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COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE- Lunar Atmospheric Contamination Due to an Apollo Landing

TM-69-2015-5

DATE- September 16, 1969

FILING CASE NO(S)- 340

AUTHOR(S)- G. K. Chang

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ABSTRACT

The lunar atmospheric contamination due to an Apollo mission is analyzed using a mathematically simplified diffusion equation. In view of the tenuous lunar atmospheric density, the mean-free-path for most gases is large; hence, one can only make a qualitative estimate at the vicinity of the LM. Qualitative results of the present study show that the contaminants are quickly dispersed from the lunar environment, when the loss factors given in the text are assumed. In less than 3 days (72 hours), the contaminant density is decreased to more than an order of magnitude below the estimated ambient atmospheric density. According to the ALSEP operational timeline, the ALSEP instruments will not be affected by these contaminants. Consequently, the ALSEP Cold Cathode Gauge Experiment would not detect the LM exhaust gas of the same landing mission, but it may detect the contaminants from a subsequent landing mission.

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TECHNICAL MEMORANDUM

1.0 INTRODUCTION

On every Apollo lunar landing mission, a scientific package will be emplaced on the lunar surface to determine certain parameters of the lunar interior, surface, and environment. On the first mission, the Early Apollo Scientific Experiment Payload (EASEP), consisting of a seismometer and laser retroreflector, was emplaced. In the subsequent landing missions, an Apollo Lunar Surface Experiments Package (ALSEP) for early missions, or a Modified ALSEP for later missions will be emplaced on many landing missions. In each ALSEP there is a Cold Cathode Ionization Gauge (CCIG) designed to measure the lunar atmospheric density and to determine the rate of attenuation of the contaminant gas contributed by the Apollo landing missions. A mass spectrometer, which will measure the compositions of the lunar atmosphere as well as the contaminants, may be included in the Modified ALSEP. To avoid high voltage arcing, some of the ALSEP experiments, including the CCIG, must be operated at pressures below 10^{-6} torr. The purpose of the present study is to investigate the effect of the contaminant gas on the CCIG experiment and to assure the operational safety of the ALSEP experiments.

The lunar contamination due to an Apollo landing may logically be separated into two categories. One is the atmospheric contamination which has a global distribution, whereas the other is the surface contamination which is primarily a local phenomenon. The lunar surface contamination may in some degree affect the purity of the returned lunar sample and has been investigated by Aronowitz, et al., in a separate study.(1) The present study treats only the atmospheric contamination and the treatment is based largely on a diffusion model proposed by Milford and Pomilla(2) (hereafter referred to as MP) for the propagation of gases in the lunar atmosphere.

The lunar atmospheric density is estimated to be about 10^6 particles/cm^3 (3) with a corresponding atmospheric pressure at the lunar surface of the order of 10^{-11} torr. The total mass of the atmosphere is estimated to be about 100 metric tons. In a single Apollo mission, the Lunar Module (LM) descent engine will release about 8 metric tons of exhaust gases from the time of CSM/LM separation at an altitude of 100 km above the surface to LM touchdown. The LM ascent engine will release about 2.5 metric tons of exhaust gases from launch to rendezvous with the CSM. These gases will either be lost directly into space or be scattered and retained in the atmosphere for some finite time. These gases may then either be gradually swept into space, by several possible gas escape mechanisms, or interact with the lunar surface. The degree of interaction with the surface depends on the species of the exhaust gas and the nature of the lunar surface. Since no reliable information is available concerning the interaction of the exhaust gases with the lunar surface, we neglect this effect in estimating the worst case contamination of the lunar atmosphere and assume that all the exhaust gases diffuse into the lunar atmosphere and eventually escape into space.

Below, we briefly summarize the gas diffusion model proposed by MP and then discuss the source and loss mechanisms for the LM exhaust gases. The present study introduces an extended contaminant source instead of the delta source function treated by MP in their study. In the final section, we summarize the present study and apply it to a consideration of the lunar atmospheric contamination on the operation of the ALSEP instruments.

2.0 MATHEMATICAL MODEL

A simplified two-dimensional diffusion of gas in a tenuous atmosphere of density n is given by,(2)

$$\frac{\partial n}{\partial t} = D \nabla^2 n + q - Kn, \qquad (1)$$

where D is the diffusion constant, q is the source term, and K is the loss factor. In this expression, we neglect the vertical variation effect and only consider particle diffusion along the lunar surface. The diffusion constant is given by,

$$D = \frac{1}{3} \lambda \mathbf{v}$$

where λ is the mean free path of a gas particle along the lunar surface and $\mathbf{v}$ is the velocity of gas particle along the lunar surface.

