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AEROSOL BEHAVIOR IN HIGH PRESSURE ENVIRONMENTS

Robert A. Gussman

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SECTION 1.0: INTRODUCTION

The goal of this project was to investigate hazards that might arise from aerosols in a high-pressure environment. The specific environment considered was the helium-oxygen atmosphere used in saturation diving vehicles for depths to 1,000 ft. The study included theoretical evaluations of the physical properties of the atmosphere, variations in aerosol behavior due to the pressure and composition of the atmosphere, a consideration of aerosol formation, how air-cleaning mechanisms would be affected, how the toxicological effects of aerosols might be altered, and appropriate first order experiments within the scope of the project.

Because of the nature of the atmosphere and the lack of information in available literature, a great deal of tabulated information had to be developed for successive project phases. Inasmuch as this data has value for design purposes, a specific style has been selected for this final report. All of the material developed and covered in the quarterly reports is completely restated, though abbreviated wherever possible. Minor rearrangements have been performed for the sake of clarity and, with the exception of referencing, each section stands as a separate discussion on the subject covered. The comclusions relevant to each subject are detailed in separate sections. However, the overall implications of the results are presented in the section entitled "Discussion and Future Studies".

SECTION 2.0: LITERATURE SURVEY

The first task in this study was to determine, through a search of the literature, the extent of available knowledge relevant to aerosol behavior under high pressures. As the search progressed, it became apparent that virtually no information was available on aerosols in environments or even on process systems at elevated pressures. Numerous professional contacts were made in the United States and abroad in an effort to uncover pertinent unpublished information, but all responses were negative. While the internal hull pressures of nuclear submarines seldom exceed normal ambient conditions, they do represent a closed environment. Therefore, a large body of literature pertaining to contaminant studies within these vessels was felt to be of direct value to this study. The literature on nuclear submarines was heavily reviewed and it, along with related information, is presented in Appendix I as an annotated bibliography.

Some technological information dealing with aerosol behavior at reduced pressures, concerning electrification, agglomeration, and filtration, was uncovered. For the most part, this material proved to be of value and will be discussed in the following sections.

Without reference to any specific paper reviewed, it is possible to evolve a general picture of submarine atmosphere, contaminants, and control methods.

Chief among the gases to be removed from submarine atmospheres is carbon monoxide, which is burned catalytically with some benefits being accrued in destroying hydrocarbons; although the bulk of the hydrocarbon removal is accomplished with a charcoal adsorption system.

Carbon dioxide is currently controlled with a monoethanolamine (MEA) scrubbing system that is apparently completely satisfactory save that some aerosol problems arise from the generation of irritating MEA mists. Use of this system is based on an economic comparison between it and lithium hydroxide absorbants. For nuclear submarines, the economic balance develops in favor of the MEA system.

A long list of trace substances in submarine atmospheres has been compiled only because the environment is closed for a long period of time and concentrations of the contaminants can build up to detectable, if not troublesome, levels. Construction and finishing materials are chief sources of these substances. These toxic substances have chiefly been controlled by substitution.

According to several authors, the chief source of aerosol in closed environments is cigarette smoking, followed closely by cooking. For these activities, aerosol concentrations as high as 400 γ/M^3 can be observed. Removal of particulates is accomplished by electrostatic precipitation and recommended final levels are about 100 γ/M^3. While there is no clear statement regarding the size distribution of aerosols found in submarine atmospheres, condensation nuclei that range in concentration from 3,000 to 11,000 particles/cm^3 are frequently mentioned. Generally, aerosol particles may be as large as 100 microns; but, while virtually all aerosol particles can serve as centers of condensation, nuclei counters are seldom useful on particles of diameters greater than 1 micron. Smoking generally gives rise to submicron particles (approximately 0.3 μ); but cooking may yield a very wide spectrum, including some rather large sizes.

Both positive and negative ions are found in the submarine atmosphere; average concentrations range from 1,500 to 2,000 ions/cm^3 and excursions up to 15,000 ions/cm^3 can be recorded. Positive ions predominate, probably because of the higher mobility of negative ions that are more readily attached to aerosol particles. With an increase in aerosol concentration there appears to be a gain in the number of medium (0.003-0.03μ) and large (0.03-0.1μ) ions.

There are a large number of papers dealing with the physiological effects of air ions. The authors agree, in a general way, that negative ions seem to be beneficial while positive ions seem to provoke feelings of distress and unhappiness. Additionally, some physiological responses are noted, chiefly in the rate of ciliary action in the lung. Negative ions tend to increase the ciliary beat rate and thereby promote more rapid clearance of deposited materials from the lung. A criticism of much of the work carried out on the effects of air ions is that investigators paid little or no attention to aerosol concentration with relation to the quantity of ions generated. Therefore, because of wall losses or other unaccounted effects, the actual number of free ions reaching a subject could have been remarkably different that that which was generated.

Much consideration has been given to determining modified threshold limit values (TLV) for the closed environment. As usually defined, the threshold limit value indicates the highest exposure to which an individual may be safely exposed during a 7 or 8 hour work day, five days per week. In nuclear submarines, the exposure is continuous for periods of approximately 60 days and nights. Studies by the Navy conclude that lower limit values are necessary.

The contaminants found in the closed environments to submarines appear to be identified well and the methods of controlling their impact upon the living organism have been successfully approached and utilized.

SECTION 3.0: PROPERTIES OF THE GASEOUS MIXTURE

Before examining the behavior of aerosols in high pressure environments, one must first define the gaseous composition of that environment. Aerosols are composed of particulates, of greater than molecular dimensions, that have describable motions dependent upon the characteristics of the medium in which they are suspended. The ultimate goal of this study's parent project is to determine the toxicological impact of aerosols in high-pressure environments inhabited by man. Certain definite statements can be made at this time about the gas mixture in which the aerosol particles will be suspended. A given factor in this consideration is that the maximum pressure to be considered is 500 psia, or 34 atmospheres.

Bond(1) states that, for long term exposures under high pressures, the nitrogen component of the atmosphere is not suitable and helium must be substituted. He also noted that, as the pressure is increased, the percentage of oxygen must be decreased and what is required for life-support is a partial oxygen pressure (PO_2) of approximately 160 mm Hg. While small percentages of nitrogen and other trace gases are used, we have chosen to make a minor simplifying assumption in that we will only consider a binary mixture of oxygen and helium.

The general aerosol properties that are to be considered and extrapolated for the high pressure artificial environment include sedimentation, diffusion, agglomeration, electrification, nucleation, and the effect of inter-molecular slip. The equations for many of these motions require a numerical value for the density, viscosity, and mean free path of the gas mixture. Therefore, these items have been considered and determined.

Figure 1 shows a working graph of the atmosphere composition for pressures ranging from 10 to 500 psia. Since the partial pressure of the oxygen is to be maintained at 160 mm Hg (3.095 psi), the percentage of oxygen content of the atmosphere decreases from 21% at 1 atmosphere to 0.62% at 34 atmospheres. The balance of the mixture consists of the helium. Figure 2 indicates that the density of the varying mixture increases with increasing pressure. The calculations assumed the mixture to be an ideal gas. Errors arising from this assumption have been checked and are found to be less than 1% at 500 psia.

It should be noted at this point that there will be, throughout this project, a certain parallel usage of the metric and English systems. Aerosol physics calculations are most conveniently and commonly carried out in the metric system. Expressions of depth, cabin pressure and other measures in common use by the sponsor are usually in the English system. In all cases, our goal shall be clarity.

The viscosity of the two gases are quite similar at atmospheric pressure and $20^{o}C$ (He = 194 μpoise; O_2 = 202 μpoise). Because of this close similarity and the difficulty in applying the equations that determine viscosity

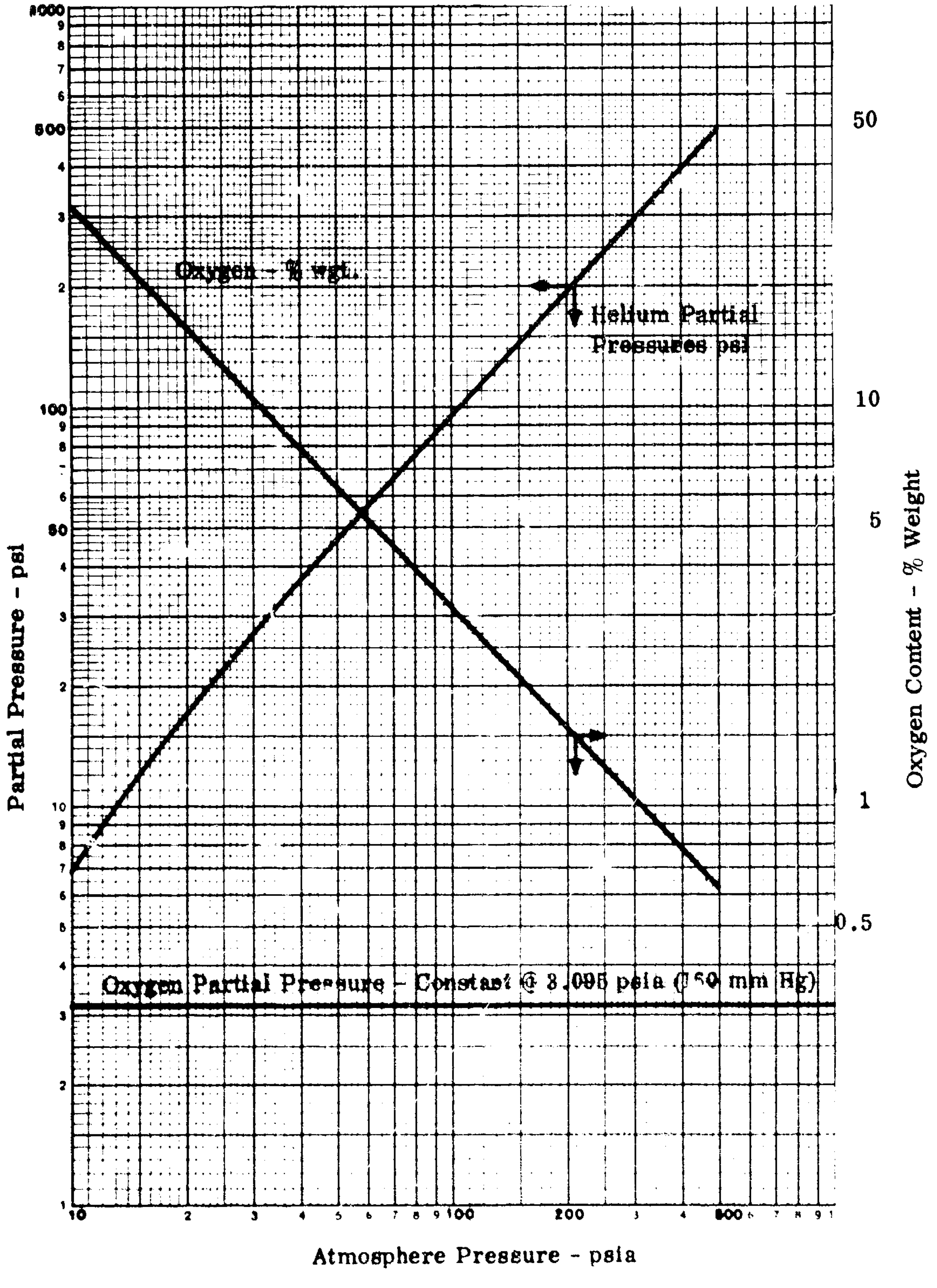
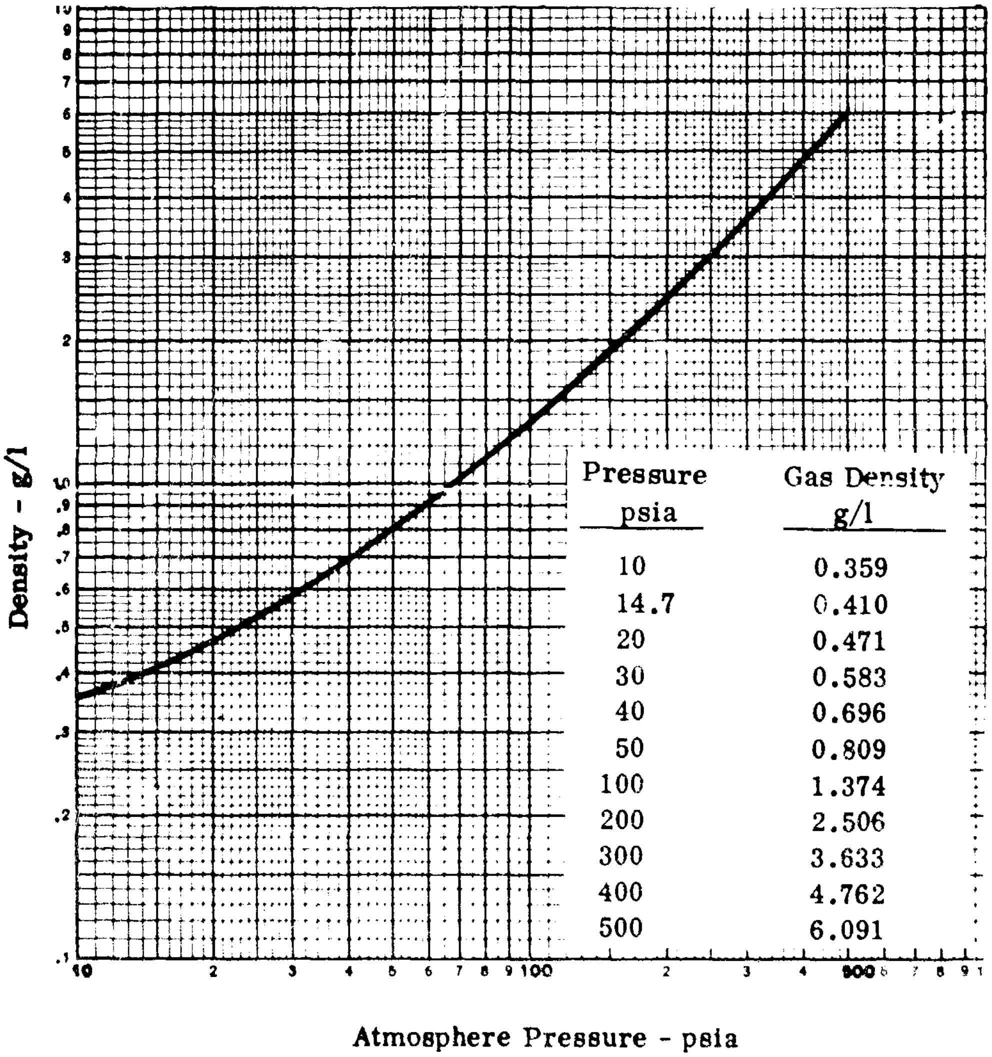


Figure 1. Oxygen-Helium Atmosphere Pressure vs Composition. (PO_2 = 160 mm Hg; T = 20°C).



Pressure psia	Gas Density g/l
10	0.359
14.7	0.410
20	0.471
30	0.583
40	0.696
50	0.809
100	1.374
200	2.506
300	3.633
400	4.762
500	6.091

Figure 2. Oxygen-Helium Atmosphere Pressure vs Density.
(PO_2 = 160 mm Hg; T = 20°C).

of mixtures to a gas as light as helium, Table 1 represents a comparison of viscosity with increasing pressure (changing composition) based on a simple averaging of the viscosities according to percentage composition.

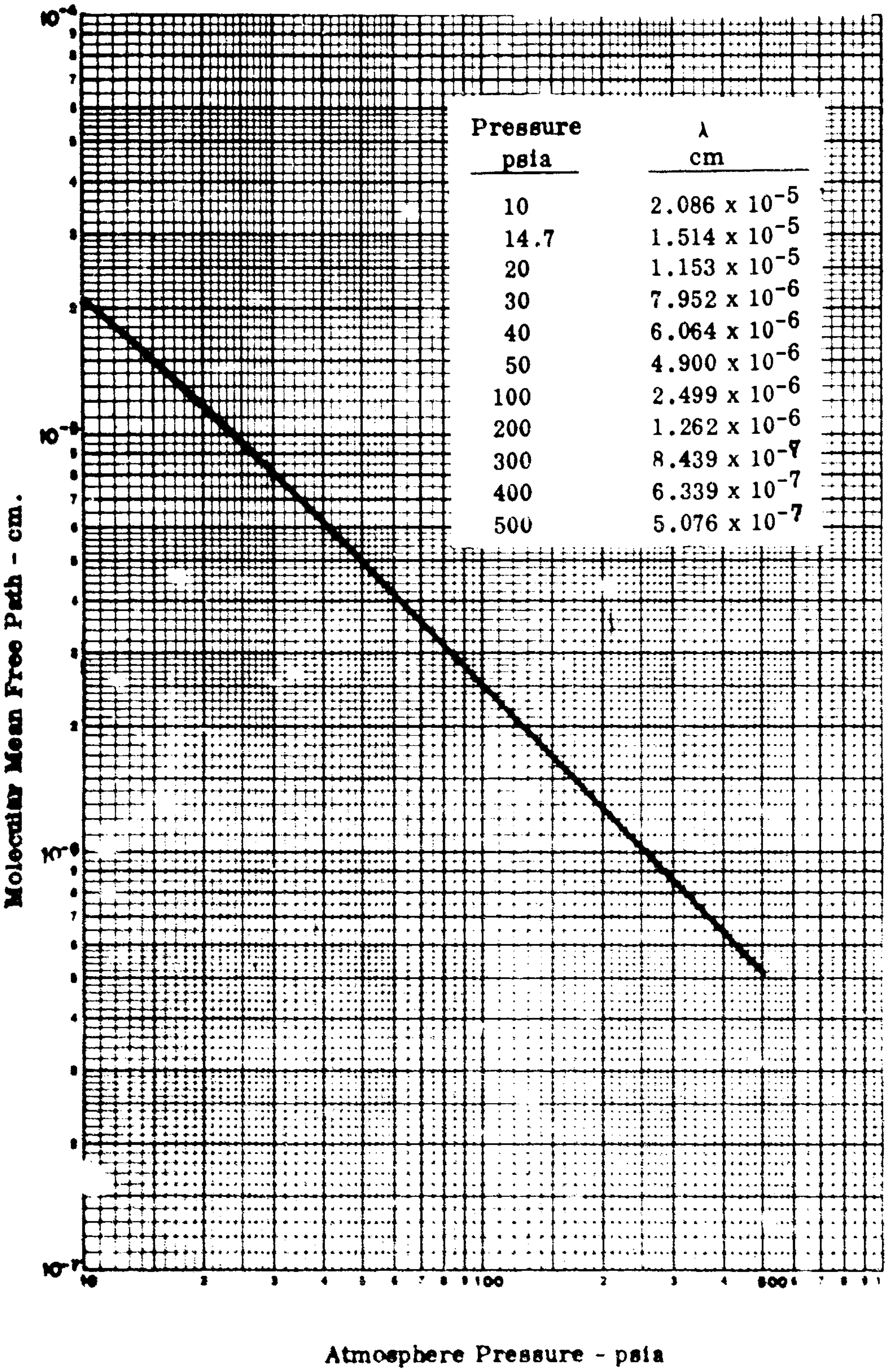
TABLE 1

He - O_2 VISCOSITY vs PRESSURE

Pressure - psia	Viscosity - micro poise
10	196.47
14.7	195.68
20	195.24
30	194.82
40	194.68
50	194.46
100	194.23
200	194.22
300	194.08
400	194.06
500	194.05

Increasing pressure does not effect viscosity for a perfect gas. The degree of deviation for an imperfect gas is similar to the pressure (density) deviation that, for our mixture, has already been noted as less than 1%.(2)

The values of the mean free path (λ) of the mixture have been calculated according to equations given by Loeb(3) for λ of one gas in the presence of a quantity of another. The values expressed in Figure 3 are, therefore, average path lengths based on the mole fractions present and include corrections for pressure, temperature, and composition.



