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MODEL ATMOSPHERE OF PLANET VENUS
ACCORDING TO THE RESULTS OF MEASUREMENTS
ON THE SOVIET AUTOMATIC INTERPLANETARY STATION
"V E N E R A - 4"

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M. K. Rozhdestvenskiy

SUMMARY

This paper presents the details of the experiment conducted on VENERA-4 as it descended on its surface by parachute from the altitude of about 28 km. These results were made available before a preliminary communication [3], was published. Based mostly on extrapolation, this paper is accompanied by 12 original diagrams. It is probable that some of the conclusions relative to pressure, temperature and density will be further adjusted for the final publication.

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* *

The purpose of the present paper is to analyze the results of measurements made by the automatic interplanetary station "Venera-4", and to establish the most probable model of the lower atmosphere of Venus.

This report is based upon the preliminary results of temperature, pressure and density measurements, on chemical analysis and on the initial altitude data summarized in the press [1, 2]. The preliminary results of analysis are presented in the paper [3].

The main objective of the soft-landing probe was to measure the pressure, temperature, density and composition of the lower atmosphere of Venus. Measurements continued for 94 minutes as the probe was making a smooth parachute descent.

The altitude above the planet's surface at time of parachute deployment was 26 ± 1.3 km, as was shown by the radioaltimeter. The chemical composition of the atmosphere was determined immediately after parachute deployment and 347 seconds later. The atmosphere was found to consist mainly of CO₂ with small amounts of water, oxygen and possibly also of nitrogen and inert gases.

SCIENTIFIC INSTRUMENTATION

An average assumed model atmosphere, obtained from astronomical observations, was used to select the device's measurement ranges. The temperature was measured by two hermetic resistance thermometers capable to operate in gaseous and liquid media in the presence of chemically aggressive substances. The sensitive elements of transducers (sensors) were made of platinum wire. They were mounted in balanced bridge circuits. The measurement range of the first transducer was 270 to 600°K and that of the second 210 to 730°K. The root-mean-square error of temperature measurement, σ_t , of these transducers did not exceed respectively $\pm 4^\circ$ and $\pm 7^\circ$. Their installation ruled out any effect by the boundary layer formed on the probe on the readings.

The pressure was measured by means of an aneroid-type manometer. The measurement range of the device was 0.13 to 7.3 kg/cm². The error of measurements was ± 0.2 kg/cm².

A special densimeter with an ionization chamber in the form of a cylinder with a filament was used to measure the density. The internal surface of the cylinder was covered with a thin layer of β -active strontium 90, inducing gas ionization in the cylinder. The densimeter operation was based upon measurement of current generated between the filament and the cylinder at a specified voltage. The densimeter's measurement range was $0.5 \cdot 10^{-3}$ - $15 \cdot 10^{-3}$ g/cm³ for CO₂, N₂, O₂ and mixtures of those gases. The root-mean square error σ_ρ was $\pm 0.1 \cdot 10^{-3}$ g/cm³ at the beginning and $\pm 2 \cdot 10^{-3}$ g/cm³ at the end of measurements.

The devices were checked in the entire measurement range and under all possible effects of overloads and environment.

The descent velocity was less than 10 m/sec and, therefore could not affect the devices' readings. The root-mean-square errors are given for the values recorded by the receiving stations.

MEASUREMENTS

The interrogation of transducers with a telemetric commutator began at 07 h. 40 min. 52 sec. Moscow time. Temperature was measured during the whole experiment and ceased only when the communication with the probe was interrupted at 09h. 13m. 57 sec. The pressure and density were measured until the readings went off scale, respectively at 08h.30m.31 s. and at 0850 hours.

The curves of temperature, pressure and density variation with time are plotted in Fig.1. Here the arrow shows the moments of time when measurements of pressure and density had ceased.

The "hump" on the density curve in Fig.1 attracts our attention.

Basing ourselves on the values of the three parameters measured up to 0830 hours and on the equation of state, the values of the molecular weight were calculated (Fig.2). As may be seen from it, these vary from 44.8 to 57.

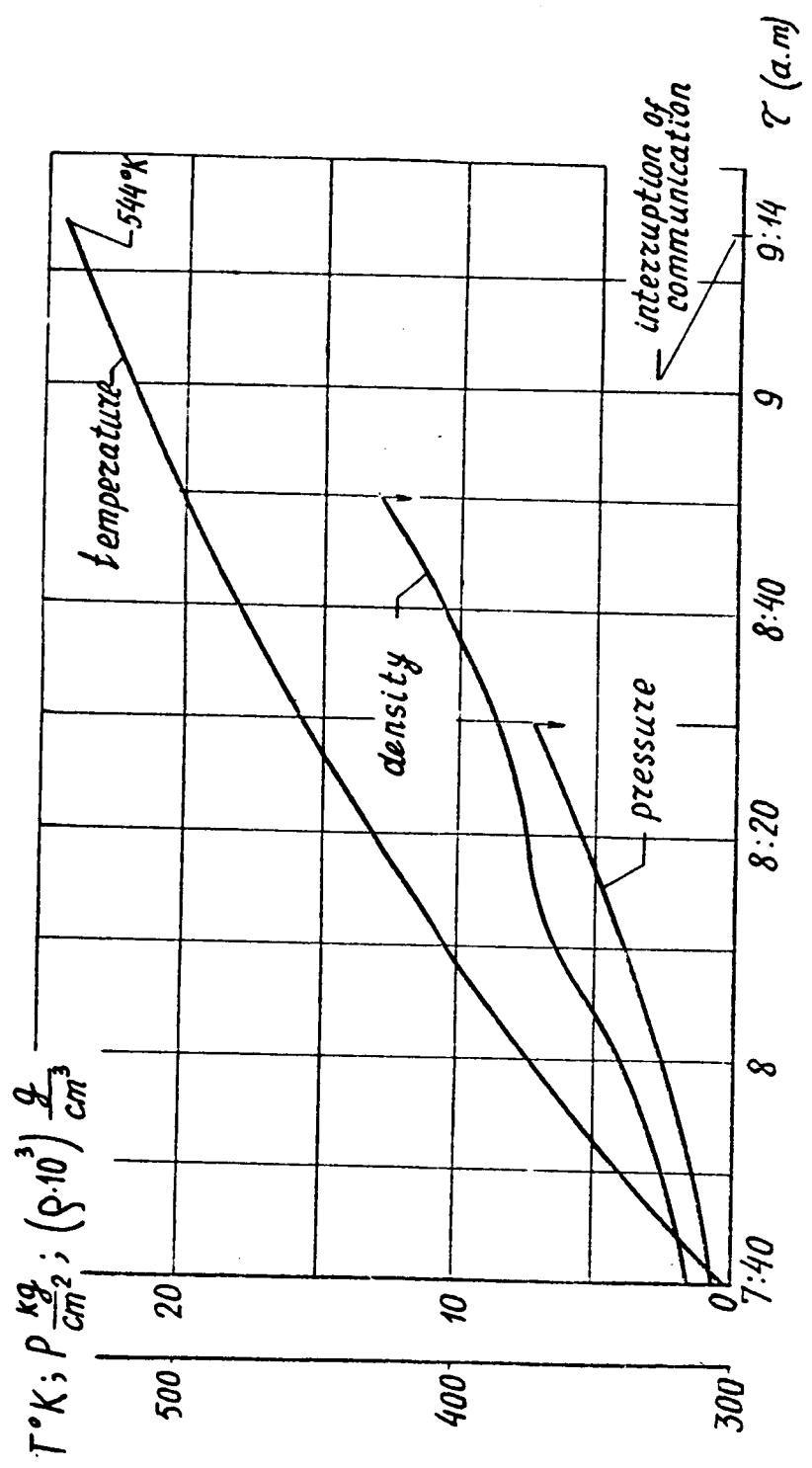


Fig. 1. Measured temperature, pressure, and density, as a function of time. \downarrow - time, when the device readings exceeded the limits of the scale.