The Laplacian operator on a spherical surface of radius r_o (taken here as the lunar radius) is given by

$$\nabla_2^2 = \frac{1}{r_o^2} \left\{ \frac{1}{\sin\theta} \frac{\partial}{\partial\theta} \left(\sin\theta \frac{\partial}{\partial\theta} \right) + \frac{1}{\sin^2\theta} \frac{\partial^2}{\partial^2\phi} \right\} , \tag{3}$$

where θ is the zenith angle and ϕ is the azimuth angle.

If we further simplify the problem by assuming n and q to be independent of ϕ and let $\mu = \cos\theta$, then equation (1) can be written as

$$\frac{\partial n(\mu,t)}{\partial t} = \frac{D}{r_o^2} \frac{\partial}{\partial\mu} \left((1-\mu^2) \frac{\partial n}{\partial\mu} \right) + q(\mu,t) - Kn. \tag{4}$$

The general solution of this equation is

$$n(\mu,t) = \sum_{\ell=0}^{\infty} \Theta_\ell(\mu) \left[S_\ell(t) + T_\ell(t) \right] , \tag{5}$$

where

$$S_\ell(t) = \int_{-1}^{1} \Theta_\ell(\mu') \left[\frac{1}{2\pi i} \int_{\varepsilon-i\infty}^{\varepsilon+i\infty} \frac{\tilde{q}(\mu',p)}{p+a_\ell} e^{pt} dp \right] d\mu' , \tag{5a}$$

$$T_\ell(t) = e^{-a_\ell t} \int_{-1}^{1} \Theta_\ell(\mu') \, n(\mu'0) d\mu' , \tag{5b}$$

and

$$\tilde{q}(\mu,p) = \int_{0}^{\infty} e^{-pt} q(\mu,t) dt,$$ the Laplace transform of the source function

$$a_\ell = K + \frac{D}{r_o^2} \ell(\ell+1)$$

$$\Theta_\ell(\mu) = \sqrt{\frac{2\ell+1}{2}} P_\ell(\mu)$$

$P_\ell(\mu)$ = Legendre Polynomial of degree ℓ.

To obtain explicit solution of $n(\mu,t)$, we must know the source function, $q(\mu,T)$, and the initial gas distribution, $n(\mu,0)$.

3.0 SOURCE TERMS

In order to obtain an explicit solution for the gas density distribution along the lunar surface, we must know both the ambient atmospheric density and the time-dependent contaminant sources. For the present study, we assume the ambient atmospheric density to be constant within the time scale of interest. Its upper limit is estimated to be about 10^6 particles/cm^3 by Elsmore(3) from his measurements of the lunar occultation of radio waves of the Crab Nebula.

Since gas particles can easily escape the lunar environment, some natural source mechanisms must exist in order to maintain even a tenuous atmosphere. Accretion of the solar wind as a source of neutral hydrogen and helium has been extensively theorized by several investigators.(4-9) Additionally, Hinton and Taeusch(4) considered the following sources: (a) the supply of H_2O, CO_2, and SO_2 from the crustal rocks, hot springs, lava flows, and volcanos; (b) the supply of H_2O from trapped ice; (c) natural radioactivity of K^{40} as a source of Ar^{40}; and (d) the production of Kr and Xe by spontaneous fission of U^{238}, decay of I^{129}, and from primeval gases trapped in rocks and released by meteoroid bombardment and volcanism.

Since the primary objective of the present study is to investigate the lunar atmospheric contamination by the LM exhaust gases, we shall not discuss the natural sources in detail but only consider them as a constant background atmosphere. Our initial concern will be the time-dependent contaminant sources that are derived from the LM exhaust gases. The LM descent and ascent engine fuel is a 50:50 mixture of UDMH and hydrazine and the oxidizer is nitrogen tetroxide. The combustion products of this propellant have been analyzed theoretically by Grumman and are listed in Table I. Experimental determinations of the combustion products were conducted in conjunction with the LM descent engine firing tests at MSC White Sands Test Facilities during the latter part of 1968.(10) The test result is yet to be analyzed, so for the time being, we shall use the results of the Grumman study since we do not expect chemical reactions between the exhaust gases and the lunar surface to take place on any significant scale. Although we might expect to have some degree of physical adsorption of the exhaust gases by the lunar surface, the time constant of any physical adsorption is short (less than 10^{-3} sec) in comparison to the time scale of interest and can therefore be neglected.

