Engineering Models of the Venus Atmosphere

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Engineering models of the Venus atmosphere are presented for use in spacecraft design and mission planning. The models are developed from 1) data measured by the US Mariner 5 and USSR Venera spacecraft, 2) Earth-based measurements, and 3) theory which best satisfies the observations. The models include a most probable model and models for extremes of molecular mass and solar activity; the most probable model is presented in tabular form. Atmospheric characteristics and parameters affecting the models are discussed including planetary radius, atmospheric composition and clouds.

Introduction

SPACE vehicles which are to orbit the planet Venus, enter its atmosphere, or land on the surface are designed on the basis of the best available information on the characteristics of the Venus atmosphere. These characteristics affect the orbital lifetime, the flight dynamics of the vehicle along its trajectory or flight path, and the performance of the vehicle and its major subsystems. In addition, consideration of the atmospheric characteristics is required to select scientific instrumentation and to establish the range of measurements within suitable limits. Engineering models, therefore, should reflect the best current knowledge of the Venus atmosphere.

Knowledge of Venus has grown rapidly in recent years.[1,2] The advance has proceeded on a variety of fronts. Radio and radar astronomy played a major role and provided the first indications that the surface temperature was exceedingly large. The evidence, however, was not generally accepted prior to 1967 and the successful flights of Mariner 5 and Venera 4. It was difficult to account physically for the observed radio brightness and a variety of more or less esoteric models were devised to account for the radio data using nonthermal emission mechanisms. A variety of interpretations of the data led to widely differing atmospheric models.[3,4] Even the models in Ref. 4, which included data from Mariner 5 and Venera 4, reflected considerable uncertainty in values of the planetary radius, surface pressure, and surface temperatures. The uncertainties have been reduced significantly since 1967, especially in the lower atmosphere where in-situ measurements have been made by the USSR Venera 5, 6, 7 and 8 spacecraft.

The engineering models for the Venus atmosphere presented in this paper were developed for NASA[5] in support of Venus spacecraft programs. These models are based on 1) data measured by spacecraft which have encountered Venus, 2) the best available Earth-based measurements, and 3) theory which best satisfies the observations. The numerical models, formulated with data and theory available through January 1972, encompass results obtained by the USSR Venera 8 spacecraft. After a thorough review by a Science Steering Group, these models were recommended for use in the design of the US Venus Pioneer spacecraft.[6]

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Venus Atmosphere

Discussion of the parameters applicable to the engineering models of the Venus atmosphere is divided into the lower and upper atmosphere as shown in Fig. 1. These regions have been subdivided into regions bearing names associated with the Earth atmosphere such as troposphere and exosphere. Planetary radius is discussed first because the value of the radius is critical to the determination of parameter values at the surface.

Planetary Radius

Prior to the determination of the radius of Venus by radio astronomy, the only available measurements referred to the optical disc. Since then, however, radio astronomy techniques have provided readings of the solid planetary sphere. Numerous values of radius are summarized in Table 1.

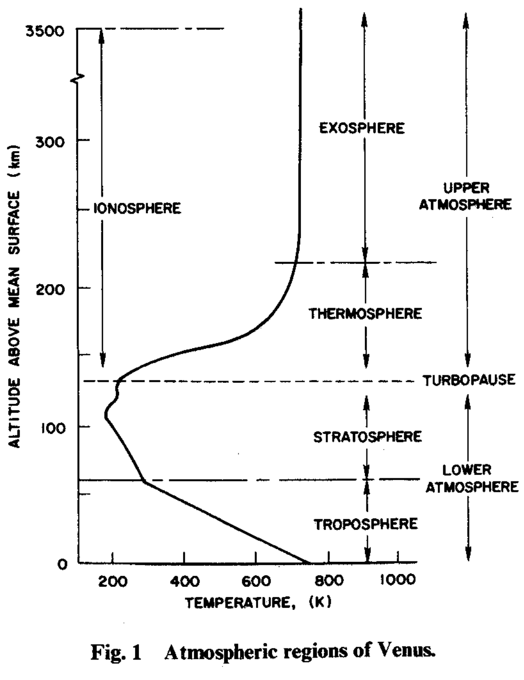

Fig. 1 Atmospheric regions of Venus.

Table 1 Radius of Venus

Radius (km)	Year	Source
6057 ± 55	1965	Clark
6056 ± 1.2	1967	Ash
6048 ± 1	1968	Ash
6052 ± 2.0	1968	Ash
6053.7 ± 2.2	1968	Melbourne
6050 ± 5	1968	Ash
6050 ± 0.5	1972	Campbell

Comparison of the experimental results of Venera 5 and 6 to Mariner 5 results indicated that the mean surface level in the descent region was 6050 km[7] which is in agreement with the most recent data in Table 1. Therefore, a radius of 6050 ± 4 km has been adopted for the engineering models; the uncertainty is considered to be realistic.

Lower Atmosphere

Composition

The components of the Venus lower atmosphere have been identified by gas analysis experiments on-board the Venera 4, 5, and 6 spacecraft and by spectroscopic measurements made from Earth. Table 2 summarizes current estimates of percentages by volume of component gases in the Venus atmosphere.