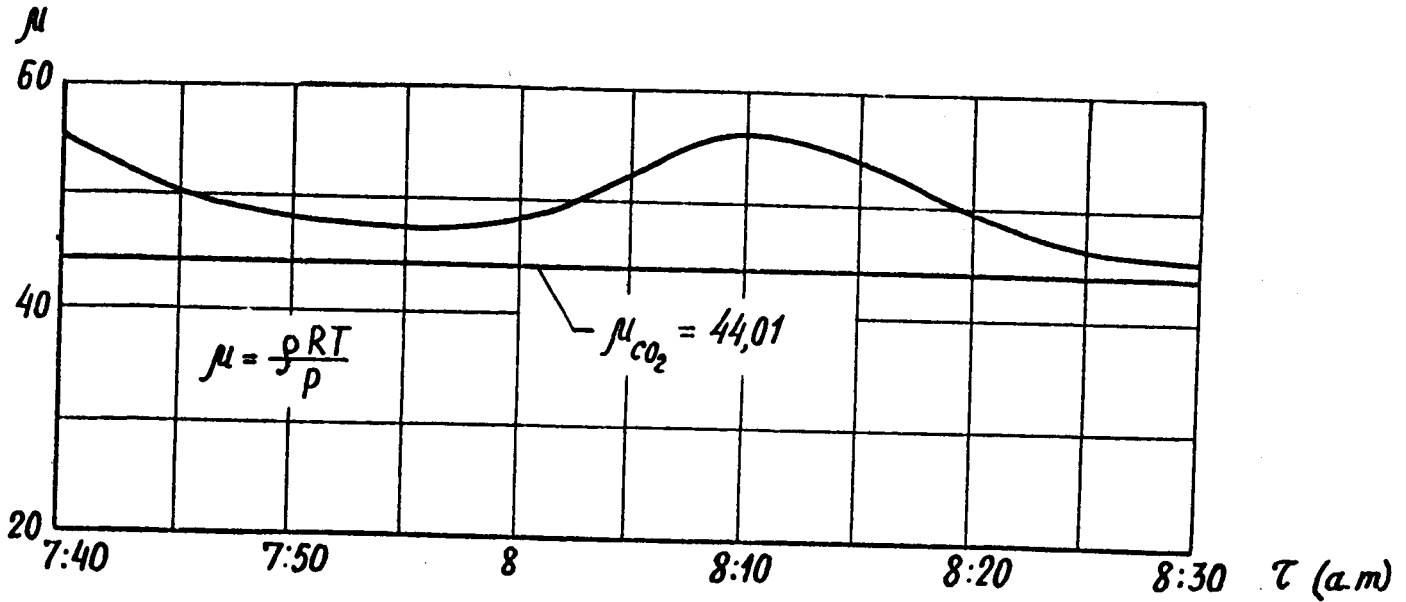


Fig. 2. Estimated values of a molecular weight in the periods of measurement of parameters p, ρ, T

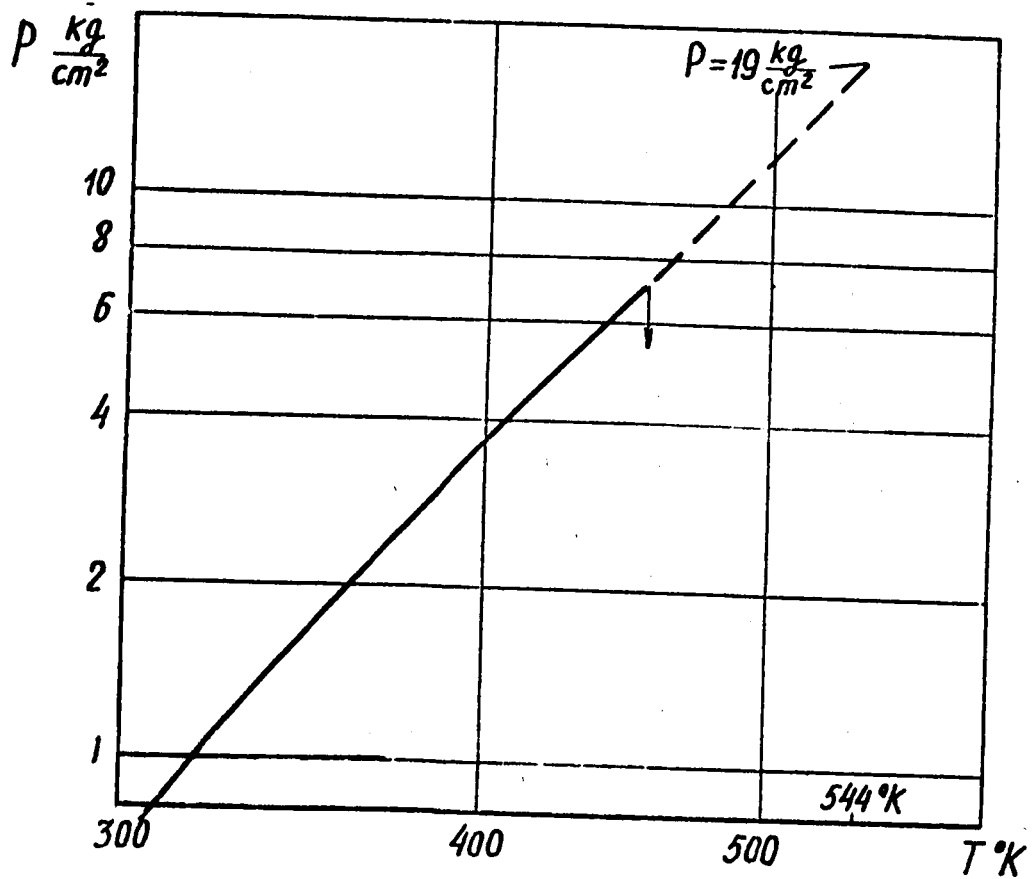


Fig. 3. Extrapolated curve of experimental pressure, supposed to be a polytrop in grid of logarithm.

It is unlikely that the altitude greatly affects the atmosphere composition. It was assumed that the densimeter readings were inaccurate on account of small admixtures. These admixtures were neglected in the chemical analysis and thus did not influence the thermometer and manometer readings.

EXTRAPOLATION

The values of pressure and density were extrapolated on the basis of the analysis of physical processes in the atmosphere for a known time dependence of temperature. The fact that the probe descended with a parachute was taken into account.

The change of state of the gas is plotted in Figures 3 and 4 in logarithmic coordinates. The inclinations of the curves are assumed to be polytropic. The simplest extrapolation of these curves by the conditional polytrop inclination gives the final (terminal) values of pressure and density, respectively equal to 19 kg/cm^2 and $19.9 \cdot 10^{-3} \text{ g/cm}^3$.