Pressure psia	λ cm
10	2.086×10^{-5}
14.7	1.514×10^{-5}
20	1.153×10^{-5}
30	7.952×10^{-6}
40	6.064×10^{-6}
50	4.900×10^{-6}
100	2.499×10^{-6}
200	1.262×10^{-6}
300	8.439×10^{-7}
400	6.339×10^{-7}
500	5.076×10^{-7}

Figure 3. Oxygen-Helium Atmosphere vs Mean Free Path.
(PO_2 = 160 mm Hg; T = 20°C).

SECTION 4.0: AEROSOL MECHANICS

4.1 SLIP CORRECTION

Common practice in aerosol physics calculations is initially to discuss the basic relationships for particulate motion, such as sedimentation, agglomeration, diffusion, etc., and then to introduce the concept of the "slip factor", which accounts for the increased mobility of particulates as their dimensions become comparable with the mean free path of the gas molecules. For air at ambient conditions, the slip factor becomes negligible for particles of diameters greater than 1 micron. However, helium has a much longer mean free path than air ($He = 27.45 \times 10^{-6}$ cm; $Air = 6.53 \times 10^{-6}$ cm); therefore, it is necessary first to consider the magnitude and importance of this factor before proceeding to other calculations.

The evolution of the slip factor and the basis for currently accepted values of its constants have been thoroughly discussed by Davies(4) and Green and Lane.(5)

Davies' studies, reported in 1945, are of particular interest. He reviews in detail the work of several earlier investigators, evaluates their findings, and evolves numerical values for the constants contained in the slip correction equation. The work of these investigators, as described in Davies' paper, present a concise history of the factor. According to Davies, the factor was first expressed in its present form by Knudsen and Webber:

$$1 + \frac{2A\lambda}{d} \quad , \tag{1}$$

where λ is the mean free path of the gas molecules, d is the particle diameter, and A is a numerical factor having a value of approximately unity.

According to Davies,(4) Knudsen and Webber, working with glass spheres in air, observed the damping of torsional oscillations of a suspended beam to which a sphere was fixed. Millikan derived values for the factor from his work with the famous oil drop apparatus and from other experiments with a rotating drum viscometer. Mattauch's studies on oil drops in nitrogen were similar to Millikan's technique. Davies does not specifically detail what procedures were used by Monch for his work with tobacco smoke.

The factor A was actually found to vary with particulate diameter according to the equation

$$A = A_o + B \exp(-Cd/2\lambda) \quad , \tag{2}$$

where $A_o = 1.257$, $B = 0.400$, and $C = 1.10$.

Davies determined values for the factor on the basis of work by each of these men. He disregarded Knudsen and Webber's values because of their methods and gave double weight to Millikan's and Mattauch's values over Monch's numbers for tobacco smoke. The reason stated for giving less weight to the work of Monch is that "there exists no confirmation that the slip coefficient for tobacco smoke particles in air is the same as for oil in nitrogen."

Subsequent to Davies' considerations, Flanagan and Tayler(6) and Metnieks and Pollak(7) constructed tabulations of the slip factor, using only the data of Millikan for oil droplets in air. The use of these data is certainly not open to dispute for the aerosols and gases investigated. Because the experimental values of A_0, B, and C are available only for air at conditions closely approximating ambient, there is not direct method of theoretically extrapolating the slip factor to other gases and pressures with any assurance of exact results.

While the needs of the project might require an approximation (in spite of its limitations) fortunately Fuchs and Stechkina(8) have developed a theoretical relationship that is a correction for the mobility of small particles.

Mobility B is defined as ratio of the velocity of a particle U_0 to the drag F:

$$B = \frac{U_0}{F} = \frac{1}{3\pi \mu d} , \qquad (3)$$

where μ is the coefficient of viscosity of the gas.

As the particulate diameter becomes small, a correction is required for slip. The correction for mobility is expressed as:(8)

$$B = \left[\frac{1}{1+\beta\chi} + \frac{2.25\chi}{\delta} \right] (3\pi \mu d)^{-1} , \qquad (4)$$

where $\beta = \frac{2.25}{1+\pi s/8} - 2\gamma \left(\frac{2}{s} - 1\right)$;

δ = 1, for specular reflection of the molecules from a particle;

δ = 1 + (π/8), for completely diffuse reflection (however, for the general case, δ = (1+π s/8), where s is the fraction of the molecules reflected diffusely);

γ = 0.499, as extracted from the current expression for λ;(6) and

χ = $\frac{2\lambda}{d}$, the Knudsen number

Extracting the slip factor from Equation (4) and substituting the above terms, we get

$$\frac{1}{1+\left[\frac{2.25}{1+\frac{\pi s}{8}} - 2(0.499)\left(\frac{2}{s}-1\right)\right]\frac{2\lambda}{d}} + \frac{2.25(2\lambda)}{\left(1+\frac{\pi s}{8}\right)d} \quad . \qquad (5)$$

Reducing this expression, we obtain

$$\left\{1+\left[\frac{4.5}{1+0.392s} - 1.996\left(\frac{2}{s}-1\right)\right]\frac{\lambda}{d}\right\}^{-1} + \frac{4.5}{1+0.392s}\,\frac{\lambda}{d} \quad . \qquad (6)$$

Equation (6) should be useful as a slip factor for aerosols in most gases under a wide variety of conditions. The remaining problem is to determine a value of s, i.e., the percentage of molecules reflected diffusely from the surface of the particles.

According to Loeb,(3) Blankenstein found that for many gases, s values approached unity. Loeb questions these values on the basis of Millikan's results and concludes that the factor is quite high, stating: "thus s for gases should increase with increasing density of the gases but is in any case near unity."

Setting s = 1 for the helium oxygen mixture considered over the pressure range of 10 to 500 psia (Eq. 6) reduces to the form:

$$\left(1 + 1.23\frac{\lambda}{d}\right)^{-1} + 3.23\frac{\lambda}{d} \qquad (7)$$

Calculated curves for several particulate diameters are given in Figure 4; Table 2 gives working values.

A method for determining the percentage of particles reflected diffusely (s) is described in great detail by Millikan.(9) His apparatus consisted of two concentric cylinders, the outer one rotating at a constant angular velocity. The cylinders contain the gas under investigation; the cylinder walls are coated with the material of which the aerosol is composed. Therefore, a measurement of the torsional moment due to the viscous drag on the inner cylinder can be obtained and the value of s is then determined through certain calculations. Millikan discusses in some detail the simplicity with which the measurement of s may be obtained with this apparatus and speaks of the high correlation of his results with the results of other experimenters using the same technique. Millikan concludes that this technique for determining s values is far superior to that using the oil drop apparatus.

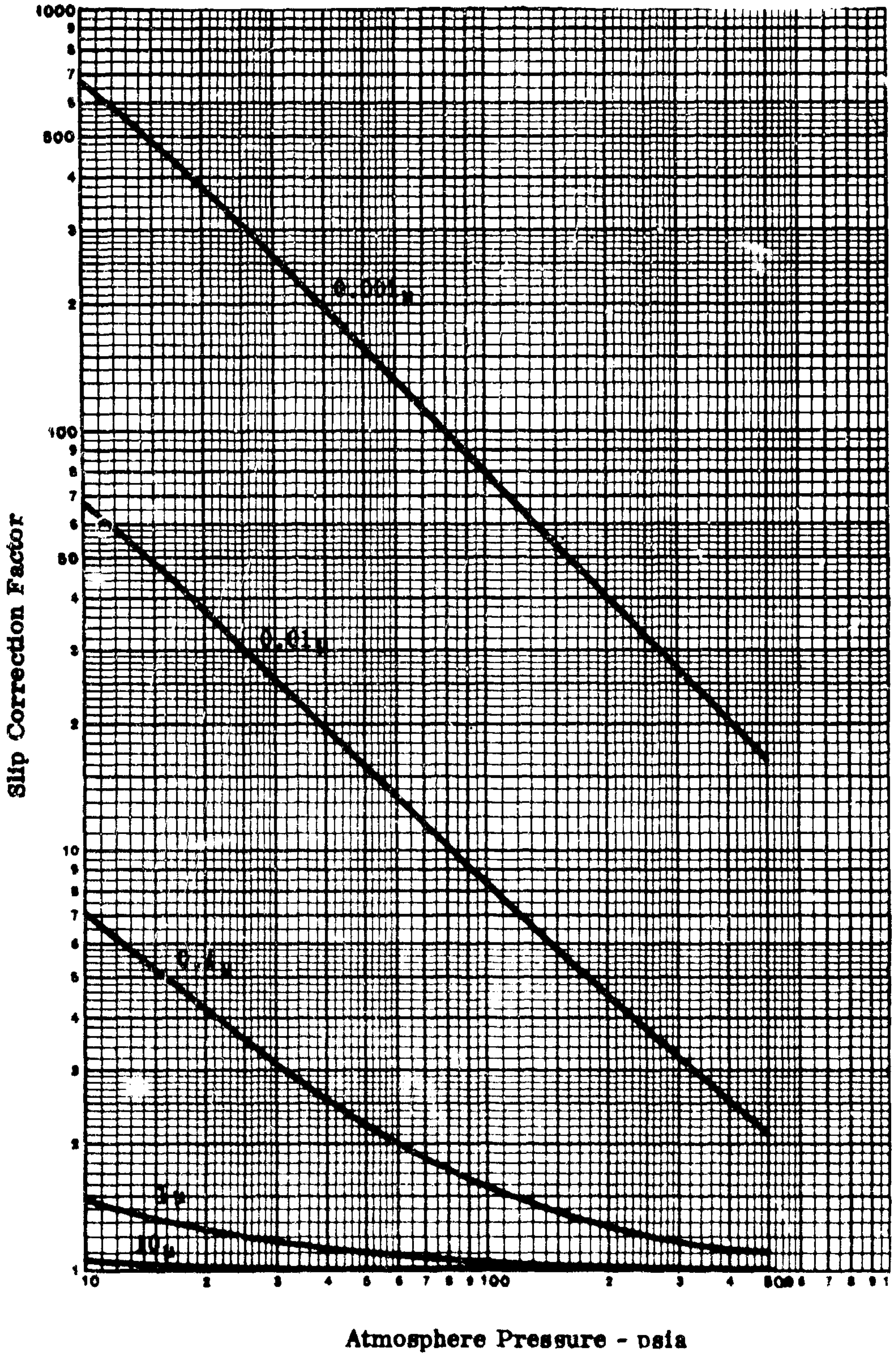


Figure 4. Oxygen - Helium Atmosphere Pressure vs Molecular Slip Correction Factor for Various Particulate Diameters. (PO_2 = 160 mm Hg; T = 20°C).

Atmosphere Pressure psia	Slip Correction Factor				
	Particle Diameter - μ				
	0.001	0.01	0.1	1	10
10.0	673.7819	67.4153	7.0182	1.4696	1.0424
14.7	489.0273	48.9532	5.2396	1.3320	1.0306
20.0	372.4260	37.3078	4.1377	1.2482	1.0233
30.0	256.8597	25.7777	3.0740	1.1678	1.0160
40.0	195.8804	19.7049	2.5315	1.1265	1.0122
50.0	158.2863	15.9693	2.2066	1.1014	1.0098
100.0	80.7492	8.3172	1.5721	1.0509	1.0050
200.0	40.8231	4.4681	1.2733	1.0255	1.0025
300.0	27.3458	3.2165	1.1785	1.0170	1.0017
400.0	20.5886	2.6094	1.1324	1.0127	1.0013
500.0	16.5335	2.2552	1.1052	1.0102	1.0010

Table 2. Molecular Slip Correction Factor for Various Pressures and Particle Diameters in a Helium-Oxygen Gas Mixture. (PO_2 = 160 mm Hg; T = 20°C).

The new relationships of Fuchs and Stechkina,(8) when used in conjunction with Millikan's apparatus for determining s, represent a positive method for determining slip corrections for virtually any gas and aerosol.

4.2 SEDIMENTATION

For the settling of aerosol particles, the primary equation for describing the sedimentation velocity of the particles is given by Stokes' law:(5)

$$v = \frac{(\rho - \rho')g\,d^2}{18\,\eta}\ \text{(slip correction)}\ , \qquad (8)$$

where

v = sedimentation velocity,
ρ = density of the particle,
ρ' = density of the fluid medium,
g = gravitational acceleration,
d = diameter of the particle, and
η = viscosity of the fluid medium.

All the values necessary for calculating a sedimentation velocity at any of the high-pressure helium-oxygen conditions are presented in the preceeding section. Usually in calculations of sedimentation velocities in air, the term ρ is substituted for the expression $\rho - \rho'$ because the density of the gas is insignificant compared to the density of the particle. Maximum density being considered in the high pressure environment is 6×10^{-3} grams per cc (which is still insignificant in comparison to particulate densities that could be encountered). The slip correction factor is applied to Stokes' law whenever the diameter of the particles approaches the mean free path of the gas molecules. For particle diameters greater than 10 microns, the correction is unnecessary.

Davies(4) upon reviewing considerable sedimentation data and performing much experimentation, found that the error incurred by using Stokes' law for particles falling in various fluids would not exceed 1% for Reynolds numbers (R_e) up to 0.05. At higher Reynolds numbers, the deviation becomes greater and Stokes' law over-estimates the settling velocity. Davies evolved an equation that is valid for Reynolds numbers up to 4; but its use requires first the introduction of other parameters. The drag coefficient (C_D) is defined as the ratio of the resistance of a particle to the product of its cross-section and the dynamic pressure:

$$C_D = \frac{\pi}{6} d^3 \rho g \cdot \frac{8}{\rho' v^2 \pi d^2} , \tag{9}$$

reducing:

$$C_D = \frac{4}{3} \frac{\rho g d}{\rho' v^2} \tag{10}$$

Stokes law may be expressed in terms of the drag coefficient and Reynolds number as:

$$C_D = 24/R_e \quad . \tag{11}$$

C_D and R_e both contain velocity, therefore the equation is usually expressed as:

$$R_e = C_D R_e^2/24 \quad . \tag{12}$$

Davies expression for sedimentation velocity up to $R_e = 4$ is given as:

$$R_e = C_D R_e^2/24 - 2.3363 \times 10^{-4} (C_D R_e^2)^2 + 2.0154 \times 10^{-6} (C_D R_e^2)^3 - 6.9105 \times 10^{-9} (C_D R_e^2)^4 \quad . \tag{13}$$

Equation (12) (for Reynolds numbers up to 0.05) and Equation (13)(for settling velocities up to $R_e = 4$) makes it possible to calculate a table of diameters vs the expression $C_D R_e^2/24$ and to perform the appropriate substitution in either Equation (12) or (13).

For Reynolds numbers in the range 3 to 400, Fuchs(10) quotes the equation derived by Klyachko:

$$C_D = 24/R_e + 4/(R_e)^{\frac{1}{3}} \quad . \tag{14}$$

To construct a working table of settling velocities from the pressure range being considered, we first calculated Table 3, which consists of Reynolds number values for particles ranging in size from 0.001 to 100 microns and

Table 3. Reynolds Number vs Particle Diameter (He-O_2; PO_2 = 160 mm Hg; T = 20°C)

$$R_e = \frac{C_D R_e^2}{24} \quad \text{(Slip Correction)}$$

	Particle Diameter- μ ↓ psia →	10.0	14.7	14.7 (Air)	20.0	30.0	40.0	50.0	100.0	200.0	300.0	400.0	500.0
	.001	3.42-13	2.85-13		2.51-13	2.15-13	1.96-13	1.85-13	1.60-13	1.48-13	1.44-13	1.42-13	1.46-13
ρ =1	.010	3.42-11	2.86-11	4.52-11	2.51-11	2.16-11	1.97-11	1.86-11	1.65-11	1.62-11	1.69-11	1.80-11	1.99-11
	.100	3.36-09	3.06-09	5.78-09	2.79-09	2.57-09	2.53-09	2.57-09	3.12-09	4.61-09	6.19-09	7.80-09	9.74-09
	1.000	7.45-07	7.77-07	2.33-06	8.41-07	9.78-07	1.13-06	1.28-06	2.09-06	3.71-06	5.35-06	6.98-06	8.91-06
	10.000	5.28-04	6.01-04	2.05-03	6.89-04	8.51-04	1.01-03	1.18-03	1.99-03	3.63-03	5.27-03	6.90-03	8.82-03
	20.000	4.05-03	4.67-03	1.61-02	5.39-03	6.70-03	8.01-03	9.33-03	1.59-02	2.90-02	4.21-02	5.51-02	7.05-02
	30.000	1.37-02	1.58-02	5.42-02	1.82-02	2.26-02	2.70-02	3.15-02	5.36-02	9.78-02	1.42-01	1.86-01	2.38-01
	40.000	3.24-02	3.73-02	1.29-01	4.31-02	5.36-02	6.41-02	7.46-02	1.27-01	2.32-01	3.36-01	4.41-01	5.64-01
	50.000	6.34-02	7.29-02	2.51-01	8.42-02	1.05-01	1.25-01	1.46-01	2.48-01	4.53-01	6.57-01	8.61-01	1.10+00
	100.000	5.07-01	5.84-01	2.01+00	6.73-01	8.37-01	1.00+00	1.17+00	1.98+00	3.62+00	5.26+00	6.89+00	8.82+00

		10.0	14.7	14.7	20.0	30.0	40.0	50.0	100.0	200.0	300.0	400.0	500.0
	.001	6.83-13	5.71-13		5.02-13	4.30-13	3.92-13	3.69-13	3.21-13	2.96-13	2.87-13	2.84-13	2.92-13
ρ =2	.010	6.83-11	5.71-11	9.04-11	5.02-11	4.32-11	3.94-11	3.72-11	3.30-11	3.24-11	3.38-11	3.60-11	3.98-11
	.100	7.11-09	6.12-09	1.16-08	5.57-09	5.15-09	5.07-09	5.15-09	6.24-09	9.22-09	1.24-08	1.56-08	1.95-08
	1.000	1.49-06	1.55-06	4.66-06	1.68-06	1.96-06	2.25-06	2.57-06	4.17-06	7.43-06	1.07-05	1.40-05	1.78-05
	10.000	1.06-03	1.20-03	4.10-03	1.38-03	1.70-03	2.03-03	2.35-03	3.99-03	7.26-03	1.05-02	1.38-02	1.76-02
	20.000	8.11-03	9.34-03	3.21-02	1.08-02	1.34-02	1.60-02	1.87-02	3.18-02	5.79-02	8.41-02	1.10-01	1.41-01
	30.000	2.74-02	3.15-02	1.08-01	3.64-02	4.52-02	5.40-02	6.30-02	1.07-01	1.96-01	2.84-01	3.72-01	4.76-01
	40.000	6.49-02	7.47-02	2.57-01	8.62-02	1.07-01	1.28-01	1.49-01	2.54-01	4.63-01	6.73-01	8.82-01	1.13+00
	50.000	1.27-01	1.46-01	5.02-01	1.68-01	2.09-01	2.50-01	2.91-01	4.96-01	9.05-01	1.31+00	1.72+00	2.20+00
	100.000	1.01+00	1.17+00	4.02+00	1.35+00	1.67+00	2.00+00	2.33+00	3.97+00	7.24+00	1.05+01	1.38+01	1.76+01

		10.0	14.7	14.7	20.0	30.0	40.0	50.0	100.0	200.0	300.0	400.0	500.0
	.001	1.02-12	8.56-13		7.52-13	6.45-13	5.88-13	5.54-13	4.81-13	4.43-13	4.31-13	4.26-13	4.37-13
ρ=3	.010	1.03-10	8.57-11	1.36-10	7.54-11	6.47-11	5.92-11	5.59-11	4.95-11	4.85-11	5.07-11	5.39-11	5.96-11
	.100	1.07-08	9.17-09	1.74-08	8.36-09	7.72-09	7.60-09	7.72-09	9.36-09	1.38-08	1.86-08	2.34-08	2.92-08
	1.000	2.23-06	2.33-06	6.99-06	2.52-06	2.93-06	3.38-06	3.85-06	6.26-06	1.11-05	1.60-05	2.09-05	2.67-05
	10.000	1.59-03	1.80-03	6.15-03	2.07-03	2.55-03	3.04-03	3.53-03	5.98-03	1.09-02	1.58-02	2.07-02	2.65-02
	20.000	1.22-02	1.40-02	4.82-02	1.62-02	2.01-02	2.40-02	2.80-02	4.76-02	8.69-02	1.26-01	1.65-01	2.12-01
	30.000	4.11-02	4.73-02	1.63-01	5.45-02	6.78-02	8.11-02	9.44-02	1.61-01	2.93-01	4.26-01	5.58-01	7.14-01
	40.000	9.73-02	1.12-01	3.86-01	1.29-01	1.61-01	1.92-01	2.24-01	3.81-01	6.95-01	1.01+00	1.32+00	1.69+00
	50.000	1.90-01	2.19-01	7.53-01	2.53-01	3.14-01	3.75-01	4.37-01	7.44-01	1.36+00	1.97+00	2.58+00	3.31+00
	100.000	1.52+00	1.75+00	6.03+00	2.02+00	2.51+00	3.00+00	3.50+00	5.95+00	1.09+01	1.58+01	2.07+01	2.64+01

pressures ranging from 10 to 500 psia. This table is presented graphically (for $\rho = 1$) in Figure 5. In the construction of the table, the gas mixture of helium and oxygen has been varied with increasing pressure while keeping the partial pressure of the oxygen constant at 160 mm. Appropriate values for density and viscosity have been used as previously determined. The slip correction has been applied in all cases where the values are significant and, for comparative purposes, a column has been added for air at ambient pressure. The heavy line running horizontally in Table 3 represents the cutoff point for values up to $R_e = 0.05$ for which Stokes' law may be used for calculating the settling velocity. Below the solid line but above the dashed line, Davies' relationship may be utilized and, below the dashed line ($R_e > 4$), the equation of Klyachko may be used. Table 4 represents corresponding values of $\eta/\rho' d$ by which Reynolds number is multiplied to obtain the sedimentation velocity. The final table, (5) represents a working chart of sedimentation velocities for particles of three densities vs particle diameter for all the ranges of gas pressure. This table and Figure 6 fully considers all the variables of composition, pressure, viscosity, etc., and the applicable equation for the actual Reynolds number range. It may be considered correct and usable within the constraints of the theories and extrapolations utilized.