The LM descent starts with a Hohmann-type orbit transfer from the 100 km circular CSM parking orbit to a pericynthion altitude of 15 km. At pericynthion, the powered descent maneuver is initiated approximately 480 km from the landing site.(11) The powered descent consists of the braking, final approach, and landing phases. The initial braking effectively reduces the LM orbital velocity and the LM reaches the final approach phase which is about 1.7 km altitude and a range-to-go of approximately 9 km (high gate). The LM pitch angle from local vertical varies slowly from 90° at pericynthion to about 68° at high gate before it drops sharply to about 40° for the final approach.(12) The LM consumes about 6 metric tons of propellant during the braking phase of the powered descent. The final phase of the LM descent takes about 3.5 minutes and consumes about 1.5 metric tons of propellant from high gate to final touchdown.(13) Since we are interested in the upper bound of the atmospheric contamination, we consider all of the LM descent exhaust to be the prime source of contaminants that would have immediate effect on the lunar surface as well as contribute to atmospheric contamination.

The LM ascent engine will contribute about 2.5 metric tons of contaminants to the lunar environment after the initial LM stay of about 20 hours on the lunar surface (the LM stay on the lunar surface will vary; the first landing mission, G1, stayed about 22 hours). The LM powered ascent starts with a vertical rise of approximately 10 seconds until the spacecraft achieves 15 m/sec vertical ascent rate and a near-optimum guidance. At this point, the spacecraft has reached an altitude of about 80 m and then pitches over to the ascent guidance altitude.(14)

Additionally, while the LM is on the surface, there will be some contaminants due to venting of the LM descent propellant tanks, water boil-off from the portable life support system, leakage from the astronaut's space unit, depressurization of the LM cabin, leakage of the LM cabin while pressurized, and outgassing of the LM spacecraft and miscellaneous hardware. The masses of these contaminants are negligible compared to the LM descent and ascent engine exhaust gases; they are primarily local contaminants and their rate of contribution to the lunar atmosphere is comparatively small. We neglect these contaminants for the present study.

We now write the time-dependent contaminant sources as follows:

$$q(\mu,t) = \delta(\mu-1)\Big\{q_{10}[u(t-t_1) - u(t-t_2)]$$

$$+ q_{20}[u(t-t_3) - u(t-t_4)],\Big\} \tag{6}$$

where

$$u(t-t_1) = \begin{cases} 1, & \text{for } t>t_1 \\ 0, & \text{for } t\leq t_1 \end{cases}$$

Here, we have assumed that the source function is due to two quasi-point sources, q_{10} and q_{20}. The quasi-point source q_{10}, situated at $\theta = 0$ (the LM touchdown point), is due to the LM descent engine during the time interval $\Delta t_a = t_2-t_1$ and the second quasi-point source q_{20}, at the same position, is due to LM ascent engine for the time interval $\Delta t_b = t_4-t_3$. The LM lunar surface staytime $\tau = t_3-t_2$ is about 20 hours for G1. Performing the Laplace transformation on equation (6), we have,

$$\tilde{q}(\mu,p) = \delta(\mu-1)\left\{q_{10}\,\frac{e^{-t_1p}-e^{-t_2p}}{p} + q_{20}\,\frac{e^{-t_3p}-e^{-t_4p}}{p}\right\} \tag{6a}$$

Additionally, we assume that the ambient atmospheric density is constant and is expressed by

$$n(\mu,o) = n_o. \tag{7}$$

Substituting (6a) and (7) into (5a) and (5b) respectively, we obtain,

$$S_\ell(t) = \int_{-1}^{+1} \theta_\ell(\mu') \, \delta(\mu'-1) d\mu' \, \frac{1}{2\pi i}$$

$$\cdot \int_{\varepsilon-i\infty}^{\varepsilon+i\infty} \left\{ q_{10} \, \frac{e^{p(t-t_1)} - e^{p(t-t_2)}}{p(p+a_\ell)} + q_{20} \, \frac{e^{p(t-t_3)} - e^{p(t-t_4)}}{p(p+a_\ell)} \right\} dp$$

$$= \sqrt{\frac{2\ell+1}{2}} \left\{ \frac{q_{10}}{a_\ell} \left[(1-e^{-a_\ell(t-t_1)})u(t-t_1) - (1-e^{-a_\ell(t-t_2)})u(t-t_2) \right] \right.$$

$$\left. + \frac{q_{20}}{a_\ell} \left[(1-e^{-a_\ell(t-t_2)})u(t-t_3) - (1-e^{-a_\ell(t-t_4)})u(t-t_4) \right] \right\} \tag{8a}$$