The Venera gas analyzers were designed to detect CO_2, inert gases, O_2, and H_2O.[8] Other component gases listed in Table 2 are derived from spectroscopic measurements except the value for the He which is an estimated amount. The major constituents are CO_2 and inert gases, principally N_2; values shown were obtained from Venera 5 and 6 measurements. The value of O_2 reflects an upper limit obtained from spectroscopic measurements. The content of oxygen as measured by Venera 5 and 6 did not exceed 0.1%, but the exact amount could not be determined because of limitations of the detector.[8]

The quantities of H_2O detected by the Venera spacecraft and spectroscopic measurements are shown in Table 2. The Venera values measured below 55 km altitude (which indicate water vapor mixing ratios of the order of 10^{-3} to 10^{-2}) are in disagreement with spectroscopic measurements which indicate water vapor mixing ratios of the order of 10^{-6} to 10^{-4}.[9] The amount of H_2O present has been widely discussed because

Table 2 Composition of the Venus atmosphere[5]

Component	Estimated % by volume	Source
CO_2	97, +3, −4	Vinogradov
N_2, A, and inert gases	<2	Vinogradov
O_2	$<10^{-3}$	Belton
H_2O	$10^{-2}-10^{-1}$	Vinogradov
	$10^{-4}-10^{-2}$	Rea
HCl	$10^{-4.2}$	Connes
HF	$10^{-6.2}$	Connes
CH_4	$<10^{-4}$	Connes
CO	$10^{-2.34}$	Connes
COS	$<10^{-6}-10^{-4}$	Cruikshank
NH_3	$<10^{-5.5}$	Kuiper
N_2O	$<5\times10^{-5}$	Benedict
He	$\approx 10^{-2}$	McElroy
CH_3Cl	$<10^{-4}$	Connes
C_2H_2	$<10^{-4}$	Connes
HCN	$<10^{-4}$	Connes
O_3	$<10^{-6}$	Jenkins
C_3O_2	$<10^{-4.3}$	Kuiper
H_2S	$<10^{-1.7}$	Cruikshank
SO_2	$<10^{-5.5}$	Cruikshank
CH_3F	$<10^{-4}$	Connes

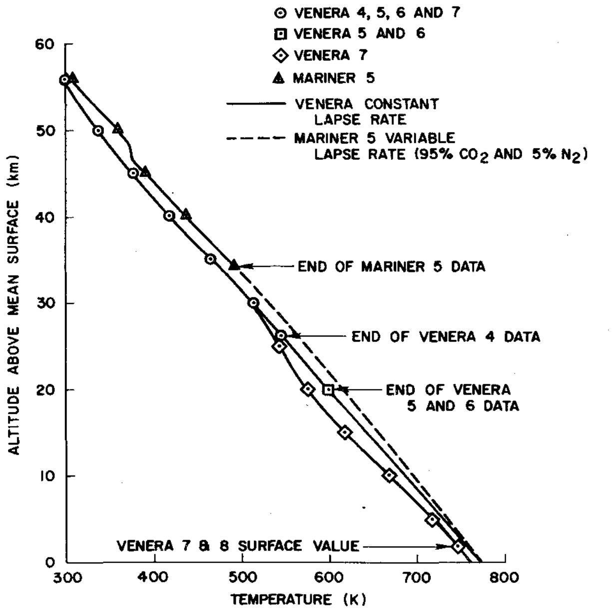

Fig. 2 Venus lower atmosphere temperature profiles.

of its importance in the theory of cloud formation, its effect on Earth-based measurements such as brightness temperature, and its effect on radiowave absorption. Thus, although H_2O has been identified as a constituent of the Venus atmosphere, the concentration is in question.

Temperature

Temperature profiles from about 90 km altitude to the surface of Venus have been obtained by spacecraft. The profiles below 60 km are compared in Fig. 2 with a mean planetary radius of 6050 km. The Venera 4, 5, and 6 data were adjusted to agree at a pressure of 6.6 atm and Venera 7 data were superposed at a temperature of 500°K because pressure data were not recorded.[10]

The data agree well in the region in which they overlap and are within rms errors. Because the Mariner 5 data were calculated from refractivity profiles which used a composition of 95% CO_2 and 5% N_2, it has been suggested that these data could be adjusted to agree more closely with the Venera data by reducing the mean molecular weight. Improved correlation has been achieved by using less CO_2, e.g., 85% (which is in conflict with the Venera composition measurements), or relatively large percentages of light inert gases, e.g., 8% He. However, there is little evidence to support these values.

The lapse rate, i.e., the change in temperature with altitude, is close to adiabatic below 50 km. The curves in Fig. 2 have been extrapolated to the surface with adiabatic gradients. The Venera 5 and 6 curve was extrapolated by using the constant lapse rate that was determined from the final segment of the observed temperature data. This results in a surface temperature of 772°K.[7] Mariner 5 data were extrapolated by using a variable lapse rate for a dry adiabatic atmosphere which included effects of compressibility. For the calculations, lapse rates were determined for an ideal 95% CO_2 and 5% N_2 atmosphere. Changes in compressibility and molecular weight had little effect on the extrapolated value of surface temperature, 774°K. Extrapolation of the Venera data by the same method (not shown) yielded 761°K at the surface. At 2 km above the mean surface, a temperature of 746°K was computed which corresponds to the surface value of 747 ± 20°K observed by Venera 7. A possible discrepancy of 2 km in measured altitude for Venera 7 was noted in Ref. 10. Preliminary reports of Venera 8 data indicate that the surface temperature in the range of 740–750°K is in agreement with Venera 7 results.[11]