Once we have established the approximate sedimentation velocities for particulates in the submarine environment, it is then of interest to determine the particulates' rate of loss. The basic differential equation for the rate of deposition of particles in an enclosed vessel is given by:(1)

Figure 5. Particle Reynolds Number vs Diameter.
(He - O_2; PO_2 = 160 mm Hg; T = 20°C; ρ = 1)

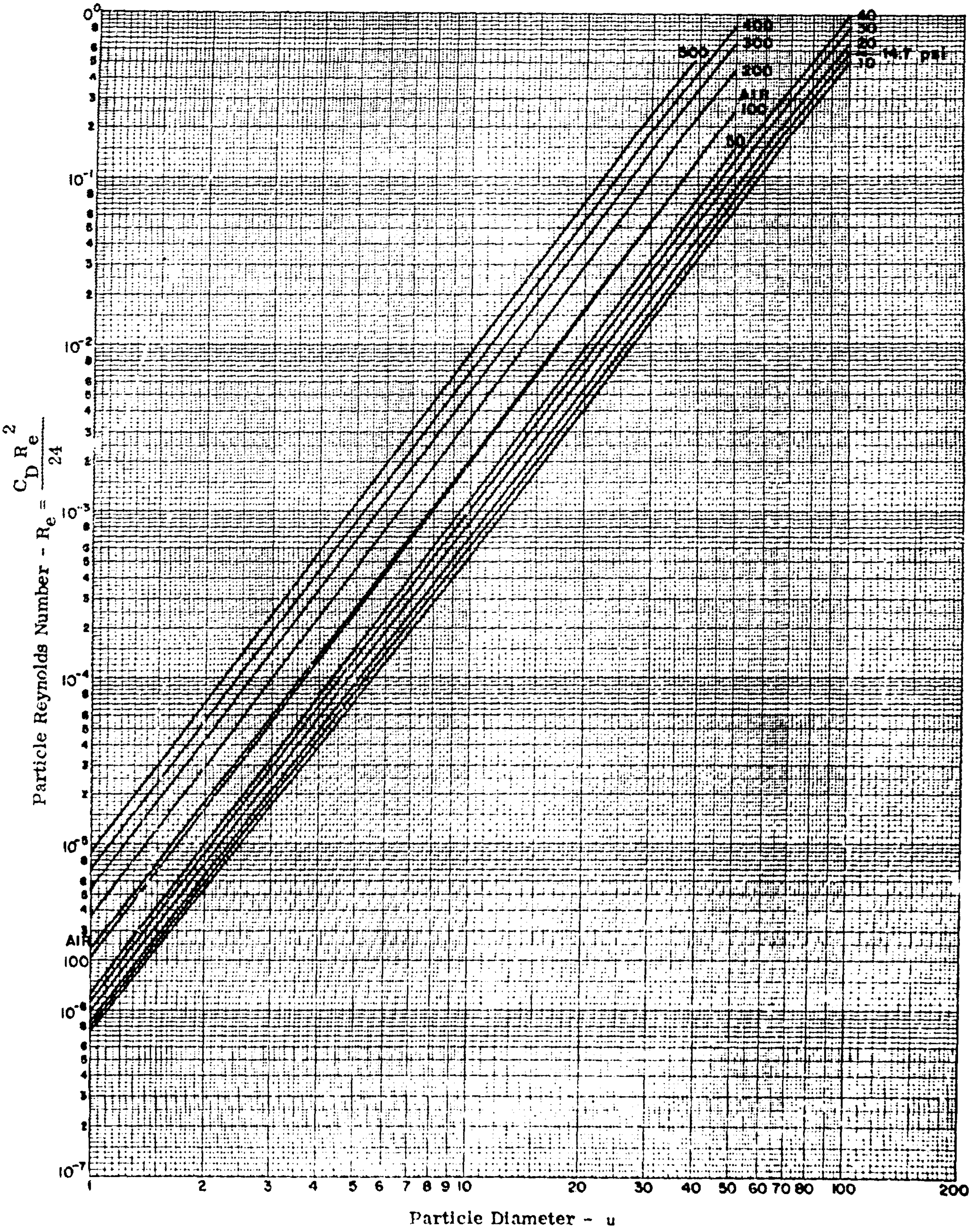


Table 4 Factor for Multiplying Particulate R_e to Determine Sedimentation Velocity

(He - O_2; PO_2 = 160 mm Hg; T = 20°C)

Particle Diameter- μ	10	14.7	14.7 (Air)	20	30	40 ←Pressure - psia
.001	5.47+06	4.77+06	1.50+06	4.15+06	3.34+06	2.80+06
.010	5.47+05	4.77+05	1.50+05	4.15+05	3.34+05	2.80+05
.100	5.47+04	4.77+04	1.50+04	4.15+04	3.34+04	2.80+04
1.000	5.47+03	4.77+03	1.50+03	4.15+03	3.34+03	2.80+03
10.000	5.47+02	4.77+02	1.50+0	4.15+02	3.34+02	2.80+02
20.000	2.74+02	2.39+02	7.50+01	2.07+02	1.67+02	1.40+02
30.000	1.82+02	1.59+02	5.00+01	1.38+02	1.11+02	9.32+01
40.000	1.37+02	1.19+02	3.75+01	1.04+02	8.35+01	6.99+01
50.000	1.09+02	9.55+01	3.00+01	8.29+01	6.68+01	5.59+01
100.000	5.47+01	4.77+01	1.50+01	4.15+01	3.34+01	2.80+01

	50	100	200	300	400	500
.001	2.40+06	1.41+06	7.75+05	5.34+05	4.08+05	3.19+05
.010	2.40+05	1.41+05	7.75+04	5.34+04	4.08+04	3.19+04
.100	2.40+04	1.41+04	7.75+03	5.34+03	4.08+03	3.19+03
1.000	2.40+03	1.41+03	7.75+02	5.34+02	4.08+02	3.19+02
10.000	2.40+02	1.41+02	7.75+01	5.34+01	4.08+01	3.19+01
20.000	1.20+02	7.07+01	3.88+01	2.67+01	2.04+01	1.59+01
30.000	8.01+01	4.71+01	2.58+01	1.78+01	1.36+01	1.06+01
40.000	6.01+01	3.53+01	1.94+01	1.34+01	1.02+01	7.96+00
50.000	4.81+01	2.83+01	1.55+01	1.07+01	8.15+00	6.37+00
100.000	2.40+01	1.41+01	7.75+00	5.34+00	4.08+00	3.19+00

Table 5. Sedimentation Velocity of Spherical Particles vs Diameter. (He - O_2; PO_2 = 160 mm Hg; T = 20°C)

Particle Diameter-

Sedimentation Velocity - cm/sec

	μ psia ⟶	10.0	14.7	14.7 (Air)	20.0	30.0	40.0	50.0	100.0	200.0	300.0	400.0	500.0
ρ= 1	.001	1.87-06	1.36-06		1.04-06	7.19-07	5.48-07	4.44-07	2.27-07	1.15-07	7.68-08	5.78-08	4.64-08
	.010	1.87-05	1.36-05	6.78-06	1.04-05	7.21-06	5.52-06	4.48-06	2.33-06	1.25-06	9.03-07	7.33-07	6.33-07
	.100	1.95-04	1.46-04	8.68-05	1.16-04	8.60-05	7.09-05	6.18-05	4.41-05	3.57-05	3.31-05	3.18-05	3.10-05
	1.000	4.08-03	3.71-03	3.50-03	3.48-03	3.27-03	3.15-03	3.09-03	2.95-03	2.88-03	2.86-03	2.84-03	2.84-03
	10.000	2.89-01	2.87-01	3.07-01	2.86-01	2.84-01	2.83-01	2.83-01	2.82-01	2.81-01	2.81-01	2.81-01	2.81-01
	20.000	1.11+00	1.11+00	1.21+00	1.12+00	1.12+00	1.12+00	1.12+00	1.12+00	1.12+00	1.12+00	1.12+00	1.11+00
	30.000	2.50+00	2.51+00	2.69+00	2.51+00	2.52+00	2.52+00	2.52+00	2.51+00	2.49+00	2.48+00	2.47+00	2.45+00
	40.000	4.44+00	4.46+00	4.74+00	4.47+00	4.44+00	4.44+00	4.44+00	4.41+00	4.36+00	4.30+00	4.25+00	4.19+00
	50.000	6.88+00	6.90+00	7.29+00	6.90+00	6.90+00	6.88+00	6.87+00	6.79+00	6.63+00	6.48+00	6.34+00	6.20+00
	100.000	2.60+01	2.59+01	2.48+01	2.57+01	2.53+01	2.49+01	2.46+01	2.31+01	2.16+01	1.87+01	1.75+01	1.64+01

		10.0	14.7	14.7	20.0	30.0	40.0	50.0	100.0	200.0	300.0	400.0	500.0
ρ =2	.001	3.74-06	2.72-06		2.08-06	1.44-06	1.10-06	8.87-07	4.53-07	2.29-07	1.54-07	1.16-07	9.29-08
	.010	3.74-05	2.73-05	1.36-05	2.08-05	1.44-05	1.10-05	8.95-06	4.67-06	2.51-06	1.81-06	1.47-06	1.27-06
	.100	3.89-04	2.92-04	1.74-04	2.31-04	1.72-04	1.42-04	1.24-04	8.82-05	7.15-05	6.62-05	6.36-05	6.21-05
	1.000	8.15-03	7.42-03	6.99-03	6.97-03	6.53-03	6.31-03	6.17-03	5.90-03	5.76-03	5.71-03	5.69-03	5.67-03
	10.000	5.78-01	5.74-01	6.15-01	5.71-01	5.68-01	5.67-01	5.66-01	5.64-01	5.63-01	5.63-01	5.62-01	5.62-01
	20.000	2.22+00	2.23+00	2.41+00	2.23+00	2.24+00	2.24+00	2.24+00	2.24+00	2.23+00	2.22+00	2.21+00	2.21+00
	30.000	4.99+00	5.01+00	5.35+00	5.02+00	5.04+00	5.00+00	5.00+00	4.98+00	4.92+00	4.87+00	4.82+00	4.76+00
	40.000	8.80+00	8.82+00	9.33+00	8.83+00	8.83+00	8.81+00	8.79+00	8.69+00	8.47+00	8.28+00	8.10+00	7.91+00
	50.000	1.36+01	1.37+01	1.42+01	1.37+01	1.36+01	1.35+01	1.35+01	1.32+01	1.26+01	1.22+01	1.18+01	1.14+01
	100.000	4.94+01	4.89+01	4.24+01	4.82+01	4.71+01	4.61+01	4.53+01	4.27+01	3.46+01	3.12+01	2.87+01	2.64+01

		10.0	14.7	14.7	20.0	30.0	40.0	50.0	100.0	200.0	300.0	400.0	500.0
ρ =3	.001	5.61-06	4.09-06		3.12-06	2.16-06	1.65-06	1.33-06	6.80-07	3.44-07	2.30-07	1.73-07	1.39-07
	.010	5.61-05	4.09-05	2.03-05	3.12-05	2.16-05	1.65-05	1.34-05	7.00-06	3.76-06	2.71-06	2.20-06	1.90-06
	.100	5.84-04	4.38-04	2.60-04	3.47-04	2.58-04	2.13-04	1.86-04	1.32-04	1.07-04	9.93-05	9.54-05	9.31-05
	1.000	1.22-02	1.11-02	1.05-02	1.05-02	9.80-03	9.46-03	9.26-03	8.85-03	8.63-03	8.57-03	8.53-03	8.51-03
	10.000	8.67-01	8.61-01	9.22-01	8.57-01	8.53-01	8.50-01	8.49-01	8.46-01	8.44-01	8.44-01	8.44-01	8.43-01
	20.000	3.33+00	3.34+00	3.62+00	3.35+00	3.36+00	3.36+00	3.36+00	3.37+00	3.33+00	3.31+00	3.30+00	3.28+00
	30.000	7.49+00	7.52+00	7.97+00	7.48+00	7.49+00	7.48+00	7.47+00	7.42+00	7.30+00	7.18+00	7.08+00	6.96+00
	40.000	1.31+01	1.32+01	1.38+01	1.32+01	1.31+01	1.31+01	1.31+01	1.28+01	1.24+01	1.20+01	1.17+01	1.13+01
	50.000	2.03+01	2.03+01	2.07+01	2.03+01	2.02+01	2.00+01	1.99+01	1.92+01	1.82+01	1.74+01	1.68+01	1.64+01
	100.000	7.09+01	7.00+01	5.83+01	6.89+01	6.73+01	6.59+01	6.49+01	5.44+01	4.63+01	4.11+01	3.74+01	3.40+01

Figure 6-a. Sedimentation Velocity of Spherical Particles vs Pressure
(He - O_2; PO_2 = 160 mm Hg; T = 20°C; ρ = 1)

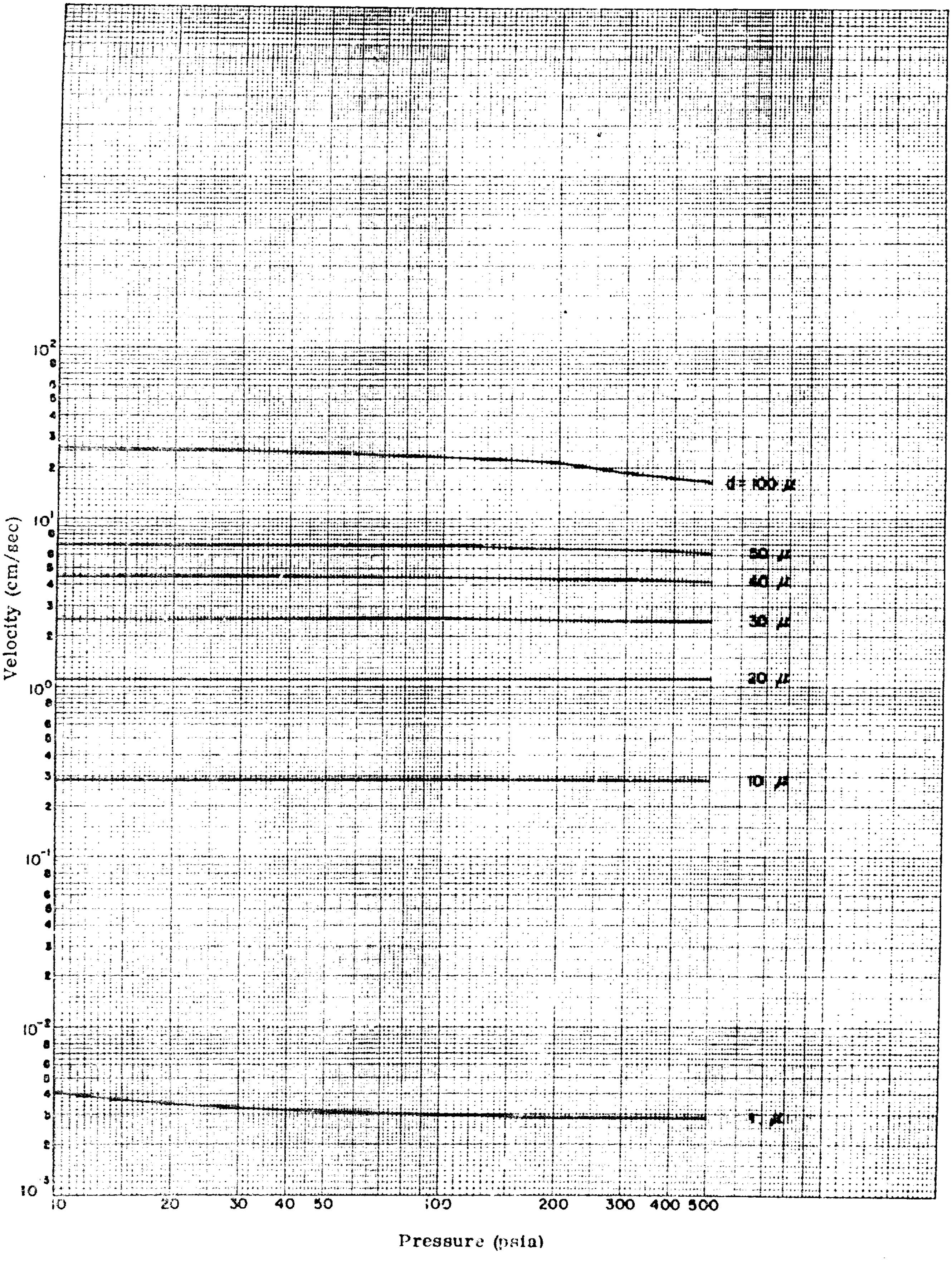
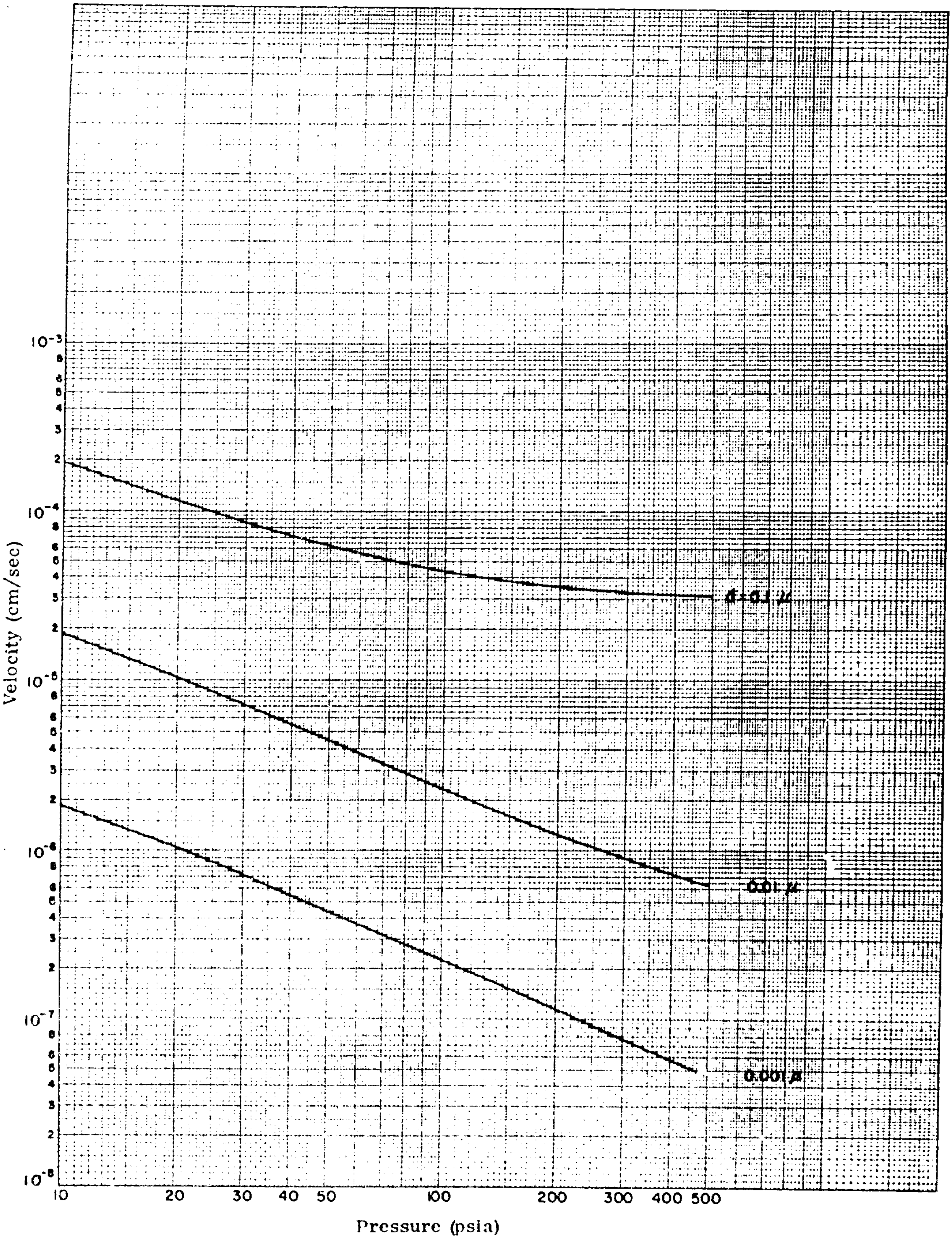


Figure 6-b. Sedimentation Velocity of Spherical Particles vs Pressure (He - O_2; PO_2 = 160 mm Hg; T = 20°C; ρ = 1)



$$-\frac{dn}{dt} = \frac{nv}{h} \quad , \qquad (15)$$

where

n = number concentration of particles,

v = sedimentation velocity, and

h = height of the vessel.