The computed exponents n_1 and n_2 of this conditional polytrop are plotted in Fig.5. As may be seen, the polytrop exponent n_1 is computed by the measured values of pressure and temperature; it increases monotonically, approaching at the end of measurements the adiabatic exponent $\gamma = c_p/c_v$ for CO_2 at corresponding terminal values of pressure and temperature.

The variation of exponent n_1 is not monotonic. The maximum value of n_2 equal to 1.65 is difficult to substantiate. This is why analysis of data is based upon manometer and thermometer readings.

The investigations of thermodynamic state were carried out in the assumption that the atmosphere consisted of CO_2 , taking into account the data of chemical analysis and the calculated values of the molecular weight, which were close to 44 toward final measurements.

The "entropy-pressure" diagram of [4] in Figure 6 shows the curves of the state of CO_2 variations over the measurement sectors; they are based on the measured values of pressure P_{meas} , and temperature, T_{meas} , (curve 1), and on P_{meas} and T_{meas} (curve 2). The thin inclined lines are isotherms.

The variation of gas state parameters in the atmosphere generally satisfies the stability condition

$$\frac{ds}{dh} = \frac{ds}{dT} \cdot \frac{dT}{dh} \geq 0$$

where S is the gas entropy. Since in our case $dT/dh < 0$, the stability condition has the form $ds/dT \leq 0$. The condition $ds/dT < 0$ is satisfied when the inclination angle of the change of state curves is negative.

Dotted lines correspond to extrapolation for the final measurement periods. The values of pressure obtained at the point of intersection of the dotted curve 1 with the 544° isotherm is 19.2 kg/cm^2 . It apparently provides us with the upper estimate of probable pressure on the surface.

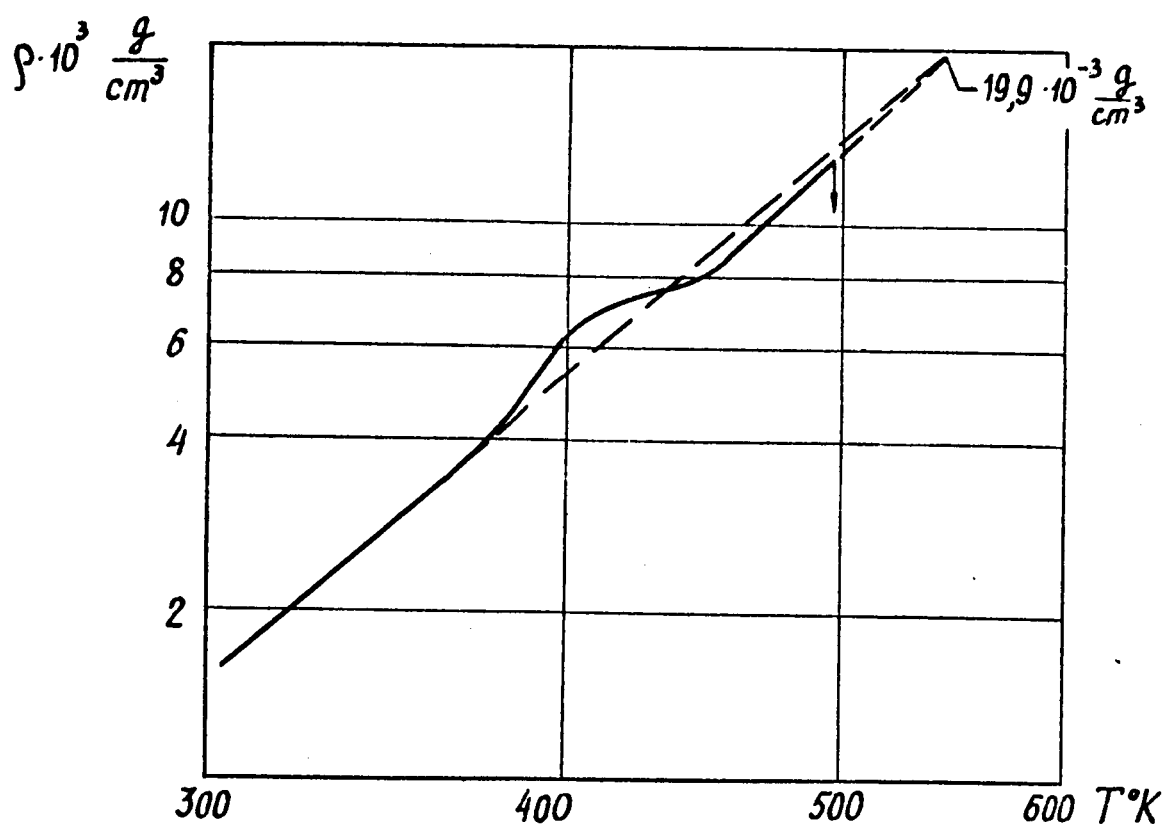


Fig. 4. Extrapolation curve of experimental values of density supposed to be a polytrope in grid of logarithm.