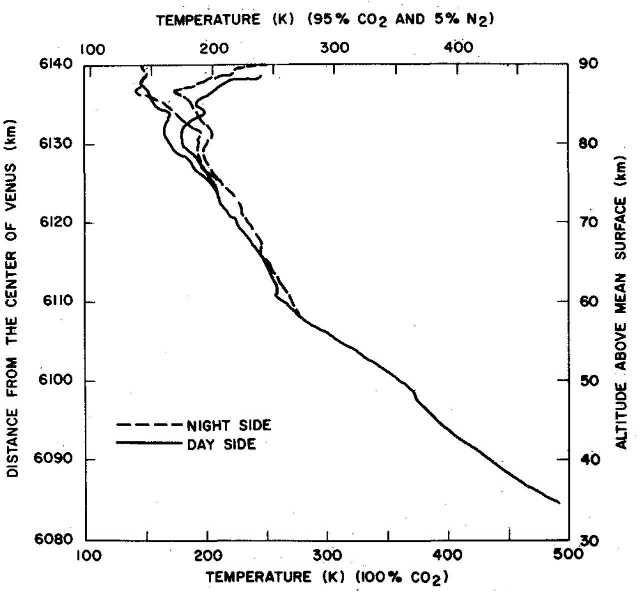

Fig. 3 Mariner 5 temperature profiles for two compositions (Ref. 12).

The temperature profile between 60 and 90 km determined from Mariner 5 observations[12] is shown in Fig. 3. The Mariner 5 occultation experiment indicated only minor diurnal temperature changes in the lower atmosphere.

Surface pressure

Direct measurements of atmospheric pressure on Venus were obtained by Venera 4, 5, and 6 and during the Mariner 5 occultation experiment. The pressure profiles are compared in Fig. 4 for a mean planetary radius of 6050 km. The Venera 4, 5, and 6 data were adjusted to agree at a pressure of 6.6 atm.[7] The Venera and Mariner 5 profiles agree remarkably well.

Because surface pressure was not measured, the profiles of Fig. 4 have been extrapolated to the surface with the adiabatic gradients used for the temperature extrapolation. Extrapolation of the Venera data with a constant lapse rate results in a surface pressure of 102 atm.[7] With a variable lapse rate, a surface pressure of 94 atm was determined from Mariner 5 data for an atmospheric composition of 100% CO_2 and 86 atm for a composition of 95% CO_2 and 5% N_2. Extrapolation was begun at 35 km, the lowest value of pressure determined from the Mariner 5 data. A similar extrapolation of Venera data at 20 km results in a surface pressure of 100 atm for a 95% CO_2 and 5% N_2 atmosphere. The surface pressure calculated on the basis of an adiabatic analysis of Venera 7 temperature data was 93.9 atm.[10] A surface pressure of about 90 atm was measured by Venera 8.[11]

Winds

The nature and theory of the general circulation of Venus' atmosphere remain uncertain although considerable progress has been reported in recent years. Earth-based observational data relevant to the question of atmospheric winds refer to regions of the atmosphere above the visible clouds. The wind field at greater depths must be inferred on the basis of detailed theoretical models.[13–15]

Pictures of Venus revealed that ultraviolet markings traveled around the planet with an apparent period of 3.6 to 4.5 days.[16] A rotation period of this magnitude implies zonal velocities of the order of 100 m/sec,[17] some 50 times larger than the rotation speed of the solid planet at the equator. These results have been confirmed by recent photographic and spectroscopic data.[18,19]

Atmospheric winds determined for Venera 4, 5, and 6 correlate well with the theoretical winds. Vertical velocities of 1.0 to 1.5 m/sec were obtained from Venera 4 and 0.3 to 0.5 m/sec from Venera 5 and 6.[20] Horizontal winds of 40 to 50 m/sec were measured during the last 18–20 km (< 50 km altitude) of the descent of Venera 4 and winds of 5 to 14 m/sec were reported for Venera 7 between 38 and 53 km.[21] Preliminary results from the Venera 8 entry indicated that winds of 50 m/sec were detected at 45 km and winds of 2 m/sec at about 10 km. Surface winds were not measured. The general direction of movement is from the terminator to the daylight side.[11]

Clouds

Knowledge of clouds is important for spacecraft design and for the design and operation of instrumentation for observing the Venus atmosphere. Possible adverse effects include absorption or distortion of radio transmissions and microwave observations, distortion of optical observations, corrosive action by aerosol or other cloud particles, and undesirable chemical action. The existence of two cloud layers in the Venus atmosphere was revealed by photographs taken in infrared and ultraviolet wavelengths. The upper layer is opaque to ultraviolet but transparent to infrared, whereas the lower layer is opaque to both ultraviolet and infrared wavelengths.

Information on the clouds has been obtained from radio brightness measurements, polarization studies, spectroscopic and interferometer observations, and spacecraft experiments.[9] The data generally agree that at least two cloud layers exist and that the temperature of the lower layer is approximately 240°K and at a level of about 60 km above the mean surface. Correlation of Mariner 5 temperature data (Fig. 3) and Earth-based measurements indicates that the upper cloud (or haze) layer is located at about 80 km with a temperature of approximately 180°K.