Integrating the above equation gives:

$$n = n_o \exp(-vt/h) \quad , \qquad (16)$$

where

n_o = the initial concentration of particles, and

n = concentration at any time t.

4.3 DIFFUSION

The diffusion of aerosol particles in a gas is the result of their bombardment by molecules of the gas, i.e., Brownian motion. Generally, the diffusional movement of particles is not considered for sizes above 10 microns and usually the calculations are applied only to particles below 1 micron. In considering the effects of the high pressure helium-oxygen atmosphere on diffusivity of aerosols, the factor to be evaluated is the diffusion coefficient, expressed as:(5)

$$D = kBT \text{ (slip correction)} \quad , \qquad (17)$$

where

k = Boltzmann's constant,

B = mobility, and

T = absolute temperature.

Boltzmann's constant is the universal gas constant divided by Avogadro's number and has an accepted value of 1.3708×10^{-16} erg/°C. Neither of these constants is affected by pressure or composition for an ideal gas.

The mobility (B) of the particle is defined as:

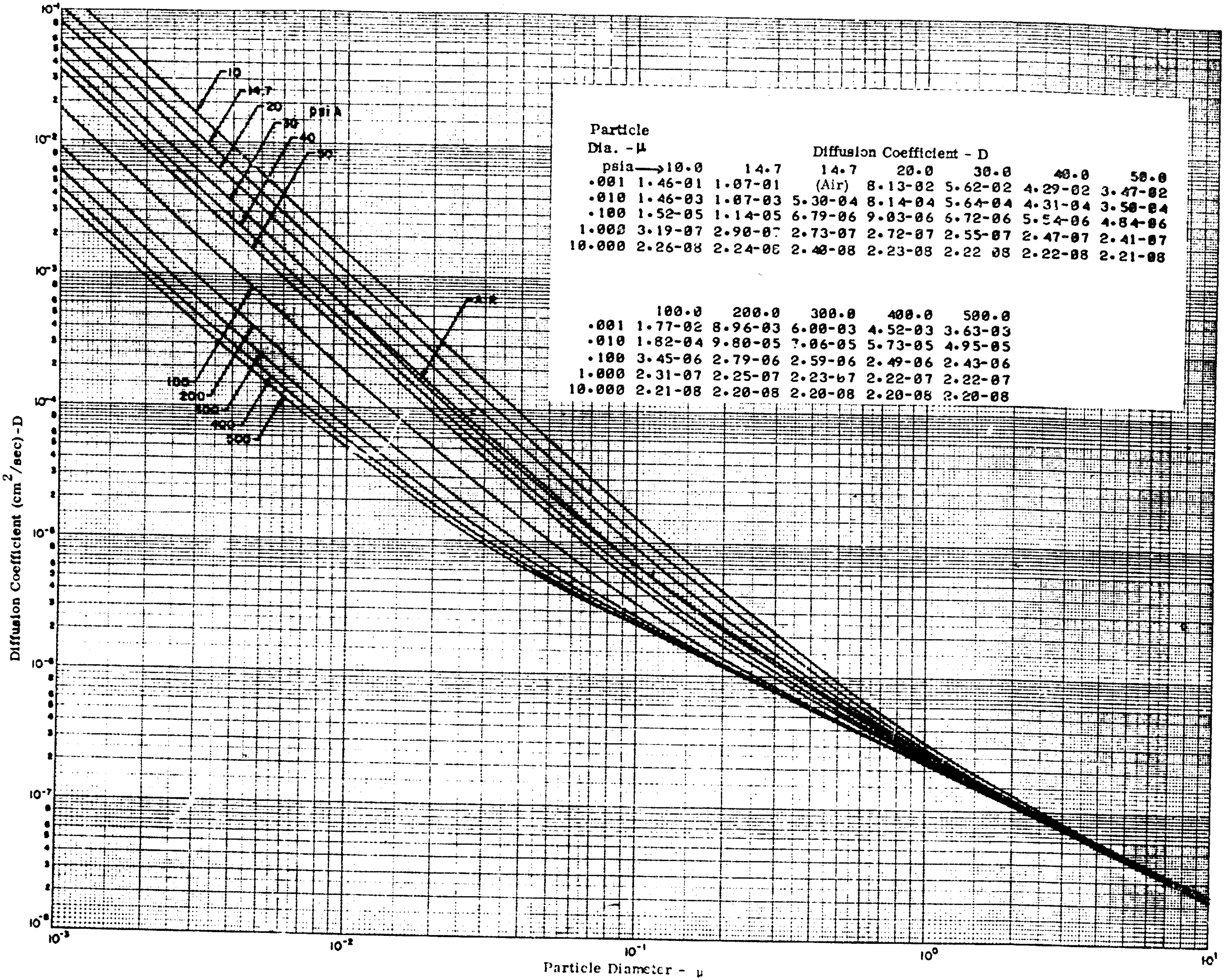
$$B = \frac{1}{3\pi \eta d} , \tag{18}$$

where

d = diameter of the particle and

η = viscosity of the fluid medium.

This is principally a definition of convenience since this quantity appears in several calculations of use in aerosol physics and tables of mobility versus diameter have been computed by various authors.(6,7) The only terms in the mobility expression that are affected by gas composition and pressure are the viscosity of the gas (which has been shown to be almost invariant over the range considered) and the slip correction (which has been discussed previously). The chart and graph shown here (Figure 7) for diffusion coefficient vs diameter are for all pressures of the mixture up to 500 psi.



Particle Dia. - μ psia →	Diffusion Coefficient - D 10.0	14.7	14.7 (Air)	20.0	30.0	40.0	50.0
.001	1.46-01	1.07-01		8.13-02	5.62-02	4.29-02	3.47-02
.010	1.46-03	1.07-03	5.30-04	8.14-04	5.64-04	4.31-04	3.50-04
.100	1.52-05	1.14-05	6.79-06	9.03-06	6.72-06	5.54-06	4.84-06
1.000	3.19-07	2.90-07	2.73-07	2.72-07	2.55-07	2.47-07	2.41-07
10.000	2.26-08	2.24-06	2.40-08	2.23-08	2.22 08	2.22-08	2.21-08

	100.0	200.0	300.0	400.0	500.0
.001	1.77-02	8.96-03	6.00-03	4.52-03	3.63-03
.010	1.82-04	9.80-05	7.06-05	5.73-05	4.95-05
.100	3.45-06	2.79-06	2.59-06	2.49-06	2.43-06
1.000	2.31-07	2.25-07	2.23-07	2.22-07	2.22-07
10.000	2.21-08	2.20-08	2.20-08	2.20-08	2.20-08

Figure 7. Particle Diffusion Coefficient vs Diameter (He - O_2; PO_2 = 160 mm Hg; T = 20°C)

Considering the reduction in numbers concentration in a confined spherical space due to diffusion, Fuchs$^{(10)}$ states the following equation in the form of an infinite series:

$$n = n_o \frac{6}{\pi^2} \sum_{\theta=1}^{\infty} \frac{1}{\theta^2} \exp\left(- D \pi^2 \theta^2 t/R^2\right) \quad , \qquad (19)$$

where

n_o = initial concentration of particles,

n = concentration at time t,

D = diffusion coefficient,

t = time,

R = radius of sphere, and

θ = integer,

Actually, there are several relationships presented by Fuchs for different specific configurations in which; or to which, diffusion is occurring. The spherical one illustrates an example relationship and is presented because there are two spherical volumes of interest to this project: viz., deep submersible vessels and the alveoli of the lung.

4.4 AGGLOMERATION

Agglomeration is a continuous and spontaneous property found, to some degree, in all aerosols. In their random Brownian movements, aerosol particles undergo numerous collisions with each other, depending upon the number concentration of the particles. Usually these collisions are "effective"; that is, when two particles touch, they remain together and form an agglomerate. The classical work on this subject was done by Whytlaw-Gray and Patterson(11) and the most recent concise reviews of all the factors that describe and effect this mechanism are presented by Green and Lane(5) and Zebel.(12) In the simple case of a monodispersed aerosol, the equation describing the decrease in numbers concentration is a coagulated aerosol may be written as:

$$-\frac{dn}{dt} = \frac{2}{3}\,\frac{k\,T\,S}{\eta}\,n^2 \text{ (slip correction)} \quad , \qquad (20)$$

where

$$\left[\frac{2}{3}\,\frac{k\,T\,S}{\eta}\right] = K = \text{coagulation coefficient,} \qquad (21)$$

k = Boltzmann's constant,

T = absolute temperature,

η = viscosity of the fluid medium,

n = number concentration of particles,

S = ratio of particles sphere of influence to particle radius = 2 for "effective" collisions, and

t = time.

This equation does not, of course, account for any other losses in the system (e.g., diffusion to containing walls or sedimentation) and, therefore, measurements are generally done on aerosols for which these factors may be neglected.

The K factor varies among aerosols. However, if it is assumed that no other losses are present and that all collisions are "effective", then the above relationship may be integrated and a general equation for the coagulation coefficient may be written as:

$$\frac{1}{n} - \frac{1}{n_o} = \frac{4}{3} \frac{kT}{\eta} t \text{ (slip correction)} \quad , \qquad (22)$$

where

n_o = initial concentration of particles, and

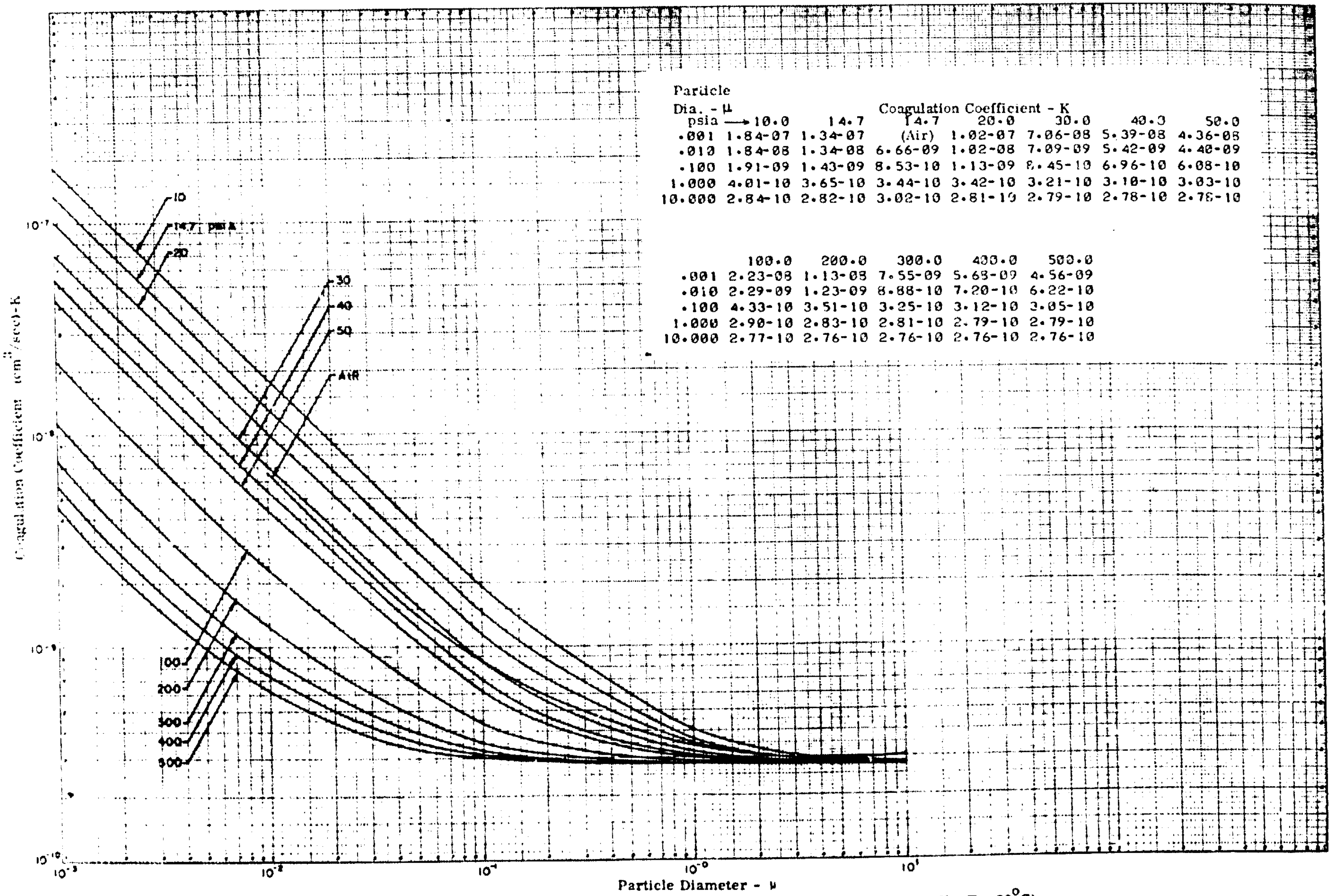
n = concentration at time t.

There are many factors that affect the rate of agglomeration, such as degree of heterogeneity (i.e., all the particles not being initially monodispersed) plus mixtures of particles of various sbustances, turbulence, particle shape, effects of the dispersion medium, differential settling, electrical effects, temperature, pressure and viscosity. All these factors have been dealt with to some degree and either increase or decrease the agglomeration rate. Specific data has been obtained for special cases; but, as a consequence of a review of these factors,(13) we have concluded that, for a specific case, the effect of interest must be evaluated and useful generalizations are very sparse.

For the purposes of this study, we have shown that changes in the medium's viscosity over the considered pressure range are slight and that therefore the only direct effect on the coagulation rate will be due to the slip correction, which decreases with increasing pressure and increasing particle size to yield a net decrease in the agglomeration rate with increasing pressure. Indirect verification of this conclusion may be obtained from the studies of Cawood and Whytlaw-Gray;(14) they worked with reduced pressures that increased the slip correction and, therefore increased the agglomeration rate. These investigators were, in fact, able to demonstrate successfully the predicted increase in the agglomeration rate with decreasing pressure. For purposes of simple calculations, Figure 8, with the accompanying table for the helium-oxygen atmosphere, gives the K factor for the pressures and size ranges of interest.

4.5 COMBINED EFFECTS OF SEDIMENTATION, DIFFUSION AND AGGLOMERATION

The preceding discussions of sedimentation, diffusion, and agglomeration have shown that for other than the slip correction factor, there is little to be considered because of the high helium content of the atmosphere and the pressure range involved. Only the simpler or purer forms of the three mechanisms have been treated - for two reasons. First, the purpose of this study must always be related to the effects on the aerosols due to the environment and then on the inhabitants of the environment. Since the effects have been found minimal for these three mechanisms, there is little point in recapitulating highly detailed information from the extensive studies referenced under each heading. Second, dealing withthe simple case permits a consideration of the combined effects of all three mechanisms.



Particle Dia. - μ / psia →	10.0	14.7	14.7 (Air)	20.0	30.0	40.3	50.0
.001	1.84-07	1.34-07		1.02-07	7.06-08	5.39-08	4.36-08
.010	1.84-08	1.34-08	6.66-09	1.02-08	7.09-09	5.42-09	4.40-09
.100	1.91-09	1.43-09	8.53-10	1.13-09	8.45-10	6.96-10	6.08-10
1.000	4.01-10	3.65-10	3.44-10	3.42-10	3.21-10	3.10-10	3.03-10
10.000	2.84-10	2.82-10	3.02-10	2.81-10	2.79-10	2.78-10	2.76-10

Coagulation Coefficient - K

	100.0	200.0	300.0	400.0	500.0
.001	2.23-08	1.13-08	7.55-09	5.68-09	4.56-09
.010	2.29-09	1.23-09	8.88-10	7.20-10	6.22-10
.100	4.33-10	3.51-10	3.25-10	3.12-10	3.05-10
1.000	2.90-10	2.83-10	2.81-10	2.79-10	2.79-10
10.000	2.77-10	2.76-10	2.76-10	2.76-10	2.76-10

Figure 8. Coagulation Coefficient vs Particle Diameter (He - O_2; PO_2 = 160 mm Hg; T - 20°C)

For the consideration of combined agglomeration, diffusion, and sedimentation, we envision a spherical vessel containing an aerosol that ideally, is monodispersed. Within this sphere, the numbers concentration, n, is continuously decreasing due to (1) loss of particles falling to the floor (sedimentation), (2) loss of particles sticking to the walls (diffusion), and (3) loss of particles sticking to each other (agglomeration). While agglomeration does not strictly constitute a reduction in the mass of material airborne, it does mean a change in numbers concentration. Investigators seldom consider these three mechanisms in junction for reasons other than the difficulty involved - which will be demonstrated shortly. The diffusion mechanism is chiefly important for submicron aerosols in which the effects of sedimentation are very slight. Conversely, when the sedimentation rate of an aerosol is considered to be of importance, the diffusional mobility of the particles is generally quite small and may not be considered. Since agglomeration is a major function of the numbers concentration of the particles, it applies to both cases. (Other size-dependent factors <u>do</u> enter into the complex (real) situation.) Sinclair$^{(10)}$ considers combined coagulation and stirred settling by simply adding the differential equations for agglomeration and settling:

$$-\frac{dn}{dt} = K n^2 + \frac{v}{h} n \quad , \qquad (23)$$

which directly integrates to the form:

$$\frac{1}{n} - \frac{Kh}{v} + \frac{Kh}{v} + \frac{1}{n_o} \exp(-vt/h) \quad . \qquad (24)$$

It is difficult to state the precise particle size range in which it is possible for the effects of both diffusion and sedimentation to be simultaneously of a degree of importance for which a combined equation must be considered. However, knowing that the effects of diffusion and diffusional mobility become quite small above 1 micron and the effects of sedimentation are (similarly) not significant below 1 micron, we may conclude that the rough order of magnitude range between 0.1 and 1 micron is worthy of consideration. Green and Lane(5) present the attempts of Davies to solve a combined equation for diffusion and sedimentation in a vessel in which it is assumed that there is no diffusional loss to the walls (i.e., infinitely wide) and that the only losses are by sedimentation and diffusion to the floor and by diffusion to the ceiling. According to Green and Lane, the results are extremely complex and involve the reduction of all physical values to dimensionless units.