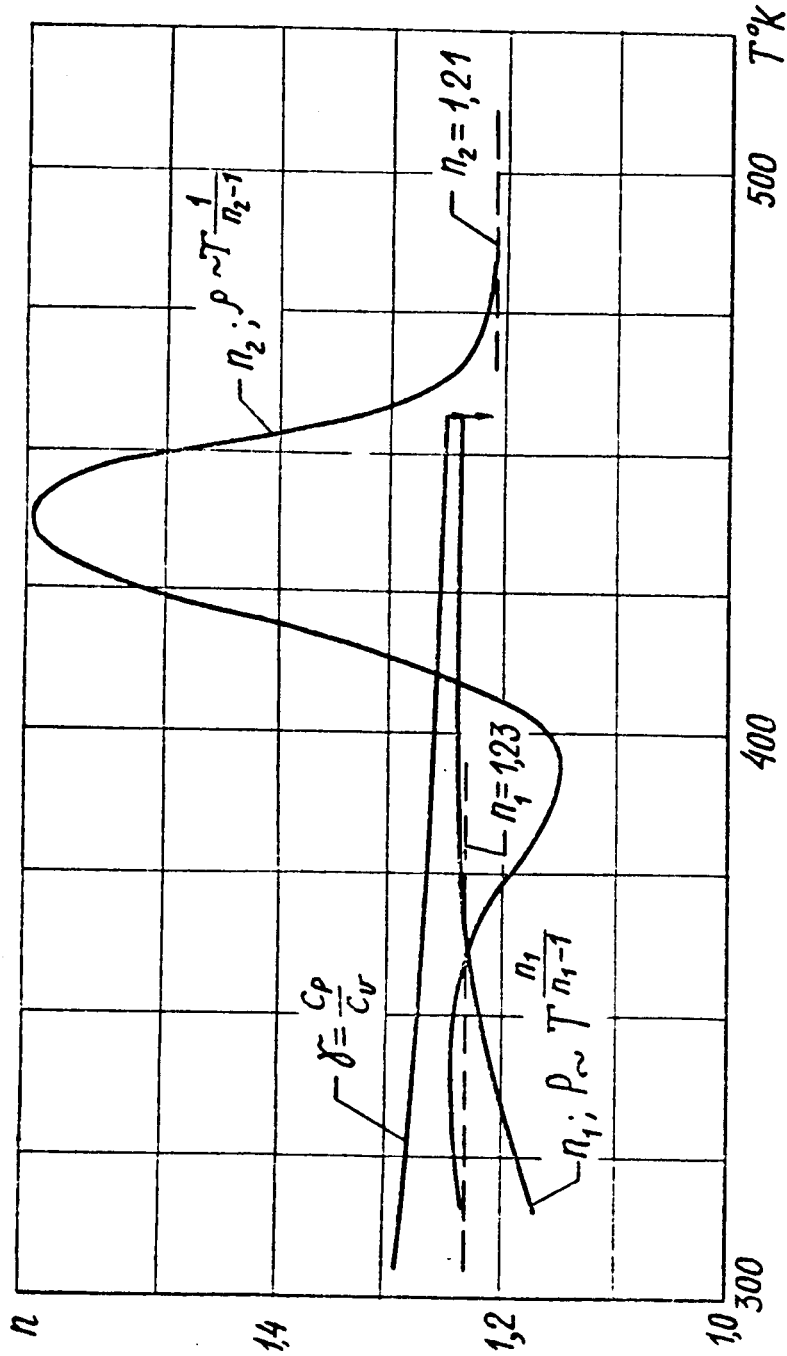


Fig. 5. The change of the exponents n_1 and n_2 of a supposed polytrope for the measurement periods as a function of the temperature.
 $\gamma = \frac{C_p}{C_v}$ - the adiabatic exponent for CO_2 at the corresponding pressures.

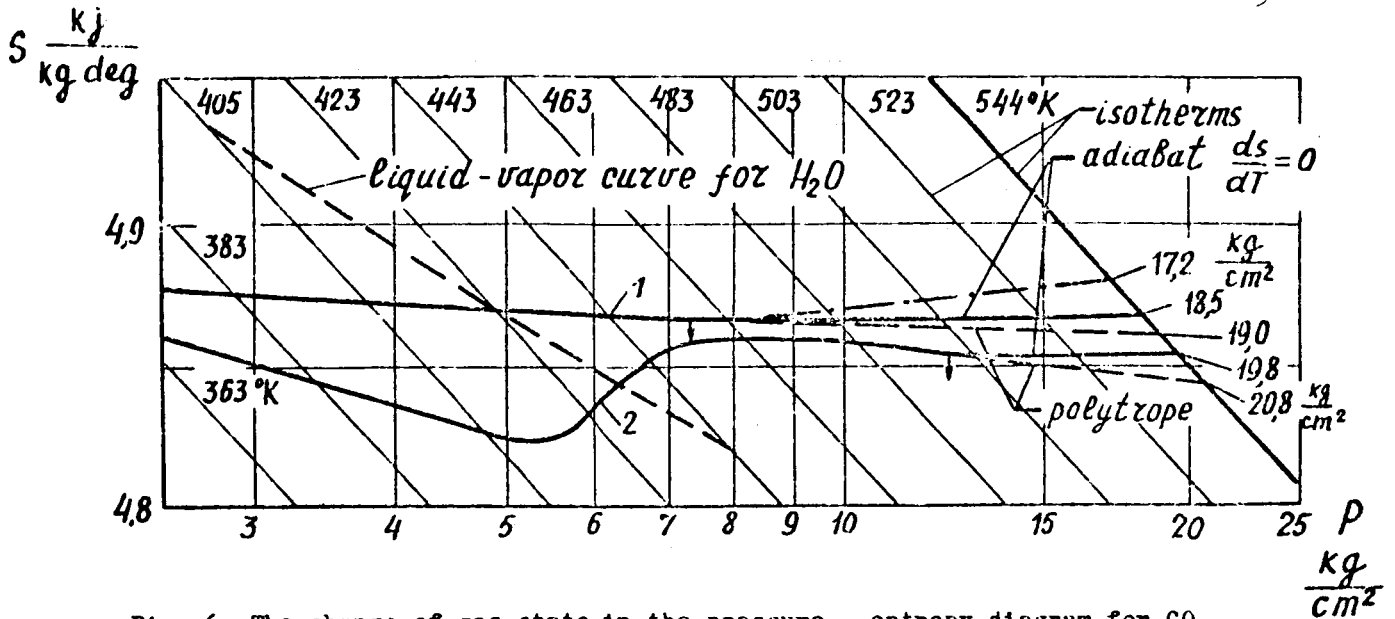


Fig. 6. The change of gas state in the pressure - entropy diagram for CO₂.
 $\frac{ds}{dT} \leq 0$ the steady state atmosphere without natural convection
 $(\frac{ds}{dh} = \frac{ds}{dT} \frac{dT}{dh} \geq 0)$

--- calculation on the base of hydrostatics equation for uniform descent velocity.

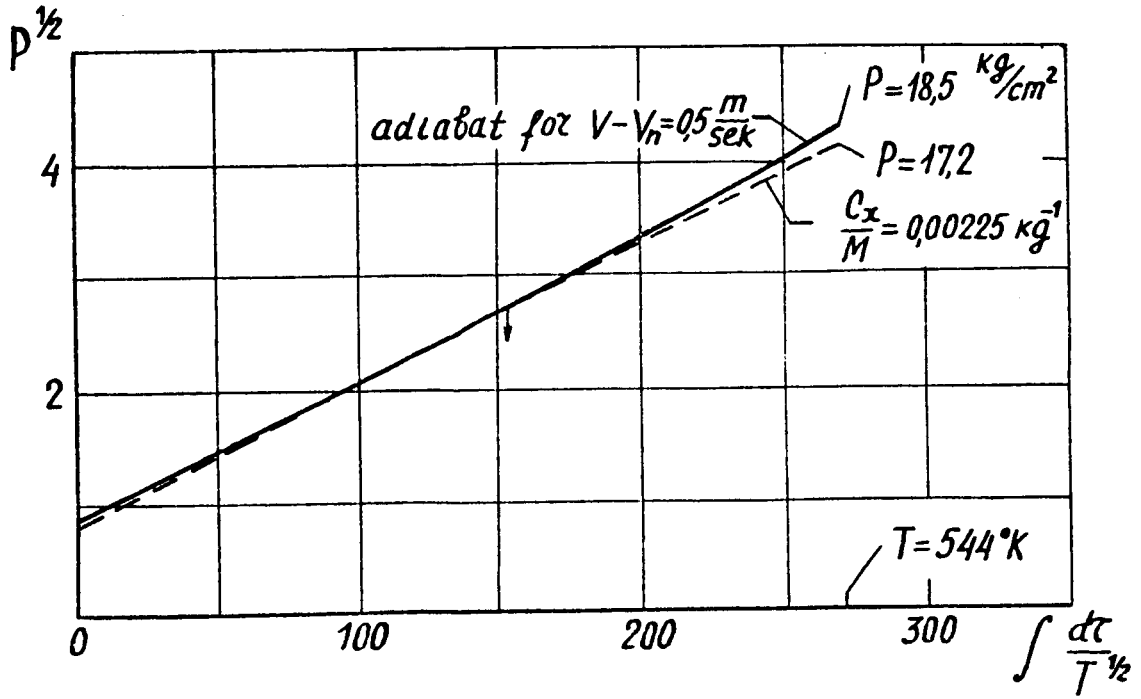


Fig. 7. Experimental values compared with values calculated both from the hydrostatics equation and from the quast-uniform descent velocity equation
 --- linear extrapolation.