Disagreement exists concerning the composition of the clouds. Dust has been suggested as a principal component of the clouds, but results of radio brightness studies and polarization observations indicate that dust cannot be a major component of the visible cloud decks. Other components such as H_2O, C_3O_2, $FeCl_2$, and NH_4Cl have been proposed with little supporting evidence.

The presence and importance of water vapor in cloud formation is still open to question. Water vapor may exist in the form of HCl solutions.[22] While ice clouds are still considered a possibility,[1] an HCl-H_2O system is presently the leading contender as the major constituent of the upper cloud layer.

Water in the amounts detected by the Venera spacecraft can be used to explain the lower cloud layer at about 60 km. These explanations are supported by Mariner 5 temperature

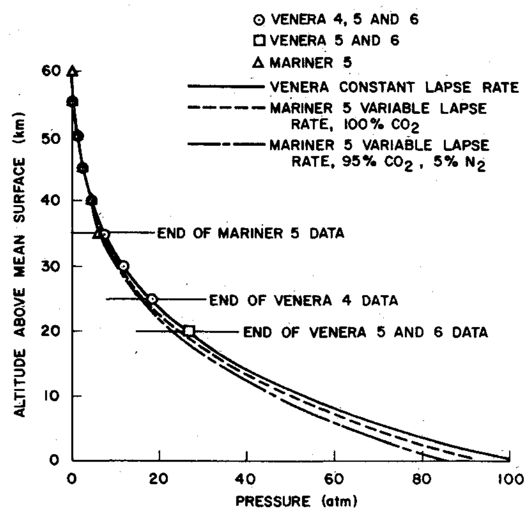

Fig. 4 Venus lower atmosphere pressure profiles.

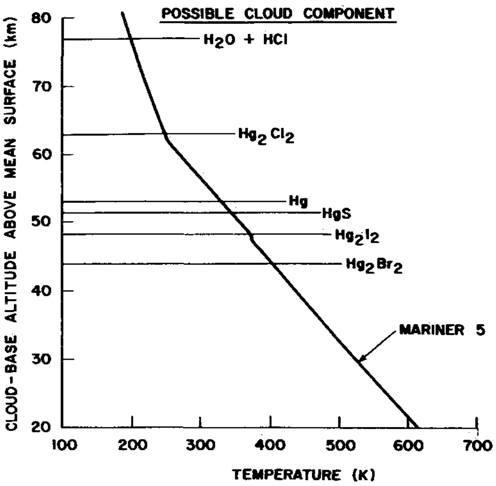

Fig. 5 Cloud layers and possible components on Venus (Ref. 23).

measurements.[12] However, analysis of the geochemistry of Venus[23] suggests mercury compounds (specifically, a thin haze of $HgCl_2$ overlaying a deep cloud of mercury droplets) as more likely components of the lower cloud layer (Fig. 5). If these compounds are the main cloud constituent, they could cause the observed pale yellow tint of Venus observed from Earth. However, recent work[24] suggests that the cloud layer at 60 km may be partially hydrated H_2SO_4. Other possible cloud layers are also shown in Fig. 5.

Upper Atmosphere

The only measurements which pertain directly to conditions in the upper atmosphere of Venus are the electron density profiles obtained from Mariner 5 and the ultraviolet airglow data obtained from Mariner 5 and Venera 4. Therefore, engineering models for the upper atmosphere must rely on a variety of theoretical studies. The range in the models, however, has been limited by spacecraft results.

Ionosphere

Mariner 5 observed an extensive ionosphere on both day and night sides of Venus.[25] The peak value for electron density was about $5 \times 10^5/cm^3$ at a planetocentric distance of 6190 km. The electron density, as indicated in Fig. 6, remained high ($>10^4/cm^3$) to an approximate planetocentric distance of 6500 km. At greater distances, the electron density decreased rapidly to typical values for the undisturbed interplanetary medium. The peak value for electron density on the night side was about $2 \times 10^4/cm^3$, and the night-side ionosphere was surprisingly extensive. Significant electron density ($>10^2/cm^3$) was observed to a planetocentric distance of at least 6800 km. Some evidence exists that on the night side a plasma trail extends to planetocentric distances of at least 7200 km.

Mariner 5 carried ultraviolet photometers sensitive to radiations emitted by atomic hydrogen and atomic oxygen. The resulting measurements provided data for the day and night sides of the planet. Venera 4 carried similar instrumentation, but the planetary data are limited to conditions during probe descent on the dark side of the planet. Neither experiment showed any evidence of a significant abundance of atomic oxygen; both experiments revealed an extensive hydrogen corona. The Mariner results indicate a day-side exospheric temperature of about 650°K.[26] Other interpretations of the Mariner data suggested appreciable abundances of H_2 and deuterium in the upper atmosphere.[27] The evidence is considered weak, however, so models requiring large concentrations of these elements are viewed as highly speculative.

Models of the ionosphere already in the literature assume that CO_2^+ is the dominant positive ion.[28] Increased understanding of Mars, however, has led to the expectation that O_2^+ is probably the important component. It is produced by reaction of CO_2^+ with O.