In view of the preceding difficulties, the highly ideal (and therefore unrealistic) nature of the calculations, it is difficult to present a strong argument for proceeding with the development of a combined equation for the three mechanisms in a spherical vessel. Nevertheless, the references on submarine atmosphere reviewed to date indicate that a good deal of the mass present will be in the 0.1 to 1 micron size range and the final development of realistic equations have usually been observed to begin from idealized considerations. Therefore, the following development is presented with the explicit proviso that it represents an initial channel of thinking not applicable to the real current situation but only as a beginning.

In the preceding sections on diffusion, sedimentation and agglomeration, the rate equations for the reduction of particle number concentration have been stated. Before an attempt at combining these can be made, it should be noted that the equation for the rate of sedimentation is for an infinitely wide container in which there is no deposition on the walls. A separate derivation is required for the sphere. Beginning with the basic relationship that the change in concentration is equal to the concentration in, minus the concentration out, the following development may be undertaken according to Wanta.(15)

Assume that the rate of loss of particles in a chamber due to gravitational settling is proportional to the product of the concentration at the bottom surface, the gravitational settling velocity, and the projected area of the bottom surface normal to the direction of gravity. Consider a stirred chamber in which the concentration at the bottom surface is identical with the average concentration within the chamber. Then, in an apparent notation,

$$\frac{dn}{dt} \propto -XvA. \tag{25}$$

The average concentration may be expressed in terms of the number of particles in the chamber and the volume of the chamber. (A particle is lost once it touches the bottom surface.)

Then integration and customary boundary conditions yield

$$n = n_o \exp\left[-v\left(\frac{A}{V}\right)t\right] \quad . \tag{26}$$

For a hollow rectangular prism with sides a and b and height h, the shape factor A/V becomes ab/abh or 1/h and

$$n = n_o \exp\left[-\frac{vt}{h}\right] . \quad \text{(rectangular prism)} \tag{27}$$

For a hollow sphere of radius r, the shape factor A/V becomes $\pi r^2 / \frac{4}{3} \pi r^3$ or 3/4r and

$$n = n_o \exp\left[-\frac{3vt}{4r}\right] . \quad \text{(sphere)} \tag{28}$$

The actual combination of the three rate equations is not amenable to direct addition and integration. This is due to the fact that the Fuch's equation for diffusion within a sphere is in the form of an infinite series and may not be put directly in integral form. However, Fuch's presents a generalized graph of concentration (n) divided by initial concentration (n_o) versus the governing parameter Dt/R^2. This plot takes the form of an exponential curve and, for the situation in which Dt/R^2 is greater than 0 and less than 0.1, the following differential equation may be written:

$$-\frac{dn}{dt} = 2.88 \frac{n_o D}{R^2} \frac{1}{(1 - \frac{n}{n_o})} . \tag{29}$$

Combining this equation with the agglomeration and sedimentation equation yields:

$$-\frac{dn}{dt} = K n^2 + \frac{3}{4}\,\frac{vn}{R} + 2.88\,\frac{n_o D}{R^2}\,\frac{1}{1-\frac{n}{n_o}} \quad . \qquad (30)$$

Given the values for a specific case where $\frac{v}{R}$, K, n_o and $\frac{D}{R^2}$ are known, it is possible to solve this differential equation by factoring the cubic polynomial.

When Dt/R^2 is greater than 0.1 and less than a large number, the following relationship may be used:

$$-\frac{dn}{dt} = \frac{\pi^2 D n}{R^2} \quad . \qquad (31)$$

Combining Equations (20) and (31):

$$-\frac{dn}{dt} = K n^2 + \left(\frac{3}{4}\,\frac{v}{R} + \frac{\pi^2 D}{R^2}\right) n \quad . \qquad (32)$$

Solving:

$$\frac{1}{n} = -\frac{KR}{V} + \left(\frac{KR}{V} + \frac{1}{n(\tau)}\right) \exp\left[v(t-\tau)/R\right] \quad , \qquad (33)$$

where τ corresponds to $\frac{Dt}{R^2} = 0.1$ or greater.

Because of the specificity and complexity of solution, no general results are offered at this time. Note that the solution of Equation (33) in the higher range requires first a solution of the Equation (30). However, for this specific case, both of these equations are amenable to computer solution by the Runge-Kutta integration method.(16)

Finally, it should be pointed out that Fuchs(10) cites examples that indicate that serious errors can result from calculations of the type presented above which operate by a simple summing of the forces. However, he states "Unfortunately one has to resort to such summation because of the great mathematical difficulties."

SECTION 5.0: FILTRATION

5.1 INTRODUCTION

When a particle-laden air stream is forced to flow through an array of fine fibers, the particles are removed from the air stream by one or a combination of six mechanisms defined by Pich.(12) These mechanisms may be listed as:

1) diffusional deposition,
2) direct interception,
3) inertial deposition,
4) electrostatic deposition,
5) gravitational deposition, and
6) deposition influenced by molecular (Van der Waals') forces.

Pich further lists three factors to be considered in a filtration situation: "The dispersed particles, the dispersion medium (represented by the gas in the present case) and the porous substance."

A large number of theories have been presented for the various filtration mechanisms and for combinations of the mechanisms. Each has its proponents and detractors, armed with supporting evidence. These theories were first summarized in a conference report published in 1960;(17) the most recent work can be found in two chapters of the book, edited by Davies, Aerosol Science.(12) Here again, several theories and variations are presented and it still remains for the individual investigator to make his own selection. Because of this multiplicity of available theories, the complexity of the subject, and the capability of the Naval Research Laboratory, our approach has been to treat the effects of the high pressure environment in a general way, applicable to any of the theories selected for actual use.

Determination of the overall efficiency of fibrous filters requires the consideration of the six individual filtration mechanisms mentioned above and their contribution to the total efficiency. Since various mechanistic efficiencies are usually calculated on the basis of an individual fiber, the effect of many fibers in close proximity must also be accounted for (interference effect). Inasmuch as the relationships for considering the interference effect and for the summation of efficiencies are not, in their present form, affected by the pressure of the environment, they will not be treated in detail here - except for some precautionary notes regarding the balance of this discussion.

A large number of efficiency terms will be referred to in the following section. The subscript nomenclature includes:

E = efficiency of the complete intact filter

E_D = single fiber collection efficiency due to diffusion

E_R = single fiber collection efficiency due to direct interception

E_I = single fiber collection efficiency due to inertial deposition

E_G = single fiber collection efficiency due to gravitational deposition

E_M = single fiber collection efficiency due to Van der Waals' forces

E_{Qq} = single fiber collection efficiency due to electrostatic deposition (This notation indicated that both the fiber and the particles are charged. When the particle is charged and the fiber is not, the nomenclature is E_{Oq}; when the fiber is charged and the particle is not, then E_{QO}.)

E_j = efficiency due to all mechanisms (j = ER [illegible] Qq)

$E_{\beta j}$ = single fiber collection efficiency for all mechanisms when the interference effect of other fibers is being considered. (This is not to be confused with E, where the efficiency of the total filter mat is being considered.)

For each of the filtration mechanisms, there is a filtration parameter, N, that becomes an important descriptor in a first approximation of a filter's efficiency. Pich^(12) states that "by a simple summation of partial efficiencies, as used by some authors, not even approximate results can be obtained as may be demonstrated by the simplest of cases." Further, according to Ranz and Wong, ^(Pich, 12) "The main mechanism is that having the greatest parameter" (N).

5.2 DIFFUSION DEPOSITION

There are at least nine equations^(12) that describe diffusional deposition of particles on a fiber. To be sure, the choice is not truly that broad and may be somewhat reduced by considering the flow regime involved. Nevertheless, all the equations involve the Peclet number (P_e) and, usually, the Reynolds number (R_e). Since there are no other components of the equations affected by pressure or environmental composition, an appreciation of the effects may be obtained by directly examining these two numbers.

$$P_e = \frac{d_f V}{D} \quad , \tag{34}$$

where

V = gas velocity at a great distance from the fiber and

d_f = fiber diameter.

$$R_e = \frac{V d_f \rho'}{\eta} \quad , \tag{35}$$

where

ρ' = gas density, and

η = viscosity of the fluid medium.

The diffusion coefficient is unaffected by pressure or composition, but does require the application of the slip correction. For a 0.1 micron diameter particle, the magnitude of this correction varies from approximately 5 at 14.7 psia in the helium-oxygen mixture to 1.1 at 500 psia; that is, as pressure increases, the magnitude of the correction decreases and may be virtually ignored at 500 psia.

The value of Reynolds number will increase with increasing pressure, due to the rise in density of the mixture and the fact that the viscosity is relatively unaffected and not remarkably different from that of air from ambient to the 500 psia condition. However, the density increases and therefore the value of Reynolds number amounts to approximately one order of magnitude.

Because of the diversified ways in which the Peclet and Reynolds numbers are utilized in the diffusion equations, it is difficult to present a more quantitative description as to what magnitude pressure will affect the diffusion mechanism. Pich(12) discusses the experimental work of Stern et.al. at low pressures and finds a remarkable increase in efficiency at very low pressures in which the mean free path of the gas molecules has become very long, i.e., the particles are highly mobile. Extrapolating Stern's work to increased pressures shows that the curve is quite flat in the vicinity of atmospheric pressures and would seem to indicate no further change with increasing pressure. Apart from this being theoretically unlikely, concern is expressed over "some obscurities in the work of Stern et.al." and a plot of one of the diffusion equations is presented by Pich demonstrating the efficiency to be falling asymptotically as the curve passes through ambient pressure. The particular equation favored by Pich is given as:

$$E_o = 2.9\ Pe^{-2/3}\ (-\beta/2 - C)^{-1/3} \quad , \qquad (36)$$

where

β = volume fraction of the fibers and

C = a numerical factor equal to 0.5 to 0.75.

Since only the Peclet number is affected by pressure in this equation, for the five-fold reduction in the slip correction (for a 0.1 micron particle) owing to the increase in pressure to 500 psia, the net effect will be to reduce the single fiber efficiency by a factor of approximately 0.3.

The parameter that describes diffusional deposition (N_D) is simply given for this mechanism as being equal to the reciprocal of the Peclet number.

5.3 DIRECT INTERCEPTION

For this deposition mechanism, the number of equations are more limited. While the equations are solely a function of the Reynolds number and the interception parameter (N_R), Langmuir and Natanson present relationships with Reynolds number in the denominator while Friedlander places Reynolds number in the numerator.(12) However, because of the nature of the algebra involved in the equations and the fact that the Reynolds number is usually less than 1, the result should always be a reduction in the efficiency value due to an increase in the density term of the Reynolds number with increasing pressure.

Previous calculations on submicron aerosols and fibers ranging from 25-130 microns indicate that the efficiency due to direct interception is so small as to be zero or negligible.(18) The descriptive parameter for direct interception is simple defined as:

$$N_R = d_p/d_f \quad . \qquad (37)$$

5.4 INERTIAL DEPOSITION

The efficiency of removal by impaction of particles from a flowing gas stream is generally held to be not directly calculable from an equation and therefore is deduced from theoretical and experimental curves of target efficiency and the impaction parameter (Stk).(12) The literature gives various curves and compilations of curves, but it is difficult to select one for a given set of conditions since they are rather specific and depend upon the Reynolds number. The impaction parameter (N_I) is also known as the Stokes number and is given by the equation:

$$\mathrm{Stk} = \underset{f}{} , \qquad (38)$$

where

τ = relaxation time = $\frac{d_p^{\,2}\rho}{18\eta}$ (slip factor) and

ρ = particle density.

For a rough evaluation of the magnitude of impaction efficiency, Landahl and Hermann have obtained an empirical formula for $R_e = 10$:

$$E_I = \frac{\mathrm{Stk}^3}{\mathrm{Stk}^3 + 0.77\ \mathrm{Stk}^2 + 0.22} \qquad (39)$$

Therefore, for this mechanism, an appreciation of the effects of increased pressures and atmospheric composition can be gained by examining the equation directly for the parameter of the mechanism. Inasmuch as none of the terms of the equation for the impaction parameter are much affected by the atmosphere in question, the principal alteration will be in terms of the slip factor. Taking a tenth micron particle as an example, the correction factor will reduce from a value of five for helium-oxygen at ambient pressures to very nearly one at the 500 psia condition.

5.5 ELECTROSTATIC DEPOSITION

The effect of electrostatic charge present on either the particles or filter fibers or both are that the charge will make the particles adhere more strongly to the fiber surface once they are deposited and that the particles may be attracted (or repelled) from a greater distance.

In discussing electrostatic deposition, there are three separate cases to consider: charged particle, charged fiber (E_{Qq}); charged fiber, neutral particle (E_{Qo}); and neutral fiber, charged particle (E_{oq}). The collection parameter and efficiency equation for each of these mechanisms is somewhat different and, inasmuch as this material is lengthy and very clearly discussed by Pich,(12) only the affected parameters will be treated here. For particles or fibers small enough to be affected by the slip correction, this parameter will certainly apply and the magnitude of that change has already been stated several times in this discussion; i.e., its effect will be small at the elevated pressure and it may be neglected. The same finding holds for the efficiency equations and the only other consideration is one of how the particles and/or the fibers become charged. A simple relationship exists for the decrease in ionic mobility with increasing pressure, which is given as:(Whitby, 12)

$$Z_r = \frac{Z}{P} \quad , \tag{40}$$

where

Z = ionic mobility

Z_r = reduced mobility, and

P = pressure in atmospheres.

Since there will be a 34-fold reduction at the 500 psia (34 atmosphere) condition, beneficial deposition effects from charged particles are not likely. On the other hand, an efficient method of fiber charging might be sought. Experimental evidency by Silverman et.al.(19) describes an improvement in filtration when the aerosol is charged.

5.6 GRAVITATIONAL DEPOSITION

Gravitational deposition to a fiber (horizontal) is simply given by the relationship:(12)

$$E_G = \frac{v}{V} = N_G \quad , \tag{41}$$

where

v = sedimentation velocity.

It is also pointed out(12) that, for particles with a diameter of less than 0.6 microns, the mechanism is of little importance and therefore we will not consider it further.

5.7 VAN DER WAALS' FORCES

Van der Waals' or molecular forces resemble electrostatic forces in that they may influence the process of deposition and also tend to keep the particle on the floor. The constants given in the equation for the characteristic parameters and the efficiency are apparently unaffected by pressure except for the usual slip correction factor and for the viscous flow regime, for which a Reynolds number term is presented.(12)

5.8 FILTRATION CONCLUSIONS

The preceding comments on the effects of the high pressure environment on filtration were purposely kept as brief as possible because of the excellence and completeness of the review presented by Pich.(12) Of particular merit is the system developed by Pich for a filtration parameter (N); a system that permits a first order evaluation of the predominant effect in any given fiber filter system.

The conclusion that we can draw is that effective filtration is entirely possible in the high-pressure environment. The apparent starting point for both a series of calculations and experiments would appear to be the "absolute" type filter configuration commonly in use for all types of environmental situations. The probability seems high that the necessary experiments would entail verification, rather than primary investigation, of the mechanisms.

SECTION 6.0: EVAPORATION, CONDENSATION AND NUCLEATION

Considering the evaporation, condensation, and nucleation of materials within the helium-oxygen environment is to permit a determination of the promotion or inhibition of aerosol existence due to the high-pressure and helium-rich atmosphere involved. While it would be desirable to examine a long list of materials and consider their propensity to exist as aerosols with the increasing pressure, we have observed a singular lack of the necessary information and a complexity in the computations that has [illegible]ed the consideration to be limited to water vapor.

The evaporation (condensation) rate of droplets is given varied presentation in modern literature, especially by Fuchs,(20) Orr,(21) Amelin,(22) and Green and Lane.(5) The basic equation is presented in various ways; however, all the developments may be stated in the following form:

$$-\frac{dm}{dt} = \frac{2\pi\ d\ M_l\ D_{l(23)}}{R\ T} \times \frac{(\delta\ p_t - p)}{2\ D_{l(23)}/d\ \upsilon\ \alpha + \frac{2}{d + 2\Delta}} \qquad (42)$$

where

d = droplet diameter - cm,

M_l - molecular weight of the liquid vapor - g/mole,

$D_{l(23)}$ - diffusivity of the liquid vapor through the gas - cm^2/sec,

R = gas constant - 8.317×10^7 ergs/$^{\circ}$K-mole,

T = temperature - $^{\circ}K$,

δ = degree of saturation (1 = 100% RH, this value used for all calculations),

p_t = vapor pressure of the liquid - dynes/cm^2 (see Appendix II)

p = vapor pressure of the droplet - dynes/cm^2 (see Appendix II)

$\upsilon = (RT/2\pi M_1)^{1/2}$ - cm/sec,

α = evaporation (condensation) coefficient - 0.04 for H_2O, and

$\Delta \approx \lambda$ the mean free path of the molecules - cm.

The Δ function given in the above equation is a development of Fuchs;(20) he found certain deficiencies in Langmuir's(5) relationship when the droplets considered were small or the pressure was low. Basically, Fuchs' theory considers that molecules are coming to or leaving a spherical shell that envelops the droplet and whose thickness equals approximately the mean free path length of a molecule (λ). Green and Lane report that this theory has been tested and found to account for the deficiencies in Langmuir's formula. While it is not a necessary correction over the entire size range considered, it is simpler, for machine computations, to use it in all cases. The results of these calculations are shown in Figure 9 and Table 6; these illustrations show that increasing pressure and an increasing mole fraction of helium results in decreased evaporation (condensation) rate. In addition, Figure 9, points up that the rate is nearly constant for the smallest size droplets considered but undergoes order of magnitude decreases for the larger particles when the pressure is increased.

