-08	1.1345183E 00	2.8119000E 01	1.0170147E 01
120000.	2.6152728E-08	2.1707542E-08	1.1582723E 00	2.8070000E 01	1.0170147E 01
121000.	2.3933873E-08	1.8822041E-08	1.2047912E 00	2.8031670E 01	1.0170147E 01
122000.	2.2003549E-08	1.6440203E-08	1.2500664E 00	2.7993340E 01	1.0170147E 01
123000.	2.0312489E-08	1.4455124E-08	1.2941800E 00	2.7955009E 01	1.0170147E 01
124000.	1.8821667E-08	1.2786271E-08	1.3372063E 00	2.7916680E 01	1.0170147E 01
125000.	1.7499817E-08	1.1372135E-08	1.3792127E 00	2.7878349E 01	1.0170147E 01
126000.	1.6321637E-08	1.0165163E-08	1.4202604E 00	2.7840019E 01	1.0170147E 01
127000.	1.5266460E-08	9.1281695E-09	1.4604051E 00	2.7801690E 01	1.0170147E 01
128000.	1.4317268E-08	8.2317816E-09	1.4996980E 00	2.7763360E 01	1.0170147E 01
129000.	1.3459928E-08	7.4525707E-09	1.5381856E 00	2.7725030E 01	1.0170147E 01
130000.	1.2682626E-08	6.7716876E-09	1.5759108E 00	2.7686700E 01	1.0170147E 01
131000.	1.1975416E-08	6.1738456E-09	1.6129130E 00	2.7648370E 01	1.0170147E 01
132000.	1.1329876E-08	5.6465508E-09	1.6492286E 00	2.7610039E 01	1.0170147E 01
133000.	1.0738833E-08	5.1795245E-09	1.6848911E 00	2.7571710E 01	1.0170147E 01
134000.	1.0196142E-08	4.7642509E-09	1.7199315E 00	2.7533379E 01	1.0170147E 01
135000.	9.6965170E-09	4.3936343E-09	1.7543789E 00	2.7495050E 01	1.0170147E 01
136000.	9.2353829E-09	4.0617262E-09	1.7882598E 00	2.7456720E 01	1.0170147E 01
137000.	8.8087711E-09	3.7635161E-09	1.8215992E 00	2.7418390E 01	1.0170147E 01
138000.	8.4132175E-09	3.4947596E-09	1.8544204E 00	2.7380059E 01	1.0170147E 01
139000.	8.0456877E-09	3.2518442E-09	1.8867451E 00	2.7341730E 01	1.0170147E 01
140000.	7.7035178E-09	3.0316831E-09	1.9185936E 00	2.7303399E 01	1.0170147E 01
141000.	7.3843582E-09	2.8316265E-09	1.9499848E 00	2.7265069E 01	1.0170147E 01
142000.	7.0861259E-09	2.6493891E-09	1.9809368E 00	2.7226740E 01	1.0170147E 01
143000.	6.8069769E-09	2.4829952E-09	2.0114661E 00	2.7188410E 01	1.0170147E 01
144000.	6.5452677E-09	2.3307289E-09	2.0415886E 00	2.7150080E 01	1.0170147E 01
145000.	6.2995325E-09	2.1910956E-09	2.0713192E 00	2.7111750E 01	1.0170147E 01
146000.	6.0684548E-09	2.0627869E-09	2.1006718E 00	2.7073420E 01	1.0170147E 01
147000.	5.8508579E-09	1.9446573E-09	2.1296597E 00	2.7035089E 01	1.0170147E 01
148000.	5.6456797E-09	1.8356981E-09	2.1582954E 00	2.6996760E 01	1.0170147E 01
149000.	5.4519637E-09	1.7350200E-09	2.1865906E 00	2.6958430E 01	1.0170147E 01
150000.	5.2688464E-09	1.6418366E-09	2.2145567E 00	2.6920000E 01	1.0170147E 01
151000.	5.0946420E-09	1.5631448E-09	2.2353216E 00	2.6894000E 01	1.0170147E 01
152000.	4.9287749E-09	1.4893553E-09	2.2559117E 00	2.6868000E 01	1.0170147E 01
153000.	4.7707291E-09	1.4200952E-09	2.2763309E 00	2.6842000E 01	1.0170147E 01
154000.	4.6200272E-09	1.3550249E-09	2.2965834E 00	2.6816000E 01	1.0170147E 01
155000.	4.4762262E-09	1.2938341E-09	2.3166729E 00	2.6790000E 01	1.0170147E 01
156000.	4.3389168E-09	1.2362401E-09	2.3366031E 00	2.6764000E 01	1.0170147E 01
157000.	4.2077191E-09	1.1819844E-09	2.3563775E 00	2.6738000E 01	1.0170147E 01
158000.	4.0822789E-09	1.1308297E-09	2.3759995E 00	2.6712000E 01	1.0170147E 01
159000.	3.9622708E-09	1.0825598E-09	2.3954726E 00	2.6686000E 01	1.0170147E 01

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE meters	PRESSURE newtons cm^{-2}	KINETIC TEMPERATURE degrees K	MOLECULAR TEMPERATURE degrees K	DENSITY kg m^{-3}	COEFFICIENT OF VISCOSITY newton-sec m^{-2}	SPEED OF SOUND m sec^{-1}
160000.	3.9128496E-08	1.0222870E 03	1.1106500E 03	1.2273083E-09	4.4136706E-05	6.6808798E 02
161000.	3.8006765E-08	1.0304854E 03	1.1206500E 03	1.1814862E-09	4.4431075E-05	6.7108889E 02
162000.	3.6927060E-08	1.0386659E 03	1.1306500E 03	1.1377695E-09	4.4664298E-05	6.7407643E 02
163000.	3.5887447E-08	1.0468284E 03	1.1406500E 03	1.0960438E-09	4.4896393E-05	6.7705080E 02
164000.	3.4886099E-08	1.0549730E 03	1.1506500E 03	1.0562018E-09	4.5127375E-05	6.8001215E 02
165000.	3.3921305E-08	1.0630997E 03	1.1606500E 03	1.0181436E-09	4.5357258E-05	6.8296066E 02
166000.	3.2991411E-08	1.0712083E 03	1.1706500E 03	9.8177412E-10	4.5586058E-05	6.8589650E 02
167000.	3.2094881E-08	1.0792991E 03	1.1806500E 03	9.4700518E-10	4.5813789E-05	6.8881981E 02
168000.	3.1230234E-08	1.0873719E 03	1.1906500E 03	9.1375313E-10	4.6040465E-05	6.9173079E 02
169000.	3.0396090E-08	1.0954267E 03	1.2006500E 03	8.8194002E-10	4.6266100E-05	6.9462955E 02
170000.	2.9591111E-08	1.1034635E 03	1.2106500E 03	8.5149170E-10	4.6490709E-05	6.9751629E 02
171000.	2.8813069E-08	1.1086877E 03	1.2176500E 03	8.2433703E-10	4.6647331E-05	6.9952990E 02
172000.	2.8059993E-08	1.1138995E 03	1.2246500E 03	7.9820295E-10	4.6803460E-05	7.0153775E 02
173000.	2.7330945E-08	1.1190961E 03	1.2316500E 03	7.7304559E-10	4.6959102E-05	7.0353985E 02
174000.	2.6625029E-08	1.1242834E 03	1.2386500E 03	7.4882312E-10	4.7114260E-05	7.0553628E 02
175000.	2.5941384E-08	1.1294514E 03	1.2456500E 03	7.2549574E-10	4.7268939E-05	7.0752708E 02
176000.	2.5279174E-08	1.1346091E 03	1.2526500E 03	7.0302521E-10	4.7423143E-05	7.0951229E 02
177000.	2.4637622E-08	1.1397535E 03	1.2596500E 03	6.8137571E-10	4.7576877E-05	7.1149195E 02
178000.	2.4015958E-08	1.1448846E 03	1.2666500E 03	6.6051251E-10	4.7730144E-05	7.1346613E 02
179000.	2.3413469E-08	1.1500024E 03	1.2736500E 03	6.4040310E-10	4.7882948E-05	7.1543486E 02
180000.	2.2829452E-08	1.1551070E 03	1.2806500E 03	6.2101602E-10	4.8035293E-05	7.1739818E 02
181000.	2.2263246E-08	1.1601982E 03	1.2876500E 03	6.0232157E-10	4.8187184E-05	7.1935616E 02
182000.	2.1714210E-08	1.1652761E 03	1.2946500E 03	5.8429129E-10	4.8338625E-05	7.2130880E 02
183000.	2.1181733E-08	1.1703408E 03	1.3016500E 03	5.6689814E-10	4.8489619E-05	7.2325619E 02
184000.	2.0665225E-08	1.1753924E 03	1.3086500E 03	5.5011615E-10	4.8640170E-05	7.2519835E 02
185000.	2.0164124E-08	1.1804302E 03	1.3156500E 03	5.3392071E-10	4.8790280E-05	7.2713531E 02
186000.	1.9677896E-08	1.1854550E 03	1.3226500E 03	5.1828839E-10	4.8939956E-05	7.2906713E 02
187000.	1.9206311E-08	1.1904665E 03	1.3296500E 03	5.0319647E-10	4.9089199E-05	7.3099384E 02
188000.	1.8747980E-08	1.1954647E 03	1.3366500E 03	4.8862371E-10	4.9238014E-05	7.3291548E 02
189000.	1.8303317E-08	1.2004496E 03	1.3436500E 03	4.7454937E-10	4.9386404E-05	7.3483211E 02
190000.	1.7871564E-08	1.2054212E 03	1.3506500E 03	4.6095390E-10	4.9534373E-05	7.3674375E 02
191000.	1.7451910E-08	1.2085380E 03	1.3556500E 03	4.4846974E-10	4.9639808E-05	7.3810617E 02
192000.	1.7043719E-08	1.2116446E 03	1.3606500E 03	4.3637082E-10	4.9745032E-05	7.3946609E 02
193000.	1.6646644E-08	1.2147417E 03	1.3656500E 03	4.2464403E-10	4.9850045E-05	7.4082351E 02
194000.	1.6260338E-08	1.2178287E 03	1.3706500E 03	4.1327655E-10	4.9954849E-05	7.4217845E 02
195000.	1.5884471E-08	1.2209057E 03	1.3756500E 03	4.0225603E-10	5.0059444E-05	7.4353091E 02
196000.	1.5518716E-08	1.2239729E 03	1.3806500E 03	3.9157048E-10	5.0163831E-05	7.4488092E 02
197000.	1.5162775E-08	1.2270301E 03	1.3856500E 03	3.8120879E-10	5.0268014E-05	7.4622849E 02
198000.	1.4816337E-08	1.2300773E 03	1.3906500E 03	3.7115965E-10	5.0371991E-05	7.4757363E 02
199000.	1.4479118E-08	1.2331147E 03	1.3956500E 03	3.6141266E-10	5.0475764E-05	7.4891635E 02
200000.	1.4150844E-08	1.2361421E 03	1.4006500E 03	3.5195770E-10	5.0579335E-05	7.5025666E 02
201000.	1.3831239E-08	1.2391596E 03	1.4056500E 03	3.4278486E-10	5.0682705E-05	7.5159460E 02
202000.	1.3520045E-08	1.2421672E 03	1.4106500E 03	3.3388477E-10	5.0785874E-05	7.5293015E 02
203000.	1.3217012E-08	1.2451644E 03	1.4156500E 03	3.2524838E-10	5.0888844E-05	7.5426334E 02
204000.	1.2921892E-08	1.2481526E 03	1.4206500E 03	3.1686683E-10	5.0991617E-05	7.5559417E 02
205000.	1.2634456E-08	1.2511304E 03	1.4256500E 03	3.0873182E-10	5.1094193E-05	7.5692267E 02
206000.	1.2354471E-08	1.2540982E 03	1.4306500E 03	3.0083510E-10	5.1196572E-05	7.5824883E 02
207000.	1.2081722E-08	1.2570561E 03	1.4356500E 03	2.9316897E-10	5.1298757E-05	7.5957268E 02
208000.	1.1815994E-08	1.2600042E 03	1.4406500E 03	2.8572594E-10	5.1400748E-05	7.6089423E 02
209000.	1.1557080E-08	1.2629423E 03	1.4456500E 03	2.7849841E-10	5.1502547E-05	7.6221349E 02
210000.	1.1304783E-08	1.2658705E 03	1.4506500E 03	2.7147970E-10	5.1604154E-05	7.6353047E 02
211000.	1.1058912E-08	1.2687887E 03	1.4556500E 03	2.6466296E-10	5.1705571E-05	7.6484517E 02
212000.	1.0819280E-08	1.2716970E 03	1.4606500E 03	2.5804174E-10	5.1806798E-05	7.6615764E 02
213000.	1.0585704E-08	1.2745954E 03	1.4656500E 03	2.5160961E-10	5.1907837E-05	7.6746784E 02
214000.	1.0358013E-08	1.2774839E 03	1.4706500E 03	2.4536062E-10	5.2008688E-05	7.6877581E 02
215000.	1.0136038E-08	1.2803624E 03	1.4756500E 03	2.3928894E-10	5.2109353E-05	7.7008157E 02
216000.	9.9196129E-09	1.2832310E 03	1.4806500E 03	2.3338883E-10	5.2209833E-05	7.7138512E 02
217000.	9.7085841E-09	1.2860897E 03	1.4856500E 03	2.2765497E-10	5.2310127E-05	7.7268646E 02
218000.	9.5027945E-09	1.2889384E 03	1.4906500E 03	2.2208202E-10	5.2410240E-05	7.7398562E 02
219000.	9.3020988E-09	1.2917773E 03	1.4956500E 03	2.1666498E-10	5.2510169E-05	7.7528260E 02
220000.	9.1063540E-09	1.2946062E 03	1.5006500E 03	2.1139807E-10	5.2609917E-05	7.7657742E 02
221000.	8.9154168E-09	1.2974252E 03	1.5056500E 03	2.0627917E-10	5.2709484E-05	7.7787007E 02
222000.	8.7291573E-09	1.3002342E 03	1.5106500E 03	2.0130113E-10	5.2808871E-05	7.7916059E 02
223000.	8.5474434E-09	1.3030333E 03	1.5156500E 03	1.9646042E-10	5.2908080E-05	7.8044897E 02
224000.	8.3701469E-09	1.3058225E 03	1.5206500E 03	1.9175273E-10	5.3007112E-05	7.8173523E 02
225000.	8.1971492E-09	1.3086018E 03	1.5256500E 03	1.8717407E-10	5.3105966E-05	7.8301938E 02
226000.	8.0283282E-09	1.3113712E 03	1.5306500E 03	1.8272038E-10	5.3204644E-05	7.8430142E 02
227000.	7.8635709E-09	1.3141306E 03	1.5356500E 03	1.7838787E-10	5.3303148E-05	7.8558137E 02
228000.	7.7027657E-09	1.3168801E 03	1.5406500E 03	1.7417285E-10	5.3401477E-05	7.8685923E 02
229000.	7.5458031E-09	1.3196197E 03	1.5456500E 03	1.7007170E-10	5.3499634E-05	7.8813503E 02

TABLE 14. 11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE RATIO	DENSITY RATIO	VISCOSITY RATIO	MOLECULAR WEIGHT	PRESSURE DIFFERENCE
meters	unitless	unitless	unitless	unitless	newtons cm^{-2}
160000.	3.8473873E-09	1.0369750E-09	2.4147999E 00	2.6660000E 01	1.0170147E 01
161000.	3.7370909E-09	9.9825902E-10	2.4276052E 00	2.6634000E 01	1.0170147E 01
162000.	3.6309267E-09	9.6132199E-10	2.4403480E 00	2.6608000E 01	1.0170147E 01
163000.	3.5287047E-09	9.2606717E-10	2.4530291E 00	2.6582000E 01	1.0170147E 01
164000.	3.4302453E-09	8.9240400E-10	2.4656494E 00	2.6556000E 01	1.0170147E 01
165000.	3.3353799E-09	8.6024789E-10	2.4782096E 00	2.6530000E 01	1.0170147E 01
166000.	3.2439463E-09	8.2951866E-10	2.4907107E 00	2.6504000E 01	1.0170147E 01
167000.	3.1557932E-09	8.0014176E-10	2.5031534E 00	2.6478000E 01	1.0170147E 01
168000.	3.0707750E-09	7.7204651E-10	2.5155384E 00	2.6452000E 01	1.0170147E 01
169000.	2.9887562E-09	7.4516704E-10	2.5278666E 00	2.6426000E 01	1.0170147E 01
170000.	2.9096050E-09	7.1944070E-10	2.5401386E 00	2.6400000E 01	1.0170147E 01
171000.	2.8331025E-09	6.9649723E-10	2.5486960E 00	2.6372500E 01	1.0170147E 01
172000.	2.7590547E-09	6.7441608E-10	2.5572266E 00	2.6345000E 01	1.0170147E 01
173000.	2.6873697E-09	6.5316017E-10	2.5657305E 00	2.6317500E 01	1.0170147E 01
174000.	2.6179591E-09	6.3269417E-10	2.5742079E 00	2.6290000E 01	1.0170147E 01
175000.	2.5507383E-09	6.1298444E-10	2.5826592E 00	2.6262500E 01	1.0170147E 01
176000.	2.4856252E-09	5.9399869E-10	2.5910846E 00	2.6235000E 01	1.0170147E 01
177000.	2.4225433E-09	5.7570663E-10	2.5994842E 00	2.6207500E 01	1.0170147E 01
178000.	2.3614169E-09	5.5807893E-10	2.6078583E 00	2.6180000E 01	1.0170147E 01
179000.	2.3021760E-09	5.4108813E-10	2.6162072E 00	2.6152500E 01	1.0170147E 01
180000.	2.2447514E-09	5.2470765E-10	2.6245309E 00	2.6125000E 01	1.0170147E 01
181000.	2.1890781E-09	5.0891236E-10	2.6328299E 00	2.6097500E 01	1.0170147E 01
182000.	2.1350930E-09	4.9367825E-10	2.6411043E 00	2.6070000E 01	1.0170147E 01
183000.	2.0827361E-09	4.7898246E-10	2.6493542E 00	2.6042500E 01	1.0170147E 01
184000.	2.0319495E-09	4.6480306E-10	2.6575799E 00	2.6015000E 01	1.0170147E 01
185000.	1.9826777E-09	4.5111924E-10	2.6657816E 00	2.5987500E 01	1.0170147E 01
186000.	1.9348683E-09	4.3791121E-10	2.6739595E 00	2.5960000E 01	1.0170147E 01
187000.	1.8884693E-09	4.2515978E-10	2.6821137E 00	2.5932500E 01	1.0170147E 01
188000.	1.8434325E-09	4.1284699E-10	2.6902446E 00	2.5905000E 01	1.0170147E 01
189000.	1.7997101E-09	4.0095532E-10	2.6983523E 00	2.5877500E 01	1.0170147E 01
190000.	1.7572572E-09	3.8946827E-10	2.7064370E 00	2.5850000E 01	1.0170147E 01
191000.	1.7159939E-09	3.7892017E-10	2.7121977E 00	2.5821249E 01	1.0170147E 01
192000.	1.6758577E-09	3.6869758E-10	2.7179469E 00	2.5792499E 01	1.0170147E 01
193000.	1.6368144E-09	3.5878940E-10	2.7236845E 00	2.5763749E 01	1.0170147E 01
194000.	1.5988302E-09	3.4918481E-10	2.7294108E 00	2.5735000E 01	1.0170147E 01
195000.	1.5618723E-09	3.3987338E-10	2.7351256E 00	2.5706249E 01	1.0170147E 01
196000.	1.5259087E-09	3.3084497E-10	2.7408290E 00	2.5677499E 01	1.0170147E 01
197000.	1.4909101E-09	3.2209018E-10	2.7465213E 00	2.5648749E 01	1.0170147E 01
198000.	1.4568458E-09	3.1359948E-10	2.7522024E 00	2.5620000E 01	1.0170147E 01
199000.	1.4236882E-09	3.0536407E-10	2.7578723E 00	2.5591249E 01	1.0170147E 01
200000.	1.3914099E-09	2.9737541E-10	2.7635311E 00	2.5562499E 01	1.0170147E 01
201000.	1.3599841E-09	2.8962511E-10	2.7691790E 00	2.5533749E 01	1.0170147E 01
202000.	1.3293854E-09	2.8210527E-10	2.7748159E 00	2.5505000E 01	1.0170147E 01
203000.	1.2995890E-09	2.7480822E-10	2.7804420E 00	2.5476249E 01	1.0170147E 01
204000.	1.2705708E-09	2.6772650E-10	2.7860572E 00	2.5447499E 01	1.0170147E 01
205000.	1.2423081E-09	2.6085308E-10	2.7916617E 00	2.5418749E 01	1.0170147E 01
206000.	1.2147780E-09	2.5418100E-10	2.7972554E 00	2.5390000E 01	1.0170147E 01
207000.	1.1879593E-09	2.4770375E-10	2.8028386E 00	2.5361249E 01	1.0170147E 01
208000.	1.1618311E-09	2.4141492E-10	2.8084112E 00	2.5332499E 01	1.0170147E 01
209000.	1.1363729E-09	2.3530833E-10	2.8139732E 00	2.5303749E 01	1.0170147E 01
210000.	1.1115654E-09	2.2937809E-10	2.8195248E 00	2.5275000E 01	1.0170147E 01
211000.	1.0873895E-09	2.2361851E-10	2.8250659E 00	2.5246249E 01	1.0170147E 01
212000.	1.0638273E-09	2.1802412E-10	2.8305967E 00	2.5217499E 01	1.0170147E 01
213000.	1.0408604E-09	2.1258950E-10	2.8361172E 00	2.5188749E 01	1.0170147E 01
214000.	1.0184723E-09	2.0730962E-10	2.8416275E 00	2.5160000E 01	1.0170147E 01
215000.	9.9664617E-10	2.0217955E-10	2.8471276E 00	2.5131250E 01	1.0170147E 01
216000.	9.7536570E-10	1.9719443E-10	2.8526176E 00	2.5102499E 01	1.0170147E 01
217000.	9.5461588E-10	1.9234979E-10	2.8580974E 00	2.5073749E 01	1.0170147E 01
218000.	9.3438121E-10	1.8764111E-10	2.8635673E 00	2.5045000E 01	1.0170147E 01
219000.	9.1464741E-10	1.8306416E-10	2.8690272E 00	2.5016250E 01	1.0170147E 01
220000.	8.9540042E-10	1.7861481E-10	2.8744772E 00	2.4987499E 01	1.0170147E 01
221000.	8.7662612E-10	1.7428899E-10	2.8799173E 00	2.4958749E 01	1.0170147E 01
222000.	8.5831180E-10	1.7008296E-10	2.8853475E 00	2.4930000E 01	1.0170147E 01
223000.	8.4044441E-10	1.6599295E-10	2.8907681E 00	2.4901250E 01	1.0170147E 01
224000.	8.2301136E-10	1.6201534E-10	2.8961789E 00	2.4872499E 01	1.0170147E 01
225000.	8.0600103E-10	1.5814675E-10	2.9015801E 00	2.4843749E 01	1.0170147E 01
226000.	7.8940138E-10	1.5438374E-10	2.9069716E 00	2.4815000E 01	1.0170147E 01
227000.	7.7320129E-10	1.5072313E-10	2.9123536E 00	2.4786250E 01	1.0170147E 01
228000.	7.5738980E-10	1.4716178E-10	2.9177261E 00	2.4757499E 01	1.0170147E 01
229000.	7.4195613E-10	1.4369665E-10	2.9230891E 00	2.4728749E 01	1.0170147E 01

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE	KINETIC TEMPERATURE	MOLECULAR TEMPERATURE	DENSITY	COEFFICIENT OF VISCOSITY	SPEED OF SOUND
meters	newtons cm^{-2}	degrees K	degrees K	kg m^{-3}	newton-sec m^{-2}	m sec^{-1}
230000.	7.3925818E-09	1.3223493E 03	1.5506500E 03	1.6608106E-10	5.3597617E-05	7.8940877E 02
231000.	7.2428844E-09	1.3241963E 03	1.5546500E 03	1.6229931E-10	5.3675881E-05	7.9042627E 02
232000.	7.0966346E-09	1.3260353E 03	1.5586500E 03	1.5861403E-10	5.3754035E-05	7.9144247E 02
233000.	6.9537457E-09	1.3278662E 03	1.5626500E 03	1.5502254E-10	5.3832081E-05	7.9245737E 02
234000.	6.8141302E-09	1.3296890E 03	1.5666500E 03	1.5152218E-10	5.3910018E-05	7.9347096E 02
235000.	6.6777033E-09	1.3315039E 03	1.5706500E 03	1.4811037E-10	5.3987848E-05	7.9448327E 02
236000.	6.5443868E-09	1.3333106E 03	1.5746500E 03	1.4478470E-10	5.4065570E-05	7.9549429E 02
237000.	6.4140990E-09	1.3351093E 03	1.5786500E 03	1.4154273E-10	5.4143183E-05	7.9650403E 02
238000.	6.2867616E-09	1.3369000E 03	1.5826500E 03	1.3838208E-10	5.4220692E-05	7.9751249E 02
239000.	6.1623034E-09	1.3386826E 03	1.5866500E 03	1.3530059E-10	5.4298093E-05	7.9851967E 02
240000.	6.0406505E-09	1.3404572E 03	1.5906500E 03	1.3229604E-10	5.4375389E-05	7.9952559E 02
241000.	5.9217323E-09	1.3422237E 03	1.5946500E 03	1.2936630E-10	5.4452580E-05	8.0053023E 02
242000.	5.8054790E-09	1.3439822E 03	1.5986500E 03	1.2650929E-10	5.4529665E-05	8.0153363E 02
243000.	5.6918242E-09	1.3457326E 03	1.6026500E 03	1.2372303E-10	5.4606646E-05	8.0253576E 02
244000.	5.5807045E-09	1.3474750E 03	1.6066500E 03	1.2100561E-10	5.4683524E-05	8.0353664E 02
245000.	5.4720553E-09	1.3492094E 03	1.6106500E 03	1.1835512E-10	5.4760296E-05	8.0453628E 02
246000.	5.3658158E-09	1.3509356E 03	1.6146500E 03	1.1576975E-10	5.4836967E-05	8.0553468E 02
247000.	5.2619249E-09	1.3526538E 03	1.6186500E 03	1.1324771E-10	5.4913533E-05	8.0653186E 02
248000.	5.1603259E-09	1.3543640E 03	1.6226500E 03	1.1078731E-10	5.4989998E-05	8.0752779E 02
249000.	5.0609626E-09	1.3560662E 03	1.6266500E 03	1.0838689E-10	5.5066360E-05	8.0852250E 02
250000.	4.9637800E-09	1.3577603E 03	1.6306500E 03	1.0604484E-10	5.5142621E-05	8.0951596E 02
251000.	4.8687236E-09	1.3594463E 03	1.6346500E 03	1.0375955E-10	5.5218779E-05	8.1050824E 02
252000.	4.7757415E-09	1.3611243E 03	1.6386500E 03	1.0152953E-10	5.5294838E-05	8.1149930E 02
253000.	4.6847841E-09	1.3627942E 03	1.6426500E 03	9.9353300E-11	5.5370796E-05	8.1248914E 02
254000.	4.5958012E-09	1.3644561E 03	1.6466500E 03	9.7229418E-11	5.5446653E-05	8.1347779E 02
255000.	4.5087449E-09	1.3661100E 03	1.6506500E 03	9.5156492E-11	5.5522412E-05	8.1446522E 02
256000.	4.4235698E-09	1.3677558E 03	1.6546500E 03	9.3133194E-11	5.5598070E-05	8.1545147E 02
257000.	4.3402283E-09	1.3693935E 03	1.6586500E 03	9.1158165E-11	5.5673630E-05	8.1643653E 02
258000.	4.2586772E-09	1.3710232E 03	1.6626500E 03	8.9230154E-11	5.5749090E-05	8.1742039E 02
259000.	4.1788747E-09	1.3726449E 03	1.6666500E 03	8.7347945E-11	5.5824453E-05	8.1840308E 02
260000.	4.1007767E-09	1.3742585E 03	1.6706500E 03	8.5510293E-11	5.5899718E-05	8.1938457E 02
261000.	4.0243446E-09	1.3758640E 03	1.6746500E 03	8.3716075E-11	5.5974885E-05	8.2036492E 02
262000.	3.9495377E-09	1.3774615E 03	1.6786500E 03	8.1964134E-11	5.6049955E-05	8.2134407E 02
263000.	3.8763164E-09	1.3790510E 03	1.6826500E 03	8.0253351E-11	5.6124928E-05	8.2232206E 02
264000.	3.8046447E-09	1.3806324E 03	1.6866500E 03	7.8582690E-11	5.6199805E-05	8.2329890E 02
265000.	3.7344853E-09	1.3822058E 03	1.6906500E 03	7.6951092E-11	5.6274586E-05	8.2427458E 02
266000.	3.6658013E-09	1.3837711E 03	1.6946500E 03	7.5357531E-11	5.6349271E-05	8.2524910E 02
267000.	3.5985599E-09	1.3853283E 03	1.6986500E 03	7.3801059E-11	5.6423861E-05	8.2622247E 02
268000.	3.5327263E-09	1.3868776E 03	1.7026500E 03	7.2280703E-11	5.6498355E-05	8.2719469E 02
269000.	3.4682674E-09	1.3884187E 03	1.7066500E 03	7.0795534E-11	5.6572756E-05	8.2816577E 02
270000.	3.4051519E-09	1.3899518E 03	1.7106500E 03	6.9344668E-11	5.6647062E-05	8.2913573E 02
271000.	3.3433475E-09	1.3914769E 03	1.7146500E 03	6.7927213E-11	5.6721274E-05	8.3010454E 02
272000.	3.2828238E-09	1.3929939E 03	1.7186500E 03	6.6542312E-11	5.6795392E-05	8.3107224E 02
273000.	3.2235518E-09	1.3945029E 03	1.7226500E 03	6.5189155E-11	5.6869417E-05	8.3203880E 02
274000.	3.1655008E-09	1.3960038E 03	1.7266500E 03	6.3866904E-11	5.6943349E-05	8.3300422E 02
275000.	3.1086450E-09	1.3974967E 03	1.7306500E 03	6.2574823E-11	5.7017189E-05	8.3396854E 02
276000.	3.0529552E-09	1.3989815E 03	1.7346500E 03	6.1312119E-11	5.7090937E-05	8.3493176E 02
277000.	2.9984053E-09	1.4004583E 03	1.7386500E 03	6.0078065E-11	5.7164592E-05	8.3589386E 02
278000.	2.9449691E-09	1.4019270E 03	1.7426500E 03	5.8871938E-11	5.7238156E-05	8.3685485E 02
279000.	2.8926212E-09	1.4033877E 03	1.7466500E 03	5.7693040E-11	5.7311629E-05	8.3781472E 02
280000.	2.8413364E-09	1.4048403E 03	1.7506500E 03	5.6540688E-11	5.7385010E-05	8.3877352E 02
281000.	2.7910914E-09	1.4062849E 03	1.7546500E 03	5.5414231E-11	5.7458303E-05	8.3973122E 02
282000.	2.7418610E-09	1.4077214E 03	1.7586500E 03	5.4312999E-11	5.7531503E-05	8.4068781E 02
283000.	2.6936236E-09	1.4091499E 03	1.7626500E 03	5.3236388E-11	5.7604614E-05	8.4164335E 02
284000.	2.6463566E-09	1.4105704E 03	1.7666500E 03	5.2183788E-11	5.7677636E-05	8.4259777E 02
285000.	2.6000374E-09	1.4119828E 03	1.7706500E 03	5.1154591E-11	5.7750568E-05	8.4355112E 02
286000.	2.5546459E-09	1.4133871E 03	1.7746500E 03	5.0148246E-11	5.7823412E-05	8.4450340E 02
287000.	2.5101599E-09	1.4147834E 03	1.7786500E 03	4.9164162E-11	5.7896167E-05	8.4545461E 02
288000.	2.4665603E-09	1.4161716E 03	1.7826500E 03	4.8201817E-11	5.7968833E-05	8.4640476E 02
289000.	2.4238261E-09	1.4175518E 03	1.7866500E 03	4.7260654E-11	5.8041411E-05	8.4735382E 02
290000.	2.3819396E-09	1.4189240E 03	1.7906500E 03	4.6340187E-11	5.8113902E-05	8.4830183E 02
291000.	2.3408808E-09	1.4202881E 03	1.7946500E 03	4.5439891E-11	5.8186305E-05	8.4924878E 02
292000.	2.3006322E-09	1.4216441E 03	1.7986500E 03	4.4559293E-11	5.8258622E-05	8.5019467E 02
293000.	2.2611749E-09	1.4229921E 03	1.8026500E 03	4.3697893E-11	5.8330851E-05	8.5113952E 02
294000.	2.2224918E-09	1.4243321E 03	1.8066500E 03	4.2855237E-11	5.8402995E-05	8.5208331E 02
295000.	2.1845663E-09	1.4256640E 03	1.8106500E 03	4.2030879E-11	5.8475052E-05	8.5302607E 02
296000.	2.1473817E-09	1.4269878E 03	1.8146500E 03	4.1224380E-11	5.8547023E-05	8.5396777E 02
297000.	2.1109216E-09	1.4283036E 03	1.8186500E 03	4.0435306E-11	5.8618908E-05	8.5490845E 02
298000.	2.0751696E-09	1.4296114E 03	1.8226500E 03	3.9663230E-11	5.8690707E-05	8.5584810E 02
299000.	2.0401117E-09	1.4309111E 03	1.8266500E 03	3.8907771E-11	5.8762424E-05	8.5678670E 02