Neutral atmosphere

The major uncertainties in neutral densities of the upper atmosphere relate to the location of the turbopause and the abundance of light constituents, O, N_2, CO, and He at the turbopause. The relative abundance of these gases is expected to increase rapidly with increasing altitude. The drag experienced by an orbiting spacecraft will be particularly sensitive to O and He, but knowledge concerning abundances of these constituents is minimal.

Atomic oxygen is produced copiously by photodissociation of CO_2. On theoretical grounds one might expect atomic oxygen to be a dominant species in the upper atmosphere. However, detailed theoretical analysis of the ionospheric profiles suggests that oxygen is a minor constituent ($<10\%$) at the ionospheric peak, as is the case for Mars; Venus models are constructed subject to this constraint.[29]

There is no positive evidence for helium, but it has been noted previously that apparent discrepancies between Mariner 5 and Venera data in the lower atmosphere may be removed if

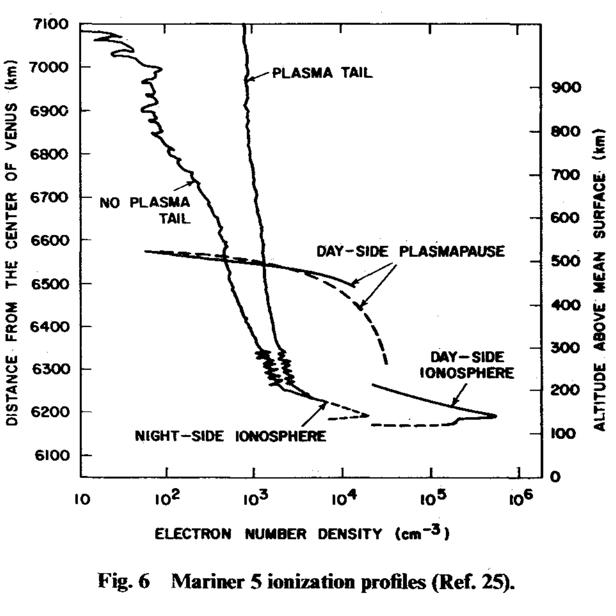

Fig. 6 Mariner 5 ionization profiles (Ref. 25).

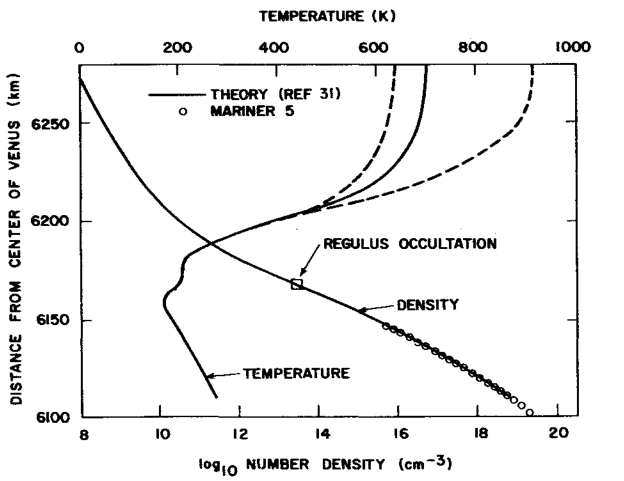

Fig. 7 Model of Venus neutral atmosphere and measured density data (Refs. 23, 31).

Venus' atmosphere includes a significant abundance of He (~5%). Moreover, the extended night-time ionosphere can be understood if helium is a major component of the upper atmosphere.[30] Although the evidence is inconclusive, engineering models must allow at least for the possibility of a significant helium concentration. The lifetime of an orbiting spacecraft is affected by the assumed value for the mixing ratio of He at the turbopause.

The neutral atmosphere of Venus is described by the theoretical thermal model shown in Fig. 7.[28,31] Number density calculations derived from Mariner 5 data are compared to the theoretical values. The Regulus occultation density value at 6196 km is also given in Fig. 7. The model yielded an exospheric temperature of 700°K. This value compares favorably with the value of 650°K derived in Ref. 26 from Mariner 5 Lyman-alpha results. The exospheric temperature varies with solar flux. Estimates for Venus exospheric temperatures at periods of minimum and maximum solar activity are shown in Fig. 7.

Dynamics

Preliminary models for dynamics of the upper atmosphere suggest that the night side may be significantly colder than the day side.[32] The night-side exospheric temperature could be as low as 250°K, compared to day-side values of about 750°K. If valid, the dynamic studies imply large lateral gradients in the neutral density from day to night.

Lifetime for orbital spacecraft would then depend critically on the position of the perigee because orbits with perigees on the dark side of the planet would encounter markedly less drag than orbits with perigees at similar heights on the sunlit side. To take into account the possibility of a low night-side exospheric temperature, an appropriate model has been developed.

Atmospheric Models

Calculation

The models presented here were generated by the computer program described in Ref. 5. The basic inputs to the computer program are the temperature profile, the surface pressure, the near-surface atmospheric composition and corresponding molecular mass, the planetary radius, the acceleration of gravity at the planet's surface, and the atmospheric density at the turbopause.