and

$$T_\ell(t) = e^{-a_\ell t} n_o \int_{-1}^{+1} \theta_\ell(\mu') d\mu'$$

Substituting (8a) and (8b) into (5), we have the explicit solution for the gas density distribution along the lunar surface which is given by

$$n(\mu,t) = \sum_{\ell=o}^{\infty} \sqrt{\frac{2\ell+1}{2}} \, \theta_\ell(\mu) \left\{ \frac{q_{10}}{a_\ell} \left[(1-e^{-a_\ell(t-t_1)})u(t-t_1) - (1-e^{-a_\ell(t-t_2)})u(t-t_2) \right] \right.$$

$$\left. + \frac{q_{20}}{a} \left[(1-e^{-a_\ell(t-t_3)})u(t-t_3) - (1-e^{-a_\ell(t-t_4)})u(t-t_4) \right] \right\}$$

$$+ n_o e^{-Kt} \tag{9}$$

The basic difference between the calculation of MP and the present study is that we assume an extended boxcar source function of a finite time Δt_a for the LM descent exhaust gas instead of a δ-function. We also take the LM ascent exhaust into consideration. We can easily show that in the limit as $\Delta t_a \to o$, the first term (due to the LM descent exhaust) in the curly brackets in equation (9) is identical to the result of MP, i.e.,

$$\frac{q_{10}}{a_\ell}\left[(1-e^{-a_\ell(t-t_1)})u(t-t_1)-(1-e^{-a_\ell(t-t_2)})u(t-t_2)\right]_{t_2\to t_1} \longrightarrow q_{10}\Delta t_a\, e^{-a_\ell(t-t_1)}$$

$$(q_{10}\Delta t_a = q_o \text{ in MP's expression})$$

The correctness of the expression for gas density distribution derived above depends largely on the proper choice of the production and the loss mechanisms for various gases on the lunar surface. No detailed information is yet available concerning the production and the loss processes of gases as well as gas interaction with the lunar surface. All investigations for the lunar atmosphere(4-9,15) carried out previously have been based entirely on theoretical calculations. Several approximations were made in deriving the diffusion equation for the lunar atmosphere. In view of the many uncertainties in computing the time varying density distribution of the exhaust gas in the lunar atmosphere, the proposed simplified mathematical model for obtaining qualitative knowledge of gas diffusion in the lunar atmosphere appears justified.

4.0 LOSS MECHANISMS

There are several mechanisms for escape of LM exhaust gases from the lunar environment shortly after the gases are released into the lunar atmosphere. Direct impingement of the solar wind flux on the lunar atmosphere is believed to be an effective mechanism for sweeping the gas particles away from the Moon. The ionization of gas particles by solar ultraviolet radiation is also a mechanism of depleting the lunar atmospheric density. The thermal evaporation of lighter gas particles is an effective means of reducing the lunar atmospheric density.(16) Additionally, the adsorption of gas particles by the surface could also alter the lunar atmospheric density. The effectiveness of different loss mechanisms on various gas particles under lunar environmental conditions has been discussed in detail elsewhere.(2,4,5,7-9) For the present computation, we use the values of the loss factors presented by MP(2) and Hinton and Taeusch.(4). We also express the loss factors as follows:

$$K = K_1 + K_2 + K_3$$

where K_1, K_2, and K_3 are respectively the loss mechanisms due to the solar wind flux, the solar ultraviolet radiation, and the thermal evaporation and are listed in Table II for the various gases. Since we are interested in the worst case of lunar atmospheric contamination, we ignore the loss mechanism due to the adsorption of gas particles by the lunar surface. In view of the assumed low particle density of the lunar atmosphere and the resulting large mean-free-path between collision, we also neglect collisions between particles as a loss mechanism. However, the interaction between particles and the lunar surface is considered in the treatment.