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE RATIO	DENSITY RATIO	VISCOSITY RATIO	MOLECULAR WEIGHT	PRESSURE DIFFERENCE
meters	unitless	unitless	unitless	unitless	newtons cm⁻²
230000.	7.2689034E-10	1.4032488E-10	2.9284427E 00	2.4700000E 01	1.0170147E 01
231000.	7.1217104E-10	1.3712962E-10	2.9327188E 00	2.4670860E 01	1.0170147E 01
232000.	6.9779074E-10	1.3401585E-10	2.9369890E 00	2.4641719E 01	1.0170147E 01
233000.	6.8374090E-10	1.3098134E-10	2.9412532E 00	2.4612580E 01	1.0170147E 01
234000.	6.7001294E-10	1.2802382E-10	2.9455115E 00	2.4583440E 01	1.0170147E 01
235000.	6.5659848E-10	1.2514112E-10	2.9497639E 00	2.4554300E 01	1.0170147E 01
236000.	6.4348988E-10	1.2233121E-10	2.9540105E 00	2.4525160E 01	1.0170147E 01
237000.	6.3067907E-10	1.1959200E-10	2.9582511E 00	2.4496019E 01	1.0170147E 01
238000.	6.1815837E-10	1.1692152E-10	2.9624860E 00	2.4466880E 01	1.0170147E 01
239000.	6.0592077E-10	1.1431791E-10	2.9667150E 00	2.4437740E 01	1.0170147E 01
240000.	5.9395900E-10	1.1177931E-10	2.9709383E 00	2.4408600E 01	1.0170147E 01
241000.	5.8226613E-10	1.0930392E-10	2.9751558E 00	2.4379460E 01	1.0170147E 01
242000.	5.7083530E-10	1.0688998E-10	2.9793675E 00	2.4350320E 01	1.0170147E 01
243000.	5.5965996E-10	1.0453582E-10	2.9835736E 00	2.4321180E 01	1.0170147E 01
244000.	5.4873389E-10	1.0223982E-10	2.9877740E 00	2.4292040E 01	1.0170147E 01
245000.	5.3805075E-10	1.0000038E-10	2.9919687E 00	2.4262900E 01	1.0170147E 01
246000.	5.2760453E-10	9.7815955E-11	2.9961577E 00	2.4233760E 01	1.0170147E 01
247000.	5.1738926E-10	9.5685037E-11	3.0003411E 00	2.4204620E 01	1.0170147E 01
248000.	5.0739933E-10	9.3606200E-11	3.0045190E 00	2.4175480E 01	1.0170147E 01
249000.	4.9762924E-10	9.1578043E-11	3.0086912E 00	2.4146340E 01	1.0170147E 01
250000.	4.8807356E-10	8.9599197E-11	3.0128579E 00	2.4117200E 01	1.0170147E 01
251000.	4.7872695E-10	8.7668320E-11	3.0170190E 00	2.4088060E 01	1.0170147E 01
252000.	4.6958430E-10	8.5784129E-11	3.0211747E 00	2.4058920E 01	1.0170147E 01
253000.	4.6064073E-10	8.3945396E-11	3.0253249E 00	2.4029780E 01	1.0170147E 01
254000.	4.5189131E-10	8.2150890E-11	3.0294695E 00	2.4000640E 01	1.0170147E 01
255000.	4.4333133E-10	8.0399437E-11	3.0336088E 00	2.3971500E 01	1.0170147E 01
256000.	4.3495632E-10	7.8689916E-11	3.0377425E 00	2.3942360E 01	1.0170147E 01
257000.	4.2676160E-10	7.7021178E-11	3.0418710E 00	2.3913220E 01	1.0170147E 01
258000.	4.1874292E-10	7.5392167E-11	3.0459939E 00	2.3884080E 01	1.0170147E 01
259000.	4.1089618E-10	7.3801855E-11	3.0501116E 00	2.3854940E 01	1.0170147E 01
260000.	4.0321704E-10	7.2249190E-11	3.0542238E 00	2.3825800E 01	1.0170147E 01
261000.	3.9570171E-10	7.0733223E-11	3.0583308E 00	2.3796660E 01	1.0170147E 01
262000.	3.8834617E-10	6.9252976E-11	3.0624324E 00	2.3767520E 01	1.0170147E 01
263000.	3.8114653E-10	6.7807505E-11	3.0665288E 00	2.3738380E 01	1.0170147E 01
264000.	3.7409928E-10	6.6395932E-11	3.0706199E 00	2.3709240E 01	1.0170147E 01
265000.	3.6720071E-10	6.5017367E-11	3.0747057E 00	2.3680100E 01	1.0170147E 01
266000.	3.6044722E-10	6.3670937E-11	3.0787863E 00	2.3650960E 01	1.0170147E 01
267000.	3.5383558E-10	6.2355846E-11	3.0828618E 00	2.3621820E 01	1.0170147E 01
268000.	3.4736236E-10	6.1071270E-11	3.0869319E 00	2.3592680E 01	1.0170147E 01
269000.	3.4102430E-10	5.9816424E-11	3.0909970E 00	2.3563540E 01	1.0170147E 01
270000.	3.3481835E-10	5.8590562E-11	3.0950569E 00	2.3534400E 01	1.0170147E 01
271000.	3.2874131E-10	5.7392928E-11	3.0991116E 00	2.3505260E 01	1.0170147E 01
272000.	3.2279020E-10	5.6222801E-11	3.1031613E 00	2.3476120E 01	1.0170147E 01
273000.	3.1696215E-10	5.5079493E-11	3.1072059E 00	2.3446980E 01	1.0170147E 01
274000.	3.1125417E-10	5.3962300E-11	3.1112453E 00	2.3417840E 01	1.0170147E 01
275000.	3.0566371E-10	5.2870597E-11	3.1152798E 00	2.3388700E 01	1.0170147E 01
276000.	3.0018791E-10	5.1803716E-11	3.1193091E 00	2.3359560E 01	1.0170147E 01
277000.	2.9482418E-10	5.0761041E-11	3.1233335E 00	2.3330420E 01	1.0170147E 01
278000.	2.8956996E-10	4.9741963E-11	3.1273528E 00	2.3301280E 01	1.0170147E 01
279000.	2.8442274E-10	4.8745891E-11	3.1313672E 00	2.3272140E 01	1.0170147E 01
280000.	2.7938007E-10	4.7772247E-11	3.1353766E 00	2.3243000E 01	1.0170147E 01
281000.	2.7443963E-10	4.6820484E-11	3.1393811E 00	2.3213860E 01	1.0170147E 01
282000.	2.6959895E-10	4.5890033E-11	3.1433806E 00	2.3184720E 01	1.0170147E 01
283000.	2.6485591E-10	4.4980385E-11	3.1473752E 00	2.3155580E 01	1.0170147E 01
284000.	2.6020829E-10	4.4091025E-11	3.1513649E 00	2.3126440E 01	1.0170147E 01
285000.	2.5565386E-10	4.3221437E-11	3.1553498E 00	2.3097300E 01	1.0170147E 01
286000.	2.5119065E-10	4.2371158E-11	3.1593298E 00	2.3068160E 01	1.0170147E 01
287000.	2.4681647E-10	4.1539688E-11	3.1633049E 00	2.3039020E 01	1.0170147E 01
288000.	2.4252946E-10	4.0726585E-11	3.1672752E 00	2.3009880E 01	1.0170147E 01
289000.	2.3832753E-10	3.9931379E-11	3.1712407E 00	2.2980739E 01	1.0170147E 01
290000.	2.3420896E-10	3.9153661E-11	3.1752014E 00	2.2951600E 01	1.0170147E 01
291000.	2.3017177E-10	3.8392984E-11	3.1791574E 00	2.2922460E 01	1.0170147E 01
292000.	2.2621425E-10	3.7648951E-11	3.1831086E 00	2.2893320E 01	1.0170147E 01
293000.	2.2233453E-10	3.6921138E-11	3.1870550E 00	2.2864180E 01	1.0170147E 01
294000.	2.1853094E-10	3.6209163E-11	3.1909968E 00	2.2835039E 01	1.0170147E 01
295000.	2.1480184E-10	3.5512648E-11	3.1949338E 00	2.2805900E 01	1.0170147E 01
296000.	2.1114559E-10	3.4831222E-11	3.1988661E 00	2.2776760E 01	1.0170147E 01
297000.	2.0756057E-10	3.4164520E-11	3.2027937E 00	2.2747620E 01	1.0170147E 01
298000.	2.0404519E-10	3.3512179E-11	3.2067167E 00	2.2718480E 01	1.0170147E 01
299000.	2.0059805E-10	3.2873878E-11	3.2106351E 00	2.2689340E 01	1.0170147E 01

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE	KINETIC TEMPERATURE	MOLECULAR TEMPERATURE	DENSITY	COEFFICIENT OF VISCOSITY	SPEED OF SOUND
meters	newtons cm^{-2}	degrees K	degrees K	kg m^{-3}	newton-sec m^{-2}	m sec^{-1}
300000.	2.0057311E-09	1.4321902E 03	1.8306500E 03	3.8168505E-11	5.8834054E-05	8.5772430E 02
302000.	1.9388602E-09	1.4339029E 03	1.8372500E 03	3.6763428E-11	5.8952060E-05	8.5926906E 02
304000.	1.8744851E-09	1.4355909E 03	1.8438500E 03	3.5415564E-11	5.9069838E-05	8.6081107E 02
306000.	1.8125028E-09	1.4372541E 03	1.8504500E 03	3.4122362E-11	5.9187388E-05	8.6235031E 02
308000.	1.7528153E-09	1.4388925E 03	1.8570500E 03	3.2881401E-11	5.9304712E-05	8.6388681E 02
310000.	1.6953286E-09	1.4405061E 03	1.8636500E 03	3.1690368E-11	5.9421813E-05	8.6542059E 02
312000.	1.6399540E-09	1.4420949E 03	1.8702500E 03	3.0547084E-11	5.9538689E-05	8.6695164E 02
314000.	1.5866056E-09	1.4436590E 03	1.8768500E 03	2.9449450E-11	5.9655344E-05	8.6848003E 02
316000.	1.5352017E-09	1.4451982E 03	1.8834500E 03	2.8395473E-11	5.9771778E-05	8.7000570E 02
318000.	1.4856637E-09	1.4467126E 03	1.8900500E 03	2.7383248E-11	5.9887992E-05	8.7152870E 02
320000.	1.4379174E-09	1.4482023E 03	1.8966500E 03	2.6410980E-11	6.0003988E-05	8.7304906E 02
322000.	1.3918915E-09	1.4496672E 03	1.9032500E 03	2.5476943E-11	6.0119767E-05	8.7456676E 02
324000.	1.3475168E-09	1.4511072E 03	1.9098500E 03	2.4579480E-11	6.0235330E-05	8.7608185E 02
326000.	1.3047288E-09	1.4525225E 03	1.9164500E 03	2.3717042E-11	6.0350677E-05	8.7759430E 02
328000.	1.2634642E-09	1.4539130E 03	1.9230500E 03	2.2888120E-11	6.0465811E-05	8.7910416E 02
330000.	1.2236637E-09	1.4552787E 03	1.9296500E 03	2.2091301E-11	6.0580732E-05	8.8061143E 02
332000.	1.1852696E-09	1.4566196E 03	1.9362500E 03	2.1325217E-11	6.0695443E-05	8.8211613E 02
334000.	1.1482273E-09	1.4579357E 03	1.9428500E 03	2.0588579E-11	6.0809942E-05	8.8361827E 02
336000.	1.1124841E-09	1.4592270E 03	1.9494500E 03	1.9880142E-11	6.0924233E-05	8.8511784E 02
338000.	1.0779898E-09	1.4604935E 03	1.9560500E 03	1.9198728E-11	6.1038315E-05	8.8661491E 02
340000.	1.0446960E-09	1.4617353E 03	1.9626500E 03	1.8543206E-11	6.1152192E-05	8.8810942E 02
342000.	1.0125567E-09	1.4629522E 03	1.9692500E 03	1.7912503E-11	6.1265862E-05	8.8960143E 02
344000.	9.8152788E-10	1.4641444E 03	1.9758500E 03	1.7305591E-11	6.1379327E-05	8.9109095E 02
346000.	9.5156696E-10	1.4653117E 03	1.9824500E 03	1.6721486E-11	6.1492588E-05	8.9257798E 02
348000.	9.2263318E-10	1.4664543E 03	1.9890500E 03	1.6159247E-11	6.1605647E-05	8.9406253E 02
350000.	8.9468797E-10	1.4675721E 03	1.9956500E 03	1.5617984E-11	6.1718505E-05	8.9554464E 02
352000.	8.6769385E-10	1.4686650E 03	2.0022500E 03	1.5096837E-11	6.1831163E-05	8.9702429E 02
354000.	8.4161512E-10	1.4697332E 03	2.0088500E 03	1.4594989E-11	6.1943621E-05	8.9850150E 02
356000.	8.1641749E-10	1.4707766E 03	2.0154500E 03	1.4111658E-11	6.2055880E-05	8.9997628E 02
358000.	7.9206777E-10	1.4717952E 03	2.0220500E 03	1.3646089E-11	6.2167941E-05	9.0144866E 02
360000.	7.6853477E-10	1.4727891E 03	2.0286500E 03	1.3197576E-11	6.2279808E-05	9.0291862E 02
362000.	7.4578808E-10	1.4737581E 03	2.0352500E 03	1.2765429E-11	6.2391479E-05	9.0438620E 02
364000.	7.2379869E-10	1.4747023E 03	2.0418500E 03	1.2348998E-11	6.2502956E-05	9.0585142E 02
366000.	7.0253869E-10	1.4756217E 03	2.0484500E 03	1.1947654E-11	6.2614238E-05	9.0731425E 02
368000.	6.8198121E-10	1.4765164E 03	2.0550500E 03	1.1560797E-11	6.2725328E-05	9.0877473E 02
370000.	6.6210057E-10	1.4773863E 03	2.0616500E 03	1.1187854E-11	6.2836227E-05	9.1023288E 02
372000.	6.4287257E-10	1.4782313E 03	2.0682500E 03	1.0828284E-11	6.2946935E-05	9.1168869E 02
374000.	6.2427294E-10	1.4790516E 03	2.0748500E 03	1.0481551E-11	6.3057455E-05	9.1314217E 02
376000.	6.0627922E-10	1.4798471E 03	2.0814500E 03	1.0147159E-11	6.3167787E-05	9.1459335E 02
378000.	5.8886955E-10	1.4806177E 03	2.0880500E 03	9.8246245E-12	6.3277930E-05	9.1604222E 02
380000.	5.7202296E-10	1.4813637E 03	2.0946500E 03	9.5134873E-12	6.3387887E-05	9.1748883E 02
382000.	5.5571926E-10	1.4820848E 03	2.1012500E 03	9.2133057E-12	6.3497657E-05	9.1893313E 02
384000.	5.3993908E-10	1.4827811E 03	2.1078500E 03	8.9236559E-12	6.3607243E-05	9.2037518E 02
386000.	5.2466391E-10	1.4834526E 03	2.1144500E 03	8.6441346E-12	6.3716646E-05	9.2181497E 02
388000.	5.0987570E-10	1.4840993E 03	2.1210500E 03	8.3743510E-12	6.3825865E-05	9.2325252E 02
390000.	4.9555736E-10	1.4847213E 03	2.1276500E 03	8.1139344E-12	6.3934903E-05	9.2468783E 02
392000.	4.8169243E-10	1.4853184E 03	2.1342500E 03	7.8625296E-12	6.4043758E-05	9.2612091E 02
394000.	4.6826477E-10	1.4858908E 03	2.1408500E 03	7.6197901E-12	6.4152434E-05	9.2755179E 02
396000.	4.5525939E-10	1.4864383E 03	2.1474500E 03	7.3853930E-12	6.4260931E-05	9.2898046E 02
398000.	4.4266133E-10	1.4869611E 03	2.1540500E 03	7.1590199E-12	6.4369250E-05	9.3040694E 02
400000.	4.3045664E-10	1.4874591E 03	2.1606500E 03	6.9403720E-12	6.4477389E-05	9.3183123E 02
402000.	4.1861271E-10	1.4880479E 03	2.1658500E 03	6.7332042E-12	6.4562467E-05	9.3295186E 02
404000.	4.0712851E-10	1.4886223E 03	2.1710500E 03	6.5328014E-12	6.4647434E-05	9.3407116E 02
406000.	3.9599224E-10	1.4891824E 03	2.1762500E 03	6.3389257E-12	6.4732293E-05	9.3518910E 02
408000.	3.8519245E-10	1.4897281E 03	2.1814500E 03	6.1513475E-12	6.4817043E-05	9.3630573E 02
410000.	3.7471793E-10	1.4902594E 03	2.1866500E 03	5.9698436E-12	6.4901686E-05	9.3742101E 02
412000.	3.6455822E-10	1.4907764E 03	2.1918500E 03	5.7942047E-12	6.4986220E-05	9.3853498E 02
414000.	3.5470273E-10	1.4912790E 03	2.1970500E 03	5.6242206E-12	6.5070646E-05	9.3964763E 02
416000.	3.4514181E-10	1.4917673E 03	2.2022500E 03	5.4596992E-12	6.5154967E-05	9.4075894E 02
418000.	3.3586559E-10	1.4922412E 03	2.2074500E 03	5.3004458E-12	6.5239180E-05	9.4186896E 02
420000.	3.2686502E-10	1.4927007E 03	2.2126500E 03	5.1462808E-12	6.5323289E-05	9.4297767E 02
422000.	3.1813105E-10	1.4931459E 03	2.2178500E 03	4.9970266E-12	6.5407290E-05	9.4408507E 02
424000.	3.0965513E-10	1.4935767E 03	2.2230500E 03	4.8525140E-12	6.5491187E-05	9.4519119E 02
426000.	3.0142895E-10	1.4939931E 03	2.2282500E 03	4.7125807E-12	6.5574978E-05	9.4629600E 02
428000.	2.9344432E-10	1.4943952E 03	2.2334500E 03	4.5770667E-12	6.5658665E-05	9.4739953E 02
430000.	2.8569375E-10	1.4947829E 03	2.2386500E 03	4.4458243E-12	6.5742248E-05	9.4850178E 02
432000.	2.7816958E-10	1.4951562E 03	2.2438500E 03	4.3187053E-12	6.5825728E-05	9.4960274E 02
434000.	2.7086468E-10	1.4955153E 03	2.2490500E 03	4.1955704E-12	6.5909103E-05	9.5070243E 02
436000.	2.6377198E-10	1.4958599E 03	2.2542500E 03	4.0762832E-12	6.5992375E-05	9.5180085E 02
438000.	2.5688480E-10	1.4961901E 03	2.2594500E 03	3.9607135E-12	6.6075546E-05	9.5289800E 02

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE RATIO	DENSITY RATIO	VISCOSITY RATIO	MOLECULAR WEIGHT	PRESSURE DIFFERENCE
meters	unitless	unitless	unitless	unitless	newtons cm^{-2}
300000.	1.9721751E-10	3.2249259E-11	3.2145488E 00	2.2660000E 01	1.0170147E 01
302000.	1.9064230E-10	3.1062084E-11	3.2209964E 00	2.2605600E 01	1.0170147E 01
304000.	1.8431249E-10	2.9923249E-11	3.2274314E 00	2.2551200E 01	1.0170147E 01
306000.	1.7821795E-10	2.8830599E-11	3.2338541E 00	2.2496800E 01	1.0170147E 01
308000.	1.7234906E-10	2.7782089E-11	3.2402644E 00	2.2442400E 01	1.0170147E 01
310000.	1.6669656E-10	2.6775764E-11	3.2466625E 00	2.2388000E 01	1.0170147E 01
312000.	1.6125175E-10	2.5809783E-11	3.2530483E 00	2.2333600E 01	1.0170147E 01
314000.	1.5600616E-10	2.4882371E-11	3.2594221E 00	2.2279200E 01	1.0170147E 01
316000.	1.5095177E-10	2.3991847E-11	3.2657837E 00	2.2224800E 01	1.0170147E 01
318000.	1.4608084E-10	2.3136601E-11	3.2721334E 00	2.2170400E 01	1.0170147E 01
320000.	1.4138610E-10	2.2315113E-11	3.2784711E 00	2.2116000E 01	1.0170147E 01
322000.	1.3686051E-10	2.1525929E-11	3.2847970E 00	2.2061600E 01	1.0170147E 01
324000.	1.3249728E-10	2.0767646E-11	3.2911111E 00	2.2007200E 01	1.0170147E 01
326000.	1.2829006E-10	2.0038957E-11	3.2974133E 00	2.1952800E 01	1.0170147E 01
328000.	1.2423264E-10	1.9338586E-11	3.3037040E 00	2.1898400E 01	1.0170147E 01
330000.	1.2031917E-10	1.8665339E-11	3.3099830E 00	2.1844000E 01	1.0170147E 01
332000.	1.1654399E-10	1.8018061E-11	3.3162505E 00	2.1789600E 01	1.0170147E 01
334000.	1.1290174E-10	1.7395662E-11	3.3225065E 00	2.1735200E 01	1.0170147E 01
336000.	1.0938722E-10	1.6797091E-11	3.3287511E 00	2.1680800E 01	1.0170147E 01
338000.	1.0599549E-10	1.6221351E-11	3.3349842E 00	2.1626400E 01	1.0170147E 01
340000.	1.0272181E-10	1.5667489E-11	3.3412062E 00	2.1572000E 01	1.0170147E 01
342000.	9.9561659E-11	1.5134597E-11	3.3474168E 00	2.1517600E 01	1.0170147E 01
344000.	9.6510686E-11	1.4621806E-11	3.3536163E 00	2.1463200E 01	1.0170147E 01
346000.	9.3564718E-11	1.4128285E-11	3.3598046E 00	2.1408800E 01	1.0170147E 01
348000.	9.0719748E-11	1.3653240E-11	3.3659819E 00	2.1354400E 01	1.0170147E 01
350000.	8.7971978E-11	1.3195917E-11	3.3721481E 00	2.1300000E 01	1.0170147E 01
352000.	8.5317729E-11	1.2755590E-11	3.3783035E 00	2.1245600E 01	1.0170147E 01
354000.	8.2753484E-11	1.2331570E-11	3.3844479E 00	2.1191200E 01	1.0170147E 01
356000.	8.0275878E-11	1.1923194E-11	3.3905815E 00	2.1136800E 01	1.0170147E 01
358000.	7.7881643E-11	1.1529827E-11	3.3967043E 00	2.1082400E 01	1.0170147E 01
360000.	7.5567713E-11	1.1150870E-11	3.4028164E 00	2.1028000E 01	1.0170147E 01
362000.	7.3331100E-11	1.0785742E-11	3.4089178E 00	2.0973600E 01	1.0170147E 01
364000.	7.1168948E-11	1.0433891E-11	3.4150086E 00	2.0919200E 01	1.0170147E 01
366000.	6.9078517E-11	1.0094788E-11	3.4210888E 00	2.0864800E 01	1.0170147E 01
368000.	6.7057161E-11	9.7679259E-12	3.4271585E 00	2.0810400E 01	1.0170147E 01
370000.	6.5102358E-11	9.4528193E-12	3.4332178E 00	2.0756000E 01	1.0170147E 01
372000.	6.3211727E-11	9.1490122E-12	3.4392665E 00	2.0701600E 01	1.0170147E 01
374000.	6.1382881E-11	8.8560518E-12	3.4453051E 00	2.0647200E 01	1.0170147E 01
376000.	5.9613612E-11	8.5735176E-12	3.4513333E 00	2.0592800E 01	1.0170147E 01
378000.	5.7901772E-11	8.3010025E-12	3.4573513E 00	2.0538400E 01	1.0170147E 01
380000.	5.6245297E-11	8.0381171E-12	3.4633591E 00	2.0484000E 01	1.0170147E 01
382000.	5.4642204E-11	7.7844882E-12	3.4693566E 00	2.0429600E 01	1.0170147E 01
384000.	5.3090586E-11	7.5397579E-12	3.4753442E 00	2.0375200E 01	1.0170147E 01
386000.	5.1588625E-11	7.3035854E-12	3.4813217E 00	2.0320800E 01	1.0170147E 01
388000.	5.0134544E-11	7.0756403E-12	3.4872891E 00	2.0266400E 01	1.0170147E 01
390000.	4.8726665E-11	6.8556096E-12	3.4932467E 00	2.0212000E 01	1.0170147E 01
392000.	4.7363369E-11	6.6431931E-12	3.4991943E 00	2.0157600E 01	1.0170147E 01
394000.	4.6043067E-11	6.4380981E-12	3.5051321E 00	2.0103200E 01	1.0170147E 01
396000.	4.4764287E-11	6.2400517E-12	3.5110601E 00	2.0048800E 01	1.0170147E 01
398000.	4.3525558E-11	6.0487851E-12	3.5169784E 00	1.9994400E 01	1.0170147E 01
400000.	4.2325508E-11	5.8640456E-12	3.5228868E 00	1.9940000E 01	1.0170147E 01
402000.	4.1160929E-11	5.6890058E-12	3.5275352E 00	1.9900000E 01	1.0170147E 01
404000.	4.0031723E-11	5.5196818E-12	3.5321777E 00	1.9860000E 01	1.0170147E 01
406000.	3.8936727E-11	5.3558727E-12	3.5368142E 00	1.9820000E 01	1.0170147E 01
408000.	3.7874815E-11	5.1973845E-12	3.5414447E 00	1.9780000E 01	1.0170147E 01
410000.	3.6844887E-11	5.0440286E-12	3.5460694E 00	1.9740000E 01	1.0170147E 01
412000.	3.5845914E-11	4.8956280E-12	3.5506881E 00	1.9700000E 01	1.0170147E 01
414000.	3.4876853E-11	4.7520055E-12	3.5553010E 00	1.9660000E 01	1.0170147E 01
416000.	3.3936757E-11	4.6129984E-12	3.5599080E 00	1.9620000E 01	1.0170147E 01
418000.	3.3024653E-11	4.4784423E-12	3.5645092E 00	1.9580000E 01	1.0170147E 01
420000.	3.2139654E-11	4.3481855E-12	3.5691047E 00	1.9540000E 01	1.0170147E 01
422000.	3.1280870E-11	4.2220779E-12	3.5736943E 00	1.9500000E 01	1.0170147E 01
424000.	3.0447457E-11	4.0999767E-12	3.5782783E 00	1.9460000E 01	1.0170147E 01
426000.	2.9638602E-11	3.9817445E-12	3.5828564E 00	1.9420000E 01	1.0170147E 01
428000.	2.8853498E-11	3.8672462E-12	3.5874288E 00	1.9380000E 01	1.0170147E 01
430000.	2.8091406E-11	3.7563572E-12	3.5919957E 00	1.9340000E 01	1.0170147E 01
432000.	2.7351578E-11	3.6489520E-12	3.5965567E 00	1.9300000E 01	1.0170147E 01
434000.	2.6633309E-11	3.5449132E-12	3.6011122E 00	1.9260000E 01	1.0170147E 01
436000.	2.5935906E-11	3.4441252E-12	3.6056620E 00	1.9220000E 01	1.0170147E 01
438000.	2.5258710E-11	3.3464783E-12	3.6102062E 00	1.9180000E 01	1.0170147E 01