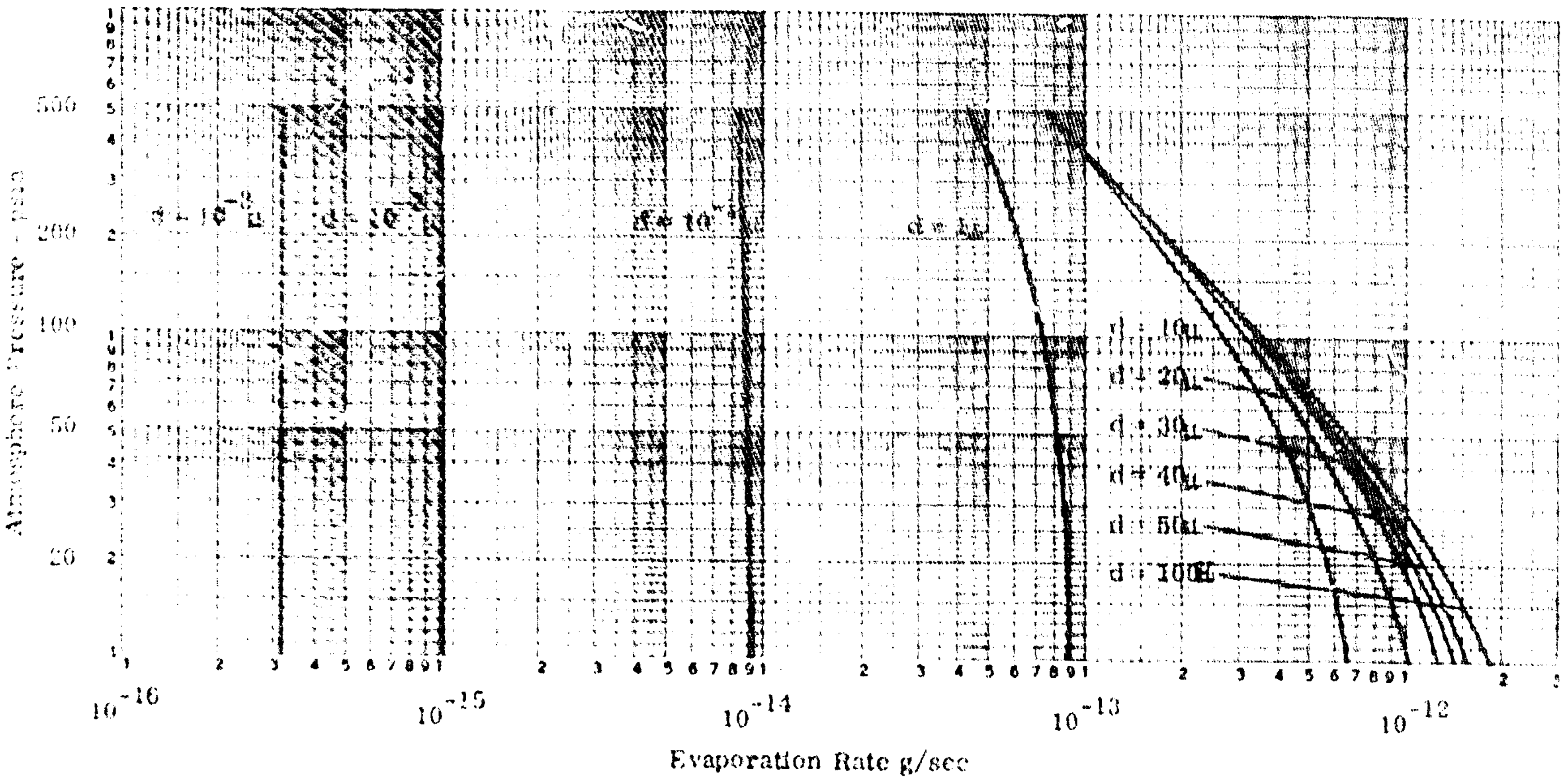


Figure 9. Oxygen-Helium Atmosphere Pressure vs: H_2O Droplet Evaporation Rate. (PO_2 = 160 mm Hg; PH_2O = 23.37 mm Hg; T = 20°C)

Table 6. Oxygen Helium Atmosphere Pressure and Droplet Diameter vs:
Droplet Vapor Pressure
Droplet Temperature
Droplet Evaporation Rate
Droplet Evaporation Time

	P Atmosphere Pressure psia	p Droplet Vapor Pressure dynes/cm^2	$T_d = 293-$ Droplet Temp. (depression) ^oK	dm/dt Droplet Evap. (cond.) Rate g/sec	t Droplet Evap. Time sec
$d = 10^{-3}\mu$	10.0	.26734572+06	.25711516-01	-.32181549-14	-.48703032-06
	14.7	.26733573+06	.20617039-01	-.32180186-14	-.48714447-06
	20.0	.26732983+06	.17590911-01	-.32179379-14	-.48721438-06
	30.0	.26732411+06	.14693715-01	-.32178590-14	-.48728037-06
	40.0	.26732122+06	.13206584-01	-.32178185-14	-.48731320-06
	50.0	.26731948+06	.12301578-01	-.32177935-14	-.48733185-06
	100.0	.26731578+06	.10462177-01	-.32177322-14	-.48736022-06
	200.0	.26731401+06	.95273826-02	-.32176667-14	-.48735094-06
	300.0	.26731337+06	.92133751-02	-.32175915-14	-.48733051-06
	400.0	.26731308+06	.90557902-02	-.32174977-14	-.48730972-06
	500.0	.26731291+06	.89609442-02	-.32173832-14	-.48729082-06
$d = 10^{-2}\mu$	10.0	.38622619+05	.81320512-02	-.10178396-13	-.15396663-03
	14.7	.38622573+05	.65209600-02	-.10178266-13	-.15399311-03
	20.0	.38622547+05	.55638927-02	-.10178132-13	-.15400762-03
	30.0	.38622520+05	.46475142-02	-.10177852-13	-.15401807-03
	40.0	.38622506+05	.41770608-02	-.10177517-13	-.15402074-03
	50.0	.38622499+05	.38906987-02	-.10177121-13	-.15402062-03
	100.0	.38622482+05	.33080700-02	-.10174252-13	-.15401584-03
	200.0	.38622473+05	.30098165-02	-.10165002-13	-.15403692-03
	300.0	.38622470+05	.29071068-02	-.10152504-13	-.15409549-03
	400.0	.38622469+05	.28533432-02	-.10137851-13	-.15417898-03
	500.0	.38622468+05	.28190629-02	-.10121708-13	-.15427959-03
$d = 10^{-1}\mu$	10.0	.31829084+05	.73626242-02	-.92153511-13	-.16983965-01
	14.7	.31829080+05	.59012367-02	-.92109685-13	-.16989034-01
	20.0	.31829078+05	.50320456-02	-.92052138-13	-.16994231-01
	30.0	.31829076+05	.41976395-02	-.91926463-13	-.17004547-01
	40.0	.31829075+05	.37670186-02	-.91784388-13	-.17016199-01
	50.0	.31829075+05	.35330392-02	-.91630981-13	-.17029009-01
	100.0	.31829073+05	.29515466-02	-.90777344-13	-.17103693-01
	200.0	.31829073+05	.26337934-02	-.88950656-13	-.17274407-01
	300.0	.31829072+05	.24950241-02	-.87133849-13	-.17454427-01
	400.0	.31829072+05	.24027696-02	-.85369751-13	-.17637929-01
	500.0	.31829072+05	.23302616-02	-.83666905-13	-.17823156-01

Table 6. Continued

	P Atmosphere Pressure psia	p Droplet Vapor Pressure dynes/cm^2	T_d 293-. Droplet Temp. (depression) °K	dm/dt Droplet Evap. (cond.) Rate g/sec	t Droplet Evap. Time sec
d = 1μ	10.0	.31219245+05	.70975289-02	-.88835474-12	-.17346023+01
	14.7	.31219244+05	.56351613-02	-.87956636-12	-.17437458+01
	20.0	.31219244+05	.47545789-02	-.86976388-12	-.17539561+01
	30.0	.31219244+05	.38896377-02	-.85181363-12	-.17730528+01
	40.0	.31219244+05	.34252060-02	-.83456034-12	-.17921060+01
	50.0	.31219244+05	.31271420-02	-.81798425-12	-.18111464+01
	100.0	.31219243+05	.24192474-02	-.74406024-12	-.19063790+01
	200.0	.31219243+05	.18658367-02	-.63014583-12	-.20970136+01
	300.0	.31219243+05	.15648042-02	-.54647734-12	-.22877485+01
	400.0	.31219243+05	.13578010-02	-.48242301-12	-.24785182+01
	500.0	.31219243+05	.12026602-02	-.43180927-12	-.26693056+01
d = 10μ	10.0	.31158907+05	.52720059-02	-.65986506-11	-.20381115+03
	14.7	.31158907+05	.39349192-02	-.61418339-11	-.21275358+03
	20.0	.31158907+05	.31122174-02	-.56932364-11	-.22288624+03
	30.0	.31158907+05	.22841803-02	-.50022546-11	-.24199692+03
	40.0	.31158907+05	.18305571-02	-.44601993-11	-.26110725+03
	50.0	.31158907+05	.15383532-02	-.40239575-11	-.28021491+03
	100.0	.31158907+05	.87855145-03	-.27020598-11	-.37573628+03
	200.0	.31158907+05	.48280757-03	-.16305778-11	-.56675572+03
	300.0	.31158907+05	.33432673-03	-.11675708-11	-.75776297+03
	400.0	.31158907+05	.25594210-03	-.90935531-12	-.94878243+03
	500.0	.31158907+05	.20740208-03	-.74466699-12	-.11397944+04
d = 20μ	10.0	.31155558+05	.40924798-02	-.10244619-10	-.95226296+03
	14.7	.31155558+05	.29437147-02	-.91894169-11	-.10231020+04
	20.0	.31155558+05	.22475676-02	-.82230336-11	-.11037174+04
	30.0	.31155558+05	.15655905-02	-.68571471-11	-.12561728+04
	40.0	.31155558+05	.12063515-02	-.58786130-11	-.14088310+04
	50.0	.31155558+05	.98326646-03	-.51439701-11	-.15615584+04
	100.0	.31155558+05	.51453403-03	-.31649860-11	-.20254783+04
	200.0	.31155558+05	.26477478-03	-.17884362-11	-.38535703+04
	300.0	.31155558+05	.17843971-03	-.12463314-11	-.53817188+04
	400.0	.31155558+05	.13459428-03	-.95641939-12	-.69098767+04
	500.0	.31155558+05	.10865439-03	-.77592781-12	-.84380391+04
d = 30μ	10.0	.31154442+05	.33439820-02	-.12556374-10	-.24512836+04
	14.7	.31154442+05	.23512966-02	-.11010092-10	-.26894520+04
	20.0	.31154442+05	.17588581-02	-.96525346-11	-.29609552+04
	30.0	.31154442+05	.11909196-02	-.78241852-11	-.34749311+04
	40.0	.31154442+05	.89959353-03	-.65756483-11	-.39898603+04
	50.0	.31154442+05	.72254784-03	-.56700280-11	-.45051380+04
	100.0	.31154442+05	.36379908-03	-.33566842-11	-.70830391+04
	200.0	.31154442+05	.18240310-03	-.18480805-11	-.12240247+05
	300.0	.31154442+05	.12169637-03	-.12750020-11	-.17397780+05
	400.0	.31154442+05	.91304760-04	-.97320950-12	-.22555375+05
	500.0	.31154442+05	.73056635-04	-.78694003-12	-.27712999+05

Table 6. Continued

	P Atmosphere Pressure psia	p Droplet Vapor Pressure dynes/cm^2	$T_d = 293-$ Droplet Temp. (depression) °K	dm/dt Droplet Evap. (cond.) Rate g/sec	t Droplet Evap. Time sec
d = 40μ	10.0	.31153884+05	.28268928-02	-.14153003-10	-.49068336+04
	14.7	.31153884+05	.19573590-02	-.12220606-10	-.54702338+04
	20.0	.31153884+05	.14447128-02	-.10571353-10	-.61130765+04
	30.0	.31153884+05	.96094698-03	-.84177250-11	-.73306918+04
	40.0	.31153884+05	.71721514-03	-.69900493-11	-.85508987+04
	50.0	.31153884+05	.57111354-03	-.59755762-11	-.97720744+04
	100.0	.31153884+05	.28137065-03	-.34615181-11	-.15882219+05
	200.0	.31153884+05	.13912223-03	-.18794194-11	-.28106589+05
	300.0	.31153884+05	.92334443-04	-.12898401-11	-.40331820+05
	400.0	.31153884+05	.69085094-04	-.98182985-12	-.52557281+05
	500.0	.31153884+05	.55185658-04	-.79256518-12	-.64782864+05
d = 50μ	10.0	.31153549+05	.24482906-02	-.15321886-10	-.85248769+04
	14.7	.31153549+05	.16764736-02	-.13083643-10	-.96238957+04
	20.0	.31153549+05	.12257769-02	-.11211682-10	-.10878552+05
	30.0	.31153549+05	.80541634-03	-.88191322-11	-.13255867+05
	40.0	.31153549+05	.59631987-03	-.72647391-11	-.15638657+05
	50.0	.31153549+05	.47215689-03	-.61752333-11	-.18023503+05
	100.0	.31153549+05	.22939509-03	-.35276201-11	-.29956848+05
	200.0	.31153549+05	.11244174-03	-.18987365-11	-.53832455+05
	300.0	.31153549+05	.74386848-04	-.12989978-11	-.77709901+05
	400.0	.31153549+05	.55563267-04	-.98707390-12	-.10158785+06
	500.0	.31153549+05	.44338630-04	-.79597842-12	-.12546599+06
d = 100μ	10.0	.31152880+05	.14663280-02	-.18353114-10	-.51261526+05
	14.7	.31152880+05	.97609804-03	-.15235465-10	-.60030483+05
	20.0	.31152880+05	.69736633-03	-.12757033-10	-.70053303+05
	30.0	.31152880+05	.44516237-03	-.97488467-11	-.89057971+05
	40.0	.31152880+05	.32359262-03	-.78844071-11	-.10811278+06
	50.0	.31152880+05	.25298412-03	-.66174395-11	-.12718718+06
	100.0	.31152880+05	.11925196-03	-.36676961-11	-.22264536+06
	200.0	.31152880+05	.57400923-04	-.19385916-11	-.41364704+06
	300.0	.31152880+05	.37723878-04	-.13174328-11	-.60466740+06
	400.0	.31152880+05	.28081644-04	-.99773178-12	-.79569349+06
	500.0	.31152880+05	.22361924-04	-.80289396-12	-.98671915+06

Two formulas determine the lifetime of a given size droplet. One is according to Langmuir; the other is derived from Fuchs and includes his expression for the vapor shell (Δ) surrounding the droplet. According to Green and Lane,(5) the difference between the two becomes significant below 1 micron initial droplet diameter and therefore the Fuchs relationship will be utilized here as being more correct for all purposes. The net effect of utilizing the Fuchs expression is that longer droplet lifetimes are found than with the Langmuir expression:

$$t = \frac{d\,R\,T\,\rho_L}{2\alpha\,\nu(\delta p_t - p)\,M_1} \quad \frac{R\,T\,\rho_L}{D_{1(23)}(\delta p_t - p)\,M_1} \left[\frac{d^2}{8} - \frac{d}{2}\Delta + \Delta^2 \log\left(1 + \frac{d}{2\Delta}\right)\right] , \qquad (43)$$

where

ρ_L = liquid density - g/cm^3,

It can be readily observed in Figure 10 and Table 6 that, for increasing pressures, the droplet lifetime will be increased and the evaporation rate depressed. This will significantly increase the existence time for aerosols formed from the bulk liquid in the high pressure environment.

The "critical diameter" of a droplet is that particle size that, for a given saturation value, will grow by condensation to a larger size. Particles below the critical diameter in size will not grow and their mass will be lost to the

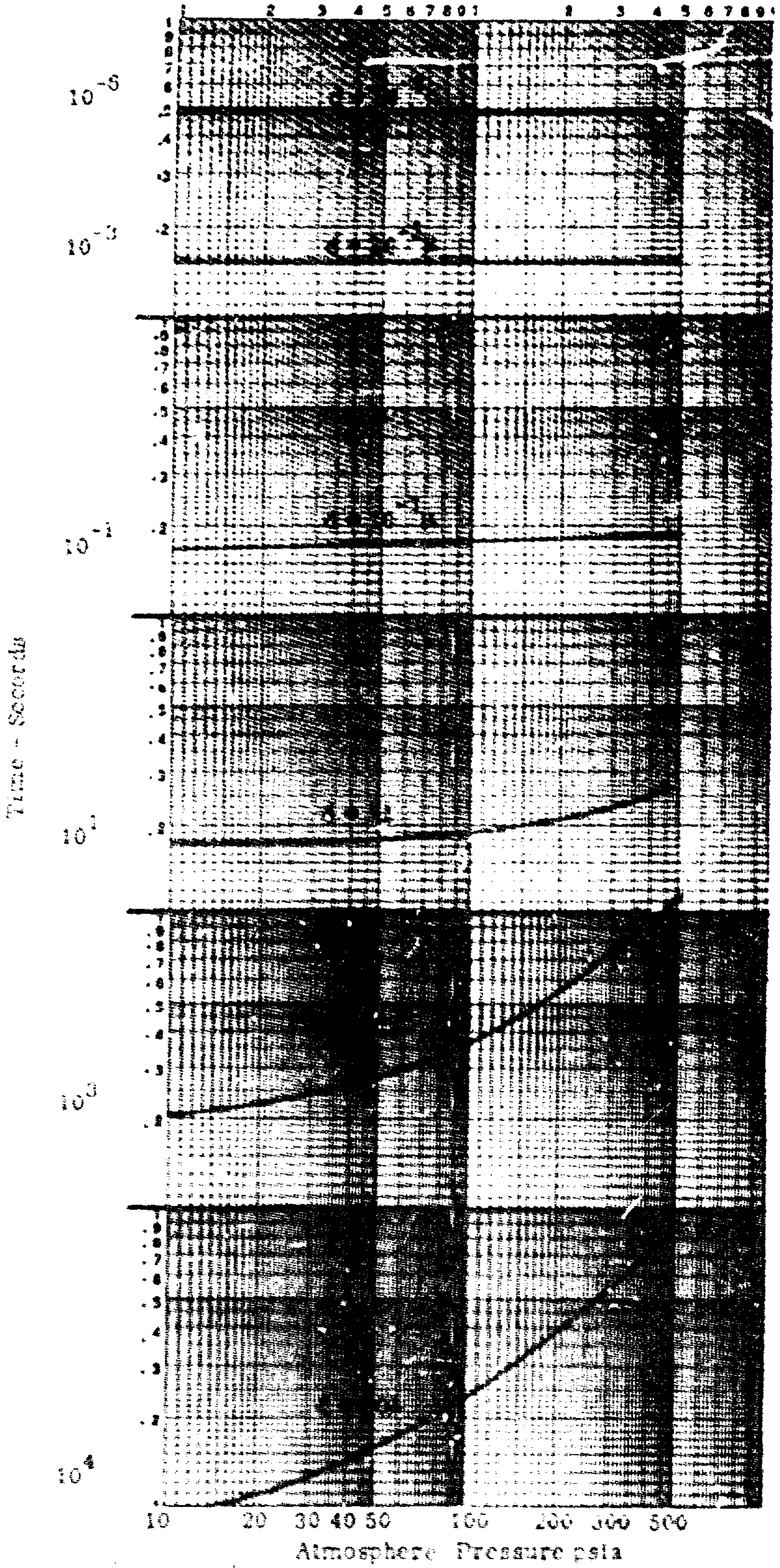


Figure 10. Droplet Evaporation Time vs Pressure for Various Droplet Diameters (PO_2 = 160 mm Hg; PH_2O = 23.37 mm Hg; T = 20°C.