5.0 RESULTS AND DISCUSSION

The results of the computer calculation for the diffusion of various exhaust gases are plotted in Figures 1, 2, and 3. Figure 1 shows the density variation of nitrogen as a function of time at 240 km (Curve A), 450 km (Curve B), 900 km (Curve C), 1,400 km (Curve D), 1,800 km (Curve E) and 2,700 km (Curve F) from the LM touchdown point. Figure 2 depicts the density variation of water vapor as a function of time at the same distance as in Figure 1. Density curves in Figures 1 and 2 indicate that about 20 hours after LM touchdown the gas densities are approaching uniform distribution throughout the hemisphere. For simplicity, we assume that the gas is uniformly distributed in the half scale volume* about 20 hours after release of the gas into the lunar environment. Normalization of the gas density with respect to its half scale volume, indicated that the nitrogen gas density at $t = 7x10^4$ sec is about 10^5 particles/cm^3, and the corresponding scale of the relative density of 10^5 in Figure 1 should read about $5x\,10^4$ particles/cm^3. Similarly, the water vapor density at $t = 4x10^4$ sec is about $5x10^4$ particles/cm^3, and the corresponding scale of the relative density of 10^4 in Figure 2 is about $5x10^3$ particles/cm^3. The sharp rise of the gas density curves at $t = 7.1x10^4$ sec is due to the LM ascent exhaust gas that was initiated at $t = 7.0x10^4$ sec. Again, these gases quickly reach uniform distributions within a period of one day (24 hours). Figure 3 shows the density variation of CO, CO_2, OH, and NO as a function of time at a distance of 240 km from the LM touchdown point. The density variation of these contaminants along the lunar surface is similar to that of nitrogen or to water vapor. In this study, we have assumed no surface adsorption. All contaminants except the lighter gases, such as H_2, diffuse into the

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*The lunar scale volume is defined as, $V = \frac{4}{3}\pi[(r_o+h)^3-r_o^2]$ where r_o is the lunar radius and h is the scale height which is defined as $h = KT/mg$.

lunar environment and approach a uniform distribution in about one day and then disappear from the lunar atmosphere after several days. The lighter gases disappear from the lunar environment in less than one day. Attenuation of the gas density will be enhanced if surface adsorption is taken into consideration. Since we are primarily interested in the worst case of atmospheric contamination and the effect of these contaminants in the operation of ALSEP instruments, we shall discuss only the case where no surface adsorption takes place.

As shown in Figure 1, the nitrogen density decreases to less than 10^4 particles/cm^3 within 7 days ($\sim 6\times10^5$ sec) after LM touchdown. The water vapor density reduces to below 10^3 particles/cm^3 in about 3 days as indicated in Figure 2. Other atmospheric contaminants, such as CO, CO_2, OH, and NO, also quickly disappear from the lunar environment in a few days as shown in Figure 3. According to the ALSEP operational timeline, the ALSEP instruments will not be in operation until at least 72 hours after the astronauts have departed the lunar surface. At that time, the integrated contaminants density would be less than 5×10^4 particles/cm^3 which is more than an order of magnitude below the estimated ambient lunar atmospheric density. We do not expect contaminants at such a low density level to cause any problems in the successful operation of ALSEP.

One of the ALSEP experiments, the Cold Cathode Gauge Experiment (CCGE), is designed to measure the lunar atmospheric density and the atmospheric contaminants due to an Apollo mission. If, in fact, the ambient atmospheric density is 10^6 particles/cm^3 as predicted, the CCGE will have difficulty in detecting the contaminants contributed by the same landing mission if the ALSEP is not in operation until 72 hours after the LM ascent. However, the CCGE may detect contaminants contributed by a subsequent mission and determine the attenuation rate of those contaminants.

In conclusion, we would like to point out that our treatment is qualitative. In order for the diffusion theory to be valid, the distance from the source point to the observation point must be at least several mean-free-paths. For a typical gas in the lunar atmosphere, the mean free-path is on the order of 100 km. Consequently, the diffusion theory discussed in this report is not applicable in the vicinity of the LM. The best answer one can get is a qualitative estimate. In general, our results agree well with MP's calculation(2) except in the neighborhood of $t = 7.1\times10^4$ sec where a sharp rise in gas density due to the LM ascent exhaust is observed. This was not considered by MP. In addition, our estimate on the loss rate is conservative. First, we considered no surface adsorption; secondly, we considered an average solar wind flux ($J = 10^9 cm^{-2} sec^{-1}$). The early Apollo missions will occur near solar maximum, and a larger solar wind flux will lead to smaller decay times for the exhaust contaminants and thereby effect a faster removal of the contaminants from the lunar atmosphere. It is important to point out that the variation of the contaminant density depends strongly (exponentially) on the loss factors that were assumed. If the actual loss factors are considerably smaller than the values given in Table II, the rate of decay of the contaminants would be slower, whereby, the CCGE may detect the contaminants left by the same landing mission.