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE meters	PRESSURE newtons cm^{-2}	KINETIC TEMPERATURE degrees K	MOLECULAR TEMPERATURE degrees K	DENSITY kg m^{-3}	COEFFICIENT OF VISCOSITY newton-sec m^{-2}	SPEED OF SOUND m sec^{-1}
440000.	2.5019664E-10	1.4965061E 03	2.2646500E 03	3.8487362E-12	6.6158612E-05	9.5399390E 02
442000.	2.4370127E-10	1.4968076E 03	2.2698500E 03	3.7402308E-12	6.6241579E-05	9.5508853E 02
444000.	2.3739258E-10	1.4970948E 03	2.2750500E 03	3.6350798E-12	6.6324444E-05	9.5618191E 02
446000.	2.3126473E-10	1.4973676E 03	2.2802500E 03	3.5331714E-12	6.6407207E-05	9.5727403E 02
448000.	2.2531199E-10	1.4976261E 03	2.2854500E 03	3.4343957E-12	6.6489869E-05	9.5836493E 02
450000.	2.1952890E-10	1.4978702E 03	2.2906500E 03	3.3386486E-12	6.6572431E-05	9.5945457E 02
452000.	2.1391031E-10	1.4980998E 03	2.2958500E 03	3.2458315E-12	6.6654892E-05	9.6054298E 02
454000.	2.0845093E-10	1.4983152E 03	2.3010500E 03	3.1558441E-12	6.6737255E-05	9.6163017E 02
456000.	2.0314599E-10	1.4985162E 03	2.3062500E 03	3.0685954E-12	6.6819517E-05	9.6271610E 02
458000.	1.9799060E-10	1.4987029E 03	2.3114500E 03	2.9839931E-12	6.6901681E-05	9.6380085E 02
460000.	1.9298021E-10	1.4988752E 03	2.3166500E 03	2.9019512E-12	6.6983746E-05	9.6488435E 02
462000.	1.8811034E-10	1.4990331E 03	2.3218500E 03	2.8223851E-12	6.7065712E-05	9.6596664E 02
464000.	1.8337669E-10	1.4991767E 03	2.3270500E 03	2.7452138E-12	6.7147580E-05	9.6704772E 02
466000.	1.7877516E-10	1.4993058E 03	2.3322500E 03	2.6703602E-12	6.7229351E-05	9.6812760E 02
468000.	1.7430157E-10	1.4994207E 03	2.3374500E 03	2.5977463E-12	6.7311026E-05	9.6920626E 02
470000.	1.6995216E-10	1.4995212E 03	2.3426500E 03	2.5273014E-12	6.7392603E-05	9.7028373E 02
472000.	1.6572313E-10	1.4996073E 03	2.3478500E 03	2.4589548E-12	6.7474083E-05	9.7136002E 02
474000.	1.6161082E-10	1.4996790E 03	2.3530500E 03	2.3926382E-12	6.7555466E-05	9.7243510E 02
476000.	1.5761171E-10	1.4997363E 03	2.3582500E 03	2.3282864E-12	6.7636753E-05	9.7350900E 02
478000.	1.5372238E-10	1.4997794E 03	2.3634500E 03	2.2658358E-12	6.7717947E-05	9.7458172E 02
480000.	1.4993956E-10	1.4998080E 03	2.3686500E 03	2.2052260E-12	6.7799044E-05	9.7565325E 02
482000.	1.4626006E-10	1.4998223E 03	2.3738500E 03	2.1463978E-12	6.7880046E-05	9.7672361E 02
484000.	1.4268077E-10	1.4998223E 03	2.3790500E 03	2.0892944E-12	6.7960953E-05	9.7779280E 02
486000.	1.3919874E-10	1.4998078E 03	2.3842500E 03	2.0338610E-12	6.8041767E-05	9.7886081E 02
488000.	1.3581101E-10	1.4997790E 03	2.3894500E 03	1.9800438E-12	6.8122485E-05	9.7992767E 02
490000.	1.3251486E-10	1.4997359E 03	2.3946500E 03	1.9277925E-12	6.8203111E-05	9.8099338E 02
492000.	1.2930755E-10	1.4996784E 03	2.3998500E 03	1.8770573E-12	6.8283644E-05	9.8205791E 02
494000.	1.2618645E-10	1.4996065E 03	2.4050500E 03	1.8277902E-12	6.8364083E-05	9.8312130E 02
496000.	1.2314902E-10	1.4995202E 03	2.4102500E 03	1.7799451E-12	6.8444428E-05	9.8418353E 02
498000.	1.2019283E-10	1.4994196E 03	2.4154500E 03	1.7334778E-12	6.8524683E-05	9.8524462E 02
500000.	1.1731545E-10	1.4993047E 03	2.4206500E 03	1.6883441E-12	6.8604845E-05	9.8630458E 02
502000.	1.1451121E-10	1.4995694E 03	2.4240500E 03	1.6456754E-12	6.8657209E-05	9.8699701E 02
504000.	1.1177938E-10	1.4998289E 03	2.4274500E 03	1.6041654E-12	6.8709534E-05	9.8768895E 02
506000.	1.0911792E-10	1.5000833E 03	2.4308500E 03	1.5637801E-12	6.8761820E-05	9.8838041E 02
508000.	1.0652497E-10	1.5003325E 03	2.4342500E 03	1.5244880E-12	6.8814067E-05	9.8907138E 02
510000.	1.0399854E-10	1.5005765E 03	2.4376500E 03	1.4862561E-12	6.8866274E-05	9.8976188E 02
512000.	1.0153685E-10	1.5008154E 03	2.4410500E 03	1.4490546E-12	6.8918444E-05	9.9045190E 02
514000.	9.9138149E-11	1.5010491E 03	2.4444500E 03	1.4128544E-12	6.8970575E-05	9.9114143E 02
516000.	9.6800666E-11	1.5012776E 03	2.4478500E 03	1.3776259E-12	6.9022667E-05	9.9183048E 02
518000.	9.4522758E-11	1.5015010E 03	2.4512500E 03	1.3433418E-12	6.9074719E-05	9.9251904E 02
520000.	9.2302788E-11	1.5017193E 03	2.4546500E 03	1.3099750E-12	6.9126735E-05	9.9320714E 02
522000.	9.0139147E-11	1.5019323E 03	2.4580500E 03	1.2774988E-12	6.9178711E-05	9.9389477E 02
524000.	8.8030359E-11	1.5021402E 03	2.4614500E 03	1.2458886E-12	6.9230649E-05	9.9458191E 02
526000.	8.5974921E-11	1.5023429E 03	2.4648500E 03	1.2151197E-12	6.9282550E-05	9.9526858E 02
528000.	8.3971362E-11	1.5025405E 03	2.4682500E 03	1.1851677E-12	6.9334410E-05	9.9595479E 02
530000.	8.2018286E-11	1.5027328E 03	2.4716499E 03	1.1560097E-12	6.9386234E-05	9.9664050E 02
532000.	8.0114324E-11	1.5029201E 03	2.4750500E 03	1.1276231E-12	6.9438021E-05	9.9732577E 02
534000.	7.8258179E-11	1.5031021E 03	2.4784500E 03	1.0999864E-12	6.9489769E-05	9.9801055E 02
536000.	7.6448556E-11	1.5032790E 03	2.4818500E 03	1.0730785E-12	6.9541479E-05	9.9869486E 02
538000.	7.4684181E-11	1.5034507E 03	2.4852500E 03	1.0468785E-12	6.9593151E-05	9.9937871E 02
540000.	7.2963864E-11	1.5036173E 03	2.4886500E 03	1.0213668E-12	6.9644787E-05	1.0000621E 03
542000.	7.1286404E-11	1.5037787E 03	2.4920500E 03	9.9652387E-13	6.9696384E-05	1.0007450E 03
544000.	6.9650681E-11	1.5039350E 03	2.4954500E 03	9.7233125E-13	6.9747944E-05	1.0014274E 03
546000.	6.8055573E-11	1.5040860E 03	2.4988500E 03	9.4877069E-13	6.9799466E-05	1.0021094E 03
548000.	6.6500008E-11	1.5042319E 03	2.5022500E 03	9.2582468E-13	6.9850951E-05	1.0027909E 03
550000.	6.4982911E-11	1.5043727E 03	2.5056500E 03	9.0347577E-13	6.9902399E-05	1.0034720E 03
552000.	6.3503272E-11	1.5045083E 03	2.5090500E 03	8.8170750E-13	6.9953810E-05	1.0041526E 03
554000.	6.2060105E-11	1.5046387E 03	2.5124500E 03	8.6050388E-13	7.0005184E-05	1.0048327E 03
556000.	6.0652455E-11	1.5047639E 03	2.5158500E 03	8.3984936E-13	7.0056520E-05	1.0055124E 03
558000.	5.9279361E-11	1.5048840E 03	2.5192500E 03	8.1972843E-13	7.0107821E-05	1.0061916E 03
560000.	5.7939934E-11	1.5049989E 03	2.5226499E 03	8.0012667E-13	7.0159083E-05	1.0068703E 03
562000.	5.6633257E-11	1.5051087E 03	2.5260500E 03	7.8102934E-13	7.0210310E-05	1.0075486E 03
564000.	5.5358504E-11	1.5052133E 03	2.5294500E 03	7.6242301E-13	7.0261499E-05	1.0082265E 03
566000.	5.4114844E-11	1.5053127E 03	2.5328500E 03	7.4429430E-13	7.0312652E-05	1.0089039E 03
568000.	5.2901430E-11	1.5054069E 03	2.5362500E 03	7.2662964E-13	7.0363768E-05	1.0095808E 03
570000.	5.1717495E-11	1.5054960E 03	2.5396500E 03	7.0941664E-13	7.0414848E-05	1.0102573E 03
572000.	5.0562249E-11	1.5055800E 03	2.5430500E 03	6.9264266E-13	7.0465892E-05	1.0109333E 03
574000.	4.9434978E-11	1.5056587E 03	2.5464500E 03	6.7629619E-13	7.0516899E-05	1.0116089E 03
576000.	4.8334925E-11	1.5057323E 03	2.5498500E 03	6.6036518E-13	7.0567870E-05	1.0122840E 03
578000.	4.7261423E-11	1.5058008E 03	2.5532500E 03	6.4483888E-13	7.0618805E-05	1.0129586E 03

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE RATIO	DENSITY RATIO	VISCOSITY RATIO	MOLECULAR WEIGHT	PRESSURE DIFFERENCE
meters	unitless	unitless	unitless	unitless	newtons cm^{-2}
440000.	2.4601083E-11	3.2518666E-12	3.6147448E 00	1.9140000E 01	1.0170147E 01
442000.	2.3962413E-11	3.1601885E-12	3.6192779E 00	1.9100000E 01	1.0170147E 01
444000.	2.3342098E-11	3.0713445E-12	3.6238054E 00	1.9060000E 01	1.0170147E 01
446000.	2.2739566E-11	2.9852403E-12	3.6283273E 00	1.9020000E 01	1.0170147E 01
448000.	2.2154250E-11	2.9017829E-12	3.6328438E 00	1.8980000E 01	1.0170147E 01
450000.	2.1585616E-11	2.8208845E-12	3.6373548E 00	1.8940000E 01	1.0170147E 01
452000.	2.1033157E-11	2.7424616E-12	3.6418602E 00	1.8900000E 01	1.0170147E 01
454000.	2.0496353E-11	2.6664296E-12	3.6463604E 00	1.8860000E 01	1.0170147E 01
456000.	1.9974735E-11	2.5927117E-12	3.6508549E 00	1.8820000E 01	1.0170147E 01
458000.	1.9467820E-11	2.5212297E-12	3.6553442E 00	1.8780000E 01	1.0170147E 01
460000.	1.8975164E-11	2.4519109E-12	3.6598280E 00	1.8740000E 01	1.0170147E 01
462000.	1.8496324E-11	2.3846841E-12	3.6643064E 00	1.8700000E 01	1.0170147E 01
464000.	1.8030879E-11	2.3194807E-12	3.6687796E 00	1.8660000E 01	1.0170147E 01
466000.	1.7578424E-11	2.2562355E-12	3.6732473E 00	1.8620000E 01	1.0170147E 01
468000.	1.7138550E-11	2.1948827E-12	3.6777098E 00	1.8580000E 01	1.0170147E 01
470000.	1.6710885E-11	2.1353625E-12	3.6821670E 00	1.8540000E 01	1.0170147E 01
472000.	1.6295057E-11	2.0776153E-12	3.6866188E 00	1.8500000E 01	1.0170147E 01
474000.	1.5890706E-11	2.0215832E-12	3.6910654E 00	1.8460000E 01	1.0170147E 01
476000.	1.5497486E-11	1.9672112E-12	3.6955068E 00	1.8420000E 01	1.0170147E 01
478000.	1.5115059E-11	1.9144455E-12	3.6999429E 00	1.8380000E 01	1.0170147E 01
480000.	1.4743106E-11	1.8632352E-12	3.7043739E 00	1.8340000E 01	1.0170147E 01
482000.	1.4381312E-11	1.8135303E-12	3.7087997E 00	1.8300000E 01	1.0170147E 01
484000.	1.4029371E-11	1.7652825E-12	3.7132202E 00	1.8260000E 01	1.0170147E 01
486000.	1.3686994E-11	1.7184459E-12	3.7176357E 00	1.8220000E 01	1.0170147E 01
488000.	1.3353888E-11	1.6729747E-12	3.7220460E 00	1.8180000E 01	1.0170147E 01
490000.	1.3029787E-11	1.6288266E-12	3.7264512E 00	1.8140000E 01	1.0170147E 01
492000.	1.2714423E-11	1.5859596E-12	3.7308513E 00	1.8100000E 01	1.0170147E 01
494000.	1.2407534E-11	1.5443330E-12	3.7352462E 00	1.8060000E 01	1.0170147E 01
496000.	1.2108872E-11	1.5039077E-12	3.7396361E 00	1.8020000E 01	1.0170147E 01
498000.	1.1818200E-11	1.4646467E-12	3.7440211E 00	1.7980000E 01	1.0170147E 01
500000.	1.1535275E-11	1.4265124E-12	3.7484009E 00	1.7940000E 01	1.0170147E 01
502000.	1.1259543E-11	1.3904608E-12	3.7512619E 00	1.7918000E 01	1.0170147E 01
504000.	1.0990930E-11	1.3553883E-12	3.7541209E 00	1.7896000E 01	1.0170147E 01
506000.	1.0729237E-11	1.3212660E-12	3.7569776E 00	1.7874000E 01	1.0170147E 01
508000.	1.0474280E-11	1.2880674E-12	3.7598323E 00	1.7852000E 01	1.0170147E 01
510000.	1.0225864E-11	1.2557646E-12	3.7626848E 00	1.7830000E 01	1.0170147E 01
512000.	9.9838128E-12	1.2243324E-12	3.7655352E 00	1.7808000E 01	1.0170147E 01
514000.	9.7479562E-12	1.1937462E-12	3.7683835E 00	1.7786000E 01	1.0170147E 01
516000.	9.5181185E-12	1.1639810E-12	3.7712297E 00	1.7764000E 01	1.0170147E 01
518000.	9.2941386E-12	1.1350137E-12	3.7740737E 00	1.7742000E 01	1.0170147E 01
520000.	9.0758557E-12	1.1068215E-12	3.7769157E 00	1.7720000E 01	1.0170147E 01
522000.	8.8631114E-12	1.0793818E-12	3.7797555E 00	1.7698000E 01	1.0170147E 01
524000.	8.6557605E-12	1.0526737E-12	3.7825933E 00	1.7676000E 01	1.0170147E 01
526000.	8.4536555E-12	1.0266765E-12	3.7854290E 00	1.7654000E 01	1.0170147E 01
528000.	8.2566516E-12	1.0013696E-12	3.7882626E 00	1.7632000E 01	1.0170147E 01
530000.	8.0646114E-12	9.7673345E-13	3.7910941E 00	1.7610000E 01	1.0170147E 01
532000.	7.8774006E-12	9.5274907E-13	3.7939236E 00	1.7588000E 01	1.0170147E 01
534000.	7.6948915E-12	9.2939839E-13	3.7967510E 00	1.7566000E 01	1.0170147E 01
536000.	7.5169567E-12	9.0666342E-13	3.7995763E 00	1.7544000E 01	1.0170147E 01
538000.	7.3434709E-12	8.8452656E-13	3.8023995E 00	1.7522000E 01	1.0170147E 01
540000.	7.1743174E-12	8.6297128E-13	3.8052208E 00	1.7500000E 01	1.0170147E 01
542000.	7.0093778E-12	8.4198101E-13	3.8080399E 00	1.7478000E 01	1.0170147E 01
544000.	6.8485421E-12	8.2154022E-13	3.8108571E 00	1.7456000E 01	1.0170147E 01
546000.	6.6916999E-12	8.0163348E-13	3.8136721E 00	1.7434000E 01	1.0170147E 01
548000.	6.5387459E-12	7.8224598E-13	3.8164851E 00	1.7412000E 01	1.0170147E 01
550000.	6.3895743E-12	7.6336299E-13	3.8192961E 00	1.7390000E 01	1.0170147E 01
552000.	6.2440858E-12	7.4497059E-13	3.8221051E 00	1.7368000E 01	1.0170147E 01
554000.	6.1021836E-12	7.2705526E-13	3.8249120E 00	1.7346000E 01	1.0170147E 01
556000.	5.9637735E-12	7.0960388E-13	3.8277169E 00	1.7324000E 01	1.0170147E 01
558000.	5.8287613E-12	6.9260335E-13	3.8305198E 00	1.7302000E 01	1.0170147E 01
560000.	5.6970595E-12	6.7604147E-13	3.8333207E 00	1.7280000E 01	1.0170147E 01
562000.	5.5685779E-12	6.5990578E-13	3.8361196E 00	1.7258000E 01	1.0170147E 01
564000.	5.4432353E-12	6.4418496E-13	3.8389165E 00	1.7236000E 01	1.0170147E 01
566000.	5.3209499E-12	6.2886768E-13	3.8417113E 00	1.7214000E 01	1.0170147E 01
568000.	5.2016386E-12	6.1394249E-13	3.8445041E 00	1.7192000E 01	1.0170147E 01
570000.	5.0852258E-12	5.9939892E-13	3.8472950E 00	1.7170000E 01	1.0170147E 01
572000.	4.9716340E-12	5.8522629E-13	3.8500840E 00	1.7148000E 01	1.0170147E 01
574000.	4.8607928E-12	5.7141486E-13	3.8528709E 00	1.7126000E 01	1.0170147E 01
576000.	4.7526278E-12	5.5795445E-13	3.8556558E 00	1.7104000E 01	1.0170147E 01
578000.	4.6470737E-12	5.4483600E-13	3.8584388E 00	1.7082000E 01	1.0170147E 01

TABLE 14. 11 (Concluded)

GEOMETRIC ALTITUDE	PRESSURE	KINETIC TEMPERATURE	MOLECULAR TEMPERATURE	DENSITY	COEFFICIENT OF VISCOSITY	SPEED OF SOUND
meters	newtons cm^{-2}	degrees K	degrees K	kg m^{-3}	newton-sec m^{-2}	m sec^{-1}
580000.	4.6213737E-11	1.5058640E 03	2.5566500E 03	6.2970561E-13	7.0669703E-05	1.0136329E 03
582000.	4.5191225E-11	1.5059221E 03	2.5600500E 03	6.1495511E-13	7.0720567E-05	1.0143067E 03
584000.	4.4193244E-11	1.5059751E 03	2.5634500E 03	6.0057713E-13	7.0771394E-05	1.0149800E 03
586000.	4.3219147E-11	1.5060228E 03	2.5668500E 03	5.8656136E-13	7.0822185E-05	1.0156529E 03
588000.	4.2268324E-11	1.5060654E 03	2.5702500E 03	5.7289814E-13	7.0872940E-05	1.0163253E 03
590000.	4.1340184E-11	1.5061029E 03	2.5736500E 03	5.5957806E-13	7.0923660E-05	1.0169973E 03
592000.	4.0434149E-11	1.5061352E 03	2.5770500E 03	5.4659193E-13	7.0974344E-05	1.0176688E 03
594000.	3.9549641E-11	1.5061623E 03	2.5804500E 03	5.3393065E-13	7.1024992E-05	1.0183399E 03
596000.	3.8686114E-11	1.5061842E 03	2.5838500E 03	5.2158557E-13	7.1075606E-05	1.0190106E 03
598000.	3.7843038E-11	1.5062010E 03	2.5872500E 03	5.0954831E-13	7.1126183E-05	1.0196808E 03
600000.	3.7019889E-11	1.5062126E 03	2.5906500E 03	4.9781058E-13	7.1176726E-05	1.0203506E 03
602000.	3.6215577E-11	1.5062921E 03	2.5928500E 03	4.8658169E-13	7.1209410E-05	1.0207837E 03
604000.	3.5429846E-11	1.5063697E 03	2.5950500E 03	4.7562129E-13	7.1242081E-05	1.0212167E 03
606000.	3.4662245E-11	1.5064451E 03	2.5972500E 03	4.6492264E-13	7.1274736E-05	1.0216495E 03
608000.	3.3912334E-11	1.5065186E 03	2.5994500E 03	4.5447915E-13	7.1307377E-05	1.0220821E 03
610000.	3.3179683E-11	1.5065899E 03	2.6016500E 03	4.4428445E-13	7.1340003E-05	1.0225145E 03
612000.	3.2463859E-11	1.5066593E 03	2.6038500E 03	4.3433210E-13	7.1372615E-05	1.0229468E 03
614000.	3.1764455E-11	1.5067267E 03	2.6060500E 03	4.2461606E-13	7.1405212E-05	1.0233788E 03
616000.	3.1081098E-11	1.5067919E 03	2.6082500E 03	4.1513073E-13	7.1437795E-05	1.0238107E 03
618000.	3.0413369E-11	1.5068552E 03	2.6104500E 03	4.0586995E-13	7.1470361E-05	1.0242424E 03
620000.	2.9760908E-11	1.5069164E 03	2.6126499E 03	3.9682836E-13	7.1502915E-05	1.0246739E 03
622000.	2.9123341E-11	1.5069756E 03	2.6148500E 03	3.8800040E-13	7.1535454E-05	1.0251052E 03
624000.	2.8500294E-11	1.5070327E 03	2.6170500E 03	3.7938056E-13	7.1567978E-05	1.0255363E 03
626000.	2.7891442E-11	1.5070878E 03	2.6192500E 03	3.7096400E-13	7.1600487E-05	1.0259673E 03
628000.	2.7296429E-11	1.5071409E 03	2.6214500E 03	3.6274548E-13	7.1632982E-05	1.0263981E 03
630000.	2.6714925E-11	1.5071919E 03	2.6236500E 03	3.5472012E-13	7.1665463E-05	1.0268287E 03
632000.	2.6146607E-11	1.5072410E 03	2.6258500E 03	3.4688313E-13	7.1697928E-05	1.0272591E 03
634000.	2.5591154E-11	1.5072879E 03	2.6280500E 03	3.3922980E-13	7.1730380E-05	1.0276894E 03
636000.	2.5048265E-11	1.5073328E 03	2.6302500E 03	3.3175568E-13	7.1762818E-05	1.0281194E 03
638000.	2.4517629E-11	1.5073758E 03	2.6324500E 03	3.2445621E-13	7.1795239E-05	1.0285493E 03
640000.	2.3998967E-11	1.5074166E 03	2.6346500E 03	3.1732726E-13	7.1827648E-05	1.0289790E 03
642000.	2.3491983E-11	1.5074555E 03	2.6368500E 03	3.1036448E-13	7.1860043E-05	1.0294085E 03
644000.	2.2996400E-11	1.5074923E 03	2.6390500E 03	3.0356381E-13	7.1892422E-05	1.0298379E 03
646000.	2.2511953E-11	1.5075270E 03	2.6412500E 03	2.9692135E-13	7.1924787E-05	1.0302670E 03
648000.	2.2038369E-11	1.5075597E 03	2.6434500E 03	2.9043309E-13	7.1957139E-05	1.0306960E 03
650000.	2.1575395E-11	1.5075904E 03	2.6456500E 03	2.8409535E-13	7.1989475E-05	1.0311248E 03
652000.	2.1122777E-11	1.5076191E 03	2.6478500E 03	2.7790439E-13	7.2021797E-05	1.0315534E 03
654000.	2.0680276E-11	1.5076457E 03	2.6500500E 03	2.7185668E-13	7.2054106E-05	1.0319819E 03
656000.	2.0247647E-11	1.5076703E 03	2.6522500E 03	2.6594870E-13	7.2086399E-05	1.0324102E 03
658000.	1.9824656E-11	1.5076928E 03	2.6544500E 03	2.6017698E-13	7.2118679E-05	1.0328383E 03
660000.	1.9411084E-11	1.5077133E 03	2.6566499E 03	2.5453834E-13	7.2150944E-05	1.0332662E 03
662000.	1.9006698E-11	1.5077318E 03	2.6588500E 03	2.4902938E-13	7.2183195E-05	1.0336939E 03
664000.	1.8611281E-11	1.5077482E 03	2.6610500E 03	2.4364696E-13	7.2215433E-05	1.0341215E 03
666000.	1.8224638E-11	1.5077626E 03	2.6632500E 03	2.3838819E-13	7.2247656E-05	1.0345489E 03
668000.	1.7846547E-11	1.5077750E 03	2.6654500E 03	2.3324987E-13	7.2279864E-05	1.0349761E 03
670000.	1.7476821E-11	1.5077853E 03	2.6676500E 03	2.2822927E-13	7.2312059E-05	1.0354031E 03
672000.	1.7115252E-11	1.5077936E 03	2.6698500E 03	2.2332338E-13	7.2344239E-05	1.0358300E 03
674000.	1.6761651E-11	1.5077999E 03	2.6720500E 03	2.1852944E-13	7.2376407E-05	1.0362567E 03
676000.	1.6415844E-11	1.5078041E 03	2.6742500E 03	2.1384493E-13	7.2408558E-05	1.0366832E 03
678000.	1.6077632E-11	1.5078063E 03	2.6764500E 03	2.0926697E-13	7.2440697E-05	1.0371095E 03
680000.	1.5746857E-11	1.5078064E 03	2.6786500E 03	2.0479326E-13	7.2472821E-05	1.0375357E 03
682000.	1.5423325E-11	1.5078045E 03	2.6808500E 03	2.0042101E-13	7.2504931E-05	1.0379616E 03
684000.	1.5106879E-11	1.5078006E 03	2.6830500E 03	1.9614794E-13	7.2537029E-05	1.0383874E 03
686000.	1.4797364E-11	1.5077946E 03	2.6852500E 03	1.9197178E-13	7.2569111E-05	1.0388131E 03
688000.	1.4494605E-11	1.5077867E 03	2.6874500E 03	1.8789003E-13	7.2601179E-05	1.0392385E 03
690000.	1.4198453E-11	1.5077766E 03	2.6896500E 03	1.8390054E-13	7.2633234E-05	1.0396638E 03
692000.	1.3908750E-11	1.5077646E 03	2.6918500E 03	1.8000104E-13	7.2665275E-05	1.0400889E 03
694000.	1.3625348E-11	1.5077505E 03	2.6940500E 03	1.7618937E-13	7.2697302E-05	1.0405139E 03
696000.	1.3348109E-11	1.5077343E 03	2.6962500E 03	1.7246356E-13	7.2729314E-05	1.0409386E 03
698000.	1.3076882E-11	1.5077162E 03	2.6984500E 03	1.6882143E-13	7.2761313E-05	1.0413632E 03
700000.	1.2811533E-11	1.5076960E 03	2.7006500E 03	1.6526106E-13	7.2793300E-05	1.0417877E 03

TABLE 14.11 (Continued)

GEOMETRIC ALTITUDE	PRESSURE RATIO	DENSITY RATIO	VISCOSITY RATIO	MOLECULAR WEIGHT	PRESSURE DIFFERENCE
meters	unitless	unitless	unitless	unitless	newtons cm^{-2}
580000.	4.5440578E-12	5.3204963E-13	3.8612197E 00	1.7060000E 01	1.0170147E 01
582000.	4.4435173E-12	5.1958667E-13	3.8639988E 00	1.7038000E 01	1.0170147E 01
584000.	4.3453888E-12	5.0743845E-13	3.8667759E 00	1.7016000E 01	1.0170147E 01
586000.	4.2496088E-12	4.9559628E-13	3.8695509E 00	1.6994000E 01	1.0170147E 01
588000.	4.1561172E-12	4.8405197E-13	3.8723241E 00	1.6972000E 01	1.0170147E 01
590000.	4.0648560E-12	4.7279759E-13	3.8750953E 00	1.6950000E 01	1.0170147E 01
592000.	3.9757683E-12	4.6182538E-13	3.8778645E 00	1.6928000E 01	1.0170147E 01
594000.	3.8887973E-12	4.5112764E-13	3.8806318E 00	1.6906000E 01	1.0170147E 01
596000.	3.8038893E-12	4.4069706E-13	3.8833972E 00	1.6884000E 01	1.0170147E 01
598000.	3.7209922E-12	4.3052656E-13	3.8861607E 00	1.6862000E 01	1.0170147E 01
600000.	3.6400543E-12	4.2060913E-13	3.8889222E 00	1.6840000E 01	1.0170147E 01
602000.	3.5609688E-12	4.1112165E-13	3.8907080E 00	1.6826600E 01	1.0170147E 01
604000.	3.4837103E-12	4.0186101E-13	3.8924930E 00	1.6813200E 01	1.0170147E 01
606000.	3.4082344E-12	3.9282153E-13	3.8942772E 00	1.6799800E 01	1.0170147E 01
608000.	3.3344978E-12	3.8399763E-13	3.8960607E 00	1.6786400E 01	1.0170147E 01
610000.	3.2624585E-12	3.7538395E-13	3.8978432E 00	1.6773000E 01	1.0170147E 01
612000.	3.1920736E-12	3.6697503E-13	3.8996251E 00	1.6759600E 01	1.0170147E 01
614000.	3.1233034E-12	3.5876577E-13	3.9014061E 00	1.6746200E 01	1.0170147E 01
616000.	3.0561109E-12	3.5075145E-13	3.9031864E 00	1.6732800E 01	1.0170147E 01
618000.	2.9904551E-12	3.4292684E-13	3.9049657E 00	1.6719400E 01	1.0170147E 01
620000.	2.9263006E-12	3.3528744E-13	3.9067444E 00	1.6706000E 01	1.0170147E 01
622000.	2.8636105E-12	3.2782854E-13	3.9085222E 00	1.6692600E 01	1.0170147E 01
624000.	2.8023482E-12	3.2054548E-13	3.9102992E 00	1.6679199E 01	1.0170147E 01
626000.	2.7424816E-12	3.1343417E-13	3.9120755E 00	1.6665800E 01	1.0170147E 01
628000.	2.6839758E-12	3.0649020E-13	3.9138509E 00	1.6652400E 01	1.0170147E 01
630000.	2.6267982E-12	2.9970942E-13	3.9156256E 00	1.6639000E 01	1.0170147E 01
632000.	2.5709172E-12	2.9308781E-13	3.9173994E 00	1.6625600E 01	1.0170147E 01
634000.	2.5163012E-12	2.8662138E-13	3.9191725E 00	1.6612200E 01	1.0170147E 01
636000.	2.4629205E-12	2.8030636E-13	3.9209448E 00	1.6598800E 01	1.0170147E 01
638000.	2.4107448E-12	2.7413891E-13	3.9227163E 00	1.6585400E 01	1.0170147E 01
640000.	2.3597463E-12	2.6811552E-13	3.9244870E 00	1.6572000E 01	1.0170147E 01
642000.	2.3098961E-12	2.6223255E-13	3.9262570E 00	1.6558600E 01	1.0170147E 01
644000.	2.2611669E-12	2.5648654E-13	3.9280261E 00	1.6545200E 01	1.0170147E 01
646000.	2.2135327E-12	2.5087421E-13	3.9297944E 00	1.6531800E 01	1.0170147E 01
648000.	2.1669666E-12	2.4539216E-13	3.9315620E 00	1.6518400E 01	1.0170147E 01
650000.	2.1214438E-12	2.4003729E-13	3.9333288E 00	1.6505000E 01	1.0170147E 01
652000.	2.0769392E-12	2.3480643E-13	3.9350948E 00	1.6491600E 01	1.0170147E 01
654000.	2.0334294E-12	2.2969662E-13	3.9368601E 00	1.6478200E 01	1.0170147E 01
656000.	1.9908903E-12	2.2470486E-13	3.9386245E 00	1.6464800E 01	1.0170147E 01
658000.	1.9492988E-12	2.1982822E-13	3.9403882E 00	1.6451400E 01	1.0170147E 01
660000.	1.9086335E-12	2.1506403E-13	3.9421511E 00	1.6438000E 01	1.0170147E 01
662000.	1.8688714E-12	2.1040941E-13	3.9439132E 00	1.6424600E 01	1.0170147E 01
664000.	1.8299913E-12	2.0586171E-13	3.9456746E 00	1.6411200E 01	1.0170147E 01
666000.	1.7919739E-12	2.0141848E-13	3.9474352E 00	1.6397800E 01	1.0170147E 01
668000.	1.7547973E-12	1.9707703E-13	3.9491949E 00	1.6384400E 01	1.0170147E 01
670000.	1.7184432E-12	1.9283503E-13	3.9509540E 00	1.6371000E 01	1.0170147E 01
672000.	1.6828913E-12	1.8868995E-13	3.9527123E 00	1.6357600E 01	1.0170147E 01
674000.	1.6481227E-12	1.8463947E-13	3.9544698E 00	1.6344200E 01	1.0170147E 01
676000.	1.6141206E-12	1.8068144E-13	3.9562265E 00	1.6330800E 01	1.0170147E 01
678000.	1.5808652E-12	1.7681344E-13	3.9579825E 00	1.6317400E 01	1.0170147E 01
680000.	1.5483411E-12	1.7303352E-13	3.9597377E 00	1.6304000E 01	1.0170147E 01
682000.	1.5165292E-12	1.6933933E-13	3.9614921E 00	1.6290600E 01	1.0170147E 01
684000.	1.4854140E-12	1.6572893E-13	3.9632458E 00	1.6277200E 01	1.0170147E 01
686000.	1.4549803E-12	1.6220042E-13	3.9649987E 00	1.6263800E 01	1.0170147E 01
688000.	1.4252109E-12	1.5875168E-13	3.9667508E 00	1.6250400E 01	1.0170147E 01
690000.	1.3960912E-12	1.5538089E-13	3.9685022E 00	1.6237000E 01	1.0170147E 01
692000.	1.3676056E-12	1.5208613E-13	3.9702529E 00	1.6223600E 01	1.0170147E 01
694000.	1.3397395E-12	1.4886558E-13	3.9720027E 00	1.6210200E 01	1.0170147E 01
696000.	1.3124794E-12	1.4571757E-13	3.9737518E 00	1.6196800E 01	1.0170147E 01
698000.	1.2858105E-12	1.4264028E-13	3.9755002E 00	1.6183400E 01	1.0170147E 01
700000.	1.2597195E-12	1.3963205E-13	3.9772478E 00	1.6170000E 01	1.0170147E 01

Even though only mean values are tabulated in the U. S. Standard Supplements, 1966, extreme density values suitable for use in vehicle design calculations can be obtained from the document. To insure uniformity for space shuttle designers, those extreme densities are listed in Table 14.12. For all computations, these tabulated maximum and minimum values may be used with the appropriate mean values of temperature and pressure.