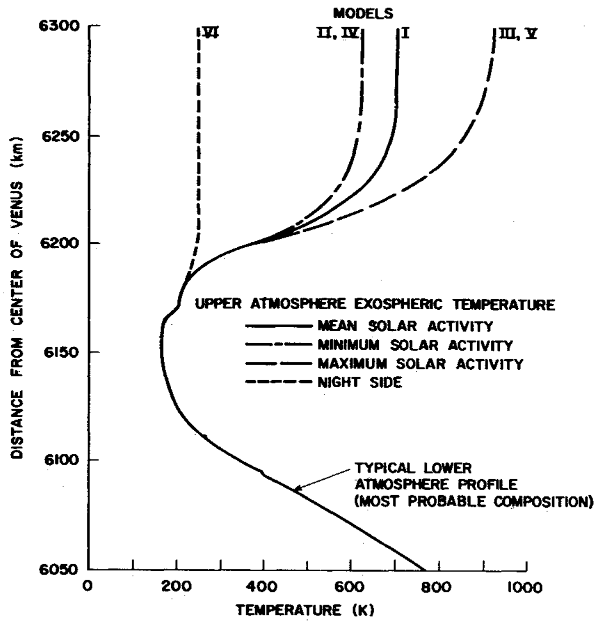

Fig. 8 Temperature profiles for models of Venus atmosphere (see Fig. 1).

Choice of Model Parameters

Atmospheric models were computed for the lower and upper atmospheres to account for uncertainties in the atmospheric parameters. Table 3 shows the input parameters for the engineering models of the Venus atmosphere that have been developed. The input temperature profiles are shown in Fig. 8. All models account for the variation of gravitational acceleration with altitude. A value of 887.6 cm/sec^2 was used for the acceleration of gravity at the surface of Venus with a radius of 6050 km.

Lower atmosphere

The lower atmosphere was based on temperature profiles determined from spacecraft measurements with surface values obtained by adiabatic extrapolation to the surface. A mean

Table 3 Computer inputs for models of Venus atmosphere (1972)

	Most probable molecular mass		Maximum molecular mass		Minimum molecular mass	
Parameters	Model I	Model II	Model III	Model VI	Model IV	Model V
Surface pressure, atm	93.8	95.5	95.5	95.5	86.7	86.7
Surface temperature, °K	767.5	772.5	772.5	772.5	738.7	738.7
Composition (% by volume)						
below turbopause						
CO_2	97	100	100	100	93	93
N_2	3	...	...	...	...	...
He	...	...	...	...	7	7
at turbopause						
CO_2	95.99	100	100	100	93	93
N_2	3	...	...	...	...	...
He	0.01	...	...	...	5	5
O	1	...	...	...	2	2
Molecular mass, g/g-mole						
below turbopause	43.52	44.00	44.00	44.00	41.20	41.20
at turbopause	43.24	44.00	44.00	44.00	41.20	41.20
Turbopause density, g/cm^3	1.44×10^{-11}	1.46×10^{-13}	1.46×10^{-13}	1.46×10^{-13}	1.37×10^{-9}	1.37×10^{-9}
Exospheric temperature, °K	710 (Mean Solar Activity)	625 (Minimum Solar Activity)	931 (Maximum Solar Activity)	250 (Night-Side Temperature)	625 (Minimum Solar Activity)	931 (Maximum Solar Activity)

Table 4 1972 Venus atmosphere (model I) (most probable molecular mass and mean solar activity)