The horizontal solid lines correspond to the case of extrapolated adiabat $ds/dT = 0$. According to curve 1, the corresponding value is 18.5 kg/cm^2 and the mean polytrop exponent is 1.24,

Curve 2 is based on density and temperature measurements for $\mu = 44$. Extrapolating it, we have the higher terminal pressure values, 20.8 kg/cm^2 and 19.8 kg/cm^2 . These estimates are less probable.

The water-vapor phase transition curves are also given in Fig.6. It is of interest to note that the densimeter readings show better agreement with manometer measurements immediately beyond this curve.

Extrapolation of initial experimental data can be performed independently by utilizing two equations (hydrostatics equation and the equation of quasi uniform motion for the parachute descent of the probe. These equations may be written in the form

$$dp = g^0 dh = g^0 v dt \quad (1)$$

$$Mg = c_x F \frac{\rho v_n^2}{2} \quad (2)$$

where g is the gravitational acceleration on Venus, equal to 860 to 800 cm/s^2 ; h is the altitude; M is the mass of the descending probe; c_x is the aerodynamic drag coefficient; F is the cross section area; v_n is the descent velocity relative to the gas; v is the descent velocity relative to the surface.

If we assume the absence of vertical flows in the atmosphere, $v_n = v$. Let us use the equation of state for a perfect gas

$$P = \frac{\rho RT}{\mu} \quad (3)$$

where R is the universal gas constant. It is valid for CO_2 with a precision to 2-3 percent in the measured temperature and pressure ranges. Then

$$dp^{1/2} = g^{3/2} \sqrt{\frac{M\mu}{2c_x FR}} \cdot \frac{d\tau}{T^{1/2}} = A \frac{d\tau}{T^{1/2}} \quad (4)$$

Factor A can be calculated on the basis of the known probe and parachute characteristics and of the assumed value of weight. Attempts may be made to determine its value according to the results of measurements of P and T .

Figure 7 gives the experimental values of $p^{1/2}$ as a function of integral $\frac{d\tau}{T^{1/2}}$

A straight line can be drawn with high accuracy through the large group of points in the region of most reliable manometer indications, $P = (2-7 \text{ kg/cm}^2)$.

Hence it follows that the conditions of quasi-uniform descent are satisfied and that vertical flows are practically absent. The tangent of the inclination angle of the straight line (equal to factor A) agrees well with the calculated value of A for $c_x/M = 0.00225 \text{ kg}^{-1}$ and $\mu = 44$.

When $P < 2 \text{ kg/cm}^2$, the experimental points lie above the line drawn, which is either evidence of existence of updrafts $v \approx 0.2 - 0.3 \text{ m/sec}$, or of manometer inaccuracies at time of initial measurements. In the last case the mean value of initial pressure decreases from 0.76 to approximately 0.62 kg/cm^2 , which is within manometer range.

Extrapolating the straight line in the direction of higher values of T at terminal temperature, we obtain $P = 17.2 \text{ kg/cm}^2$.

The corresponding segment of the curve is plotted on the entropy diagram of Fig.6. by a dash-dotted line. It is evident that at such an extrapolation the atmosphere's steady-state condition $ds/dT < 0$ is disrupted.

The extrapolated curve, computed according to Eqs (1) and (2), can be made to agree with the adiabat $ds/dT = 0$ (Fig.6), provided we assume that the downward flow velocity near the surface is $v - v_n = 0.5 \text{ m/sec}$.

Finally, if we assume an argon content of $\sim 10\%$, the curve of the change of state obtained from Eq.(3) approaches very closely the adiabat for a molecular gas weight of 43.5.

Thus, the value $P = 17.2 \text{ kg/cm}^2$ may be considered as the lower estimate of the probable value at the surface.

TIME DEPENDENCE OF THE PATH COVERED

The time dependences of P , ρ and T being known, it is possible to determine the covered path by using the hydrostatic equilibrium equation (1) by formula (*), or expression (2) if vertical flows are neglected

$$Z = \int_{t_1}^{t_2} v_n d\tau = \sqrt{\frac{2Mg}{c_x F}} \int_{t_1}^{t_2} \rho^{1/2} d\tau \quad (6)$$

The curves for the covered path Z are plotted in Figure 8 as a function of time. Curve 1 is obtained from Eq.(5) by using the values of P and T and the molecular gas weight equal to 44.

The solid line in the extrapolated section corresponds to an adiabat, the dotted line - to a polytop and the dash-dotted line to extrapolation by formula (4) (Fig.9).

When using the value $c_x/M = 0.00225 \text{ kg}^{-1}$, the calculation based on Eq. (6) coincides with that made by Eq.(5), whereupon the calculated values of descent velocity varied from (10 - 11) m/sec at the altitude of 28 km to about 2.5 - 3 m/sec near the surface.

The region of all possible values of general altitude defined by the radioaltimeter is shaded in Fig.8. The range of this gauge's measurement being taken into account. As may be seen, the value of general altitude coincides in all cases with a precision to 5% with the radioaltimeter recordings. This agrees well with the assertion that the time of communication

$$(*) \quad [\text{insert}] \dots Z = \frac{1}{g} \int_{P_1}^{P_2} \frac{dP}{\rho} \quad (5)$$