G. V. Groves (Ref. 14.11) has constructed similar nominal latitudinal/ seasonal atmospheric models from 25 to 110 kilimeters altitude. Results of a study on the distributions of temperature, pressure, and density between 30 and 80 kilometers by Allen E. Cole (Ref. 14.12) gives estimates of probable worldwide extreme values.

14.8.1 Atmospheric Density for Reentry Analyses

Since atmospheric parameters are seldom constant over large areas, it is unrealistic to expect minimum, maximum, or mean values of density to exist over the entire reentry trajectory. However, if one is concerned only with instantaneous vehicle heating computations (not considering accumulated heat), the density value producing the most severe heating may be used at every point of the trajectory (for example, the July maximum values from Table 14.12 for 60° N from 90 to 70 kilometers and the July maximum values for 45° N latitude from 70 to 30 kilometers).

In some design problems, it may be useful to consider density changes along the trajectory — changes that may occur in the atmosphere. For example, when accumulated heat calculations are made, realistic results can be obtained by allowing the density to change in a somewhat regular manner over the vehicle trajectory. This problem is rather complex because both horizontal and vertical gradients must be considered. Since both high and low density extremes and extreme gradients occur at high latitudes, for design purposes it will suffice to consider only those areas.

The design procedure outlined here assumes that for heating studies the reentry flight trajectories will be calculated along a reference atmosphere (U. S. Standard Supplements, 1966) upon which a perturbation (or density gradient) will be imposed. A variety of density changes can be encountered within the bounds indicated in Figures 14.8 and 14.9. By tying all gradients to a common reference — percent departure from US 62 – the density at any point can be evaluated. Also, the horizontal and vertical gradients can be considered separately or additively. The density gradients (or perturbations) specified here are applicable to the 60° N Supplemental Atmospheres.

TABLE 14.12 RANGE[1] OF ATMOSPHERIC DENSITY FOR DESIGN ANALYSIS

Altitude (km)	60° N				45° N				30° N				15° N	
	January		July		January		July		January		July		Annual	
	Min[a]	Max[b]	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
90	-3	13	2	13	-2	13	0	13	-3	13	0	13	-1	12
85	-22	11	9	40	-18	12	2	30	-14	16	-5	19	-6	14
80	-44	6	10	48	-36	10	4	33	-20	17	-10	20	-10	16
75	-56	-6	10	45	-42	6	6	37	-24	16	-5	21	-12	17
70	-56	-6	10	42	-42	6	6	40	-20	14	0	23	-11	18
65	-54	-6	9	39	-40	6	4	40	-17	13	0	24	-10	18
60	-51	-3	8	36	-36	5	2	38	-17	15	0	25	-8	18
55	-47	2	6	36	-32	4	2	37	-17	18	-4	27	-6	18
50	-41	8	4	36	-30	2	2	34	-16	17	-6	28	-6	16
45	-36	15	6	27	-28	2	2	31	-15	16	-4	25	-6	14
40	-36	13	6	20	-25	5	0	28	-13	10	-1	19	-8	12
35	-36	10	4	16	-21	8	-2	23	-11	5	-1	14	-8	8
30	-28	6	2	13	-14	6	-1	18	-9	3	-2	10	-6	6

a. Associated with the 60° N January cold supplemental atmosphere.
b. Associated with the 60° N January warm supplemental atmosphere.

1. Percent departures from US 62.

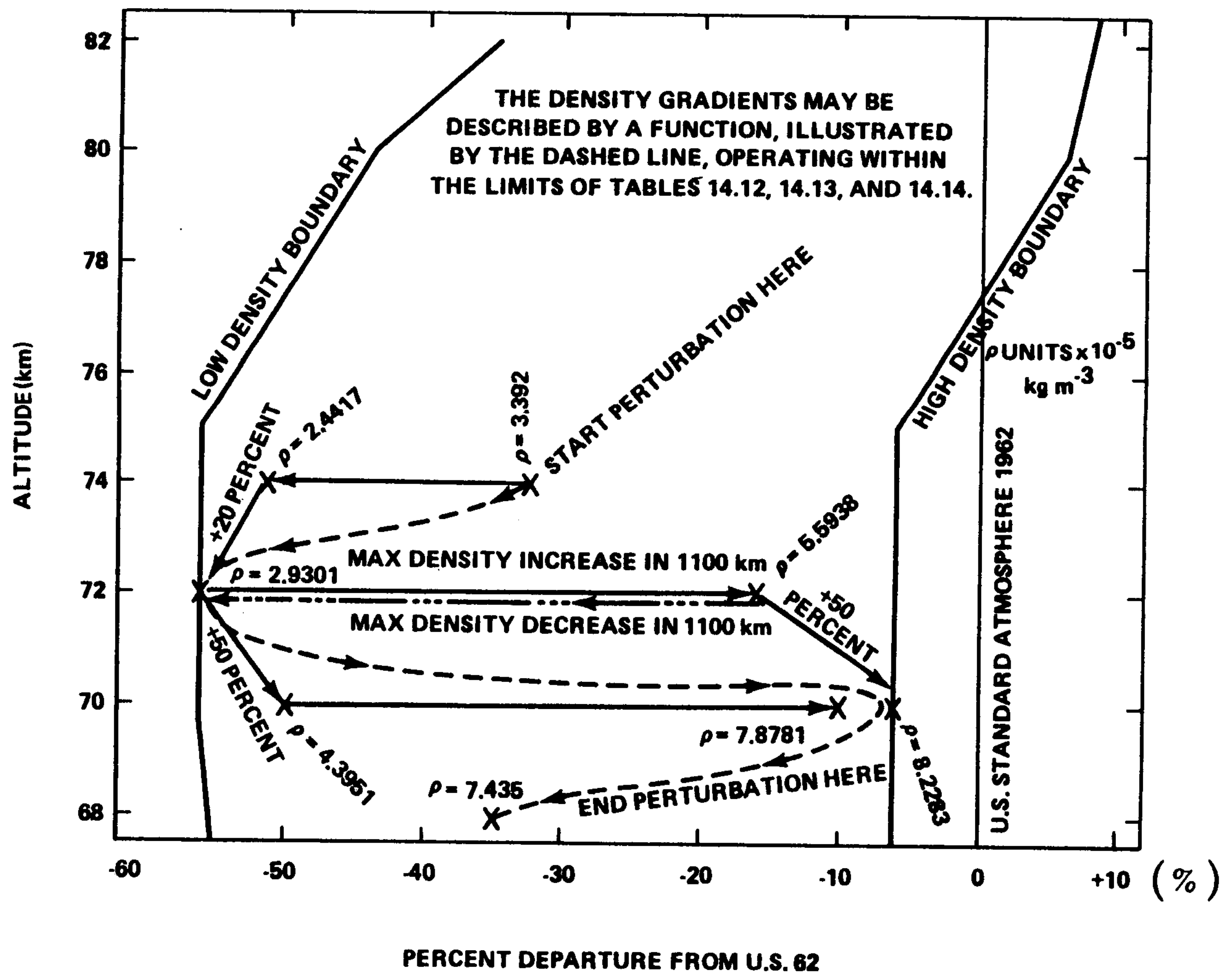

FIGURE 14. 8 DENSITY PERTURBATION, JANUARY, 60° N

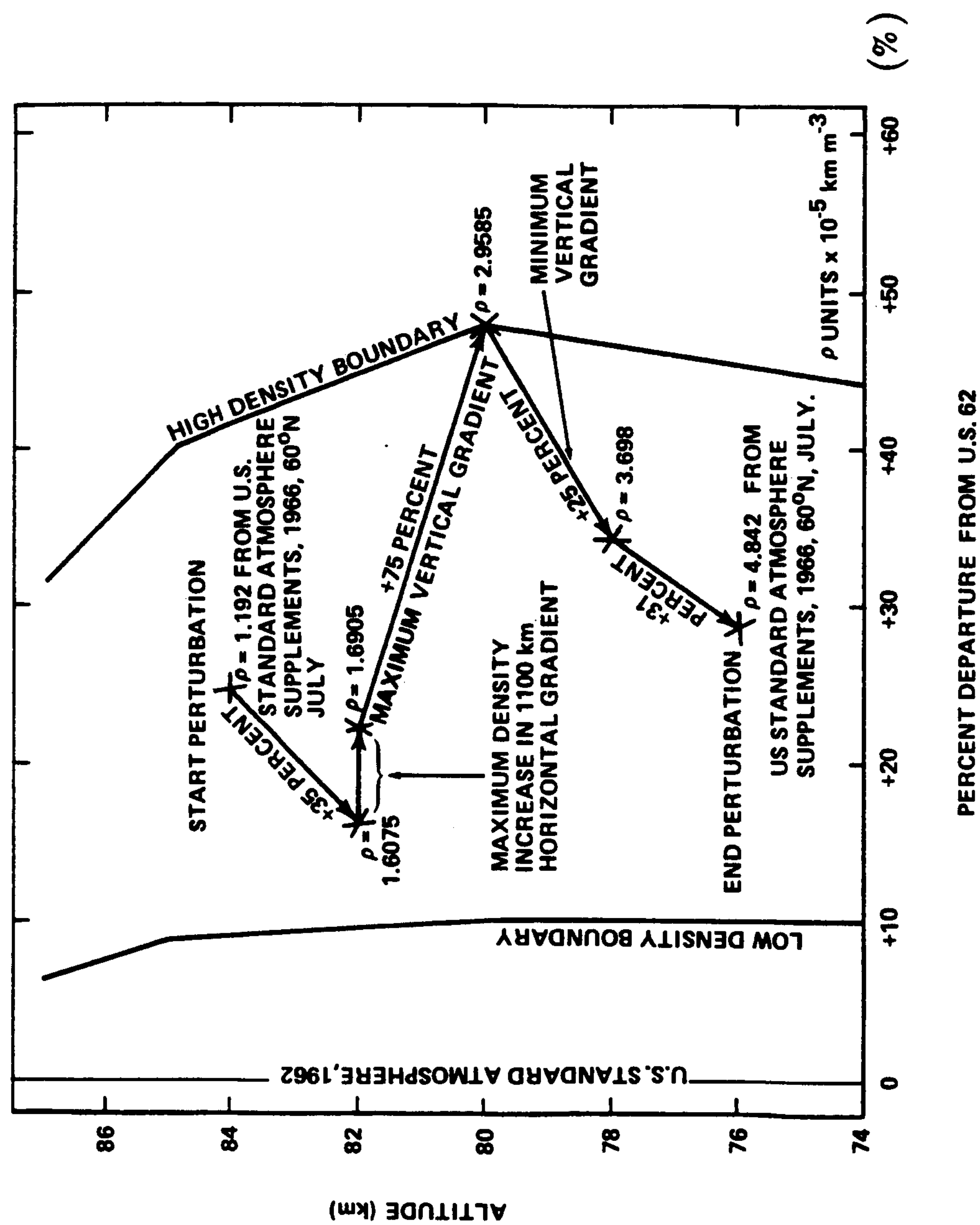

FIGURE 14.9 DENSITY PERTURBATION, JULY, 60° N

14.8.1.1 Example of Density Gradient Calculation

To illustrate the possible density gradients, three cases will be considered.

Case 1. Flight at Constant Altitude. The maximum horizontal density gradients from Table 14.13 may be applied in any direction, i.e., at any time the reentering vehicle may be flying from relatively low to high density or high to low density. This is illustrated in Figure 14.8 at 72 kilometers. In both cases the density change when referenced to percent departure from the US 62 amounts to 40 percent. The percent change relative to the density at the initial point is +91 percent for a vehicle flying toward higher density and -47 percent toward lower density.

TABLE 14.13 DESIGN HORIZONTAL DENSITY GRADIENTS — CHANGE OF PERCENT DEPARTURE FROM US 62, PER 110 km (not to exceed 1100 km)

Altitude (km)	High Latitude (above 37.5° N and S)		Low Latitude (37.5° N, 37.5° S)	
	January	July	January	July
90	1.0	0.2	0.3	0.1
80	3.6	0.6	2.0	0.5
70	4.0	0.7	2.2	0.6
60	3.7	0.6	2.0	0.5
50	3.3	0.5	1.5	0.4
40	2.8	0.4	1.1	0.3
30	1.8	0.3	0.5	0.2

Note: Use linear interpolation to obtain gradients at altitudes between those listed.

Values of change of percent departure from US 62 given in Table 14.13 were computed from

$$\left(\frac{\rho_s - \rho_{a_1}}{\rho_s}\right) 100 - \left(\frac{\rho_s - \rho_{a_2}}{\rho_s}\right) 100 = \text{change of percent departure} \qquad (14.8)$$

where

ρ_s = density of US 62

ρ_{a_1} = ambient density at initial point

ρ_{a_2} = ambient density at final point.

Case 2. Vertical Flight. The maximum and minimum density changes from Table 14.14 are relative to the density at the higher level; these values are not percent departures from the US 62. A different reference must be used in this case because the vertical percent change of density is related to the temperature and temperature gradient in a column of air. The horizontal density gradient, on the other hand, was determined from an assumption of the minimum distance between two dissimilar columns of air. Although the vertical and horizontal gradients are referenced to different bases, they can be converted to a common reference while applying the perturbation. This is also illustrated in Figure 14.8.

TABLE 14.14 DESIGN VERTICAL DENSITY GRADIENTS PERCENT INCREASE OF DENSITY IN 2-km LAYERS

Altitude (km)	January		July	
	Maximum	Minimum	Maximum	Minimum
90	85	7	75	30
80	85	7	75	25
70	50	20	50	20
60	45	20	40	20
50	45	20	40	20
40	50	20	40	20
30	50	20	45	20

Note: Use linear interpolation to obtain gradients between listed altitudes.

Values of percent increase in vertical density gradients given in Table 14.14 were computed from

$$\left(\frac{\rho_L - \rho_H}{\rho_H}\right) 100 = \text{percent increase of density} \qquad (14.9)$$

where

ρ_L = ambient density at lower altitude

ρ_H = ambient density at higher altitude.

Temperature and temperature gradients dictate that the density should not increase more than 50 percent while descending from 72 to 70 kilometers. If the density at 72 kilometers is near the minimum, a 50-percent increase amounts to about a 6-percent change in relative departures from the US 62. If the density at 72 kilometers is near the maximum value, a 50-percent increase amounts to about a 12-percent change. Since the 50-percent increase may not be exceeded, the change in percent departure from the US 62 can only be determined after the 50-percent increase is computed.

Case 3. Flight Along a Trajectory. A combination of horizontal and vertical density gradients may be encountered along the flight path. To simulate this situation (or to apply the maximum perturbation to the reference atmosphere), the vertical gradient should be converted to percent departure from the US 62 so that the difference in the deviations may be added to the horizontal gradient. For example, start with minimum density at 72 kilometers (density = 2.9301); apply the horizontal gradient for 1100 kilometers (or any fraction thereof); then increase the resultant density by 50 percent. If only a part of the 1100 kilometers were traversed at 72 kilometers, the remainder of the horizontal density gradient may be added at 70 kilometers. The perturbation must be reversed when the density reaches the maximum or minimum boundary (Figure 14.8).

14.8.1.2 Detailed Description of the Perturbation Procedure [Figure 14.8; Append to all Density (ρ) values: $\times 10^{-5}$ kg m^{-3}]

Since the density gradients illustrated in Figure 14.8 occur only during winter in high latitudes, the perturbation is imposed on the 60° N January Supplemental Atmosphere. The density at the starting point (74 km) is taken directly from Reference 14.4, Table 5.1 (60° N Jan.). Since this perturbation goes first from mean to minimum density the first objective is to apply some combination of horizontal and vertical density gradients that will accomplish a change from ρ = 3.392 at 74 kilometers to ρ = 2.9301 at 72 kilometers. Obviously horizontal (or nearly so) flight to a region of lower density must be encountered during the 2-kilometer descent. One combination of gradients that will accomplish the objective is shown in Figure 14.8. Backing off from ρ = 2.9301 with the minimum vertical gradient of + 20 percent (Table 14.13) gives ρ = 2.4417 at 74 kilometers. This value is a

-51.3 percent departure from the US 62. The difference between the starting point density converted to percent departure from the US 62 (-32.4%) and the point described above [-51.3% - (-32.4%) = - 18.9%] gives the horizontal density change. Since the maximum gradient is ± 4%/110 kilometers (Table 14.12) the minimum distance between the two density values at 74 kilometers is 18.9% ÷ 4%/110 kilometers or 519.75 kilometers.

Having reached the minimum density value at 72 kilometers (US 62 -56% US 62 or 44% × 6.6593 = 2.9301) we now wish to exercise the maximum horizontal and vertical gradients. Applying the full horizontal gradient amounts to moving 40 percent (4%/110 km for 1100 km) on the percent departure from US 62 scale. At 72 kilometers this change is from a -56 percent departure from US 62 to a -16 percent departure from US 62, or from $\rho = 2.9301$ to $\rho = 5.5938$. The full vertical gradient may be applied at this point ($\rho = 5.5938$) until the high density boundary is reached; the density during this exercise may not exceed a -6 percent departure from the US 62. If the maximum vertical gradient had been imposed before the horizontal gradient the perturbation would have stayed within the boundaries. As illustrated, the densities are: $\rho = 2.9301 + 50\% = 4.3951$ or ~ -50% departure from US 62. Then -50% + 4%/110 for 1100 kilometers = -10% departure from US 62. The computed density at this point is 90 percent US 62 or $\rho = (0.90)(8.7535) = 7.8781$. Any combination of horizontal and vertical gradients within the tabulated limits may be used. The two illustrated in Figure 14.8 show that the perturbation allows changes across the full range of density near 70 kilometers altitude.

To complete the perturbation it is only necessary to return to mean density at 68 kilometers ($\rho = 7.435$ from Reference 14.4, Table 5.1 60° N Jan.). Again, a number of combinations of vertical and horizontal gradients will permit the change from $\rho = 8.2283$ at 70 kilometers to $\rho = 7.435$ at 68 kilometers. Extra computations can be avoided by first applying the vertical gradient (either maximum or minimum).

14.8.1.3 Restrictions on Perturbation

Only one horizontal gradient may be encountered from entry to landing. This means a change from mean to minimum (or maximum) then to maximum (or minimum) then a return to mean density. A complete cycle beginning and ending with the mean density of the appropriate reference atmosphere must be used. While the perturbation, once begun, must go through a full cycle, the maximum and/or minimum values of density may exist for a distance not to exceed 200 kilometers.

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(2) White Sands Missile Range Reference Atmosphere (Part I), Aug. 1964.

(3) Fort Churchill Missile Range Reference Atmosphere for Fort Churchill, Canada (Part I), Dec. 1964.

(4) Pacific Missile Range Reference Atmosphere for Eniwetok, Marshall Islands (Part I), Dec. 1964.

(5) Fort Greely Missile Range Reference Atmosphere (Part I), Nov. 1964.

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SECTION XV. DISTRIBUTION OF SURFACE EXTREMES IN THE UNITED STATES

By

Glenn E. Daniels and Orvel E. Smith

15. 1 Introduction

For component parts manufactured, transported, or tested in geographical areas not discussed in other sections of this document, this section can be used for environments needed in design and planning. These environments may be applicable to transportation, fabrication, or testing.

15. 2 Environments Included

(a) Air temperature, extreme maximum and minimum,

(b) Snow fall - snow loads, 24-hour maximum and storm maximum,

(c) Hail, maximum size,

(d) Atmosphere pressure, extreme maximum and minimum.

15. 3 Source of Data

The extremes presented have been prepared using data from Weather Bureau stations and published articles. These extremes represent the highest or lowest extreme value measured at each station. The length of record varies from station to station, but most values represent more than 15 years of record. Where the local surroundings have a geographical area with a special influence on an extreme value (such as the minimum temperature on a high mountain peak or other local condition), it will not in general be shown on the maps presented unless a Weather Bureau station is located there. If there is a contractor at such a locality and an item of equipment is especially sensitive to an environment, a study is needed of the local environment where fabrication is to be made.

15. 4 Extreme Design Environments[1]

1. All values of extreme maxima and minima in this section are for design purposes and may or may not exactly reflect extrapolations (theoretical or otherwise) of actual measured values over the available period of record.

15.4.1 Air Temperature

The distribution of extreme maximum air temperature in the United States is shown in Figure 15.1A, while Figure 15.1B shows the extreme minimum temperature distribution. The maps (Figures 15.2A and 15.2B) from Reference 15.1 show the mean temperature and standard deviations of the temperatures from the means for January and July.

To estimate the temperature $\hat{T}$ that is attained or exceeded with a frequency p, from Figures 15.2A and 15.2B, find from the appropriate figure, by interpolation as needed, the mean temperature $\bar{T}$ and standard deviation S_T and substitute these in the equation

$$\hat{T} = \bar{T} + S_T \cdot y_s \quad [°F].$$

Values of y_s for various calculated risks are:

Cold Temperatures (Figure 15.2A)		Hot Temperatures (Figure 15.2B)		
p	y_s	p	y_s	
0.20	- 0.84	0.80	+ 0.84	
0.10	- 1.28	0.90	+ 1.28	
0.05	- 1.65	0.95	+ 1.65	(See footnote 2.)
0.025	- 1.96	0.975	+ 1.96	
0.01	- 2.33	0.99	+ 2.33	

15.4.2 Snow Fall - Snow Load

The maps in Figures 15.3 and 15.4 show the maximum depth of snow and the corresponding snow loads. Figure 15.3 shows the maximum depth for a 24-hour period; Figure 15.4 shows the maximum depth and the corresponding snow loads for a storm period. The storm total map shows the same snow depth as in the 24-hour map in the southern low elevation areas of the United States since snow storms seldom exceed 24 hours in these areas.

The terrain combined with the general movement of weather patterns has a great effect on the amount of fall, accumulation, and melting of the snow. Also the length of a single storm varies for various areas. In some

2. The 95th percentile value is recommended for hot day design ambient temperatures over runways for landing-takeoff performance calculation using Figure 15.2B, the 5th percentile is for cold day design.

areas in mountain regions much greater amounts of snowfall have been recorded than shown on the maps. Also the snow in these areas may remain for the entire winter. For example, in a small valley near Soda Springs, California, a seasonal snow accumulation of 7.9 meters (26 ft) with a density of about 0.35 was recorded. This gives a snow load of 2772 kg/m^2 (567.7 lb/ft^2). Such a snow pack can do considerable damage to improperly protected equipment buried deep in the snow. This snow pack at Soda Springs is the greatest on record in the United States and was nearly double previous records in the same area. A study of the maximum snow loads in the Wasatch Mountains of Utah (Ref. 15.2) showed that for a 100-year return period at 2740 meters (9000 ft), a snow load of 1220 kg/m^2 (250 lb/ft^2) could be expected.

15.4.3 Hail

The distribution of maximum sized hail stones in the United States is shown in Figure 15.5. The sizes are for single hailstones and not conglomerates of several hail stones frozen together.

15.4.4 Atmospheric Pressure

Atmospheric pressure extremes normally given in the literature are given as the pressure which would have occurred if the station were at sea level. The surface weather map published by the United States Weather Bureau uses sea level pressures for the pressure values to assist in map analysis and forecasting. These sea level pressure values are obtained from the station pressures by use of the hydrostatic equation:

$$dP = \rho g dZ$$

where

dP = pressure difference

ρ = density

g = gravity

dZ = altitude difference.

These sea level data are valid only for design purposes at locations with elevation near sea level. As an example, when the highest officially reported sea level pressure observed in the United States of 106 330 N/m^2 (1063.3 mb) occurred at Helena, Montana (Ref 15.3), the actual station pressure was about 92 100 N/m^2 (921 mb) because the station is 1187 meters (3893 ft) above mean sea level.

Figures 15.6 and 15.7 show the general distribution of extreme maximum and minimum station pressures in the United States. Because of the direct relationship of pressure and station elevation, Figures 15.8 through 15.11 should be used with the station elevation to obtain the extreme maximum and minimum pressure values for any location in the United States. Similar maps and graphs in U. S. Customary Units are given in Reference 15.4. Table 15.1 gives a list of the station elevations for a number of locations in the United States. These are elevations of the barometer at the local Weather Bureau office.