G. K. Chang

2015-GKC-gmr G. K. Chang

Attachments
  Figures 1, 2, and 3
  Tables I - II

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TABLE I

MAIN EXHAUST GASES (THEORETICAL VALUE) (Ref. 2)

Species	Relative % (wgt)
N_2	45
H_2O	31
CO	13
CO_2	7.9
H_2	1.3
OH	1.3
NO	.35
O_2	.23
O	.11
H	.092

TABLE II

LOSS FACTORS AND DIFFUSION CONSTANTS OF THE EXHAUST CONTAMINANTS

Species	K_1*	K_2	K_3	K	D
	$(\times 10^{-6}\,sec^{-1})$	$(\times 10^{-6}\,sec^{-1})$	(sec^{-1})	$(\times 10^{-5}\,sec^{-1})$	(km^2/sec)
N_2	0.92	5.0	small	0.592	20
H_2O	1.30	19.0	2.14×10^{-7}	2.05	39
CO	2.95	5.0	small	0.795	20
CO_2	1.01	10.0	small	1.101	10
H_2	1.04	1.0	1.29×10^{-4}	13.1	1050
OH	1.10	5.0	4.49×10^{-7}	0.655	43
NO	1.00	5.0	small	0.600	18
O_2	0.96	5.0	small	0.596	16
O	0.60	1.0	2.6×10^{-9}	0.16	47
H	0.93	0.5	1.38×10^{-4}	13.9	2960

*Solar Wind Flux $J = 10^9 cm^{-2} sec^{-1}$ was used in computing K_1.