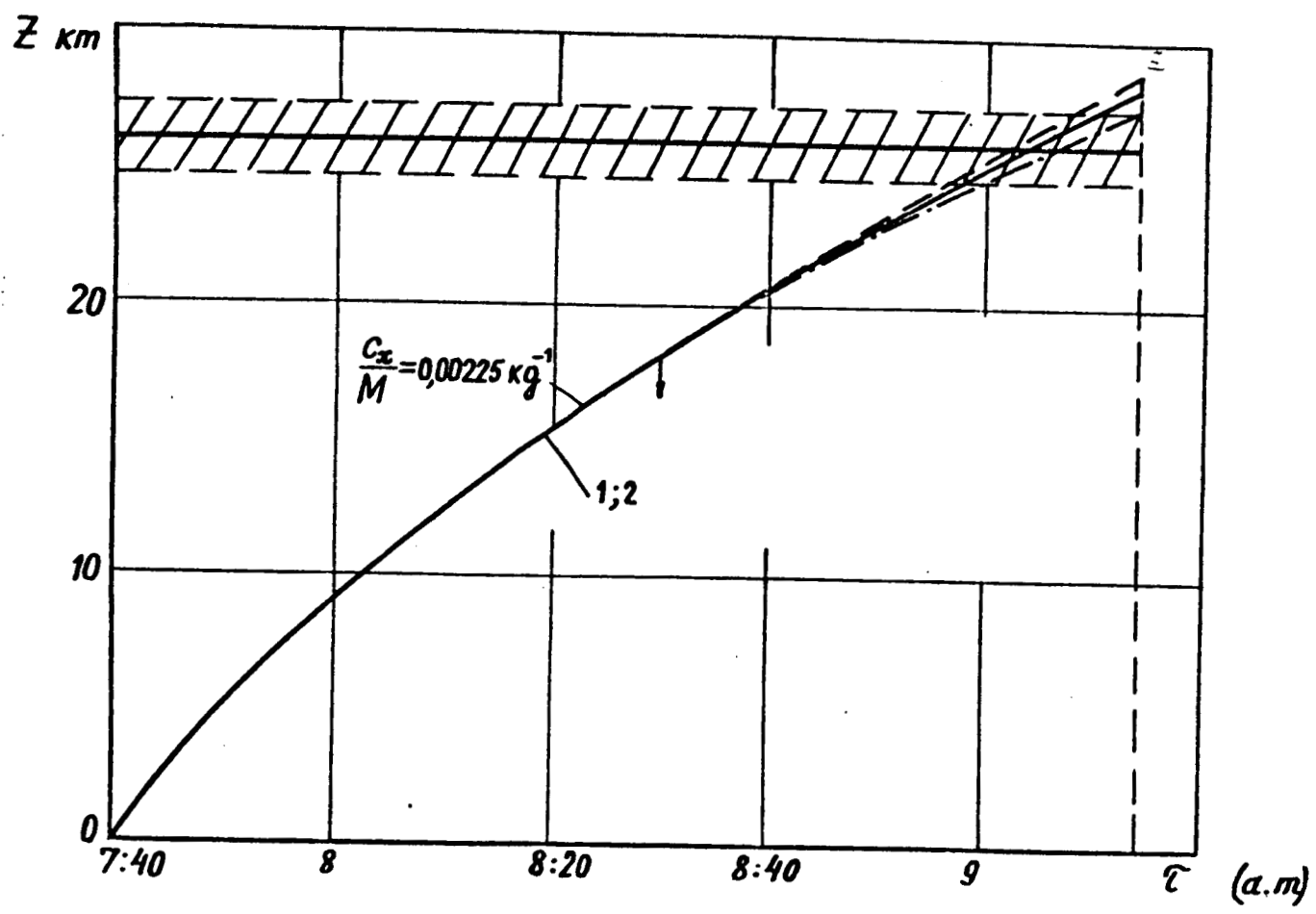


Fig. 8. The covered path versus the descent time.

interruption with the probe coincides with the time of soft landing or descent termination.

The maximum discrepancy in the initial altitude, determined by different methods, depends on the errors of all gauges, the presence of vertical flows and the local relief at time of possible probe drifting on account of wind.

THE MODEL ATMOSPHERE

In order to establish a model of the atmosphere of Venus, the values of temperature T and pressure P were taken as basic parameters, using the extrapolated adiabat. It is postulated that the atmosphere consists mainly of carbon dioxide. Thus, in order to obtain the distribution of parameters in height we utilized curve 1 of Fig.8 with the nominal altitude of 28 km (solid line).

The atmosphere profile in height ($h = (28 - Z)$ km for the night side of Venus near the morning terminator is shown in Figures 9 to 11. In all the cases the solid line corresponds to the nominal value and the dash-dotted lines delimit the region of the most probable values. The dotted lines correspond to the values that are possible, but less probable to fit the above considerations.

The pressure on the surface lies between 17 and 21 kg/cm². (see Fig.9). The most probable value is 18.5 kg/cm². At the altitude of 28 km the pressure is 0.76 ± 0.2 kg/cm² (a negative allowance having a higher probability).

On the surface the temperature is $544^\circ\text{K} \pm 10^\circ$ (see Fig.10), and at the altitude of 28 km it is $304^\circ\text{K} \pm 10^\circ$. The "scale height" $H = RT/\mu g$ varied from 11.7 km to 6.55 km respectively.

The variation of the state of gas is close to adiabatic (possibly even superadiabatic) up to 10 - 15 km; it is sub-adiabatic at higher altitudes.

It may be assumed that gas mixing is present at the surface because of natural convection, eventually caused by upward energy transfer as a result of radiation or turbulent heat conduction.

In the upper layers the heat balance is settled, which does not cause natural convection. As an average, the updraft velocity (whenever present) is not higher than 0.5 to 0.6 m/sec.

The temperature gradient near the surface is 8.8 to 8.9° per km; it decreases slowly with altitude (Fig.10). The adiabatic temperature gradient of a real gas in height is

$$\frac{dT}{dh_{ad}} = -\frac{g}{c_p} \left[1 - \rho \left(\frac{\partial i}{\partial P} \right)_T \right]$$

It is determined from the expression $di/dh = -g$, where i is the gas'enthalpy.

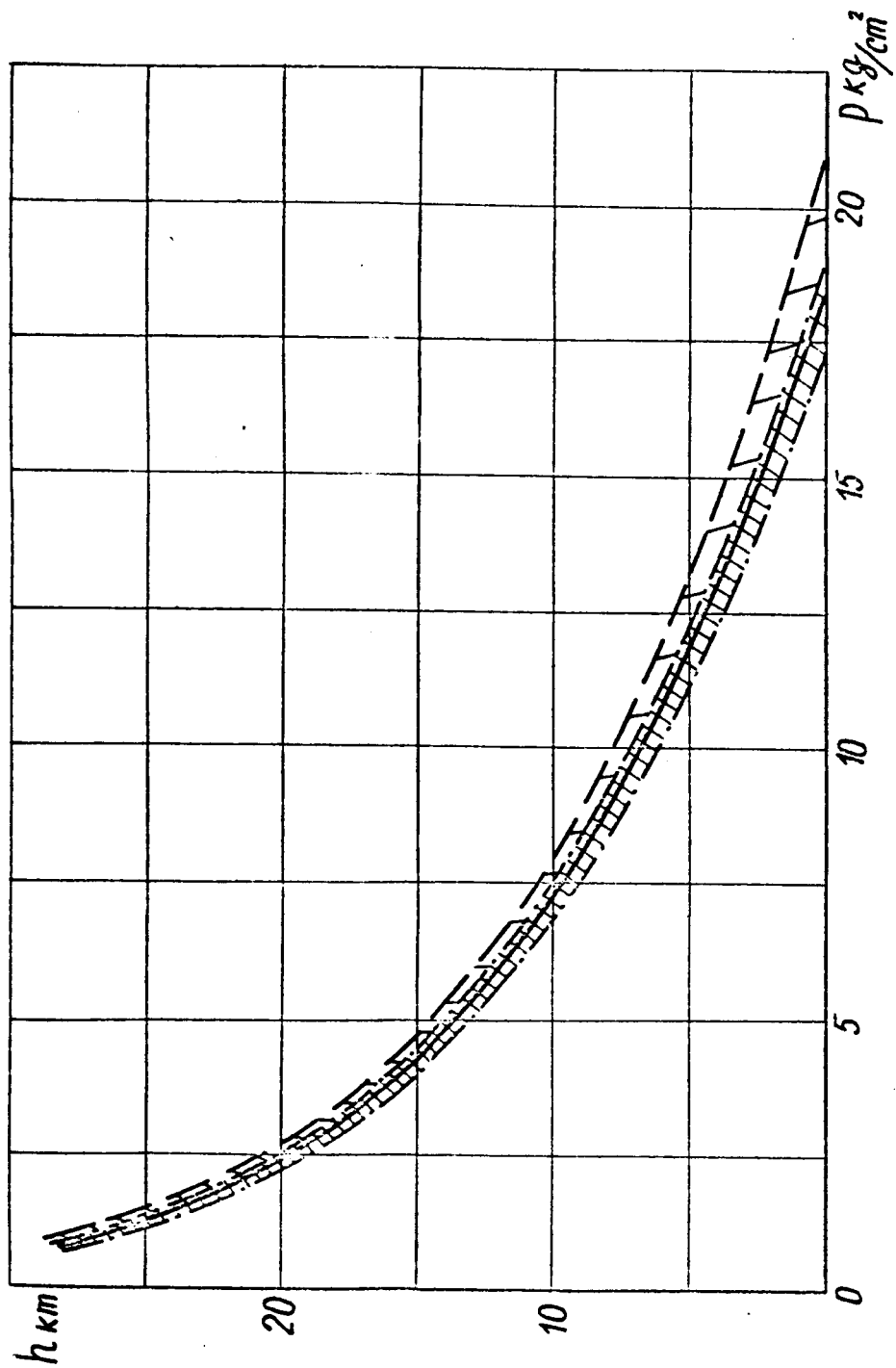


Fig. 9. Pressure against altitude.
---the region of probable values
----the region of possible values.