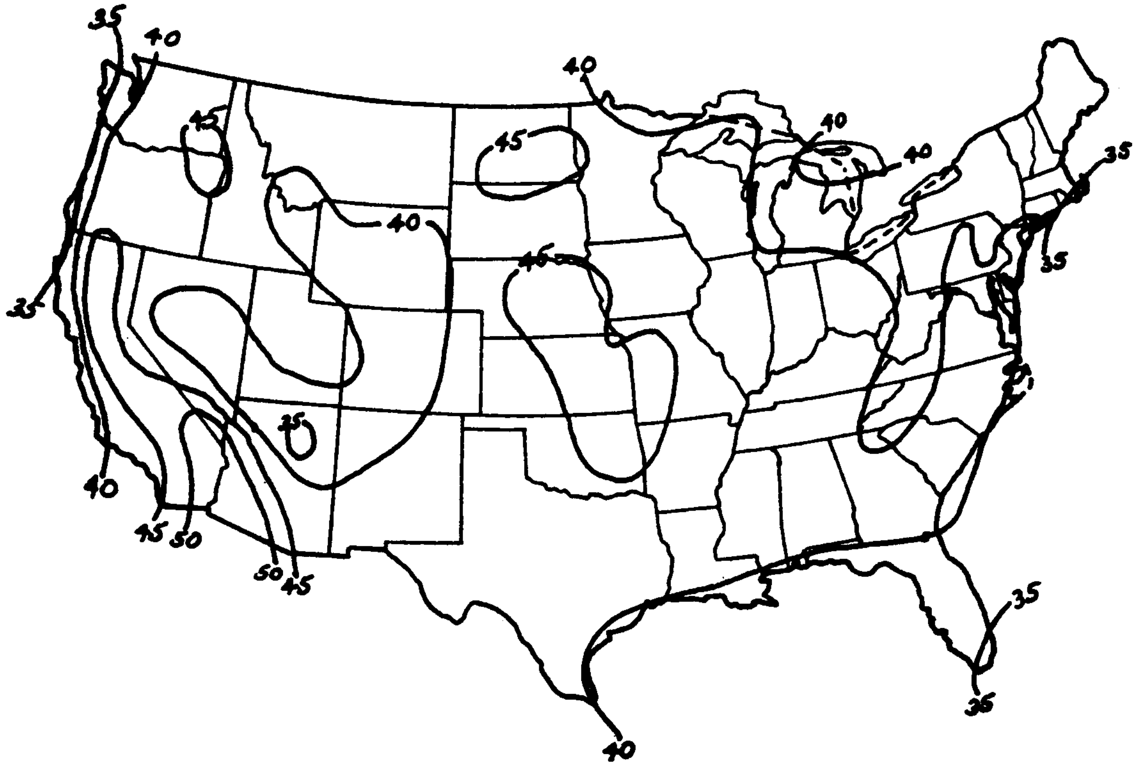

FIGURE 15. 1A EXTREME MAXIMUM TEMPERATURE (° C)

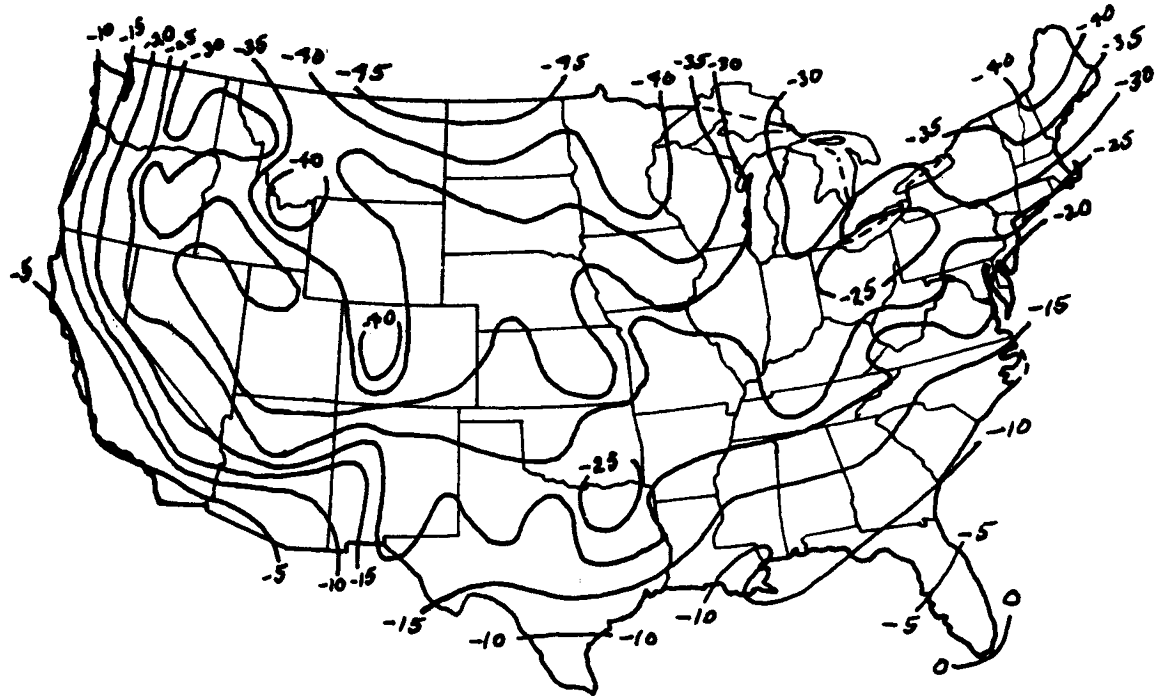

FIGURE 15. 1B EXTREME MINIMUM TEMPERATURE (° C)

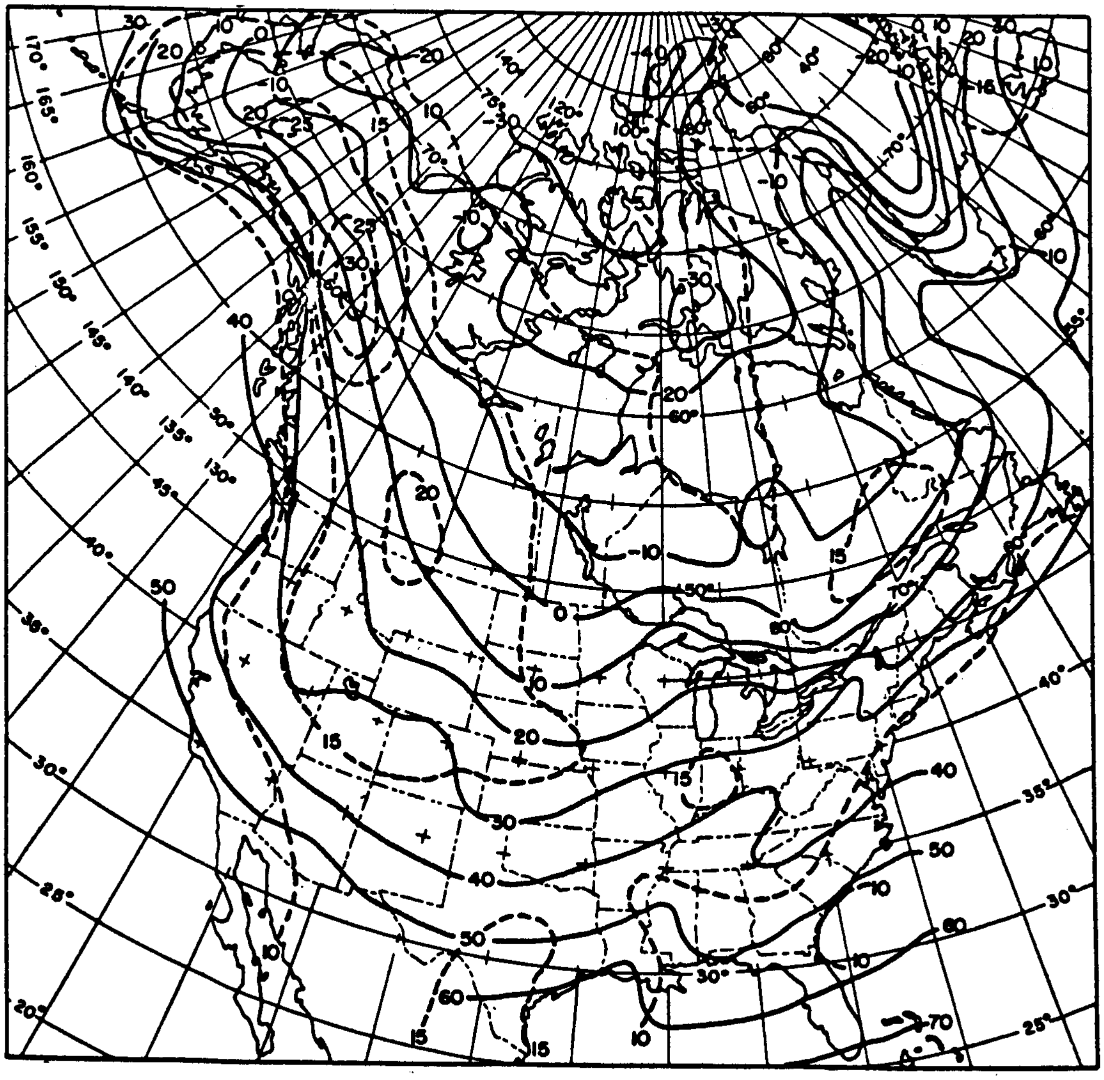

FIGURE 15. 2A ISOTHERMS OF JANUARY HOURLY SURFACE TEMPERATURES (Approximate mean values (° F) are shown by solid lines, standard deviations (° F) by broken lines. The approximations were made to give best estimates of lower 1- to 20-percentile values of temperature by normal distribution.) [3]

3. Valley, Shea L., "Handbook of Geophysics and Space Environments," McGraw-Hill Book Company, Inc., New York, 1965.

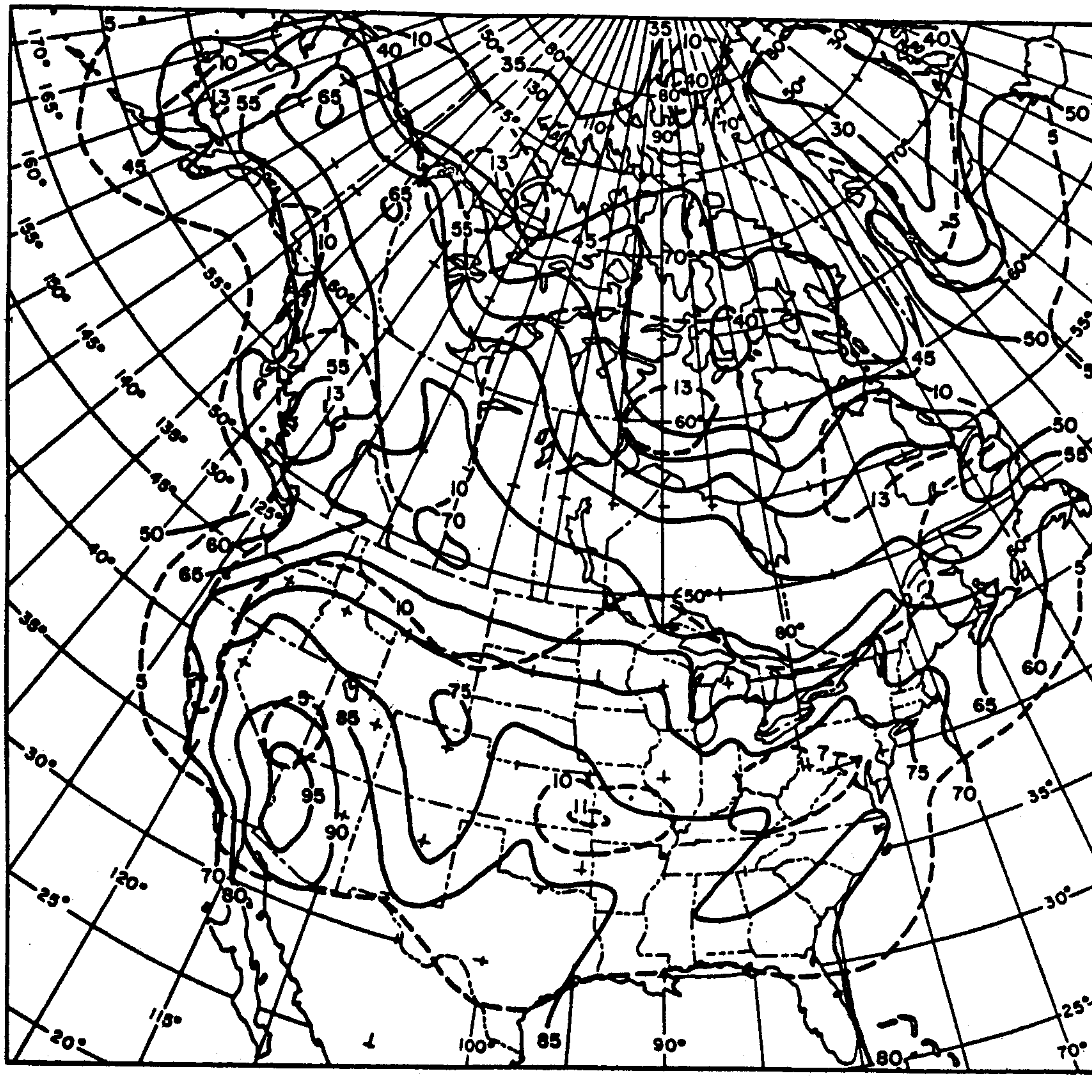

FIGURE 15. 2. B ISOTHERMS OF JULY HOURLY SURFACE TEMPERATURES (Approximate mean values (° F) are shown by solid lines, standard deviations (° F) by broken lines. The approximation were made to yield the best estimates of upper 80- to 99-percentile values by normal distribution)[3]

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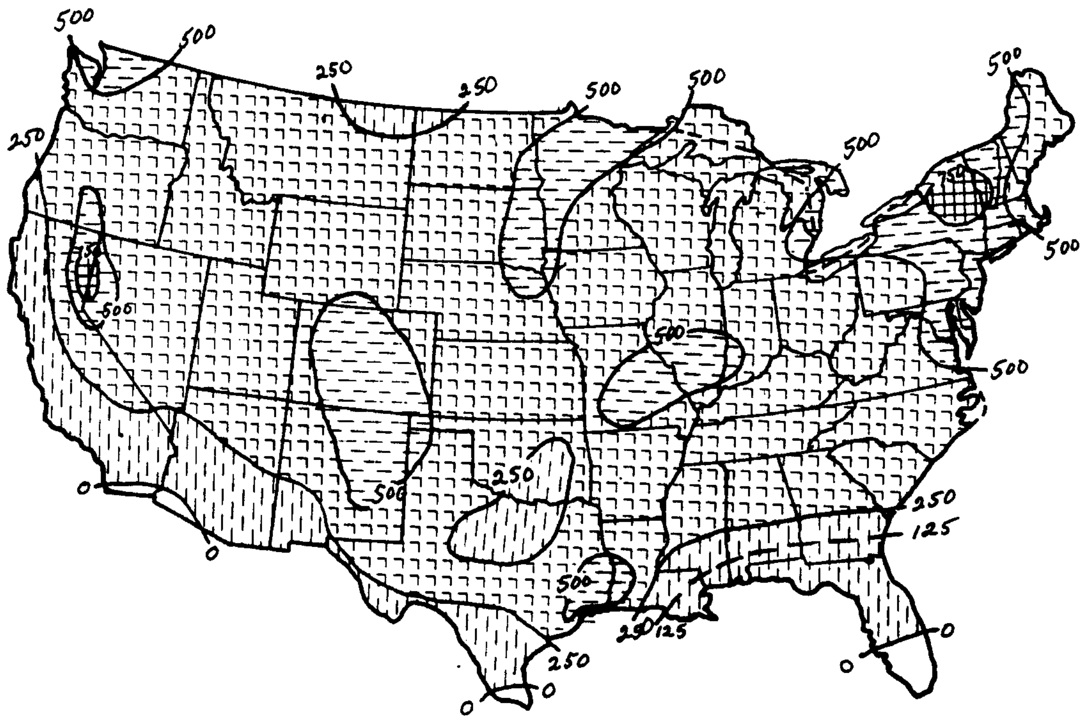
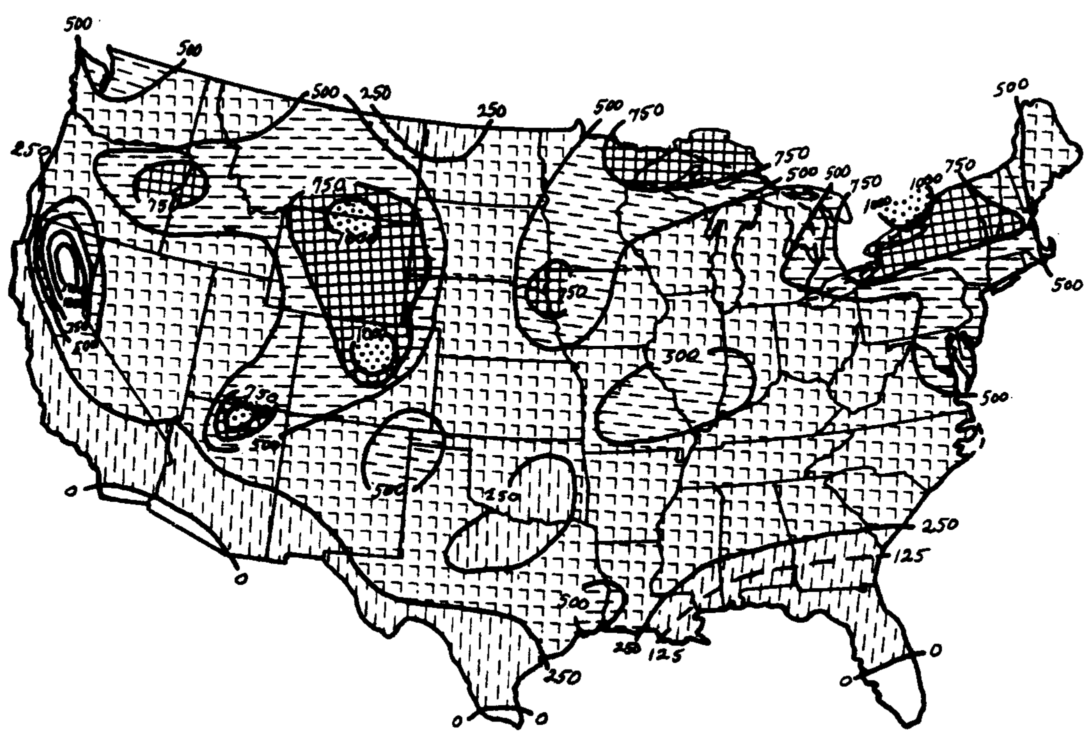
3. Ibid.



MAXIMUM SNOW LOAD

mm	kg/m^2
0-250	25
250-500	50
500-750	75
over 750	100

FIGURE 15. 3 EXTREME 24-HOUR MAXIMUM SNOW FALL (mm)



MAXIMUM SNOW LOAD

mm	kg/m^2
0-250	25
250-500	50
500-750	75
750-1000	100
1000-1250	125

FIGURE 15. 4 EXTREME STORM MAXIMUM SNOW FALL (mm)

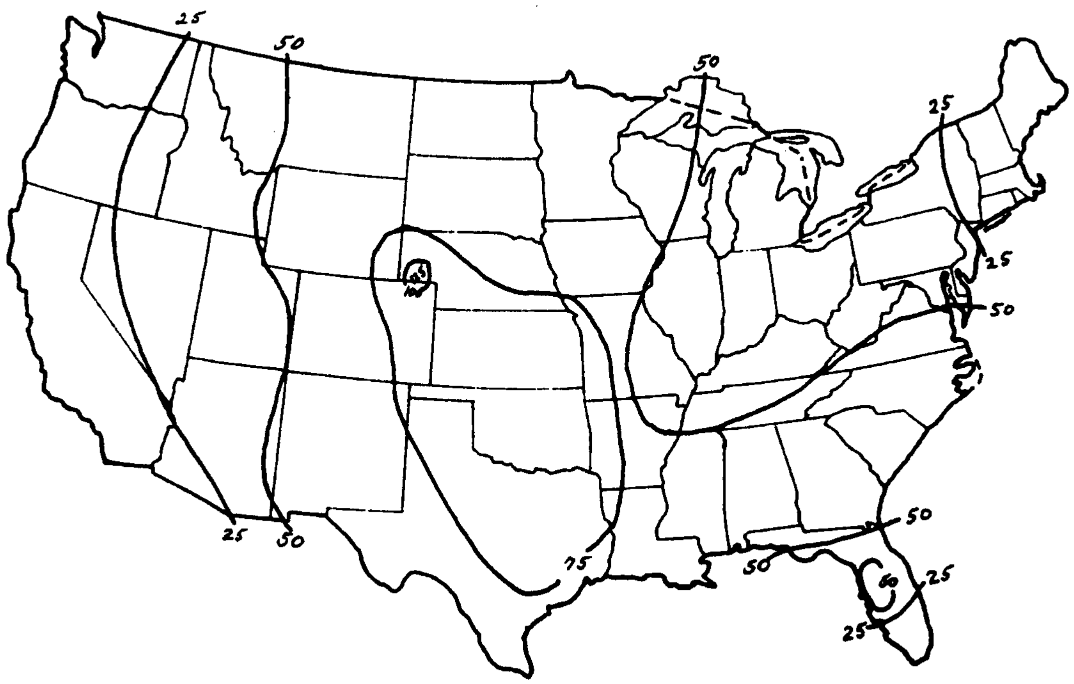


FIGURE 15. 5 EXTREME MAXIMUM HAIL STONE DIAMETERS (mm)

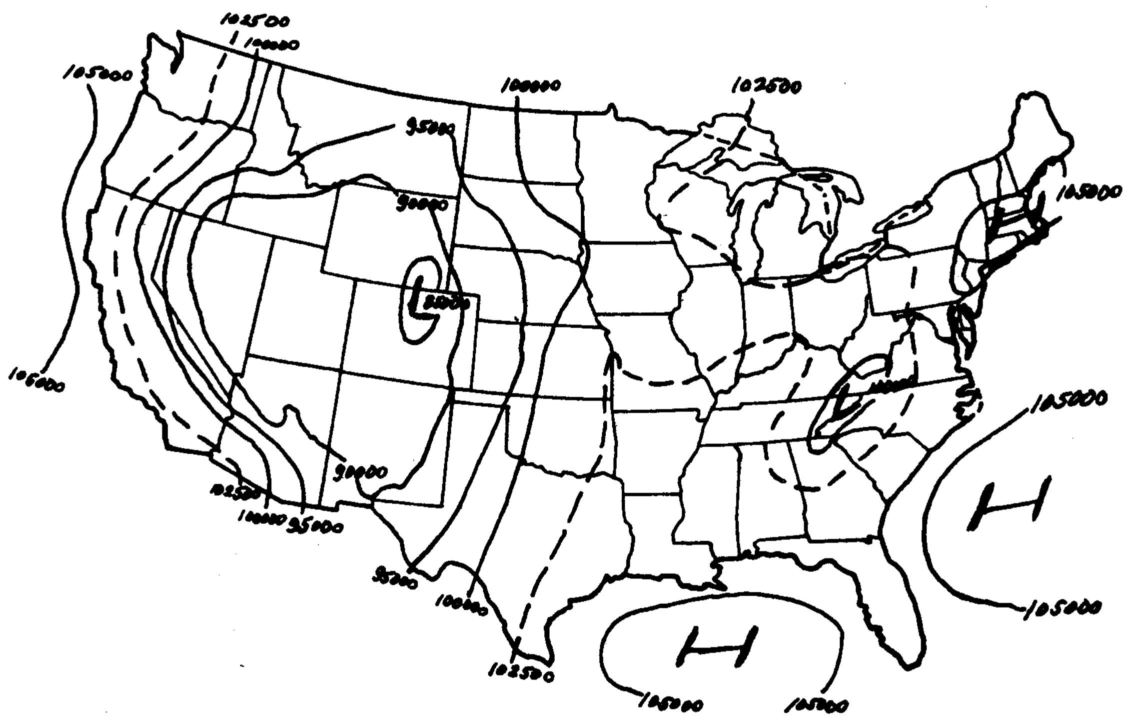


FIGURE 15. 6 MAXIMUM ABSOLUTE STATION PRESSURE (N/m^2)

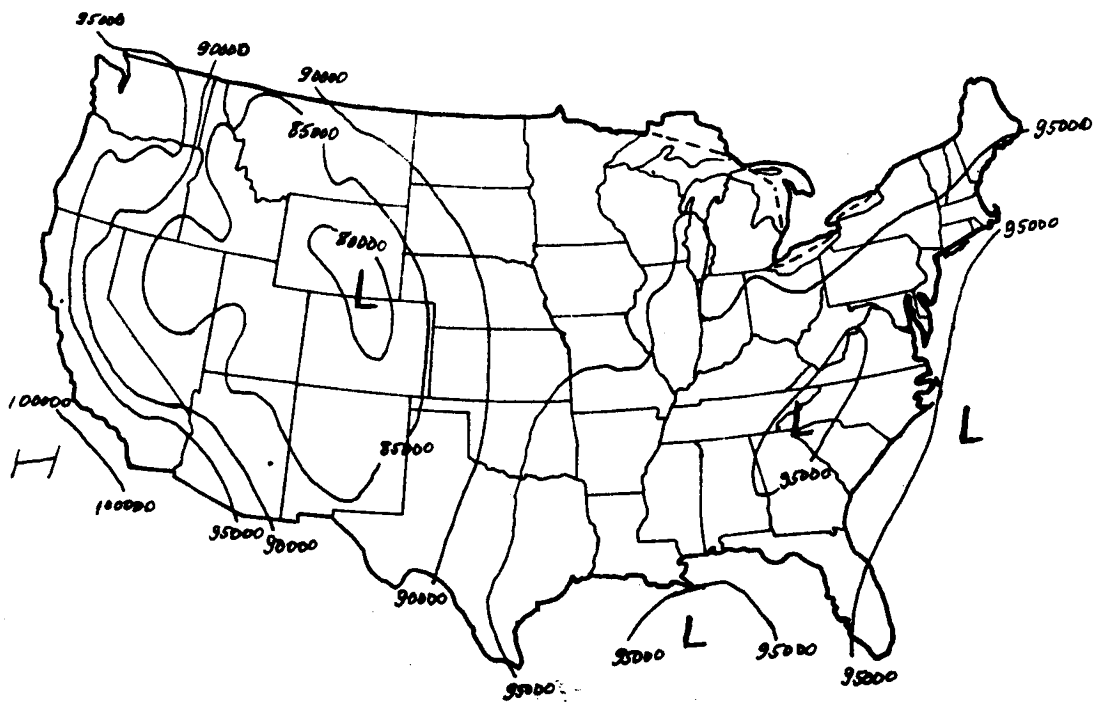


FIGURE 15. 7 MINIMUM ABSOLUTE STATION PRESSURE (N/m^2)