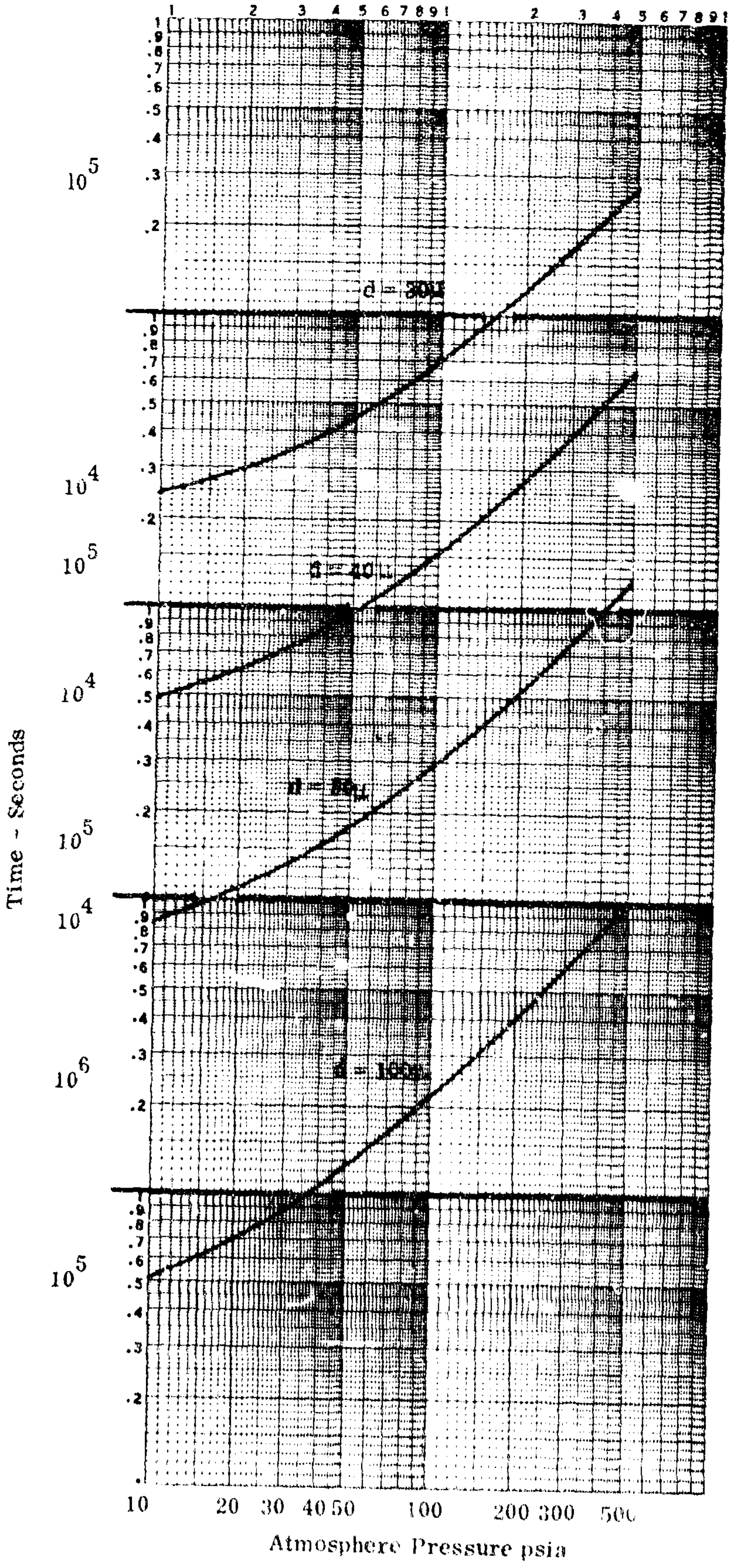


Figure 10. Continued

growth of the larger particles.(21) According to Bradley's work on high pressure nucleation, the critical radius is determined from the formula:(23)

$$d_c = \frac{4\gamma M_1}{\rho_L (r T \ln S - P' V_L)} \qquad (44)$$

where

d_c = critical diameter - cm,

γ = surface tension of the liquid - dyne/cm,

S = saturation ($S = 1 = 100\%$ RH)

V_L = molecular volume - cm^3/g-mole, and

P' = environment pressure - dynes/cm^2

An S value of 2 (200% relative humidity) has been selected for illustrative purposes only. This supersaturation could be achieved in a saturated atmosphere during a sudden,16% decrease in pressure. While this condition is not likely, it does indicate the slight pressure fluctuations that will cause relatively high saturations and promote droplet growth.(24) Table 7 presents the results of these calculations for the environment and demonstrates that the critical diameter increases with increasing pressure; however, the change is far too slight to be of importance.

The net results of the preceding series of calculations can be simply stated in the following way. The propensity of aerosols to form by condensation

P Atmosphere Pressure psia	$D_{1(23)}$ Diffusion Coefficient cm^2/sec	K_{123} Thermal Conductivity cal/sec-cm-°K	d_c Critical Diameter μ
10.0	.7362+00	1.165-04	.31033-02
14.7	.5867+00	1.453-04	.31044-02
20.0	.4761+00	1.703-04	.31056-02
30.0	.3507+00	2.039-04	.31079-02
40.0	.2774+00	2.268-04	.31102-02
50.0	.2294+00	2.435-04	.31124-02
100.0	.1229+00	2.863-04	.31240-02
200.0	.6372-01	3.144-04	.31473-02
300.0	.4301-01	3.251-04	.31709-02
400.0	.3246-01	3.307-04	.31949-02
500.0	.2606-01	3.342-04	.32193-02

Table 7. Oxygen-Helium Atmosphere Pressure vs:
H_2O Vapor Diffusivity
Atmosphere Thermal Conductivity
Critical Droplet Diameter (S = 2)
(PO_2 = 160 mm Hg; T = 20°C)

processes is retarded by the composition of the special atmosphere and its increasing pressure. However, aerosols thus formed should be found to have a longer life-time with increasing pressure of the environment.

At this point, we have not attempted to discuss or investigate the actual aerosol formation processes or early growth. The sources from which an aerosol can arise are most numerous and there is little or no information available for extrapolation or consideration.

SECTION 7.0: ELECTRIFICATION AND PRECIPITATION OF AEROSOLS

7.1 THEORY

The electrification of aerosol particles is of great importance to the purposes of this project, for two reasons. First, none of the mechanistic equations discussed take into account the charge on the aerosol particles or its nature. The force that can be exerted on a charged particle in an electric field may be many times that of gravity and this one force may override other considerations. Second, the device most successfully used for the cleansing of submarine atmospheres has been the electrostatic precipitator and it therefore becomes of vital importance to determine its projected operating characteristics in the helium-oxygen atmosphere and at the pressures to be considered. Because both particle charging and precipitation are to be considered in this discussion and because of the complex terminology involved in considering electrification, we believe that our considerations will be more understandable if presented in what is usually considered a "reverse" order. To this end, we begin with a statement of the efficiency equation for electrostatic precipitation and shall proceed backwards, introducing the terms required and the effects of the helium-oxygen atmosphere.

Consider an electrostatic precipitator to be a simple rod and tube device in which a fine wire or rod is concentrically contained in a cylindrical shell of some length, l. A positive or negative potential may be applied to the center wire electrode while maintaining the tube at ground conditions. Aerosol laden gas is passed axially through this configuration and the aerosol will be found to deposit, with some efficiency, on the inside walls of the tube. The expression for the efficiency of this collection is given by White(25) as

$$M = 1 - \exp\left(-\frac{2\,u\,l}{R\,V}\right), \tag{45}$$

where

M = collection efficiency,
u = drift velocity of the particles,
l = length of precipitator,
R = radius of the tube, and
V = axial velocity of the particles (generally taken as the gas velocity).

All of the terms in the above equation are readily determinable in the design situation with the exception of the drift velocity of the particles, which is dependent upon several conditions (including the applied potential with its resultant field, particle size, gas composition, temperature, and pressure). Particle charging occurs by two basic mechanisms. In diffusion charging, the process occurs without the presence of an applied electric field, that is, the particles were charged from collisions with ions* undergoing random thermal

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*According to Whitby,(12) "Thus, a small ion will be defined here as any molecule or atom which has a net electric charge or any charged molecular cluster which will disintegrate upon loss of charge. Any charge carrier in a gas which is not a small ion will simply be called a charged particle. The boundary between these two kinds of charge carriers will be taken as corresponding to a particle diameter of about 15Å and a mobility of about 0.1 cm^2/volt-sec."

motion. In the field charging process, the aerosols are in an applied electric field and the ions are thought to be driven along the electric force lines onto the particles. Summarizing the work of several investigators, Green and Lane(5) state that when the particles are less than 1 micron in size, charging is thought to be by diffusion rather than the field mechanism. Larger particles in an applied field are charged by the field mechanism although they may also be charged by diffusion in the absence of an applied field. After an extensive series of experiments, Liu and Yeh(26) have accepted this conclusion and developed a charge theory containing both terms which the diffusion term predominates as the particle size decreases. Inasmuch as this theory is complex and capable of solution only by numerical integration, only the separate relationships for diffusion and field charging will be presented here. The simpler approach is being adopted because at the present time the variation of ionic mobility with pressure and composition in their theory has not been clarified.

Returning to the efficiency equation, the drift velocity for field charging is given as:

$$u = \frac{(ne)\,E}{3\pi\,\eta\,d}\ \text{(slip correction)}, \qquad (46)$$

where

n = number of electronic charges, e,

note: the product ne is the charge q, acquired in time, t.

E = collection field strength,

η = viscosity of the gas, and

d = diameter of the particles.

For the above equation the quantity not directly available is the quantity of charge (q) acquired in time (t). The relationship for the value of this charge is given by Green and Lane(5) as:

$$q = n_s e = p E_o \frac{d^2}{4} \quad , \tag{47}$$

where

n_s = total or saturation charge,

E_o = charging field strength, and

p = a factor equal to 3 for conducting particles and insulating particles:

$$p = 1 + 2 \frac{\varepsilon - 1}{\varepsilon + 2} \tag{48}$$

where

ε = dielectric constant.

Note: Actually, the above equation is for the total charge (n_s) that may be placed on the particle regardless of the time. When time is considered, then the actual charge which may be placed on the particle is somewhat less than the limiting value n_s indicated above. The relationship between n and n_s is given by White$^{(25)}$ as:

$$\frac{n}{n_s} = \frac{\pi N_o e Z t}{\pi N_o e Z t + 1} , \tag{49}$$

where

N_o = ion concentration at a large distance from the particle,

Z = electric mobility of the ions, and

t = charging time.

The preceding equations may now be directly substituted and applied to the relationship for q.

$$q = ne \frac{E_o d^2}{4} \left[\frac{\pi N_o e Z t}{\pi N_o e Z t + 1}\right] \left[1 + 2 \frac{\varepsilon - 1}{\varepsilon + 2}\right] . \tag{50}$$

This relationship may then be substituted into the equation for the drift velocity (u) of the particles due to the applied field in the presence of the collecting field which takes the form:

$$u = \left[\frac{E E_o d}{12\pi \eta}\right] \left[\frac{\pi N_o e Z t}{\pi N_o e Z t + 1}\right] \left[1 + 2 \frac{\varepsilon - 1}{\varepsilon + 2}\right] \text{ (slip correction)} . \tag{51}$$

Hence, for the field charging situation, the above expression for the drift velocity of the particles may be inserted into the efficiency equation; for particles significantly greater than 1 micron, a reasonable prediction of efficiency is available.

Of the texts investigated to date, the collection efficiency for particles charged by the diffusion mechanism is not specifically developed and this is so for certain practical reasons since the field charging mechanism stemming from the corona existing in industrial electrostatic precipitators is far more effective for charging purposes than the diffusion method. Further, the aerosols treated generally consist of both micron and submicron particles and, as was stated earlier, equations for both processes are neither readily combinable nor has experiment shown it possible to do so directly. However, re-examining the equation for the drift velocity given above, the term for the rate of charge acquisition with time has been developed by White, as quoted by Liu and Yeh:

$$q = ne = \frac{d\,k\,T}{2e} \ln\left(1 + \frac{\pi\, e\, \bar{c}\, d\, N_o\, t}{2\,k\,T}\right) , \qquad (52)$$

where

k = Boltzmann's constant,

T = absolute temperature, and

$\bar{c}$ = R.M.S. velocity of the ions.

This relationship may then be substituted into the drift velocity expression giving a final equation for the diffusion case as:

$$u = \frac{E\,k\,T}{6\,e} \ln \left[1 + \frac{\pi\, e\, \bar{c}\, d\, N_0\, t}{2\,k\,T} \right] , \tag{53}$$

Having expressed the relationships for the collection efficiency of a precipitator and the methods by which the particles are charged, we may now investigate the individual components of these equations to determine the effects of the high-pressure helium-oxygen environment. Concerning the mobility of the ions (Z), Whitby(12) states that the mobility of the small ions is reduced linearly with increasing pressure according to the relationship:

$$Z_r = \frac{Z}{P} \quad , \tag{40}$$

where

Z_r = reduced mobility, and

P = pressure in atmospheres.

At the 500 psia (34 atmosphere) condition, there will be a 34-fold reduction in the mobility of the ions, thus greatly reducing the drift velocity of the particles. This problem is further complicated by the fact that, according to White,(25) negative corona will not exist in pure helium and, when the voltage is raised to a point that would correspond to corona onset, spark-over will occur. Oxygen, on the other hand, has a strong electron affinity and will produce a very stable negative corona. White(25) states that these determinations of collection efficiency under various abnormal circumstances of composition, pressure, and temperature are not amenable to theoretical treatment and are properly dealt with on a direct experimental basis.

Concerning the relationship for charge acquired by the diffusion process, it is even more difficult to stipulate the effects of the high-pressure environment. The RMS speed of the ions may be calculated according to Loeb(3) from the expression:

$$\bar{c}^2 = \frac{4}{\pi k m} , \qquad (54)$$

where

m = ion mass.

Seemingly, the speed is constant since the Boltzmann's constant will not vary under the conditions assumed, nor would the mass. However, in the Liu and Yeh(26) verification of White's equation for diffusion charging, they found that the experimental data could only be verified when the mean thermal speed of the ions was taken as a value considerably smaller than the mean thermal speed of air molecules. Quoting Liu and Yeh, "it was suggested that the discrepancy in the mean thermal speeds of the ions and the air molecules could be explained if it was assumed that the ions produced by a corona discharge were actually molecular clusters with an effective molecular weight equal to sixteen times the molecular weight of air." Actually, it can be seen that Liu and Yeh are dealing with diffusional charging of submicron particles and the charging is taking place in the field of a corona discharge. This is entirely correct, since they are dealing with submicron particles in a corona discharge that have been found to receive their charge via the diffusion process only.

7.2 CORONA STUDIES

Inasmuch as White(13) specifically states that the existence of negative corona discharge in pure helium is not possible and because of the potential utility and importance of precipitator applications in undersea vessels, it was considered necessary to perform experiments in this area to determine if the small quantities of oxygen present at the higher pressures would be sufficient to maintain a corona discharge. The experimental apparatus designed for this purpose is shown in Figures 11 and 12. A heavy wall brass tube was constructed with a 3/4 in. precision bore diameter (1.915 cm). The collecting electrode was a 1/16 in. diameter polished brass rod (0.159 cm) with an effective length of 11.7 cm. The rod was supported by the high voltage input attachment fixture (Figure 11) and the free end was rounded. Potential gradients were provided by a stabilized dc power supply (Sorensen Model 230-6P) with a capability of 0 to 32,000 volts, 0 to 8 milliamps. Pressures below 1 atmosphere were measured with a vertical mercury manometer; above 1 atmosphere, up to 500 psi, with a precision Ashcroft test gauge. The balance of the equipment attached to the test apparatus in Figure 12 consisted of the numerous needle and latch-type valves necessary to the test procedure described below. Also not shown was a vacuum pump with a capability to 15 microns Hg.

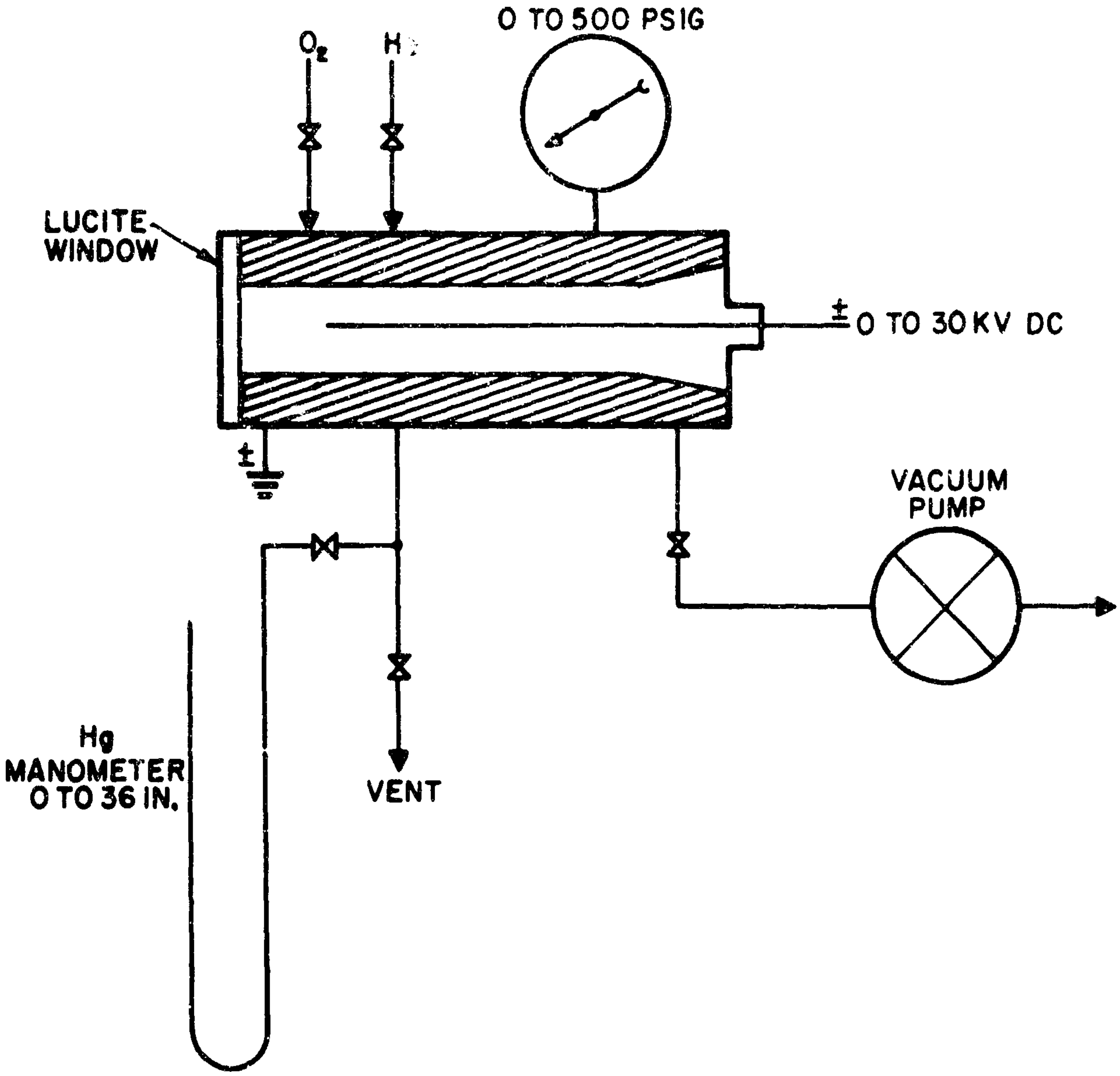

Figure 11. Schematic of Electrostatic Precipitator Experimental Apparatus.

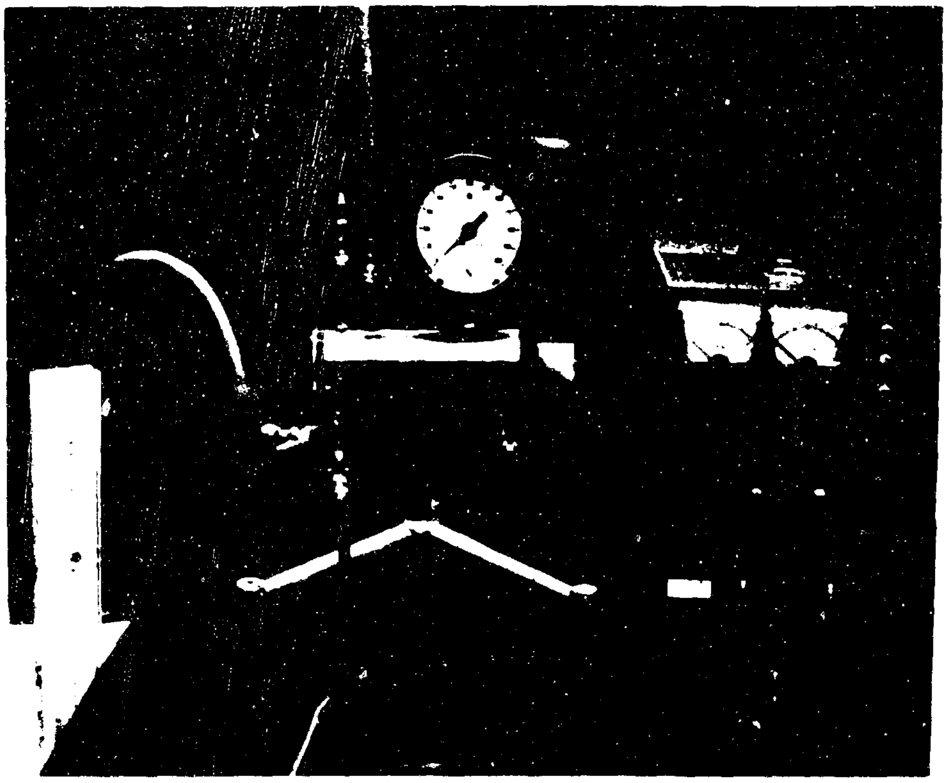

Figure 12. Electrostatic Precipitator Experimental Apparatus

Helium and oxygen was withdrawn from purchased cylinder gas, the oxygen being USP grade and the helium, standard high purity type (99.995% pure).