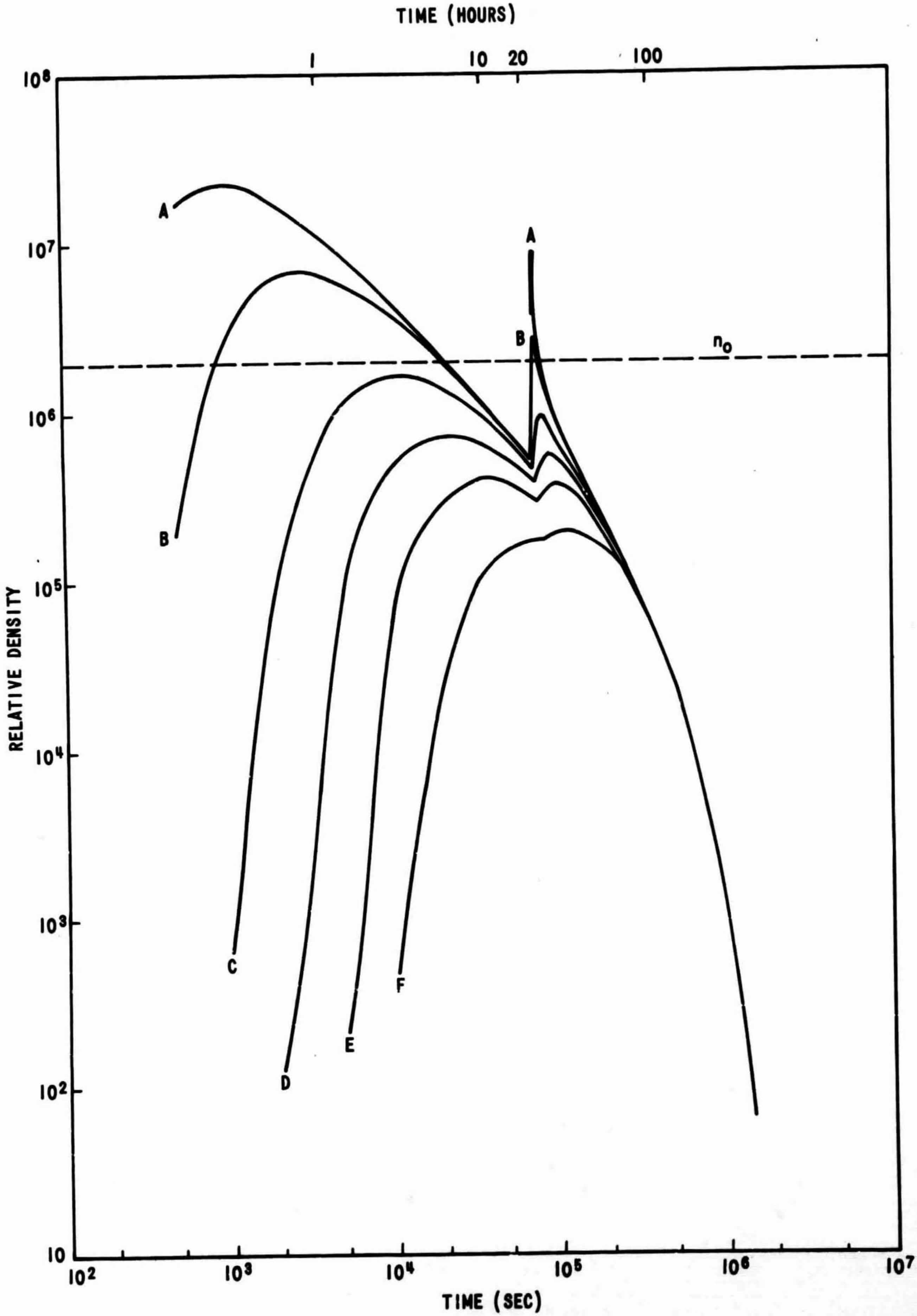

FIGURE I - DENSITY VARIATION OF N_2 AT 240 KM (A), 450 KM (B), 900 KM (C), 1400 KM (D), 1800 KM (E) AND 2700 KM (F) FROM THE LM

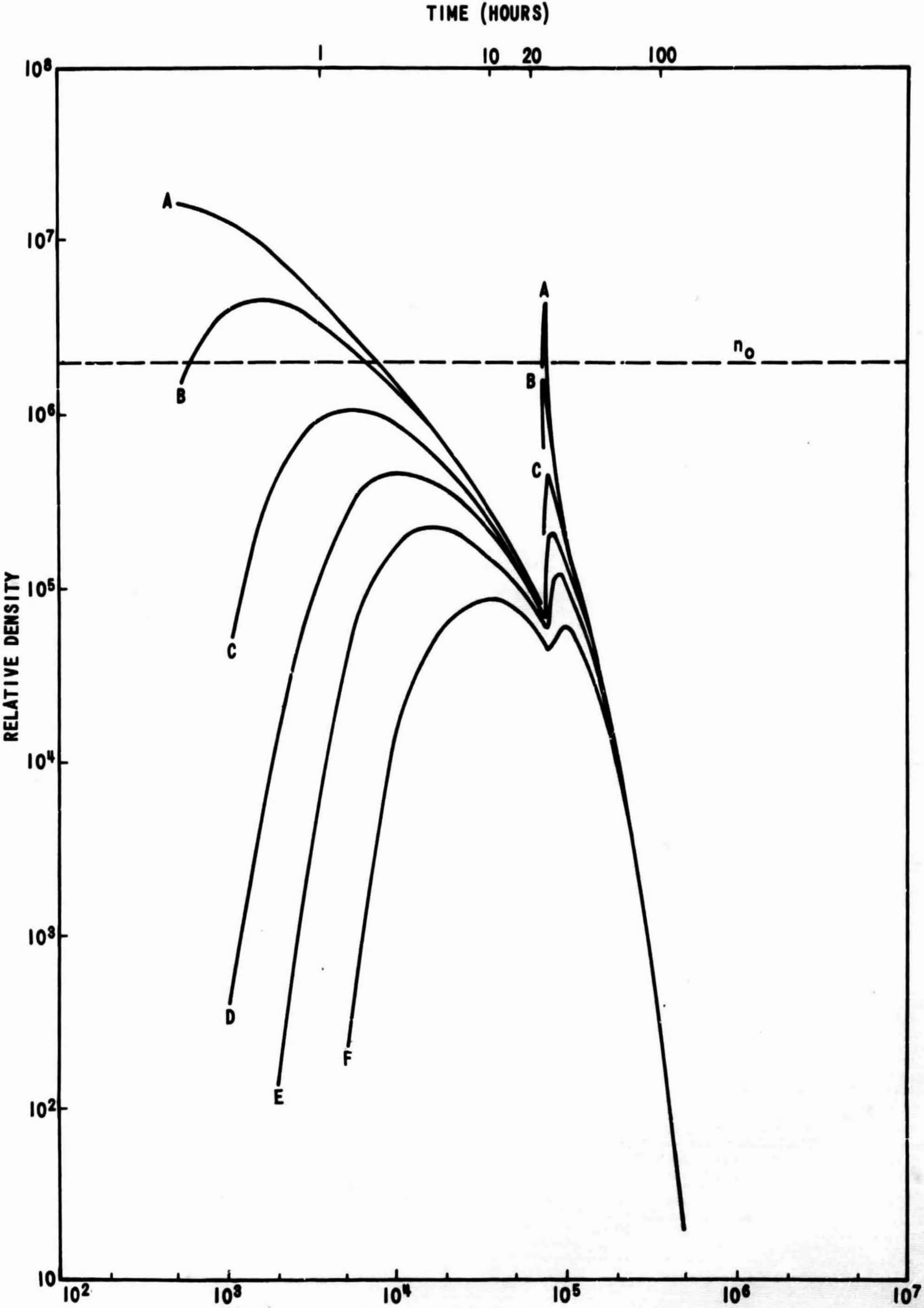

FIGURE 2 - DENSITY VARIATION OF H_2O AT 240 KM (A), 450 KM (B), 900 KM (C), 1400 KM (D), 1800 KM (E) AND 2700 KM (F) FROM THE LM