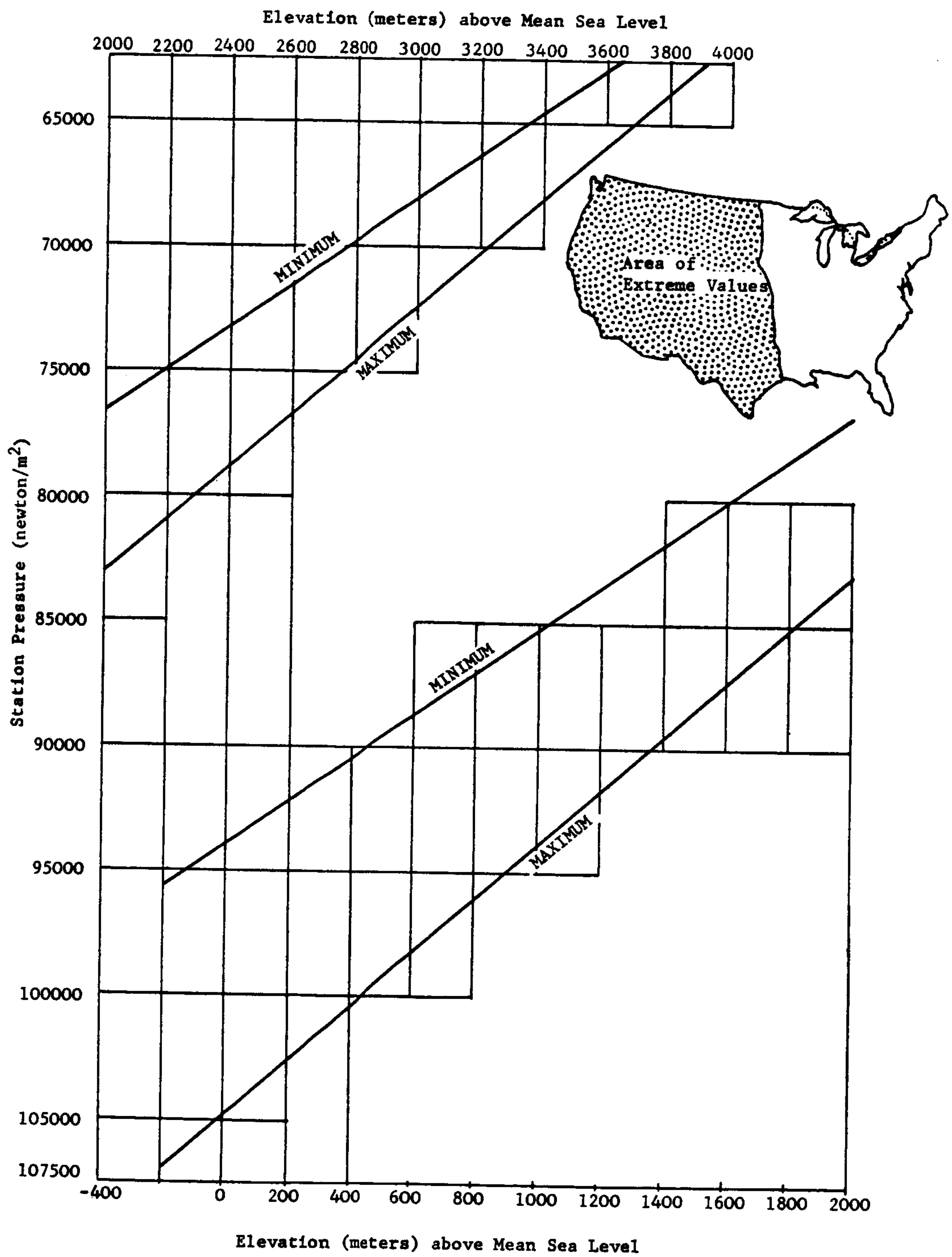


FIGURE 15. 8 EXTREME PRESSURE VALUES VERSUS ELEVATION FOR WESTERN UNITED STATES

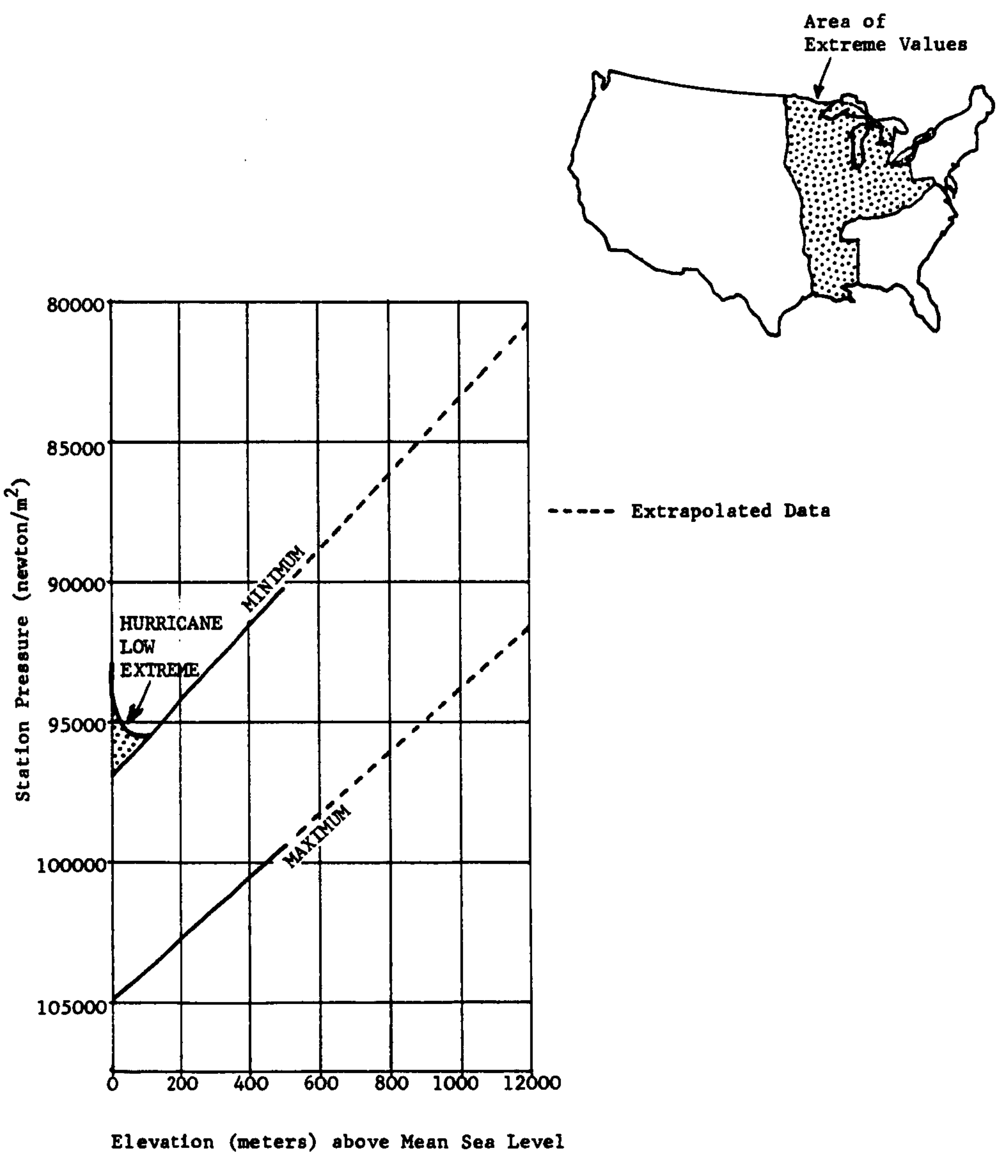


FIGURE 15. 9 EXTREME PRESSURE VALUES VERSUS ELEVATION FOR CENTRAL UNITED STATES

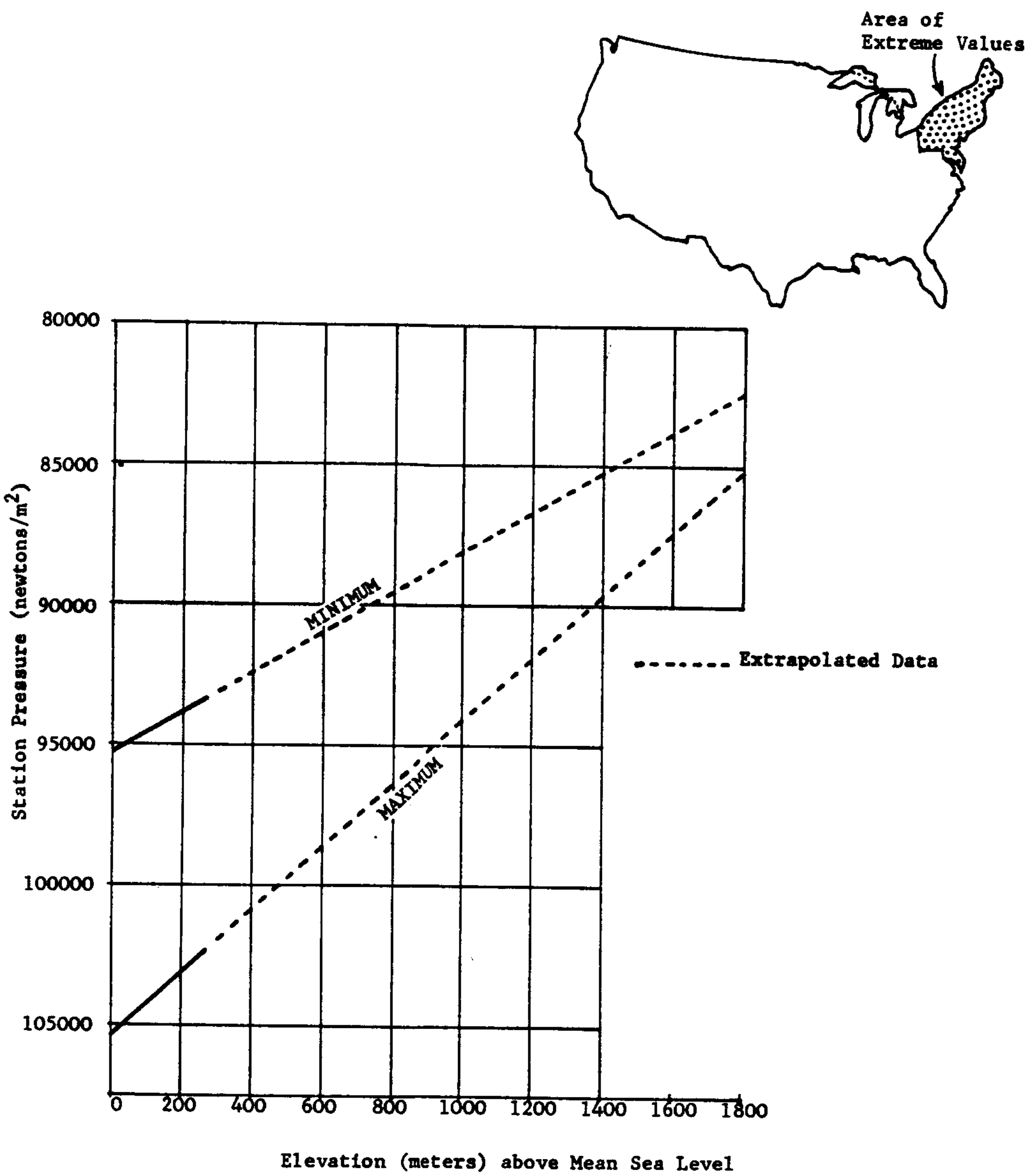


FIGURE 5. 10 EXTREME PRESSURE VALUES VERSUS ELEVATION FOR NORTHEASTERN UNITED STATES

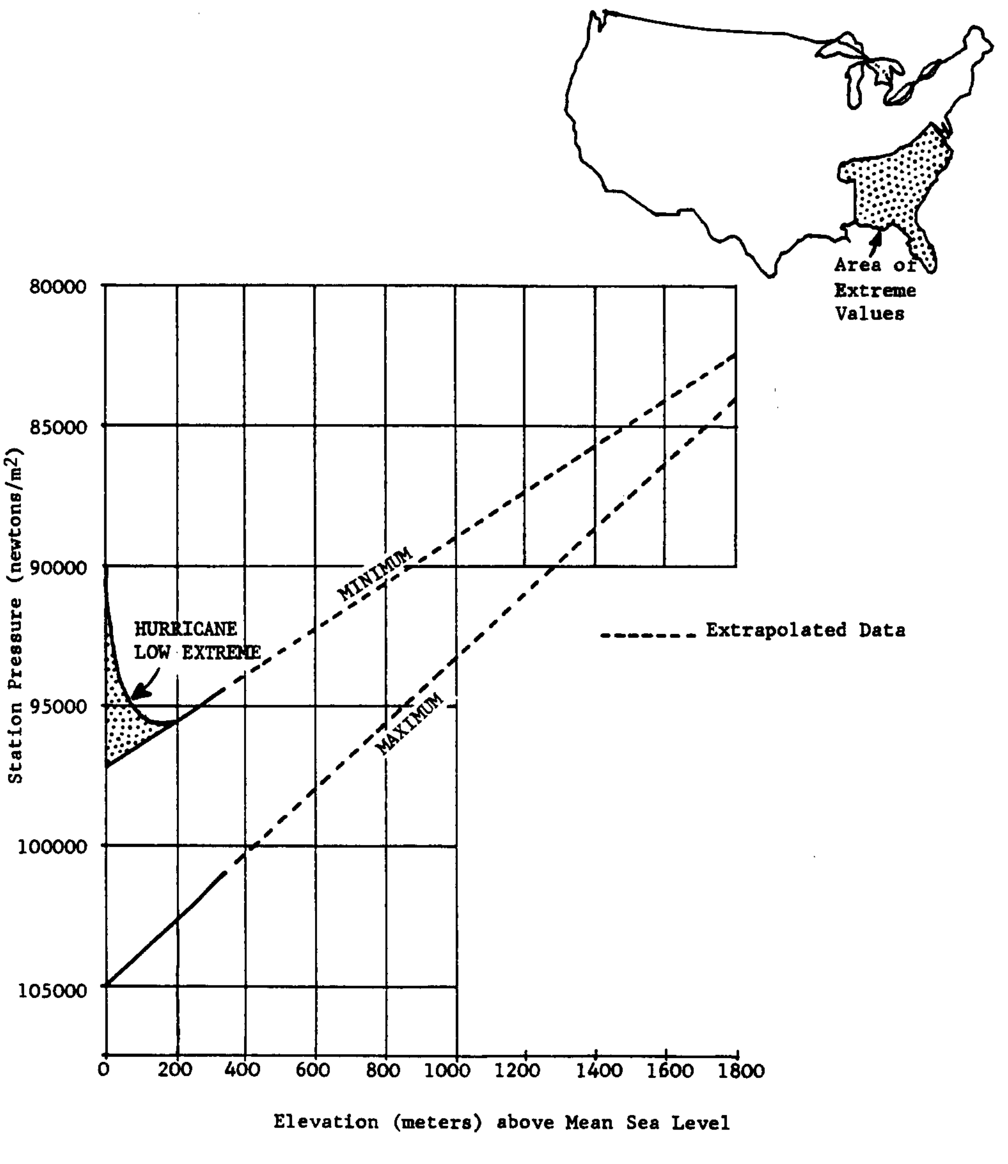


FIGURE 5.11 EXTREME PRESSURE VALUES VERSUS ELEVATION FOR SOUTHEASTERN UNITED STATES

TABLE 15.1 ELEVATIONS OF CITIES OF THE UNITED STATES
(Values are elevation of barometer at U. S. Weather Bureau Station)

Location	Elevation, MSL (feet)	Elevation, MSL (meters)
ALABAMA		
Birmingham	610	185.9
Mobile	211	64.3
ARIZONA		
Phoenix	1100	335.2
Yuma	199	60.7
ARKANSAS		
Fort Smith	499	152.1
Little Rock	257	78.3
Texarkana	361	110.0
CALIFORNIA		
Eureka	43	13.1
Fresno	331	100.9
Los Angeles	312	95.1
Sacramento	20	6.1
San Diego	19	5.8
San Francisco	52	15.8
COLORADO		
Denver	5292	1613.0
Grand Junction	4849	1478.0
Pueblo	4639	1414.0
CONNECTICUT		
Hartford	15	4.6
New Haven	6	1.8
DISTRICT OF COLUMBIA		
Washington	72	21.9
FLORIDA		
Apalachicola	13	4.0
Fort Myers	15	4.6
Jacksonville	18	5.5
Key West	5	1.5
Miami	7	2.1
Pensacola	13	4.0
GEORGIA		
Atlanta	1054	321.3
Savannah	48	14.6
IDAHO		
Boise	2842	866.2
Pocatello	4444	1354.5
ILLINOIS		
Cairo	314	95.7
Chicago	610	185.9
Springfield	587	178.9
INDIANA		
Evansville	383	116.7
Indianapolis	718	218.8
IOWA		
Des Moines	807	246.0
Sioux City	1094	333.4
KANSAS		
Dodge City	2594	790.7
Goodland	3645	1111.0
Wichita	1321	402.6
KENTUCKY		
Louisville	457	139.3
LOUISIANA		
Lake Charles	12	3.7
New Orleans	3	0.9
Shreveport	174	53.0
MAINE		
Caribou	624	190.2
Portland	61	18.6
MARYLAND		
Baltimore	14	4.3
MASSACHUSETTS		
Boston	15	4.6
Nantucket	43	13.1
MICHIGAN		
Alpena	587	178.9
Detroit	619	188.7
Marquette	677	206.3
Sault Ste. Marie	721	219.8
MINNESOTA		
Duluth	1162	354.2
International Falls	1179	359.4
Minneapolis	830	253.0
MISSISSIPPI		
Jackson	305	93.0
MISSOURI		
Kansas City	741	225.9
St. Louis	809	246.6
MONTANA		
Havre	2488	758.3
Helena	3893	1186.6
NEBRASKA		
Omaha	978	298.1
NEVADA		
Elko	5075	1546.9
Las Vegas	2162	659.0
Winnemucca	4299	1310.3
NEW HAMPSHIRE		
Concord	339	103.3
NEW JERSEY		
Atlantic City	10	3.0
Newark	11	3.4
Trenton	56	17.1
NEW YORK		
Albany	19	5.8
Buffalo	693	211.2
New York City	10	3.0
Rochester	543	165.5
Syracuse	424	129.2
NORTH CAROLINA		
Cape Hatteras	7	2.1
Raleigh	400	121.9
Wilmington	30	9.1
NORTH DAKOTA		
Fargo	900	274.3
Bismarck	1650	502.9
Williston	1877	572.1

TABLE 15.1 (Concluded)

Location	Elevation, MSL (feet)	Elevation, MSL (meters)
OHIO		
Cincinnati	553	168.6
Cleveland	653	199.0
Columbus	724	220.7
Toledo	676	206.0
OKLAHOMA		
Oklahoma City	1254	382.2
Tulsa	672	205.2
OREGON		
Medford	1312	399.9
Pendleton	1492	454.8
Portland	21	6.4
Roseburg	479	146.0
PENNSYLVANIA		
Harrisburg	335	102.1
Philadelphia	7	2.1
Pittsburg	749	228.3
RHODE ISLAND		
Block Island	110	33.5
Providence	12	3.7
SOUTH CAROLINA		
Charleston	9	2.7
Columbia	217	66.1
Greenville	1018	310.3
SOUTH DAKOTA		
Huron	1282	390.8
Rapid City	3165	964.7
Sioux Falls	1420	432.8
TENNESSEE		
Chattanooga	670	204.2
Memphis	263	80.2
Nashville	577	175.9
TEXAS		
Abilene	1759	536.1
Amarillo	3590	1094.2
Brownsville	16	4.9
Corpus Christi	43	13.1
Dallas	476	145.1
El Paso	3920	1194.8
Galveston	5	1.5
San Antonio	792	241.4
Wichita Falls	1002	305.4
UTAH		
Salt Lake City	4220	1286.3
VERMONT		
Burlington	331	100.9
VIRGINIA		
Norfolk	11	3.4
Richmond	162	49.4
WASHINGTON		
Tatoosh Island	101	30.8
Seattle	14	4.3
Spokane	2357	718.4
Walla Walla	949	289.3
WEST VIRGINIA		
Charleston	950	289.6
WISCONSIN		
Green Bay	689	210.0
La Crosse	652	198.7
Madison	857	261.2
Milwaukee	620	189.0
WYOMING		
Casper	5319	1621.2
Cheyenne	6131	1868.7
Lander	5563	1695.6
Sheridan	3942	1201.5

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15.1 Valley, Shea L., "Handbook of Geophysics and Space Environments," McGraw-Hill Book Company, Inc., New York, 1965.

15.2 Brown, Merly J.; and Williams, Philip Jr. : "Maximum Snow Loads along the Western Slopes of the Wasatch Mountains of Utah." Journal of Applied Meteorology, vol. 1, March 1962, pp. 123-126.

15.3 Ludlum, David M.: "Extremes of Atmospheric Pressure in the United States." Weatherwise, vol. 15, no. 3, 1962, pp. 106-115.

15.4 Daniels, Glenn E.: "Values of Extreme Surface Pressure for Design Criteria." Institute of Environmental Sciences, 1965 Proceedings, pp. 283-288; Institute of Environmental Sciences, Mt. Prospect, Illinois.

SECTION XVI. ATMOSPHERIC ATTENUATION RELATIVE TO EARTH-VIEWING ORBITAL SENSORS

By

S. Clark Brown

16.0 Introduction

Earth-viewing space missions offer exciting new possibilities in several earth resources disciplines – geography, hydrology, agriculture, geology, and oceanography, to name a few. A most useful tool in planning experiments and applying space technology to earth observation is a statistical description of atmospheric parameters. For example, cloud cover statistics might be used to predict mission feasibility or the probability of observing a given target area in a given number of satellite passes.

To meet the need for atmospheric statistics, NASA-MSFC has sponsored the development of the four-dimensional atmospheric models (subsection 16. 3) and the world-wide cloud model (subsection 16. 2). The goal of this is to produce atmospheric attenuation models to predict degradation effects for all classes of sensors for application to earth-sensing experiments from space-borne platforms. To insure maximum utility and application of these products NASA-MSFC also sponsored the development of an "Interaction Model of Microwave Energy and Atmospheric Variables," a complete description of the effects of atmospheric moisture upon microwaves.

16.1 Interaction Model of Microwave Energy and Atmospheric Variables

While the visible and infrared wavelengths find clouds opaque, the microwave part of the electromagnetic spectrum is unique in that cloud and rain particles vary from very weak absorbers and scatterers to very significant contributors to the electromagnetic environment. This is illustrated in Figures 16. 1, 16. 2, and 16. 3, which are extracted from the final report on the interaction model (Ref. 16. 1).

16.1.1 Scattering and Extinction Properties of Water Clouds Over the Range 10 cm to 10μ.

Figures 16. 1 and 16. 2 show the unit-volume scattering and extinction properties of two modeled cloud drop distributions computed using the Mie theory. Figure 16. 1 gives the extinction coefficient as a function

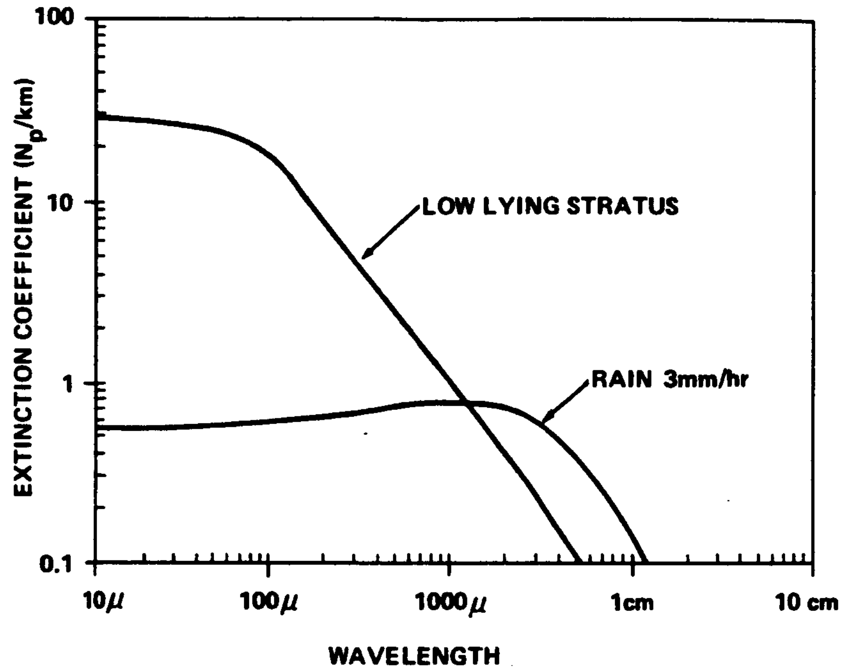

FIGURE 16. 1 EXTINCTION COEFFICIENT AS A FUNCTION OF WAVELENGTH

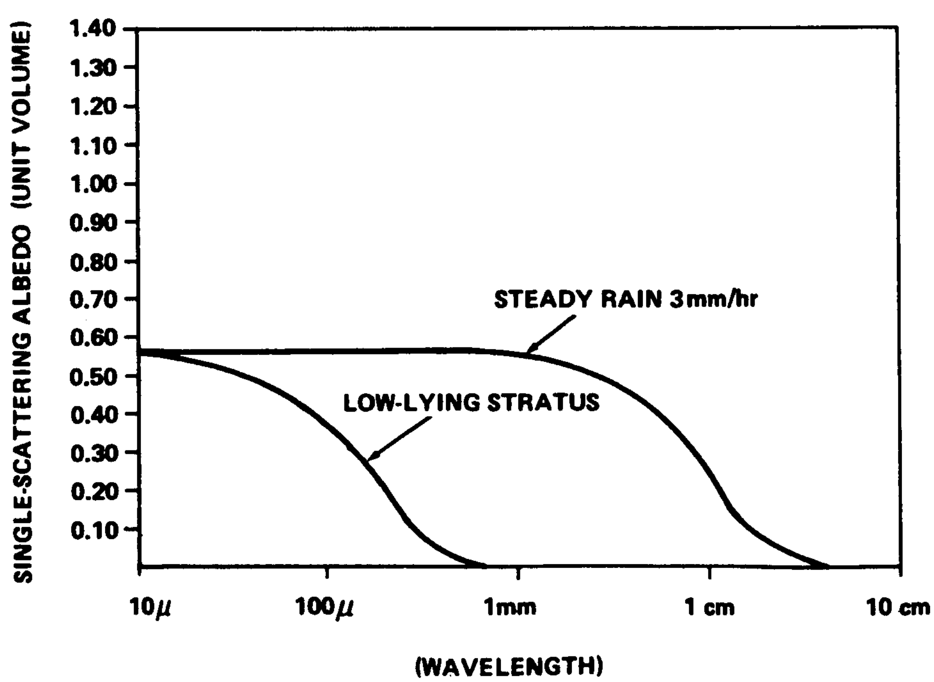

FIGURE 16. 2 SINGLE SCATTERING ALBEDO FOR TWO CLOUD MODELS

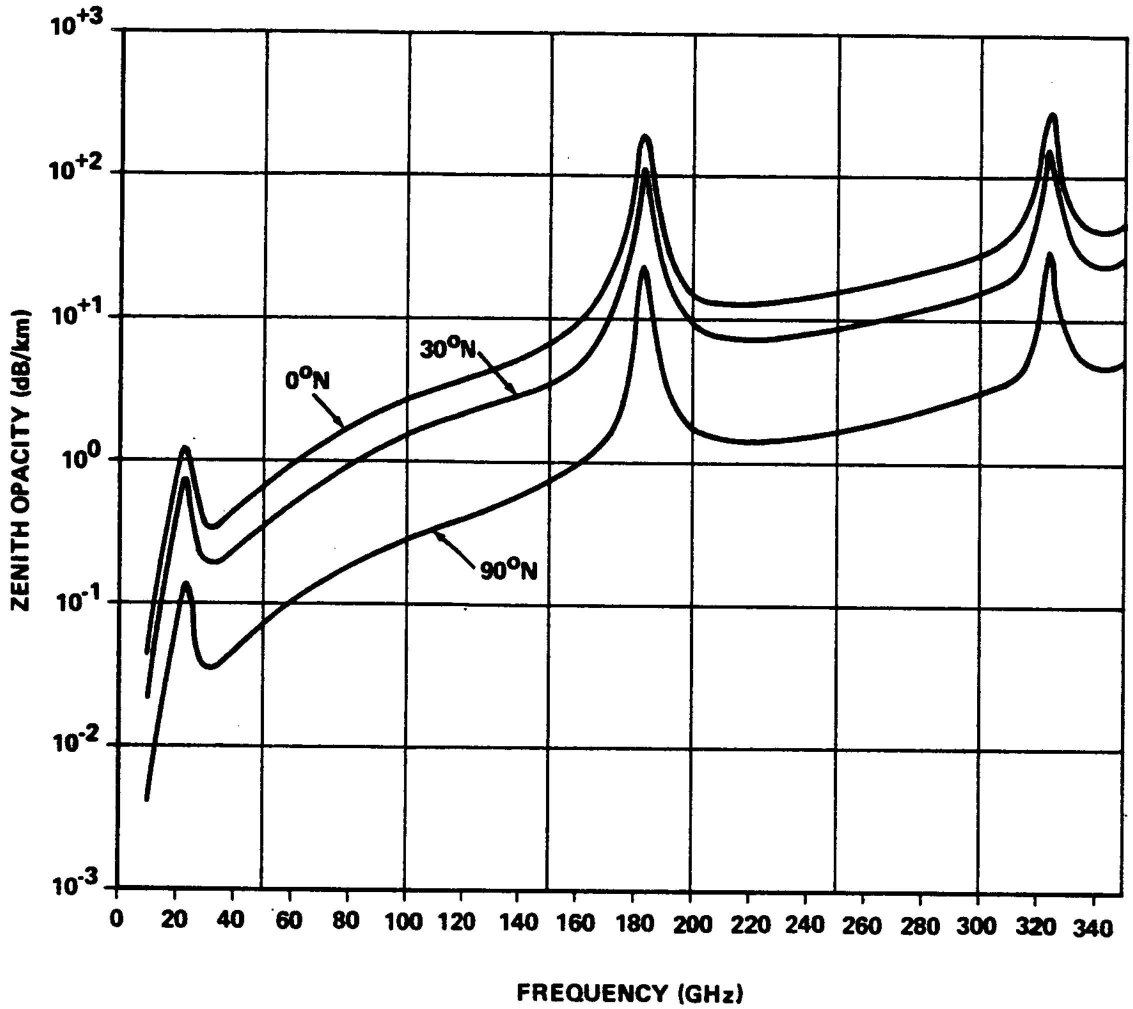

FIGURE 16. 3 ZENITH OPACITY

of wavelength while Figure 16. 2 presents the single scattering albedo for two cloud models representing fair weather and rainy conditions. The curves show the wavelength regimes appropriate to the two cloud types in which scattering effects are relatively unimportant, and in which the extinction coefficient follows the simple Rayleigh ($1/\lambda^2$) dependence.

16. 1. 2 Zenith Opacity due to Atmospheric Water Vapor as a Function of Latitude

In the preparation of Figure 16. 3 five years of climatological data from the MIT Planetary Circulations Project were used to obtain mean water vapor distributions applicable to the latitudes 0° N, 30° N, and 90° N, corresponding to tropical, mid-latitude, and arctic conditions. The total water vapor content for the three cases are 4.5, 2.5, and 0.5 g/cm^2, respectively. The curves demonstrate the effect of climatological extremes in simulating and predicting the influence of atmospheric water vapor upon surface observations from a space observer, over the range from 10 to 350 gigahertz. A detailed report on the interaction model is available upon request.

16.2 Cloud Cover

16.2.1 Introduction

One of the main obstructions to observing the earth's surface from satellite altitudes is cloud cover. Although some sensors show less cloud effect than others, of the three main classes of sensors (cameras, thermal infrared, and radar) cameras are the most advanced, but are also the most sensitive to cloud cover.

The expense and complexity of space missions demand that the consequence of cloud cover be evaluated in advance. First, mission feasibility must be determined. Then, the mission must be planned to provide sufficient time and expendables to insure a high probability of success. Previously, in computer simulations of earth-oriented space missions, clouds were either disregarded completely or were assumed to be present about 50 percent of the time. Now, by using the world-wide cloud cover statistics (Refs. 16.2, 16.3, and 16.4) and the simulation procedure described here, it is possible to provide a realistic evaluation of the consequence of cloud cover on earth-viewing space missions.

Results of the simulations, which can be made for target areas of various size on a global basis, are generally given in two forms. First, the satellite pass number and probability of success are considered as variables with the required percent photographic coverage of the target area fixed. For example, if 95 percent photographic coverage of the target area is required for success, the results would be given as the probability of success versus the pass number. A plot of these results (Figure 16.4) might show that there is a 60 percent chance of photographing 95 percent of the target area in six satellite passes. Second, the pass number is fixed while the percentage of area photographed and the chance of success are treated as variables. Results in this case are given as the percent chance of achieving some percent of photographic coverage of the target area by some limiting pass number. These results (Figure 16.5) might show that after eight satellite passes, there is a 60 percent chance of photographing 90 percent of the target area.

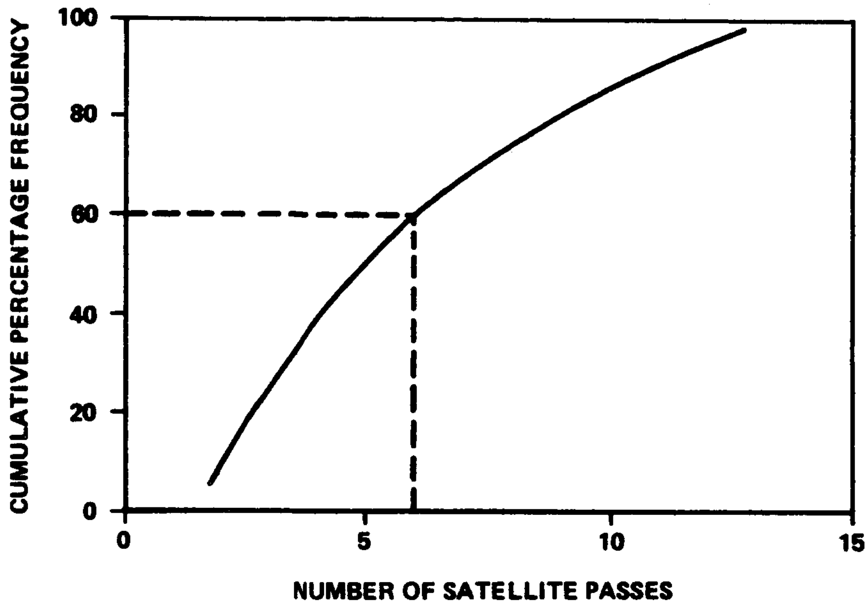

FIGURE 16.4 PROBABILITY OF 95-PERCENT PHOTOGRAPHIC COVERAGE OF TARGET AREA

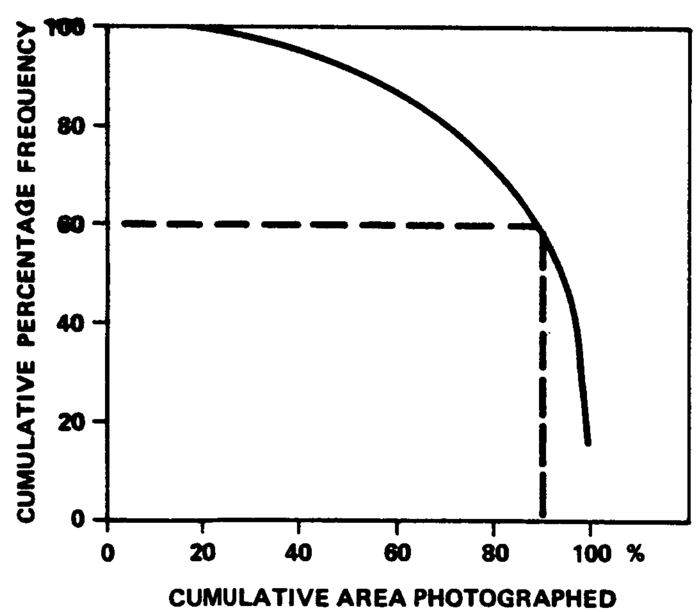

FIGURE 16.5 PHOTOGRAPHIC COVERAGE OF TARGET AREA AFTER EIGHT SATELLITE PASSES

16.2.2 Background

Before the simulation procedure is outlined, it may be helpful to briefly describe the world-wide cloud cover statistics and some simulation applications. These cloud statistics, representing a first effort toward providing cloud data designed expressly for computer simulation exercises, were developed during the period January 1967–January 1968 and March 1970–January 1971 by Allied Research Associates, Inc., under contracts NAS8-21040 and NAS8-25812. After dividing the earth into 29 homogeneous cloud regions, probability distributions for cloud categories by region and monthly reference periods were prepared for each 3-hour interval (Tables 16.1 and 16.2). For application to computer simulation programs, the cloud region boundaries were adjusted to the nearest even numbered lines of latitude and longitude (Figure 16.6).