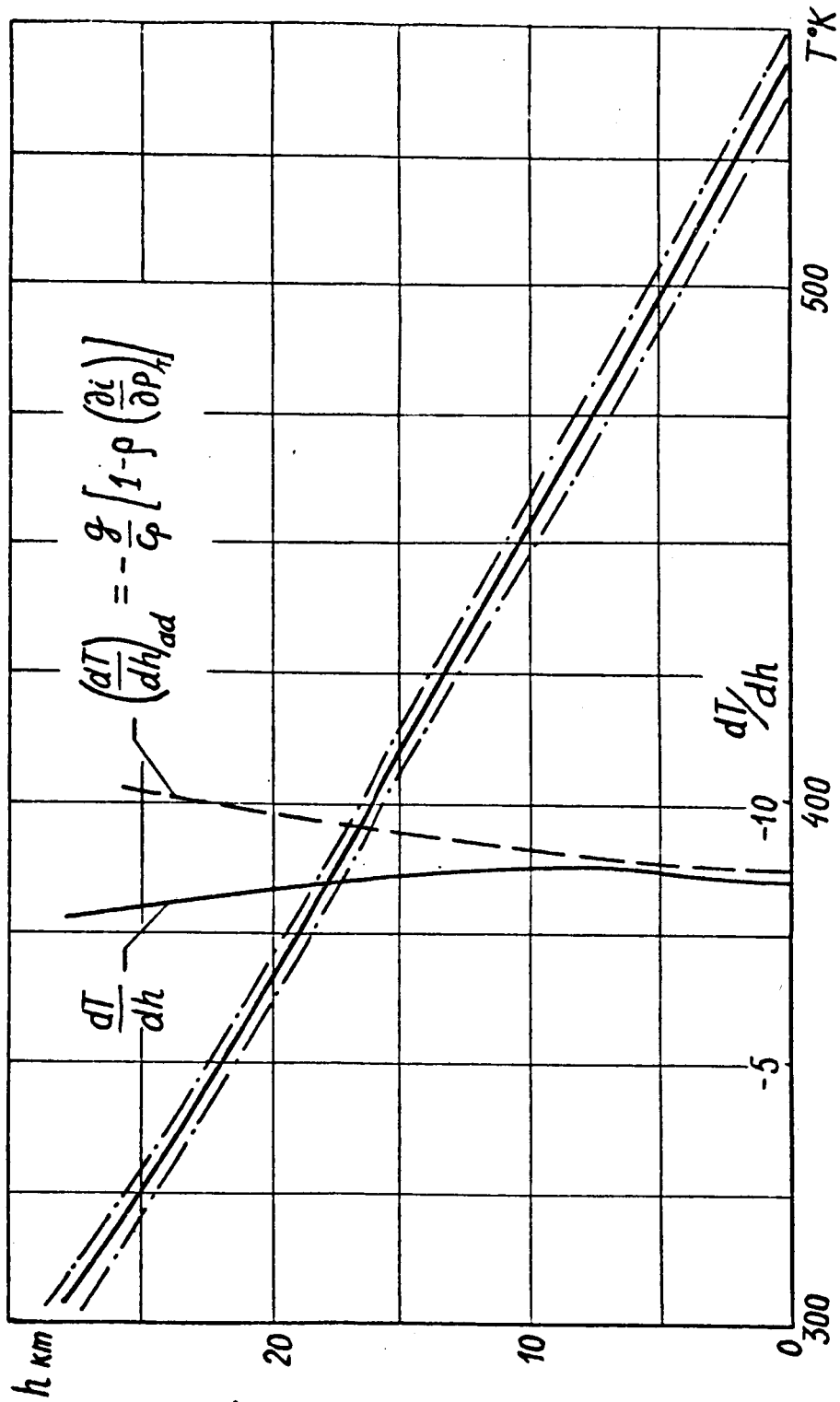


Fig. 10. Temperature and temperature gradient dT/dh versus altitude

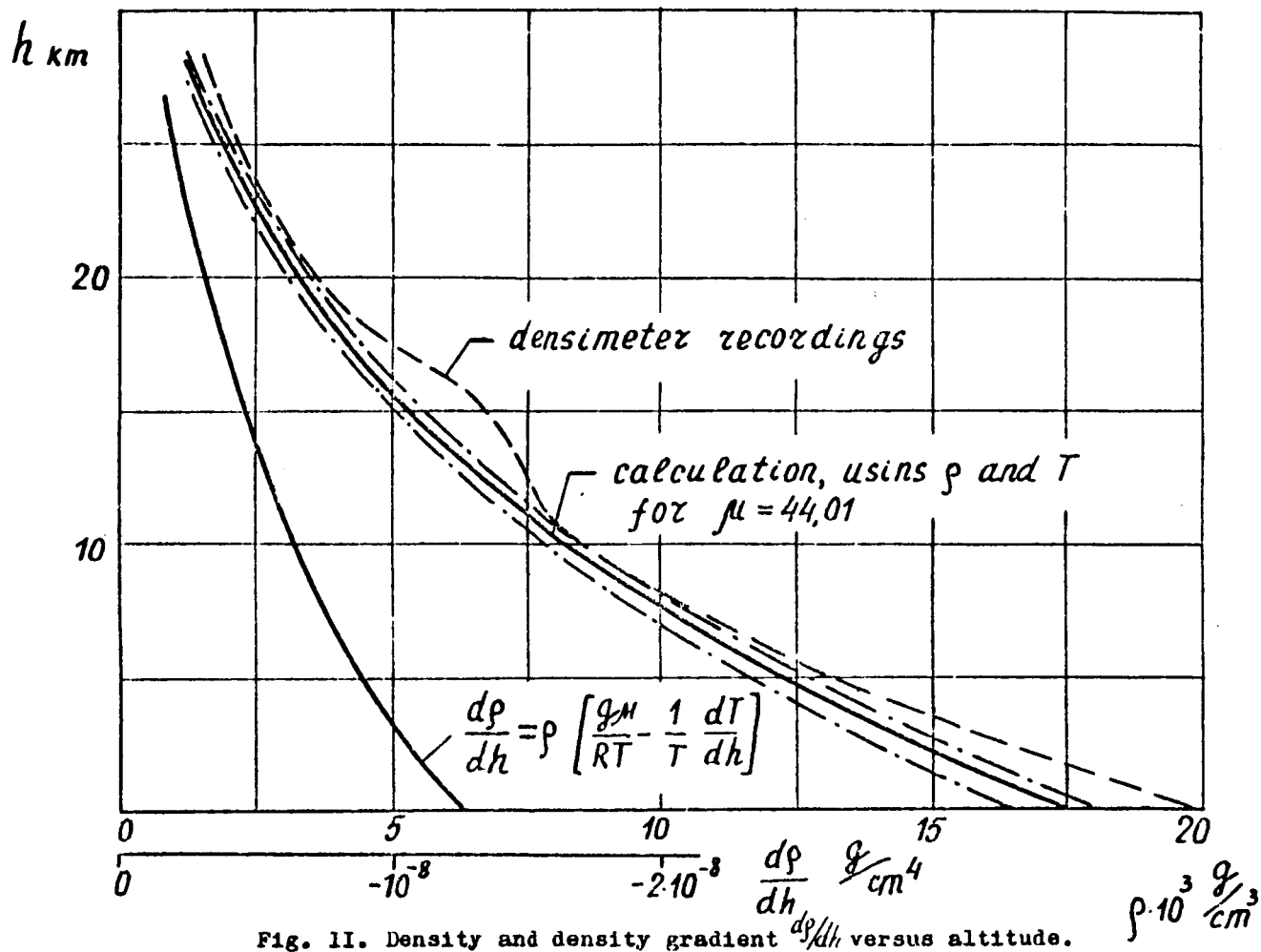


Fig. II. Density and density gradient $\frac{d\rho}{dh}$ versus altitude.