Altitude (km)	Temperature (°K)	Pressure (mb)	Density (g/cm^3)	Speed of sound (m/sec)	Molecular mass (g/g-mole)	Density scale height (km)	Number density (per cm^3)	Mean free path (m)	Viscosity (kg/m·sec)
−4	798.1	1.20+05	7.89−02	426	43.531	20.52	1.09+21	1.33−09	3.33−05
0[a]	767.5	9.49+04	6.47−02	418	43.531	19.79	8.95+20	1.62−09	3.24−05
4	736.5	7.41+04	5.27−02	410	43.531	19.06	7.29+20	1.99−09	3.15−05
8	705.2	5.73+04	4.25−02	402	43.531	18.32	5.88+20	2.46−09	3.06−05
12	673.4	4.38+04	3.40−02	393	43.531	17.57	4.71+20	3.07−09	2.96−05
16	641.2	3.30+04	2.70−02	384	43.531	16.81	3.73+20	3.88−09	2.85−05
20	608.5	2.46+04	2.11−02	375	43.531	16.03	2.93+20	4.95−09	2.74−05
24	575.3	1.80+04	1.64−02	365	43.531	15.24	2.27+20	6.39−09	2.62−05
28	541.4	1.29+04	1.25−02	355	43.531	14.43	1.73+20	8.36−09	2.51−05
32	506.8	9.10+03	9.40−03	345	43.531	13.59	1.30+20	1.11−08	2.39−05
36	471.4	6.25+03	6.94−03	334	43.531	12.74	9.61+19	1.51−08	2.25−05
40	433.0	4.16+03	5.03−03	321	43.531	11.82	6.97+19	2.08−08	2.09−05
44	397.6	2.67+03	3.52−03	308	43.531	10.51	4.87+19	2.97−08	1.95−05
48	371.4	1.66+03	2.34−03	299	43.531	9.19	3.23+19	4.47−08	1.82−05
52	336.8	9.91+02	1.54−03	286	43.531	9.36	2.13+19	6.79−08	1.65−05
56	299.6	5.57+02	9.74−04	271	43.531	7.99	1.35+19	1.07−07	1.49−05
60	267.6	2.93+02	5.72−04	258	43.531	7.12	7.92+18	1.83−07	1.33−05
64	246.2	1.44+02	3.06−04	249	43.531	6.13	4.24+18	3.42−07	1.23−05
68	231.9	6.71+01	1.51−04	242	43.531	5.47	2.10+18	6.91−07	1.16−05
72	217.0	2.99+01	7.22−05	235	43.531	5.30	9.99+17	1.45−06	1.10−05
76	200.4	1.25+01	3.27−05	227	43.531	4.76	4.53+17	3.20−06	1.03−05
80	187.9	4.92+00	1.37−05	211	43.531	4.46	1.90+17	7.63−06	0.94−05
84	180.1	1.84+00	5.35−06	203	43.531	4.16	7.40+16	1.95−05	0.89−05
88	175.2	6.65−01	1.99−06	199	43.531	3.97	2.75+16	5.27−05	0.86−05
92	171.4	2.35−01	7.16−07	195	43.531	3.88	9.91+15	1.46−04	0.83−05
96	168.3	8.11−02	2.52−07	193	43.531	3.77	3.49+15	4.15−04	0.81−05
100	166.5	2.77−02	8.70−08	191	43.531	3.74	1.20+15	1.20−03	0.80−05
110	171.0	1.86−03	5.70−09	195	43.531	3.70	7.88+13	1.84−02	0.83−05
120	203.9	1.59−04	4.10−10	229	43.531	4.09	5.67+12	2.55−01	1.04−05
130[b]	214.0	1.91−05	4.67−11	234	43.531	4.75	6.46+11	2.24+00	1.09−05
140	268.0	3.01−06	5.81−12	261	42.963	5.39	8.15+10	1.79+01	1.33−05
150	378.4	7.79−07	1.04−12	308	42.015	6.92	1.49+10	9.76+01	1.85−05
160	502.4	2.98−07	2.91−13	355	40.818	9.09	4.29+09	3.39+02	2.37−05
170	591.0	1.41−07	1.13−13	390	39.404	11.62	1.73+09	8.40+02	2.67−05
180	641.4	7.51−08	5.32−14	414	37.732	13.93	8.49+08	1.71+03	2.84−05
190	674.9	4.28−08	2.73−14	435	35.781	15.66	4.60+08	3.16+03	2.96−05
200	691.5	2.58−08	1.50−14	455	33.576	17.31	2.70+08	5.39+03	3.01−05
210	700.8	1.62−08	8.66−15	475	31.179	18.70	1.67+08	8.70+03	3.04−05
220	705.5	1.06−08	5.18−15	496	28.700	20.14	1.09+08	1.34+04	3.06−05
230	707.8	7.20−09	3.21−15	520	26.266	21.71	7.37+07	1.97+04	3.06−05
240	709.0	5.07−09	2.06−15	544	23.994	23.49	5.18+07	2.81+04	3.07−05
250	709.4	3.69−09	1.37−15	569	21.963	25.54	3.76+07	3.87+04	3.07−05
260	709.4	2.75−09	9.43−16	593	20.207	27.80	2.81+07	5.18+04	3.07−05
270	709.4	2.10−09	6.68−16	616	18.719	30.21	2.15+07	6.77+04	3.07−05
280	709.4	1.64−09	4.86−16	638	17.467	32.69	1.68+07	8.68+04	3.07−05
290	709.4	1.30−09	3.62−16	658	16.409	35.15	1.33+07	1.10+05	3.07−05
300	709.4	1.05−09	2.75−16	677	15.499	37.52	1.07+07	1.36+05	3.07−05
310	709.5	8.51−10	2.12−16	696	14.699	39.74	8.69+06	1.67+05	3.07−05
320	709.5	7.01−10	1.66−16	713	13.976	41.80	7.15+06	2.03+05	3.07−05
330	709.5	5.82−10	1.31−16	731	13.306	43.71	5.95+06	2.45+05	3.07−05
340	709.5	4.89−10	1.05−16	749	12.672	45.51	4.99+06	2.92+05	3.07−05
350	709.5	4.14−10	8.46−17	768	12.063	47.24	4.22+06	3.44+05	3.07−05

[a] Corresponds to planetary radius of 6050 km.
[b] Density is 1.44×10^{-11} g/cm^3 at the turbopause (lower boundary of upper atmosphere).

profile based on Fig. 2 is used for the most probable temperature profile and is shown in Fig. 8. The most probable model is computed for a planetary radius of 6050 km and a molecular mass of 43.5 determined for a composition of 97% CO_2 and 3% N_2. For all models of the lower atmosphere, it is assumed that the molecular mass is constant up to the turbopause.

Uncertainties in surface temperature and pressure are associated with uncertainties in values for the planetary radius and composition. A range of values for the radius of 6046 to 6054 km was used, and two atmospheric compositions were chosen to encompass a reasonable range for molecular mass. One composition is pure CO_2 which provides the maximum molecular mass, and the other composition has 93% CO_2 and 7% He which provides the minimum molecular mass.