TABLE 16.1 CLOUD COVER DEFINITION

Category	Tenths	Eighths (Octas)
1	0	0
2	1,2,3	1,2
3	4,5	3,4
4	6,7,8,9	5,6,7
5	10	8

TABLE 16.2 BASIC CLOUD STATISTICS – CLOUD REGION: 19; MONTH: JANUARY

Cloud Category	Time (LST)							
	01	04	07	10	13	16	19	22
1	0.31	0.30	0.18	0.16	0.15	0.16	0.24	0.30
2	0.08	0.06	0.09	0.08	0.12	0.10	0.10	0.08
3	0.04	0.04	0.04	0.04	0.04	0.06	0.05	0.05
4	0.11	0.10	0.15	0.16	0.17	0.21	0.16	0.14
5	0.46	0.50	0.54	0.56	0.52	0.47	0.45	0.43

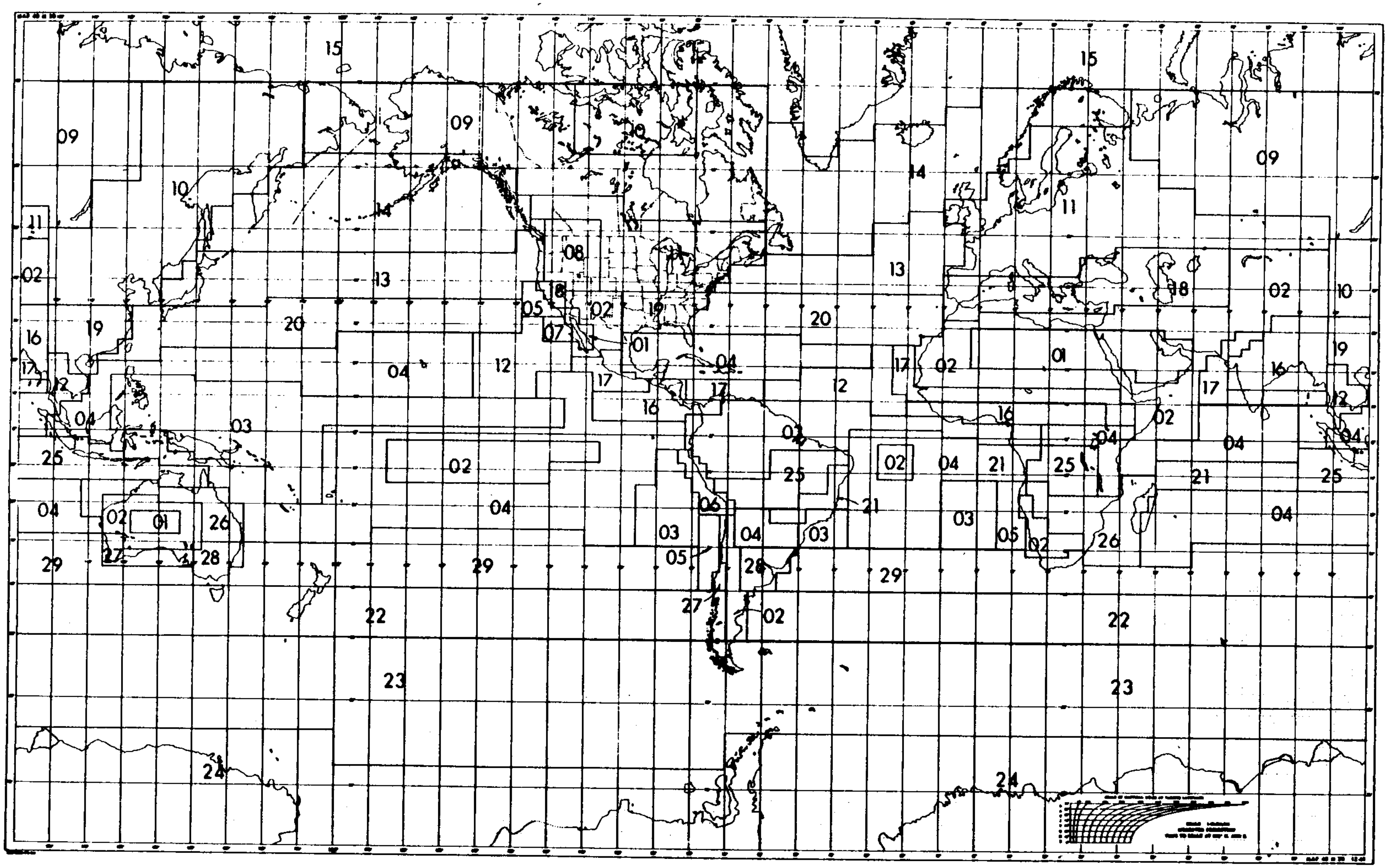

FIGURE 16.6 CLOUD REGION LOCATION MAP

Since clouds generally display some degree of persistence, time and space conditional statistics were developed for each homogeneous cloud region (Table 16. 3). The basic statistics (Table 16. 2) apply to an area approximately 48. 3 kilometers (30 n. mi.)[1] in diameter, while the conditional data are based on a time separation of 24 hours and space separation of 322 kilometers (200 n. mi). In these same studies, techniques were developed to adjust the conditional statistics for times and distances other than 24 hours and 322 kilometers (200 n. mi.), and to scale both the basic and conditional statistics for application to enlarged target areas.

TABLE 16. 3 CONDITIONAL CLOUD STATISTICS, CLOUD REGION 19, JANUARY

Given Cloud Category	Space Conditionals: Cloud Category 1	2	3	4	5	Given Cloud Category	Time Conditionals: Cloud Category 1	2	3	4	5
1	0. 68	0. 11	0. 05	0. 09	0. 07	1	0. 41	0. 12	0. 09	0. 25	0. 13
2	0. 13	0. 32	0. 07	0. 13	0. 35	2	0. 23	0. 29	0. 10	0. 23	0. 15
3	0. 09	0. 20	0. 12	0. 42	0. 17	3	0. 14	0. 26	0. 13	0. 35	0. 12
4	0. 09	0. 14	0. 10	0. 58	0. 09	4	0. 16	0. 15	0. 06	0. 43	0. 20
5	0. 11	0. 12	0. 11	0. 27	0. 39	5	0. 18	0. 07	0. 10	0. 28	0. 37

16. 2. 3 The Simulation Procedure

A typical space mission for earth resources might require that an area 161 × 161 kilometers (100 × 100 n. mi.) be photographed in color. Perhaps the orbital parameters are such that the spacecraft will pass over the target area at 24-hour intervals and the photographic requirements will be satisfied with a montage pieced together from increments obtained on each pass. The mission planner might ask, "How many passes will be required to be 95 percent confident of photographing 80 percent of the area?" If the mission were also limited to a specific number of passes by the amount of film or other expendables, the planner would also need an analysis of that limiting pass number. For example, "With what degree of confidence can one expect to photograph 80 percent of the area by pass

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1. Nautical miles (n. mi.) were used in the contract study by Allied Research Associates.

number 12?" To answer these and other questions, a computer program using a Monte Carlo mission simulation procedure was developed. In this procedure, the target area is divided into 100 equal parts so that each part represents one percent of the area. Before starting the process, the unconditional and conditional statistics, after being scaled for the area size, are arranged in cumulative form by summing across each row. The fraction of target areas that can be photographed under each cloud category is decided upon at some earlier time, primarily on the basis of the sensors being used. In any case, as part of the input, it can be changed as the experimenter desires. Table 16.4 shows a basic set of cloud statistics plus the cumulative arrangement and the maximum part of the area photographable under each cloud category. In this case, it was decided that the photographable part of the area would be 1 minus the mean cloud cover for each category.

To start the procedure, a random number is generated and used to extract from the unconditional summation the cloud category for the first satellite pass. For example, if the first random number gave cloud category 3, to which a 55 percent cloud cover had been assigned, 45 percent of the target area would be photographed on the first pass. Of course, the photographic coverage obtained from each satellite pass over the target could be incremented without specifying which 45 parts were photographed. However, specifying by number those parts of the target area photographed on each pass permits a more realistic accumulation after 80 to 90 percent of the area has been photographed and a finite probability of acquiring 100 percent of the area. The next step then is to determine which 45 parts of the area were photographed on the first pass. This is done according to the season. If frontal clouds predominate, the 45 parts are arranged in an organized contiguous pattern. On the other hand, if air mass cumulus clouds are expected (tropical regions or midlatitude summer months), the 45 parts are scattered randomly throughout the area. For the first pass, then, after the cloud cover was determined by a random number process, the locations of the cloud-free parts of the target area were specified by a prearranged design. Finally, the percentage of the target area photographed was tallied.

The cloud cover encountered on the second pass is selected from the conditional row (summed across) designated by the first pass, or the given category, by means of a new random number. If the random number selects cloud category 4, then 75 percent of the area is cloud covered and 25 percent (or 25 numbered parts) is cloud-free and can be photographed. However, all or part of the 25 percent might have been acquired on the first pass. To account for this possibility, 25 discrete random numbers are drawn to identify the numbered parts of the target area to be photographed on this pass. Of course, only the newly acquired parts of the target area are incremented; those photographed for the second time do not contribute to the total photographic coverage.

TABLE 16. 4 ARRANGEMENT OF CLOUD STATISTICS FOR COMPUTER SIMULATION

	Maximum Area Photographable per Pass				
	CC-1	CC-2	CC-3	CC-4	CC-5
	1. 000000	0. 750000	0. 450000	0. 250000	0. 000000
	Unconditional Probability Statistics				
	CC-1	CC-2	CC-3	CC-4	CC-5
	0. 000000	0. 030000	0. 050000	0. 550000	0. 370000
Given Cloud Category	**Conditional Probability Statistics**				
	CC-1	CC-2	CC-3	CC-4	CC-5
1	0. 000000	0. 110000	0. 000000	0. 000000	0. 890000
2	0. 000000	0. 130000	0. 100000	0. 360000	0. 410000
3	0. 010000	0. 100000	0. 100000	0. 470000	0. 320000
4	0. 000000	0. 070000	0. 060000	0. 460000	0. 410000
5	0. 010000	0. 090000	0. 080000	0. 410000	0. 410000
	Cumulative Unconditional Probability Statistics				
	CC-1	CC-2	CC-3	CC-4	CC-5
	0. 000000	0. 030000	0. 080000	0. 630000	1. 000000
Given Cloud Category	**Cumulative Conditional Probability Statistics**				
	CC-1	CC-2	CC-3	CC-4	CC-5
1	0. 000000	0. 110000	0. 110000	0. 110000	1. 000000
2	0. 000000	0. 130000	0. 230000	0. 590000	1. 000000
3	0. 010000	0. 110000	0. 210000	0. 680000	1. 000000
4	0. 000000	0. 070000	0. 130000	0. 590000	1. 000000
5	0. 010000	0. 100000	0. 180000	0. 590000	1. 000000

All subsequent passes are handled in the same way. The cloud cover encountered on the previous pass becomes the given condition and identifies the conditional statistics to be used on the current pass. After selecting the cloud cover, several additional random numbers are generated to identify the parts of the target area that are cloud-free. The parts acquired on each pass are accumulated until the entire area has been photographed or until the maximum number of passes has been made. This procedure is illustrated in Table 16.5. The top sections represent the target area divided into 100 parts; the "1's" depict clouds while the "0's" show the clear parts. The summary at the bottom shows the cumulative percentage of area photographed, the random number used to select each cloud cover, the cloud cover selected for each pass, and the pass number. In this example, the first random number, 0.072, specifies cloud category 3: 55 cloud-covered parts and 45 clear parts. The arrangement of the cloudy area as shown at the top left is an arbitrary design chosen because frontal clouds were considered more likely at this time and location.

To account for cloud persistence, the cloud-cover category selected for pass 2 is taken from row 3 of the cumulative conditional probability statistics (Table 16.4). Entering that row with the new random number, 0.531, give cloud category 4, or 25 clear parts, for pass 2. The locations of the 25 clear parts ("0's") as given by additional random numbers is shown in the top center section of Table 16.5. The top right section showing the cumulative area photographed after pass 2 contains 60 "0's" rather than 70(45 + 25) because 10 of the 25 clear sections of pass 2 were already photographed on pass 1.

A summary of the subsequent passes, comprising one iteration, is shown at the bottom of Table 16.5. Generally, 300 iterations are made to simulate a photographic mission.

This Monte Carlo procedure is most useful when the satellite passes over the target area at intervals of 24 hours or less, where cloud persistence must be considered. If there are long time intervals between satellite passes (perhaps 3 days or more), the cloud events may be considered independent and the probability of success computed from the basic combinatorial equation:

$$P_{100\%} = 1 - [1 - P(1)]^N \tag{16.1}$$

or

$$N = \frac{\ln\left(1 - P_{100\%}\right)}{\ln\,[1 - P(1)]} \tag{16.2}$$

TABLE 16. 5 PHOTOGRAPHIC PARTS OF THE TARGET AREA

CAP = 45. 0 PASS = 1									
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

AP = 25 PASS = 2									
1	1	0	1	1	1	1	1	0	1
0	0	0	1	0	1	0	0	1	1
1	1	1	1	0	1	1	1	1	1
1	1	0	0	1	1	0	1	1	1
1	1	1	1	1	0	1	1	1	1
0	1	1	0	1	1	0	1	1	1
1	0	0	1	0	1	0	1	1	1
1	1	1	1	1	1	1	0	1	1
0	1	0	1	1	1	1	1	1	1
0	1	0	1	1	1	1	1	1	1

CAP = 60. 0 PASS = 2									
1	1	0	1	1	1	1	1	0	1
0	0	0	1	0	1	0	0	1	1
1	1	1	1	0	1	1	1	1	1
1	1	0	0	1	1	0	1	1	1
1	1	1	1	1	0	1	1	1	1
0	1	1	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

B(N)	RAN	C(N)	N
45. 000	0. 072	3	1
60. 000	0. 531	4	2
79. 000	0. 110	3	3
84. 000	0. 609	4	4
84. 000	0. 629	5	5
84. 000	0. 659	5	6
84. 000	0. 877	5	7
89. 000	0. 410	4	8
92. 000	0. 166	4	9
93. 000	0. 392	4	10
93. 000	0. 690	5	11
93. 000	0. 733	5	12
93. 000	0. 727	5	13
93. 000	0. 913	5	14
93. 000	0. 821	5	15
93. 000	0. 875	5	16
98. 000	0. 176	3	17
98. 000	0. 359	4	18
100. 000	0. 232	4	19

CAP – Cumulative Area Photographed (%)

AP – Area Photographed (%)

B(N) – Total Area Photographed

RAN – Random Number Used to Select the Cloud Cover

C(N) – Cloud Category Encountered on Each Pass

N – Satellite Pass Number

where

$P_{100\%}$ = required probability level of photographing 100 percent of the area

P(1) = relative frequency of cloud category 1

N = number of independent satellite passes.

16. 2. 4 Results

16. 2. 4. 1 Individual Target Areas

Statistics from three homogeneous cloud regions (2, 13, and 19, Figure 16. 6) were used to illustrate the type of information available from the simulation procedure and to compare the simulation results with those obtained from the combinatorial equation.

One convenient way of comparing the two procedures was to address the question, "How many independent satellite passes are required to be 95 percent confident of encountering at least one pass with 3/10 or less (cloud categories 1 or 2) cloud cover over the target area?" The number of passes obtained from each procedure, as shown in Table 16. 6, apply to a target area 161 kilometers (100 n. mi.) in diameter. This mission is flown in January, and the satellite passes over the target area at 1300 hours LST.

TABLE 16. 6 COMPARISON OF COMPUTER SIMULATION AND COMBINATORIAL RESULTS

Cloud Region	Combinatorial	Computer Simulation
2	8	8
13	116	119
19	12	12

For this comparison, the computer simulation program was adjusted to consider only the unconditional cloud statistics.

Since the number of passes required to satisfy the conditions stated above may be excessive for some cloudy areas of the earth (for example, region 13), the mission planner may be willing to accept incremental photographic coverage. Also, the satellite may pass over the target area at such frequent intervals that the passes cannot be considered independent. When conditions such as these are imposed, a computer simulation is required to evaluate the consequence of cloud cover on the proposed mission.

Results from the simulation program giving analyses of at least 95 percent coverage of the target area and the photographic coverage after 10 satellite passes are shown in Figures 16. 7 and 16. 8. In both cases, the

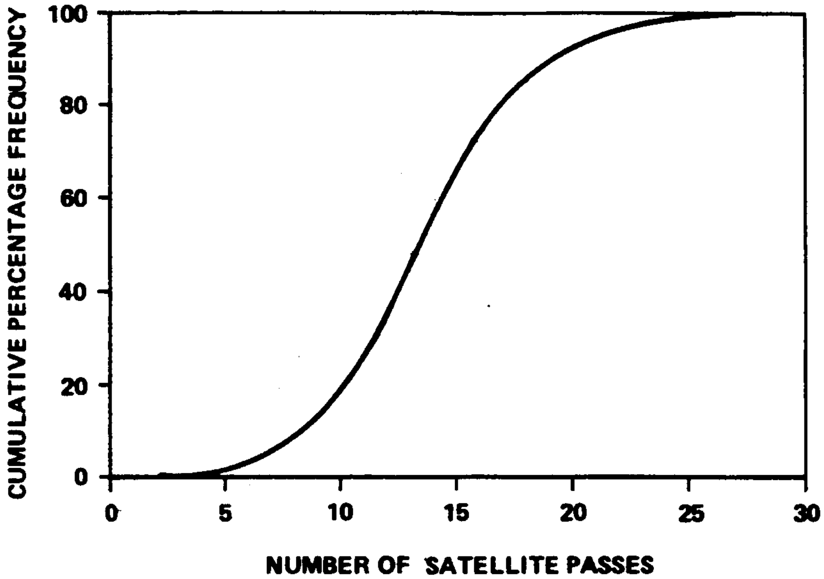

FIGURE 16.7 ANALYSIS OF AT LEAST 95 PERCENT PHOTOGRAPHIC COVERAGE

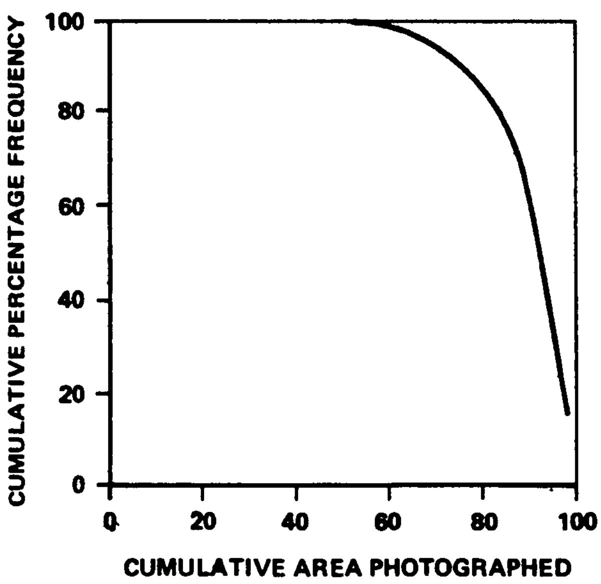

FIGURE 16.8 ANALYSIS OF PHOTOGRAPHIC COVERAGE AFTER TEN PASSES

6

target is a 161-kilometer (100-n.mi.) diameter area in cloud region 13. The mission is planned for January, and the spacecraft passes over the target area every day at 1300 LST.

Figure 16.7 shows a 50-percent chance of photographing 95 percent of the area in 13 passes, while 19 passes are required to be 90 percent confident.

After 10 passes (Figure 16.8), there is a 50-percent chance of photographing 92 percent of the area and a 90-percent chance of acquiring 76 percent of the target area. These results comprise a summary of 300 iterations of the simulation procedure.

16.2.4.2 Contiguous Target Areas – A Swath

The simulation can also be applied to a series of contiguous target areas, for example, a swath from the Texas Gulf Coast to the Canadian Border (Figure 16.9). To evaluate this type target the swath is divided into several equal-sized areas based upon the width of the swath. If the swath is 161-kilometers (100-n.mi.) wide the dimensions of each target area or "box" become 161 × 161 kilometers (100 × 100 n.mi.). In the case illustrated there are approximately six boxes in cloud region 19 and five boxes in cloud region 11. As before, random numbers dictate the cloud cover applicable to each box. The unconditional cloud distribution is used for pass number 1 over the first box but space conditionals are used for all subsequent boxes. That is, the clouds in box 2 depend upon those in box 1, box 3 depends upon box 2, etc. Box 1 of cloud region 11 depends upon box 6 of cloud region 19, but the cloud draw is made from the statistics applicable to cloud region 11.

Subsequent satellite passes over the swath may use either unconditional or time conditional statistics for box 1 of region 19 depending upon the time interval between passes. All other boxes, however, depend only upon the preceding box and always use the space conditional statistics.

Simulation results evaluating the swath are presented in the same manner as the individual target results.

A question that presents some difficulty is that of identifying and fitting into the mosaic small disjointed fractional parts of the target area. For example, can all of the "0's" of Figure 16.7 acquired on pass 2 really be considered useful? Those isolated parts may be difficult, if not impossible, to identify. Perhaps meaningful photographic results can be obtained only

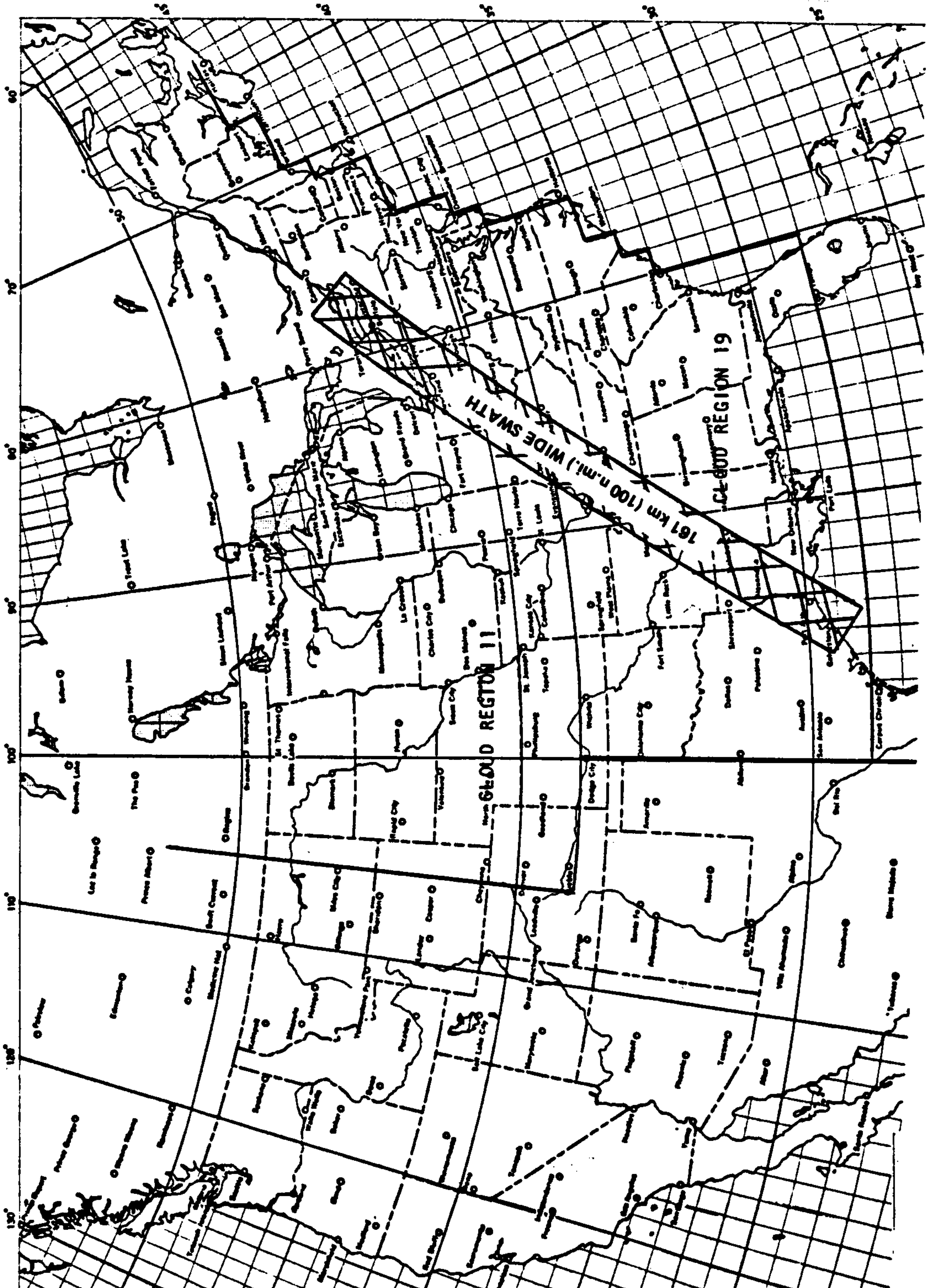

FIGURE 16.9 EXAMPLE OF 100-n. mi. WIDE SWATH

when small cloud amounts are present. Although this may be a serious problem for the experiment designer, the mission planner, and the atmospheric scientists, it does not affect the simulation program directly. If it is decided that a cloud-cover category will not provide useable photographic results, that category can be assigned 100 percent cloud cover, and nothing will be added to the cumulative coverage when it occurs. It might also be stipulated that isolated parts of the target may not contribute to the total photographic coverage. Many contingencies can be handled as input changes; some may require minor program changes.

16.3 Four-Dimensional Atmospheric Models

In this part of the attenuation model project the emphasis was placed on water vapor rather than clouds. Also, since attenuation calculations are usually made from reference atmosphere inputs the other atmospheric parameters found in reference atmospheres were included in the 4-D work. The basic data are comprised of monthly statistics (mean and standard deviations) of pressure, temperature, density, and moisture content from 0 to 25 kilometers altitude on a global grid network. These data provide information on latitudinal, longitudinal, altitudinal, and temporal variation of the parameters; hence the name "four-dimensional atmospheric models." Of course, a profile of temperature, pressure, density, and moisture content for any global location may be retrieved from these data. Still, to reduce the data to a more manageable amount it was decided to outline homogeneous moisture content regions for which a single set of profile statistics would apply. This procedure would permit the use of one set of profiles for all locations within a homogeneous region. While parts of this procedure are still under development, the basic statistics have been computed and the retrieval plans formulated. For each region analytical functions will be fitted to the statistical data. For moisture, it appears that exponential functions will be most appropriate, while for temperature, a series expansion technique may be used. The result of fitting analytic functions to the statistical climatological profile data will be a library of coefficients for the temperature and moisture profiles. These coefficients will then be used to develop computer subroutines to regenerate the model profiles of temperature and moisture which will also be a function of the homogeneous region and month of the year.

In the compilation of the global statistics, pressure and density were determined from the hypsometric equation and the equation of state, rather than linear or logarithmic interpolation. The purpose of this was to insure hydrostatic consistency, thus, it is likely that the pressure and density profiles can be generated from the temperature profile and the hydrostatic assumption.

The final result of this data analysis will be a series of computer programs that provide mean, maximum, and minimum profiles of moisture, temperature, pressure, and density from the surface to 25 kilometers altitude for any location on the globe and month of the year. The computer programs will contain the equations, data, and library of coefficients necessary to produce the desired results.

A detailed report on the entire 4-D project will be available upon request in September 1971.

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16.2 Sherr, P. E., et. al., "World Wide Cloud Cover Distribution for Use in Computer Simulations," Allied Research Associates, NASA CR-61226, Jun. 14, 1968.

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SECTION XVII. WORLDWIDE SURFACE EXTREMES

BY

Glenn E. Daniels

17.1 Introduction

In the original issue of the "Natural Environment Guidelines" document (Ref. 17.1, 1961), information was needed to fabricate, transport, test, and launch Marshall Space Flight Center space vehicles in limited geographical areas only. It became evident with the development of advanced programs such as the Apollo project that statistical meteorological data are needed from other areas as well. Thus, in a later revision, a section called "Distribution of Surface Extremes in the United States" was included. In the present revision, this brief section on worldwide surface extremes has been prepared. This section will also illustrate the much larger extreme values that occur in some areas and will compare them with those currently used in space vehicle design.

17.2 Sources of Data

A great amount of meteorological data have been collected throughout the world. Various agencies have collected such data in a form that can be used for statistical studies. Kendrew's "Climates of the Continents" (Ref. 17.2) is an excellent summary of mean values of the meteorological parameters, temperature, pressure, and precipitation, and it is also the source of many interesting discussions of local meteorological conditions around the world.

"World Weather Records, 1941-50" (Ref. 17.3), compiled by the Weather Bureau (now part of the Environmental Sciences Services Administration), provides another excellent summary of mean values of meteorological data.

Recently, in revising AR 705-15 (now AR 70-38, Ref. 17.4), the Earth Sciences Laboratory NLABS, U. S. Army Natick Laboratories at Natick, Massachusetts, has collected worldwide data on meteorological extremes. For the revised AR 70-38, the Earth Sciences Laboratory NLABS prepared world maps that show worldwide absolute maximum and absolute minimum temperatures.* These maps are reproduced in this section as

* Absolute is defined as the highest and lowest values of data of record.

Figures 17.1 and 17.2, and due credit is given to the Earth Sciences Laboratory NLABS, U. S. Army Natick Laboratories.

The several climatic atlases for various areas of the world provide other sources of data; those of interest will be referred to in the following sections.

17.3 Worldwide Extremes Over Continents

To present all the geographic extremes properly, many large maps similar to Figures 17.1 and 17.2 would be required; therefore, only worldwide extremes of each parameter will be discussed, and available references on each parameter will be given. Individual geographic extremes will be mentioned when pertinent.

17.3.1 Temperature.

Absolute maximum and absolute minimum world temperature extremes are shown in Figures 17.1 and 17.2. Some geographical extreme air temperatures of record are given in Table 17.1

TABLE 17.1 EXTREME AIR TEMPERATURES OF RECORD

Location	Air Temperatures of Record
Salah, Africa	118°F, mean daily max. for 45 days
	127°F, absolute max.
Azizia, Africa	136°F, absolute max.
Sind, India	123°F, absolute max.
Basra, Iraq	123°F, absolute max.
	78°F, mean daily min. in Aug.
Death Valley, Calif.	134°F, absolute max.
Stuart, Australia	131°F, absolute max.
Verkhoyansk, U.S.S.R.	-94°F, absolute min.
Rogers Pass, Montana	-70°F, absolute min. for U.S.
Snag, Yukon Territory, Canada	-85°F, absolute min. for North America

Temperatures of the ground are normally hotter than the air temperatures during the daytime. In the Sahara Desert of Africa, temperatures of sand as high as 172° F have been measured. At Stuart, Australia, the sand has reached temperatures so hot that matches dropped into it burst into flame.