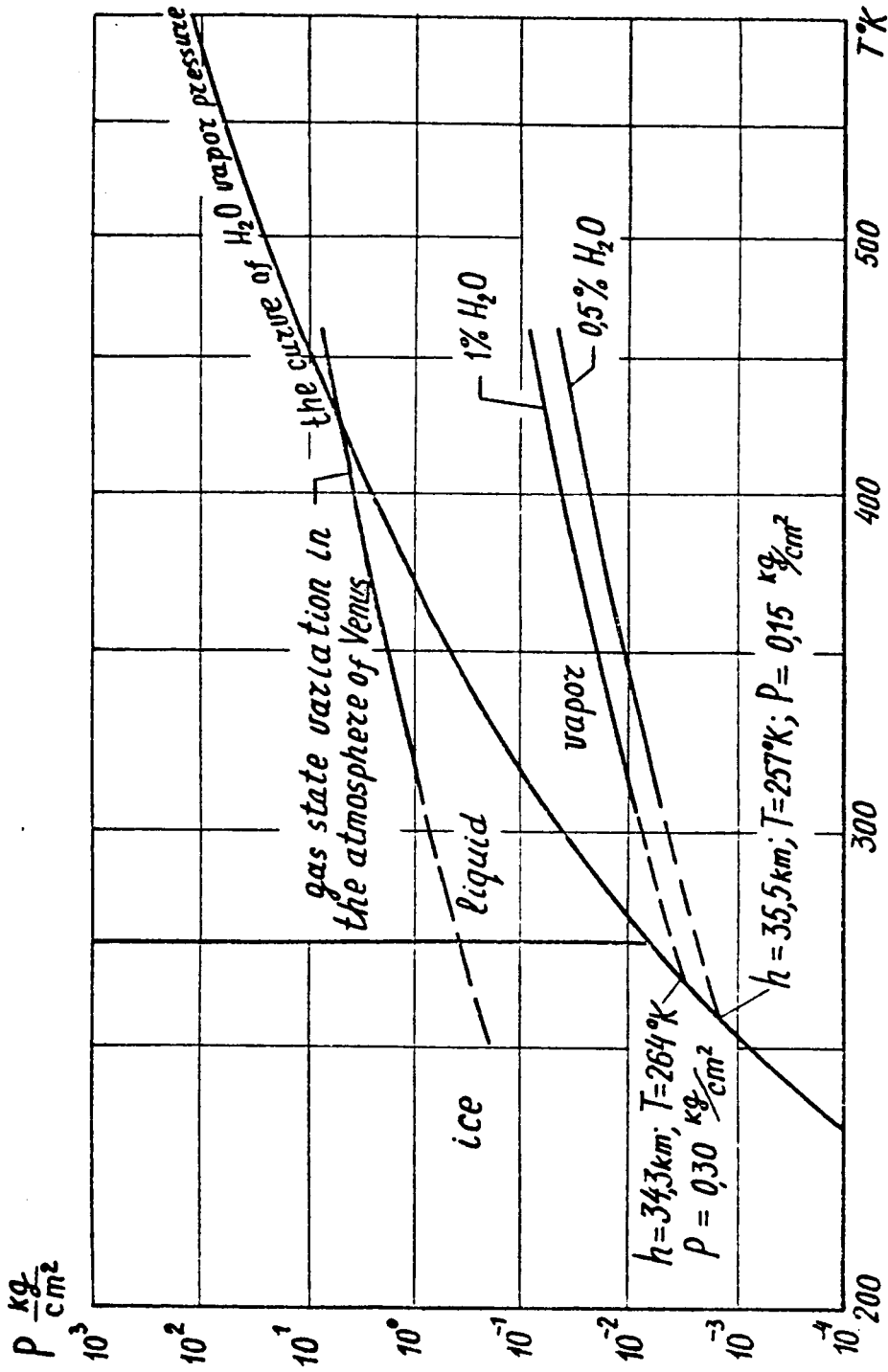


Fig. 12. The determination of the lower boundary of H₂O clouds.

As may be seen from Fig.11, the value $(dT/dh)_{ad}$ increases with altitude.

The variation of density with altitude as a function of P and T is plotted in Fig.11 in the assumption that the atmosphere consists of carbon dioxide.

The calculated density varied from $(16.5 - 18.3) \cdot 10^{-3}$ g/cm³ on the surface to about $1.2 \cdot 10^{-3}$ g/cm³ at the altitude of 28 km. The measured values of ρ are shown in Fig.11 alongside with the extrapolated ones by means of a polytrop (Fig.4).

The values of the altitude gradient of density $d\rho/dh$, linked with the gradient of the index of refraction n , are illustrated in Fig.11.

$$\frac{d\rho}{dh} = -\frac{\rho}{T} \left[\frac{g\mu}{R} - \frac{dT}{dh} \right], \quad \frac{dn}{dh} = c \frac{d\rho}{dh}, \quad \text{where } c = 0.23 \text{ cm}^3/\text{g}.$$

Calculations show that for the obtained values of density gradients in the atmosphere of Venus strong distortion of light rays takes place. At the altitude of 8.5 km the curvature radius of the light ray is equal to the radius of the planet $R_p \approx 6100$ km. The angle of total reflection is of a few degrees ($\sim 3^\circ$). The angle of total inner reflection, that is, the angle between the horizon and the light ray directed from the surface, which, because of refraction hits again the planet's surface, is close to three degrees.

Extrapolating upward the results of measurements, one may estimate the lower height of the base of the cloud layer. It is assumed that the atmosphere contains 0.5 to 1 percent of water vapor.

The curve of the state of gas and the curves of partial water vapor pressure as a function of temperature are shown in Fig.12 in logarithmic coordinates. As may be seen, at extrapolation these curves intersect the curve of water saturation below the triple point at $T = 257^\circ\text{K}$, $P = 0.15$ kg/cm² and $T = 264^\circ\text{K}$ and $P = 0.3$ kg/cm² for 0.5 to 1 percent H₂O content. Thus, if the clouds are formed on account of H₂O condensation, they consist of small ice crystals or of very supercooled water. Under the circumstances, the lower boundary lies at the altitude of 34 - 35 km. It is interesting to note that when it is raining in the atmosphere, the raindrops must completely evaporate at the altitude $h \approx 13$ km, where water vapor pressure exceeds the atmospheric pressure.

*** T H E E N D ***

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