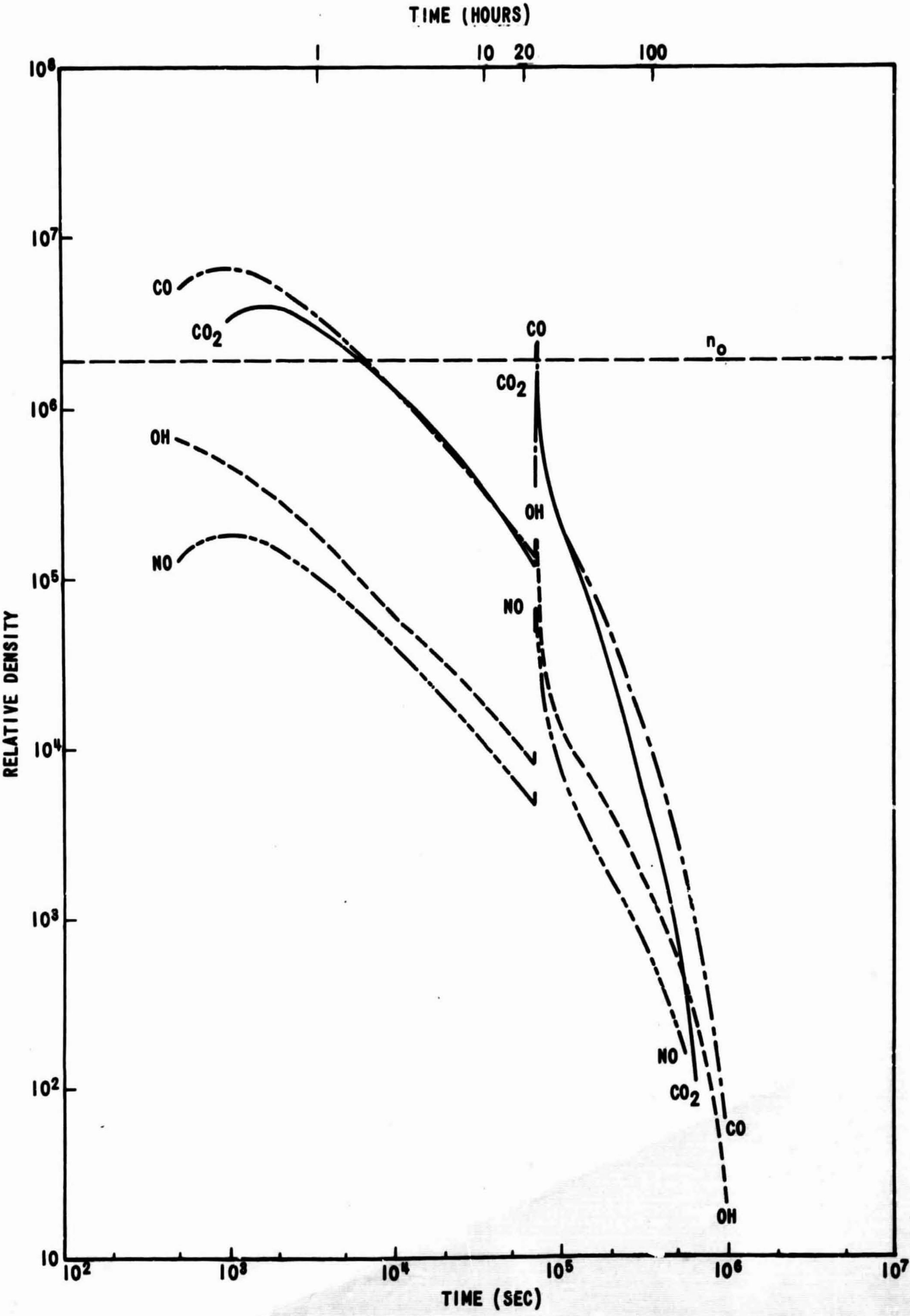

FIGURE 3 - DENSITY VARIATION OF CO, CO_2, OH AND NO AT 240 KM FROM THE LM