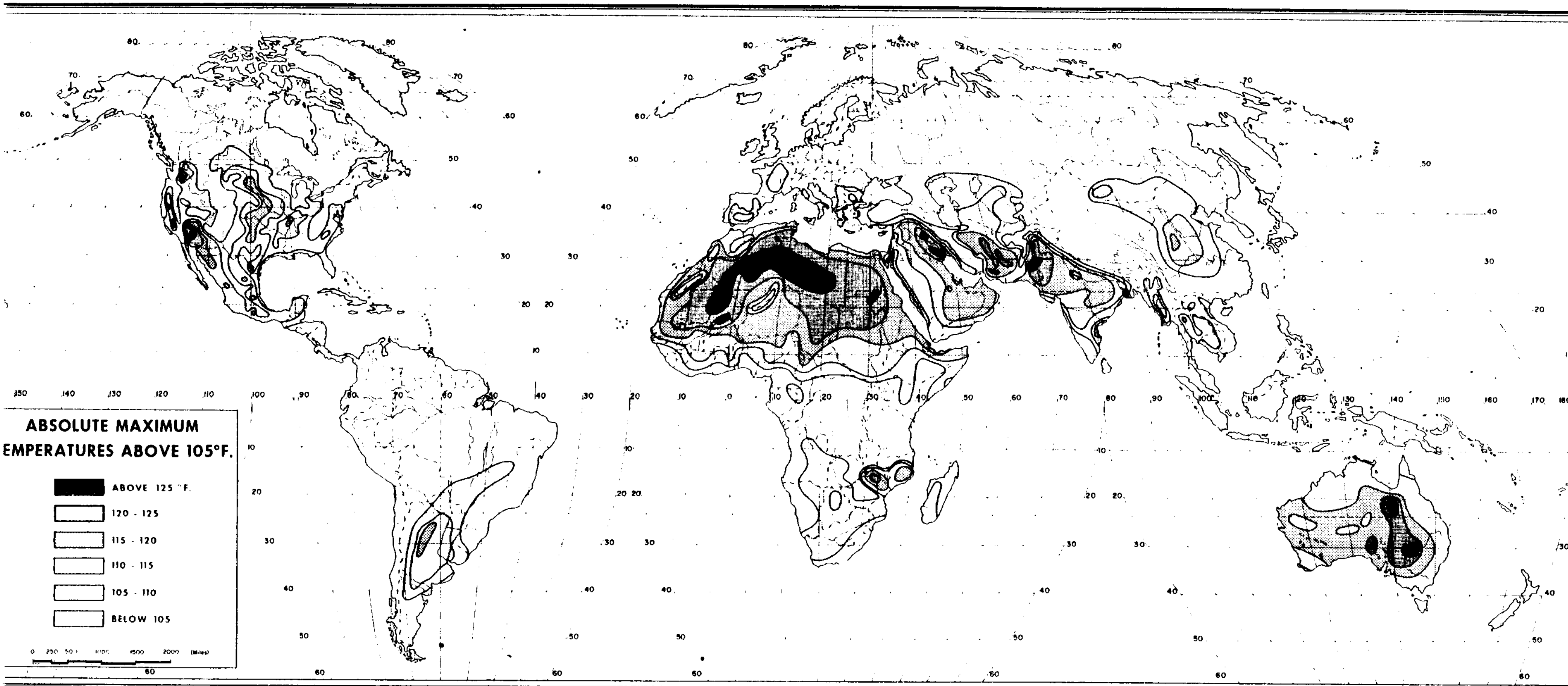

FIGURE 17.1 WORLDWIDE GEOGRAPHIC ABSOLUTE MAXIMUM TEMPERATURES ABOVE 105°F

FOLDOUT FRAME 1

FOLDOUT FRAME 2

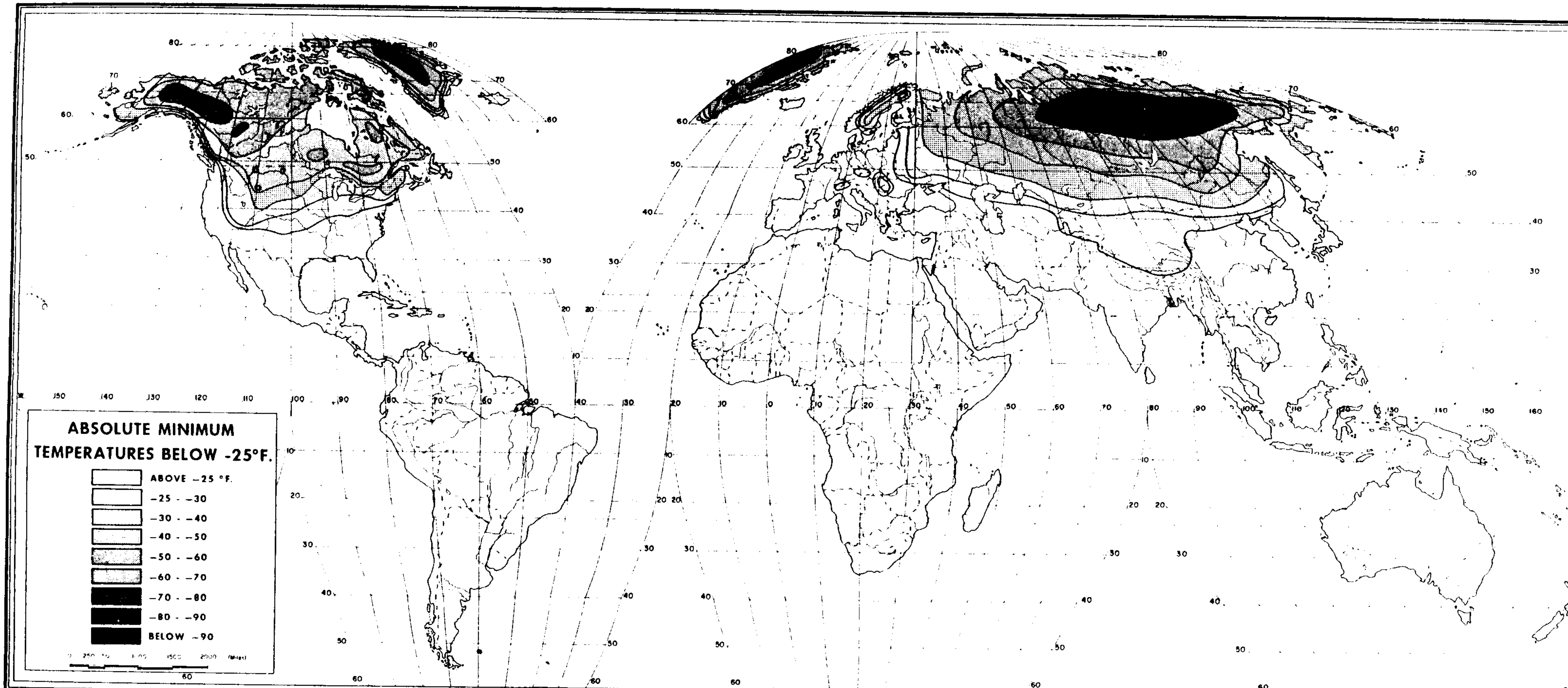

FIGURE 17.2 WORLDWIDE GEOGRAPHIC ABSOLUTE MINIMUM TEMPERATURES BELOW -25°F

FOLDOUT FRAME

FOLDOUT 2

In design of equipment for worldwide operations, MIL-STD-210A now uses extreme temperature values of 125°F for a hot temperature and -80°F for a cold temperature. Values outside these limits have been observed. In a study by the Air Force Cambridge Research Laboratories* , June 9, 1969, for Special Assistant for Environmental Service of the Joint Chiefs of Staff, to lower the risk of exposing equipment of MIL-STD-210A, it was recommended that values of 131°F and -87°F would be more realistic for the hot and cold temperatures.

The above recommendation for hot temperature was based upon risk tables, shown in Table 17.2, of extreme high temperatures developed by extreme value theory using 39 extreme annual temperatures at Death Valley, California. Such temperatures persist for one or two hours during a day.

TABLE 17.2 EXTREME HIGH TEMPERATURES WITH RELATION TO RISK AND DESIRED LIFETIME

Risk (%)	Temperatures (°F) Planned Lifetime (years)				
	1	2	5	10	25
1	131	133	134	135	137
10	127	128	130	131	133
25	125	127	128	129	131
50	124	125	127	128	130

The recommendation for cold temperature was based upon risk tables, shown in Table 17.3, of extreme low temperatures, developed by extreme

TABLE 17.3 EXTREME LOW TEMPERATURES WITH RELATION TO RISK AND DESIRED LIFETIME[a]

Risk (%)	Temperature (°F) Planned Lifetime (years)				
	1	2	5	10	25
1	-87	-91	-97	-101	-106
10	-74	-78	-83	- 87	- 92
25	-68	-72	-77	- 81	- 86
50	-63	-67	-73	- 76	- 81

a. Temperatures in Antartica were not considered in the study.

* Norman Sissenwine: "Temperature Extremes Applicable to MIL-STD-210 Area and Risk Considerations." AFCRL, a paper transmitted by a letter dated June 16, 1969, to Chief, Aerospace Environment Division, MSFC.

value theory using 23 annual extreme low temperatures at Snag, Yukon Territory, Canada. The extreme low temperatures will persist for longer periods since they occur during polar darkness.

17.3.2 Dew Point.

High dew points are associated with high temperatures near large bodies of water. Besides being detrimental to equipment, high dew points make living conditions very uncomfortable. Extremely high dew points occur in the following areas, in the vicinity of the water bodies specified:

a. The northern portion of the Arabian Sea in April and May, to 85°F dew point.

b. The Red Sea in July, to 89°F dew point.

c. The Caribbean Sea (includes the western end of Cuba and the Yucatan Penninsula, Mexico) in July, to 81°F dew point.

d. The northern portion of the Gulf of California, to 86°F dew point (data from Puerto Penasco, Mexico, Ref. 17.6).

The Air Force has published the "Atmospheric Humidity Atlas for the Northern Hemisphere" (Ref. 17.5), which shows maps for various percentile levels of dew point for midseason months (January, April, July, and October).

A new report on worldwide humidity is now being published by the U. S. Army Natick Laboratories (Ref. 17.6).

17.3.3 Precipitation.

The worldwide distribution of precipitation is extremely variable; some areas do not receive rain for years, while others receive torrential rain many months of the year. Precipitation is also seasonal; for example, Cherrapunji, India, with its world record total of 905 inches of precipitation in a year, has a mean monthly precipitation of less than one inch in December and January. The heaviest precipitation for long periods (greater than 12 hours) usually occurs in the monsoon type of weather. High rates of rainfall for short periods (less than 12 hours) usually occur in the thunderstorm type of rain and over much smaller areas than the monsoon rain. Some world records for various periods of rainfall are given in Table 17.4 (Ref. 17.2 and 17.7).

TABLE 17.4 WORLD RAINFALL RECORDS

Station	Time Period	Amount (in.)
Unionville, Maryland	1 min	1.23
Plum Point, Jamaica	15 min	8.0
Holt, Missouri	41 min	12.0
D'Hanis, Texas	3 hr	20.0
Baguio, Philippine Islands	1 day	50.0
Cherrapunji, India	30 days	360.0
Cherrapunji, India	1 yr	905.0

Even though the values given in Table 17.4 are considerably higher than the values given in Table 4.2 of Section IV, values in Table 4.2 are considered adequate for most space vehicle design problems within currently expected operational areas.

17.3.4 Pressure.

Surface atmospheric pressure extremes for use in design must be derived from the measured station pressures, not from the computed sea level pressures that are usually published.

Station pressures between stations have great variability because of the difference in altitude of the stations. The lowest station pressures occur at the highest altitudes. The highest station pressures occur at either the lowest elevation stations (below sea level), or in the arctic regions in cold air masses at or near sea level.

Court (Ref. 17.7) has an interesting discussion on worldwide pressure extremes. Some typical high and low pressure values are given in Table 17.5 (Ref. 17.2 and 17.7).

17.3.5 Ground Wind.

Worldwide extreme surface winds have occurred in several types of meteorological conditions: tornadoes, hurricanes or typhoons, mistral winds, and Santa Ana winds. In design, each type of wind needs special consideration. For example, the probability of tornado winds is very low compared with the probability of mistral winds, which may persist for days (see Section 5.2.10).

TABLE 17.5. TYPICAL PRESSURE VALUES OF SELECTED AREAS

Station	Elevation Above Sea Level (ft)	Pressure (mb)	
		Lowest	Highest
Lhasa, Tibet	12 090	645[a]	652[a]
Sedom, Israel	-1 275	—	1081.8
Portland, Maine	61	—	1056
Qutdligssat, Greenland	10	—	1063.4
In a typhoon 400 Miles East of Luzon, Philippine Islands[b]	~0	887	—

a Monthly means.
b Lowest sea level pressure of record.

17.3.5.1 Tornadoes

Tornadoes are rapidly revolving circulations normally associated with a cold front squall line or with warm, humid, unsettled weather; they usually occur in conjunction with a severe thunderstorm. Although a tornado is extremely destructive, the average tornado path is only about a quarter of a mile wide and seldom more than 16 miles long, but there have been a few instances in which tornadoes have caused heavy destruction along paths more than a mile wide and 300 miles long. The probability of any one point being in a tornado path is very small; therefore, design of structures to withstand tornadoes is usually not considered except for special situations where tornado shelters are built underground. Velocities have been estimated to exceed 134 ms^{-1} (260 knots) in tornadoes.

17.3.5.2 Hurricanes (Typhoons).

Hurricanes (also called typhoons, Willy-willies, tropical cyclones, and many other local names) are large tropical storms of considerable intensity. They originate in tropical regions between the equator and 25 degrees latitude. A hurricane may be 1600 kilometers (1000 miles) in diameter with winds in excess of 67 ms^{-1} (130 knots). A tropical storm is defined as a hurricane when winds are equal to or greater than 33 ms^{-1} (64 knots). The winds are frequently associated with heavy rain. Since the hurricanes of the West Indies are as intense as others throughout the world, design winds based upon these hurricanes would be representative for any geographical area. Section 5.2.10 gives hurricane design winds for the area of Cape Kennedy, Florida. Although the highest winds recorded in a hurricane in the area of Cape Kennedy, Florida, were lower than winds from thunderstorms in the same area, the probability still exists that much higher winds could result from hurricanes in the vicinity of Cape Kennedy.

For extremes applicable to equipment, the following Table 17.6 from a study of 39 years of wind data for Taipei, Taiwan (in the Pacific typhoon belt) * , for a height of 10 feet above the natural grade, is representative of all hurricane areas of the world.

TABLE 17.6 EXTREME WINDS IN HURRICANE (typhoon) AREAS WITH RELATION TO RISK AND DESIRED LIFETIME
(3.1-m reference height)

Risk (%)	Extreme Wind Speeds (ms^{-1}) Planned Lifetime (years)				
	1	2	5	10	25
1	38	41	46	49	54
5	30	33	38	41	46
10	26	29	34	38	42
25	21	24	29	33	37
50	16	20	25	28	33

17.3.5.3 Mistral Winds (Ref. 17.2).

The mistral wind is a strong polar current between a large anti-cyclone and a low pressure center. These winds frequently have temperatures below freezing. The mistral of the Gulf of Lions and the Rhone Valley, France, is the best known of these winds. Although winds of 37 ms^{-1} (83 mph) have been recorded in the area of Marseilles, France, much higher winds have occurred to the west of Marseilles in the more open terrain, where even rail-way trains have been blown over. Mistrals blow in the Rhone Valley for about 100 days a year. The force of the mistral wind is intensified by its coldness, and the associated greater air density.

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* Norman Sissenwine: "Surface Wind Extremes Applicable to MIL-STD-210 Area and Risk Considerations." AFCRL, a paper transmitted by a letter dated June 16, 1969, to Chief, Aerospace Environment Division, MSFC.

17.3.5.4 Santa Ana Winds.

In contrast to the mistrals, the Santa Ana Winds, which occur in Southern California west of the coast range of mountains, are hot and dry and have speeds up to 41 knots. Similar winds, called Föhn winds, occur in the Swiss Alps and in the Andes, but, because of the local topography, they have lower speeds. The destructiveness of these winds it not from their speeds, but from their high temperatures and dryness, which can do considerable damage to blooming tree and vine crops and exposed equipment and instruments whose seals and paint are critical.

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SECTION XVIII. GENERAL CLIMATOLOGICAL INFORMATION

By

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18. 1 Introduction

With the development of aerospace launch vehicles which are to be recovered by flying back to the earth's surface, additional climatic data are needed on specific landing sites not covered in other sections of this document. A short discussion is also included on tornadoes, hurricanes, and tropical storms (Ref. 18. 1).

18. 2 Tornadoes

Tornadoes are recognized as the most destructive force winds; because of differential pressures created by tornadoes, buildings have been known to literally explode. Fortunately, the aerial extent of tornadoes is small compared with hurricanes, and the occurrence of tornadoes at the seven stations of interest covered in this document is less frequent than in the Central Plain states of the United States. Tornadoes are observed at times in association with hurricanes in Florida and along the coastal states. Based on Thom's analysis of the number of tornado occurrences (Ref. 18. 2), Table 18. 1 has been prepared giving tornado statistics for stations of interest.

The probability of one or more tornadoes in N years in area (A_1) is given by[1]

$$P(E_1, A_1; N) = 1 - \exp\left(-\bar{x}\frac{A_1}{A_2}N\right) \quad . \qquad (18.1)$$

We choose for the area size for A_1 as 7. 3 km² (2. 8 mi²) because Thom (Ref. 18. 1) reports 7. 2572 km² (2. 8209 mi²) is the average ground area covered by tornadoes in Iowa, and the vital industrial complexes for most locations are of this general size. Thus, taking $A_1 = 7.3$ km² (2. 8 mi²) and $A_1 = 2.59$ km² (1 mi²) and evaluating equation (18. 1) for the values of $\bar{x}$ and A_2 for the stations given in Table 18. 1 yields the data in Table 18. 2.

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1. Credit is due Prof. J. Goldman, Institute Storm Research, St. Thomas University, Houston, Texas, for this form of the probability expression.

TABLE 18. 1 TORNADO STATISTICS FOR STATIONS SPECIFIED

Station	Number of Tornadoes	Mean Number of Tornadoes Per Year	Area		Mean Number of Tornadoes Per Year at a Point	Mean Recurrence Interval for a Tornado Striking a Point (years)
			(km^2)	(mi^2)		
Cape Kennedy	9	0. 9	10 896	4220	0. 00060	1667
Huntsville	12	1. 2	10 147	3930	0. 00086	1163
New Orleans	9	0. 9	10 689	4140	0. 00061	1639
Mississippi Test Facility	12	1. 2	10 612	4110	0. 00083	1205
Space and Missile Test Center	0	0	9 579	3710	0. 00000	∞
Wallops Island	5	0. 5	9 708	3760	0. 00038	2632
White Sands	2	0. 2	10 405	4030	0. 00015	6667

TABLE 18. 2 PROBABILITY OF ONE OR MORE TORNADO EVENTS IN A 7. 3-km^2 AREA AND A 2. 59-km^2 AREA IN 1, 10, AND 100 YEARS

Station	Mean Number of Tornadoes Per Year in Area, A_2	$P(E_1, A_1; N)$ for A_1 = 7. 3 km^2 (2. 8 mi^2)			$P(E_1, A_1; N)$ for A_1 = 2. 59 km^2 (1. 00 mi^2)		
		N = 1 year	N = 10 years	N = 100 years	N = 1 year	N = 10 years	N = 100 years
Cape Kennedy	0. 9	0. 00060	0. 00596	0. 05797	0. 00021	0. 00213	0. 02110
Huntsville	1. 2	0. 00085	0. 00851	0. 08195	0. 00031	0. 00305	0. 03007
New Orleans	0. 9	0. 00061	0. 00608	0. 05906	0. 00022	0. 00217	0. 02160
Mississippi Test Facility	1. 2	0. 00082	0. 00815	0. 07850	0. 00029	0. 00292	0. 02878
Space and Missile Test Center	0. 0	0. 00000	0. 00000	0. 00000	0. 00000	0. 00000	0. 00000
Wallops Island	0.5	0. 00037	0. 00371	0. 03655	0. 00013	0. 00133	0. 01321
White Sands	0.2	0. 00012	0. 00121	0. 01203	0. 00004	0. 00043	0. 00431

$$P(E_1, A_1; N) = 1 - e^{-\bar{x} \frac{A_1}{A_2} N}$$

Table 18.2 gives the probability of one or more tornado events in a 7.3-km^2 (2.8-mi^2) area and a 2.59-km^2 (1-mi^2) area in 1 year, 10 years, and 100 years for the indicated seven locations. It is noted that for $A_1 << A_2$ and $N < 100$, equation (18.1) can be approximated by

$$P(E_1, A_1; N) \doteq \bar{x} \frac{A_1}{A_2} N \quad . \qquad (18.2)$$

An interpretation of the statistics in Table 18.2 is given using Cape Kennedy as an example. There is a 5.8-percent chance that at least one tornado will "hit" within a 7.3-km^2 (2.8-mi^2) area on Cape Kennedy in 100 years. For a 2.59-km^2 (1-mi^2) area of Cape Kennedy, the chance of a tornado hit in 100 years is 2.1 percent. If several structures within a 7.3-km^2 (2.8-mi^2) area on Cape Kennedy are vital to a space mission and these structures are not designed to withstand the wind and internal pressure forces of a tornado, then there is a 5.8-percent chance that one or more of these vital structures will be destroyed by a tornado in 100 years. If the desired lifetime of these structures [or 7.3-km^2 (2.8-mi^2) industrial complex] is 100 years and the risk of destruction by tornadoes is accepted in the design, then the design risk or calculated risk of failure of at least one structure due to tornado occurrences is 5.8 percent. This example serves to point out that the probability of occurrence of an event which is rare in one year becomes rather large when taken over many years and that estimates for the desired lifetime versus design risk for structures discussed in subsection 5.2.10 should be made with prudence.

18.3 Hurricanes and Tropical Storms

The occurrence of hurricanes at Cape Kennedy and other locations for the Eastern Test Range is of concern to the space program because of high winds and because range support for space operations is closed during passage or near approach of a hurricane. This discussion will be restricted to the frequency of tropical storms, hurricanes, and tropical storms and hurricanes combined (tropical cyclones) for annual reference periods and certain monthly groupings, as a function of radial distances from Cape Kennedy only.

By definition, a hurricane is a tropical storm with winds greater than 33 m/sec (64 knots), and a tropical storm is a cyclone whose origin is in the tropics with winds less than 33 m/sec (64 knots). There is no known upper limit for wind speeds in hurricanes, but estimates are as high as 82 m/sec (160 knots). Also, tornadoes have been observed in association with hurricanes.

Tables 18. 3 and 18. 4 give a general indication of the frequency of tropical storms and hurricanes by months within 161- and 644-kilometer (100- and 400-n. mi.) radii of Cape Kennedy. From Table 18. 3 it is noted that hurricanes with 161 and 644 kilometers (100 and 400 n. mi) of Cape Kennedy have been observed as early as May and as late as December, with the highest frequency during September. In the 68-year period (1899 to 1966), there were 117 hurricanes whose path (eye) came within a 644-kilometer (400-n. mi.) radius of Cape Kennedy; there were nineteen hurricanes that came within a 161-kilometer (100-n. mi.) radius of Cape Kennedy during this period. From all available wind records along the coast from Melbourne, Florida, to Titusville, Florida, the highest wind gust during the passage of sixteen of the nineteen hurricanes that came within a 161-kilometer (100-n. mi.) radius of Cape Kennedy were obtained. For the three hurricanes for the years 1899, 1906, and 1925, the peak gusts were not available. Of the sixteen hurricanes that came within a 161-kilometer (100-n. mi.) radius of Cape Kennedy for which the wind records are available, five produced wind gusts greater than 33. 5 m/sec (65 knots),[2] ten produced wind gusts to 26 m/sec (50 knots), and twelve had wind gusts less than 18. 5 m/sec (36 knots). Thus, from these records, even if a defined hurricane path comes within a 161-kilometer (100-n. mi.) radius of Cape Kennedy, hurricane force winds [speeds > 33 m/sec (64 knots)] are not always observed at Cape Kennedy. Hurricanes at greater distances than 161 kilometers (100 n. mi.) could possibly produce hurricane force winds at Cape Kennedy. It is recognized that hurricanes approaching Cape Kennedy from the east (from the sea) will, in general, produce higher winds at Cape Kennedy than those approaching the Cape after crossing the peninsula of Florida (from land).

18. 3. 1 Distribution of Hurricane and Tropical Storm Frequencies

Knowing the mean number of tropical storms or hurricanes (events) per year that come within a given radius of Cape Kennedy, without knowing other information, is of little use. If the distribution of the number of tropical storms or hurricanes is known to be a Poisson distribution, then the mean number of events per year (or any reference period) can be used to completely define the Poisson distribution function.

From Figure 18. 1, the probability of no event, $P(E_0, r)$, for the following can be read: (1) tropical cyclones, tropical storms, and hurricanes for annual reference periods; and (2) tropical storms and hurricanes for

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2. Highest recorded Cape Kennedy hurricane-associated wind speed was about 39 m/sec (76 knots).

TABLE 18.3 NUMBER OF HURRICANES IN A 68-yr PERIOD (1899-1966) WITHIN A 161- AND 644-km (100- and 400-n. mi.) RADIUS OF CAPE KENNEDY

Month	Number of Hurricanes Within: 161-km (100-n. mi.) radius	644-km (400-n. mi.) radius
Jan.	0	0
Feb.	0	0
Mar.	0	0
Apr.	0	0
May	1	1
Jun.	2	3
Jul.	2	12
Aug.	3	23
Sep.	5	42
Oct.	5	30
Nov.	0	5
Dec.	1	1
Total	19	117

TABLE 18.4 NUMBER OF TROPICAL STORMS IN A 96-yr PERIOD (1871-1966) WITHIN A 161- AND 644-km (100- and 400-n. mi.) RADIUS OF CAPE KENNEDY

Month	Number of Tropical Storms Within: 161-km (100-n. mi.) radius	644-km (400-n. mi.) radius
Jan.	0	0
Feb.	1	1
Mar.	0	0
Apr.	0	0
May	2	4
Jun.	6	26
Jul.	6	27
Aug.	22	65
Sep.	22	101
Oct.	32	96
Nov.	1	17
Dec.	1	1
Total	93	338

July-August-September; and (3) tropical storms and hurricanes for July-August-September-October, versus radius, in kilometers, from Cape Kennedy. To obtain the probability for one or more events, $P(E_1, r)$, from Figure 18.1, the reader is required to subtract the $P(E_0, r)$, read from the abscissa, from unity; that is, $[1 - P(E_0, r)] = P(E_1, r)$. For example, the probability that no hurricane path (eye) will come within 556 kilometers (300 n. mi.) of Cape Kennedy in a year is 0.31, $[P(E_0, r = 300) = 0.31]$, and the probability that there will be one or more hurricanes within 556 kilometers (300 n. mi.) of Cape Kennedy in a year is 0.69, (1 - 0.31 = 0.69).

18.4 Climatological Information for Selected Geographic Locations

Climatological information pertinent to the aerospace vehicle landing operation is given in two NASA contractor reports (Refs. 18.3 and 18.4). Both documents follow the same format and contain for each site: (1) a short narrative description of the climate, (2) monthly and annual

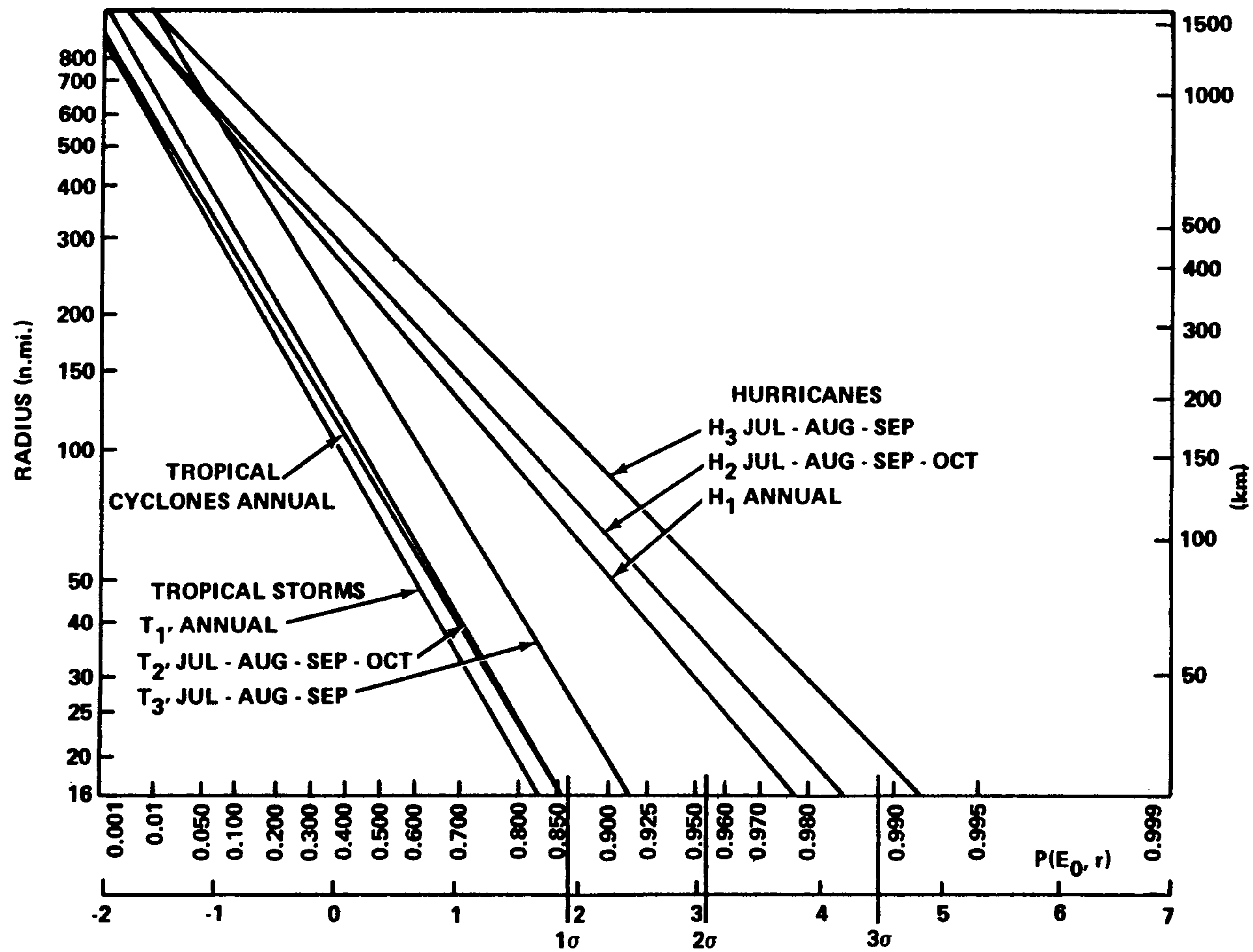

FIGURE 18.1 PROBABILITY OF NO TROPICAL CYCLONES, TROPICAL STORMS, OR HURRICANES FOR VARIOUS REFERENCE PERIODS VERSUS VARIOUS RADII FROM CAPE KENNEDY

temperature and precipitation summaries, (3) percentage frequency of occurrence of specified weather conditions for monthly and annual reference periods (the weather conditions, ceiling and visibility, thunderstorms, precipitation, fog, and other obstructions to vision are given for 3-hour periods to show the diurnal changes and for all hours combined), and (4) ground winds for monthly and annual reference periods. These data give the percentage frequency of occurrence of wind speed versus wind direction.

NASA CR-61319 contains data for nine foreign and three United States sites, while NASA CR-61342 contains twenty United States (two in Alaska) locations, as follows:

NASA CR-61319

Edward AFB, California
Langley AFB, Virginia
Patrick AFB, Florida
Moron, Argentina
Moron De LaFrontera, Spain
Ambala, India
Dhahran, Saudi Arabia
Bloemfontein, South Africa
Reggan, Algeria
Alice Springs, Australia
Honolulu, Hawaii

NASA CR-61342

Eielson AFB, Fairbanks, Alaska
Elmendorf AFB, Anchorage, Alaska
Castle AFB, Merced, California
Vandenberg AFB, Santa Maria, California
McCoy AFB, Orlando, Florida
Columbus AFB, Columbus, Mississippi
Whiteman AFB, Knob Noster, Missouri
Cherry Point MCAS, Havelock, North Carolina
Seymour-Johnson AFB, Goldsboro, North Carolina
Holloman AFB, Alamogordo, New Mexico
McGuire AFB, Wrightstown, New Jersey
Shaw AFB, Sumter, South Carolina
Ellsworth AFB, Rapid City, South Dakota
Bergstrom AFB, Austin, Texas

NASA CR-61342 (Continued)

Biggs AFB, El Paso, Texas
Carswell AFB, Ft. Worth, Texas
Dyess AFB, Abilene, Texas
Ellington AFB, Houston, Texas
Kelly AFB, San Antonio, Texas
Sheppard AFB, Wichita Falls, Texas

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WORLDWIDE EXTREMES