Upper atmosphere

Upper atmosphere models were calculated with the thermal model of Ref. 28. The lower boundary for the theoretical upper atmosphere is the turbopause. The turbopause is the altitude below which the atmospheric gases mix in constant proportions; above this altitude each constituent gas is taken to be in diffusive equilibrium, with number density decreasing with altitude at a rate which depends upon the molecular mass of the gas and the ambient atmospheric temperature. The turbopause was estimated for three possible values of eddy diffusion coefficient, 10^5, 10^7, and 10^9 cm^2/sec which were selected to span a reasonable range of values. The coefficients then were used to determine the associated density values at the turbopause. The model of maximum molecular mass is a pure CO_2 atmosphere, the model of minimum molecular mass assumes the highest mixing ratios for O and He at the turbopause, and the model of most probable molecular mass was selected to give the most likely values of mixing ratios for O and He. The upper atmosphere models are superposed on the lower atmosphere models at the turbopause.

The upper constraint on the upper atmosphere models is the exospheric temperature which is a function of both diurnal heating and solar cycle heating (Fig. 7). The upper atmosphere temperature profiles for the different exospheric temperatures are shown in Fig. 8.

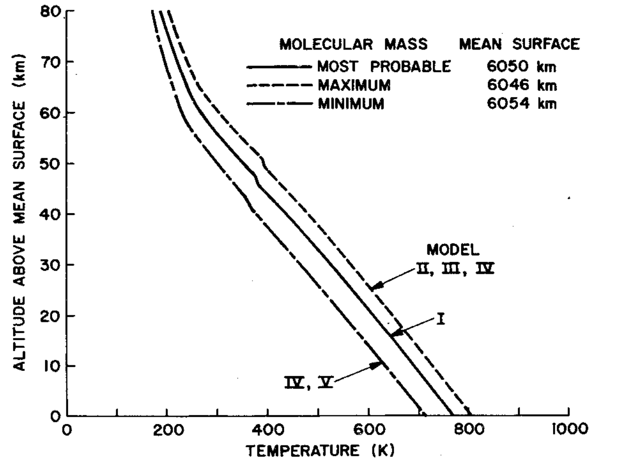

Fig. 10 Most probable temperature profile and limiting values—Venus lower atmosphere.

Engineering Models

Six engineering models have been developed for use in design and analysis of Venus space vehicles. The temperature structure and density variation of the Venus atmosphere for the models are shown in Figs. 8 and 9, respectively. Below 100 km, temperature structure varies with molecular mass as shown in Fig. 10. Surface temperatures are given in Table 3 for the molecular masses considered. Molecular mass has little effect on density variation below 120 km. Maximum density is achieved with the minimum molecular mass models (IV, V). Differences in these models appear at altitudes above 350 km. Model VI based on a night-time exospheric temperature should be used as the minimum-density model. Differences in the density in the upper atmosphere are important in the design of orbiting spacecraft.

Maximum values of surface temperature and pressure were obtained by referring the maximum molecular mass models (II, III, VI) to a planetary radius of 6046 km and minimum values were obtained by referring the minimum molecular mass models (IV, V) to 6054 km. A design range of surface temperature of 708°K to 803°K is achieved while surface pressure ranges from 68 to 121 atm.

The nominal model of the Venus atmosphere given in Table 4 illustrates the computer output. The model is based on the most probable planetary radius of 6050 km which corresponds to 0-km altitude in Table 4. However, to encompass possible extremes of surface pressure and temperature, the table has been extended downward to -4 km which corresponds to a planetary radius of 6046 km. Similar tables which take into account possible extremes of molecular mass, solar activity, and exospheric temperature in appropriate combinations are given in Ref. 7. An alternate model has been proposed in Ref. 1 which is generally consistent with the nominal model given in Table 4. This model reflects the surface temperature obtained from Venera 7; however, it does not incorporate the improved Mariner 5 results[12] which affect the model above 50 km.

The six models which have been summarized should be regarded as approximations which are based on the best available data and which encompass current uncertainties in the atmospheric parameters. The most probable model should be used as the nominal design model; it is most accurate in the lower atmosphere below an altitude of 70 km.

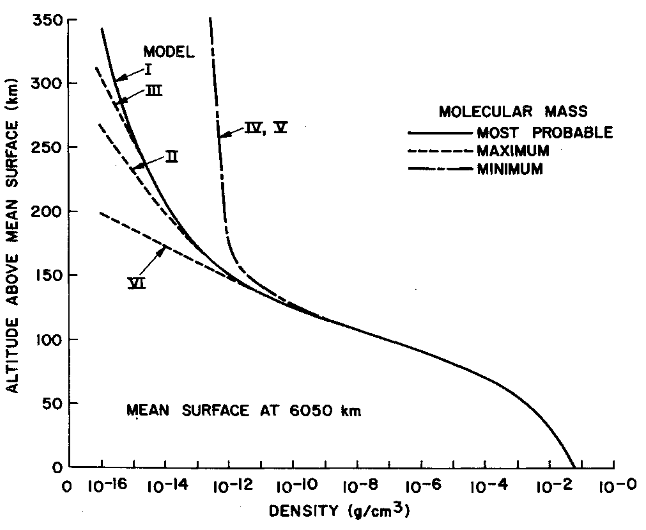

Fig. 9 Venus atmosphere density profiles.

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