Four series of runs were made at pressures ranging from 0 to 500 psig (514.7 psia). A negative corona test was run of pure helium followed by similar tests with an oxygen constant partial pressure of 160 mm Hg. Two similar series were run with positive potential applied to the center electrode. The general test procedure for a run at a given pressure was as follows:

1) Evacuate test chamber to 15 microns Hg absolute;
2) Pressurize chamber with oxygen to 160 mm of Hg absolute;
3) Add helium to desired test pressure (Note - close pressure line to mercury manometer at 14.7 psia);
4) Apply potential gradient at increasing selected current levels noting voltage.

Because it is extremely difficult to determine visually corona onset, a standardized procedure was established of beginning the readings by increasing the voltage to a point at which the measured current flowing in the system was 0.02 milliamps, the lowest scale division.

7.3 RESULTS

The first and most significant observation in all test runs was the readily observable presence of a corona discharge. In all cases, the discharge was of the classical pattern in that there were numerous spikes and points along the rod for negative applied potential and a more diffuse glowing type of discharge for the positive potential. Tabulated and plotted data from these tests are presented in Figures 13-15 and Table 8. No data for negative potential in pure helium is presented. It was found to be completely impossible to obtain a reproducible result for this set of conditions. Reruns were completely erratic and continued operation resulted in broader and broader point spreads. Inasmuch as data on pure helium is of secondary importance, this series was discontinued. No difficulty was experienced in the other runs and data on all the points proved to be highly reproducible. In all cases save one, the tests were run until a point discharge occurred. This was not the case for pure helium under negative potential. Under all pressures, the maximum potential that could be applied before exceeding the current capacity of the generating apparatus, 8 ma, was about 4 killovolts.

To determine the field strength (potential gradient) in the apparatus under the various conditions, the equation given by Gottschlich(27) was utilized:

$$E_0 = \left[\left(\frac{V'}{r \ln R_1/R_2}\right)^2 + \frac{i}{2\pi Z \varepsilon_0}\right]^{1/2} , \qquad (55)$$

where

E_0 = field strength - volts per cm,

V' = applied potential - volts,

r = radial distance measured from electrode centerline - cm,

Figure 13. Voltage vs Corona Current Helium.

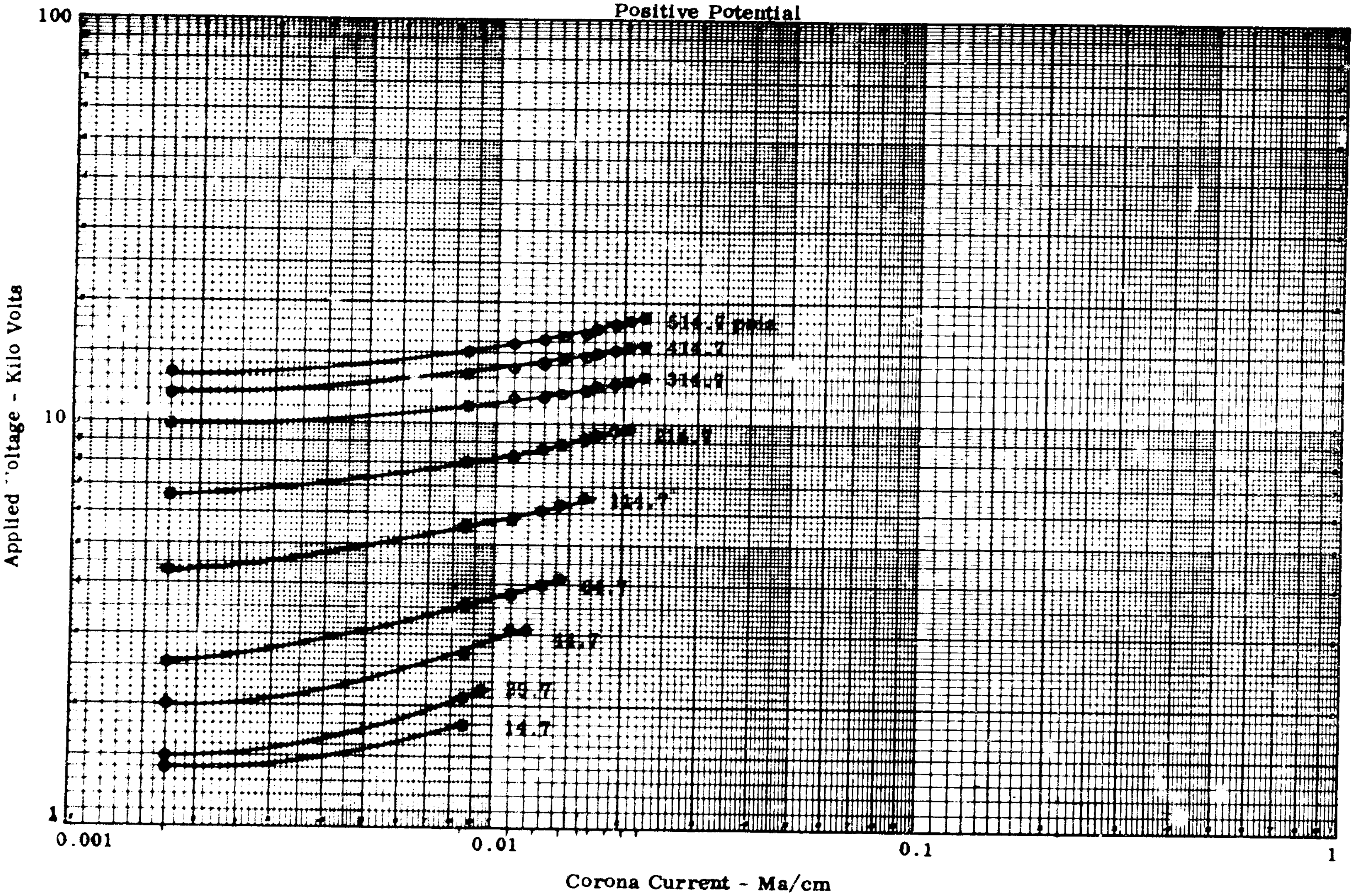

Figure 14. Voltage vs Corona Current. Helium and Oxygen (PO_2 = 160 mm Hg)

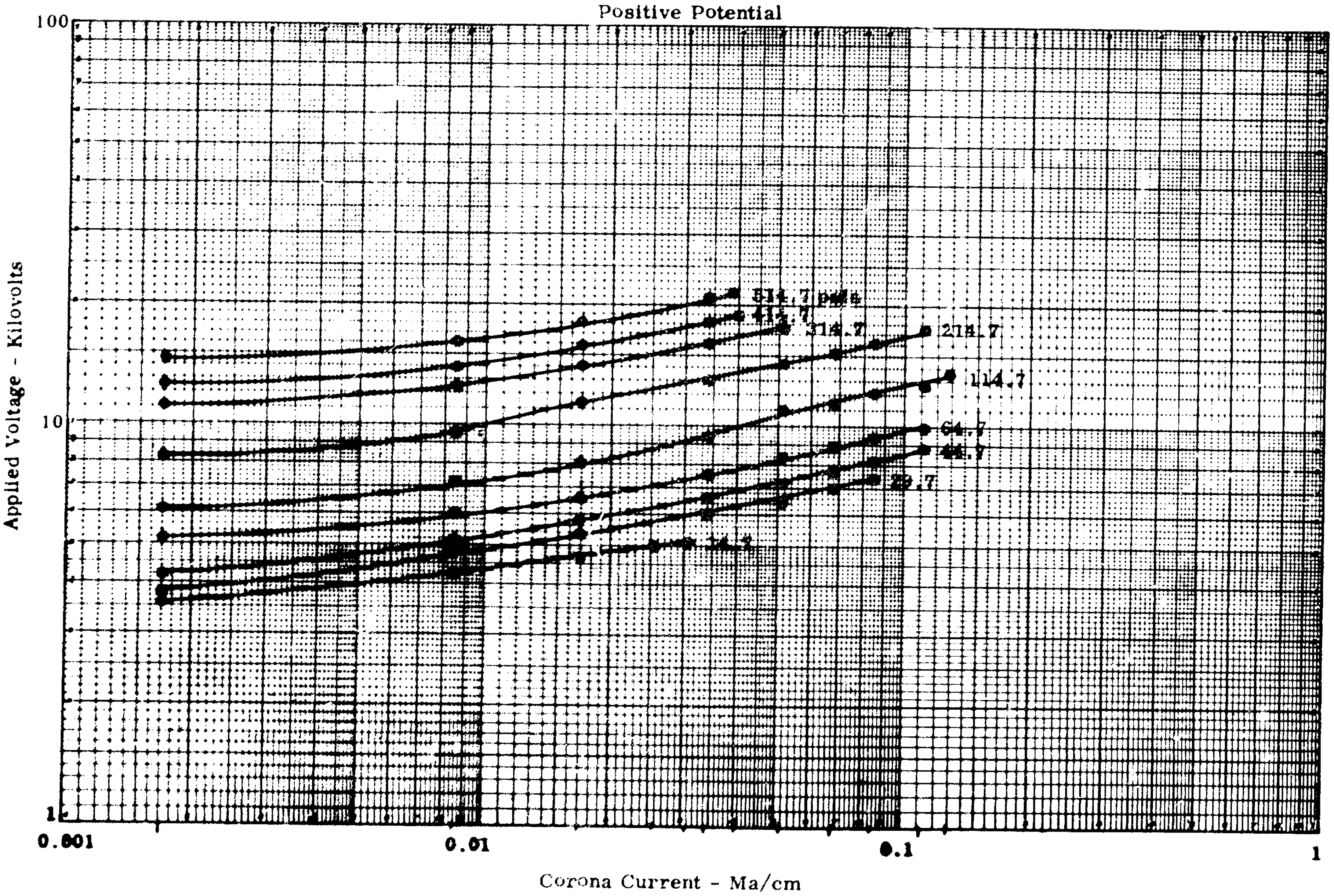

Figure 15. . Voltage vs Corona Current. Helium and Oxygen (PO_2 = 160 mm Hg)

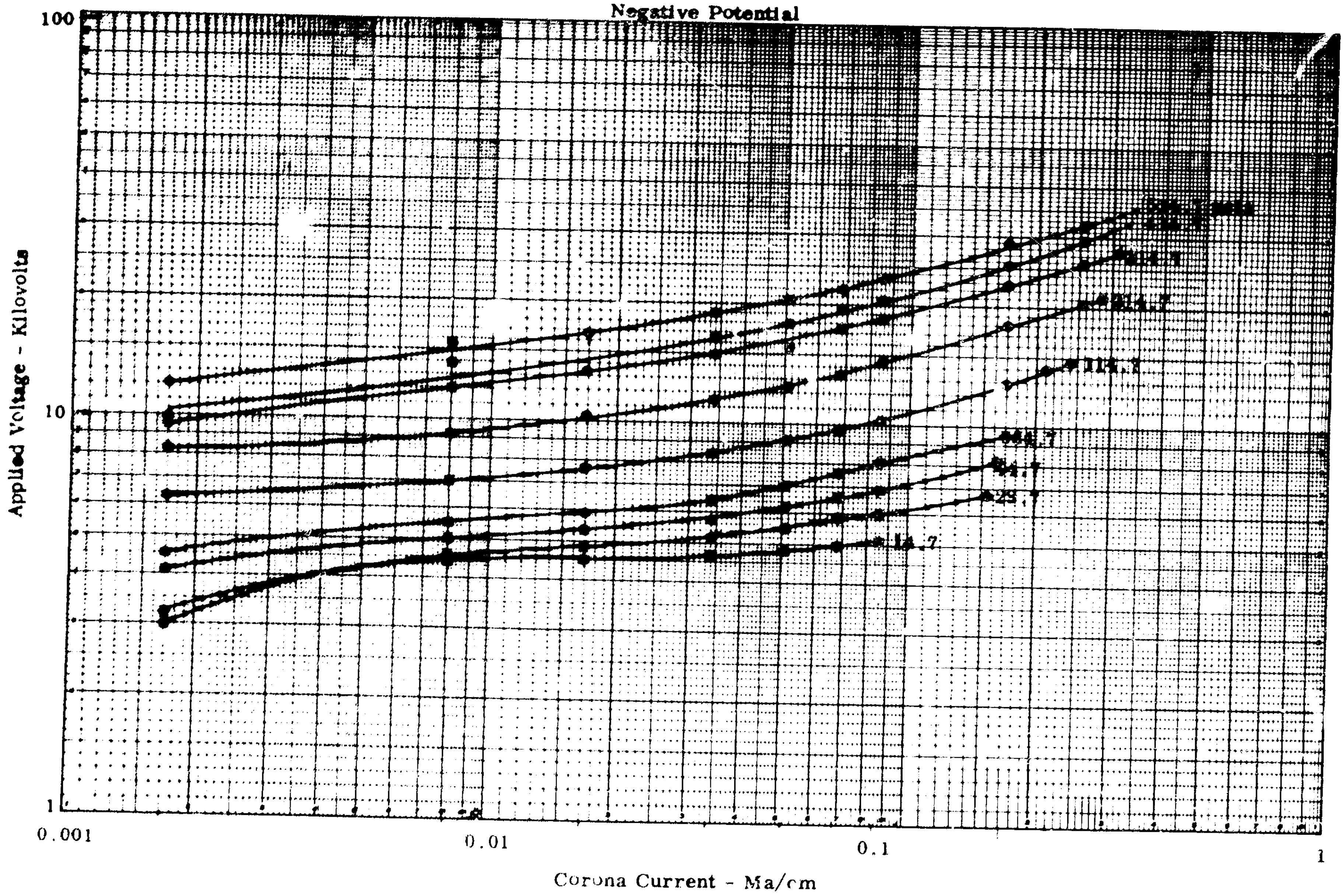

Table 8. Precipator Experiment Results. Applied Voltage vs Current at Various Pressures.

Positive Applied Voltage - Helium

Kilovolts

psia / ma/cm	0.001709	0.00855	0.01111	0.01282	0.01453	0.01624	0.01709	0.01880	0.02051	0.02222
14.7	1.4	1.8								
29.7	1.5	2.1	0.00940/2.2							
44.7	2.0	2.7	3.1	0.01197/3.1						
64.7	2.55	3.55	3.8	4.0	4.7					
114.7	4.3	5.6	5.8	6.1	6.35	6.6				
214.7	6.6	8.0	8.3	8.65	8.9	9.2	9.4	9.6	9.8	
314.7	9.95	11.1	11.6	11.9	12.1	12.1	12.4	12.6	12.8	13.1
414.7	11.7	13.3	13.8	14.1	14.5	14.8	15.0	15.2	15.7	15.8
514.7	13.2	15.2	15.8	16.1	16.5	16.9	17.2	17.5	18.0	18.3

Positive Applied Voltage - Helium + O_2 (160 mm Hg)

psia / ma/cm	0.001709	0.008547	0.017094	0.034188	0.051282	0.068376	0.085470	0.1111	0.1282
14.7	3.6	4.3	4.7	0.025641/5.0	0.03077/5.1				
29.7	3.8	4.85	5.4	6.0	6.5	7.0	7.4		
44.7	4.2	5.2	5.8	6.6	7.2	7.7	8.2	8.9	
64.7	5.2	6.0	6.6	7.6	8.4	8.9	9.4	10.0	
114.7	6.1	7.2	8.1	9.4	11.0	11.5	12.1	12.8	13.5
214.7	8.3	9.6	11.4	13.1	14.4	15.2	16.1	17.4	
314.7	11.0	12.5	14.0	16.1	17.7				
414.7	12.5	14.0	15.9	18.2	0.04017/19				
514.7	14.4	16.2	18.1	21.0	0.039316/21.7				

Negative Applied Voltage - Helium + O_2 (160 mm Hg)

psia / ma/cm	0.001709	0.008547	0.017094	0.034188	0.051282	0.068376	0.085470	0.170940		
14.7	3.0	4.4	4.5	4.65	4.8	4.95	5.2			0.08547/5.2
29.7	3.2	4.5	4.8	5.2	5.45	5.8	6.0			0.154/6.7
44.7	4.1	5.0	5.3	5.7	6.2	6.5	6.8			1.1624/8.2
64.7	4.5	5.5	5.9	6.4	7.0	7.5	8.1	9.5		1.7094/9.5
114.7	6.3	7.0	7.65	8.4	9.1	9.65	10.08	11.5	0.213675/14	0.02393/14.4
214.7	8.3	9.2	10.2	11.5	12.4	13.2	14.4	18.0	0.256410/205	0.02820/21
314.7	9.5	12.0	13.2	15.0	15.8	17.3	18.5	22.8	0.256410/25.9	0.03077/27.5
414.7	9.9	13.8	15.8	16.5	18.0	19.4	20.5	25.4	0.256410/29.1	0.02906/31.5
515.7	12.0	16.4	16.8	19.0	20.5	22.0	23.5	29.0	0.256410/32	off scale

R_1 = radius of discharge electrode - cm,

R_2 = radius of collecting electrode - cm,

i = current per unit length of electrode - amps/cm,

Z = ion mobility - cm sq/volt - sec, and

ϵ_o = dielectric constant of a vacuum - 8.85434×10^{6} amp - sec/volt - cm.

All of the terms in the above equation necessary for calculating the field strength are available from the data and the physical dimensions of the instrument, with the exception of the ion mobility. Two corrections must be made in this case. One for the fact that the gas is a mixture of two components and the other for the reduction in mobility due to increasing pressure. According to Loeb$^{(3)}$, the equation for the mobility of a mixture is given as:

$$Z_{23} = \frac{Z_2 Z_3}{f_2 Z_3 + (1 - f_2) Z_2} , \qquad (56)$$

where

Z_{23} = mobility of the mixture,

Z_2 = mobility of O_2,

Z_3 = mobility of He, and

f = fraction due to partial pressure of each gas.

The equation for reduced mobility due to increasing pressure is given by Whitby as

$$(Z_{23})_r = \frac{Z_{23}}{P} \quad . \qquad (40)$$

These simple equations for mobility have been run for the experimental pressures utilized and, for future convenience, they have also been tabulated (Table 9) for the customary range of pressures adhered to in this study. Data is presented for both positive and negative ions for the helium-oxygen mixture (PO_2 = 160 mm Hg) and for pure helium.

The calculations of field strength for the three runs on which voltage and current data are available are presented in Figures 16-18 and Table 10. Several inferences can be drawn from an examination of this data.

1) Evidence of a uniform corona discharge was observed under all conditions and at all pressures.
2) Corona onset voltage increases with increasing pressure. (Actually this is a pseudo corona onset that was uniformly determined by the presence of a current flow of 0.02 milliamps.)
3) As pressure is increased the voltage level at which stable coronas can be maintained increases, accompanied by increased current flow and field potential.
4) There is a similarity between the positive and negative voltage-current curves for the helium-oxygen mixture, except that higher voltages and greater current flows may be achieved with negative potential. A similar conclusion can be drawn from an examination of the potential gradient-current curves. For pure helium, lower voltages, potential

Table 9. Mobilities (cm^2/sec-volt) of Positive and Negative Ions in Helium-Oxygen (PO_2 = 160 mm Hg) and Pure Helium.

NEGATIVE IONS			POSITIVE IONS	
PRESS	Z_{23}	Z_3	Z_{23}	Z_3
PSIA	HE-O2	HE	HE-O2	HE
10.0	.52183842+01	.92547000+01	.39504489+01	.74772100+01
20.0	.33368548+01	.46273500+01	.25848108+01	.37386050+01
30.0	.24525637+01	.30849000+01	.19208043+01	.24924033+01
50.0	.16029674+01	.18509400+01	.12688831+01	.14954420+01
100.0	.85902605+00	92547000+00	.68643918+00	.74772100+00
200.0	.44550552+00	.46273500+00	.35788540+00	.37386050+00
300.0	.30073622+00	.30849000+00	.24203770+00	.24924033+00
400.0	.22697842+00	.23136750+00	.18284929+00	.18693025+00
500.0	.18227429+00	.18509400+00	.14692093+00	.14954420+00

Figure 16. Field Strength vs Corona Current. Helium.

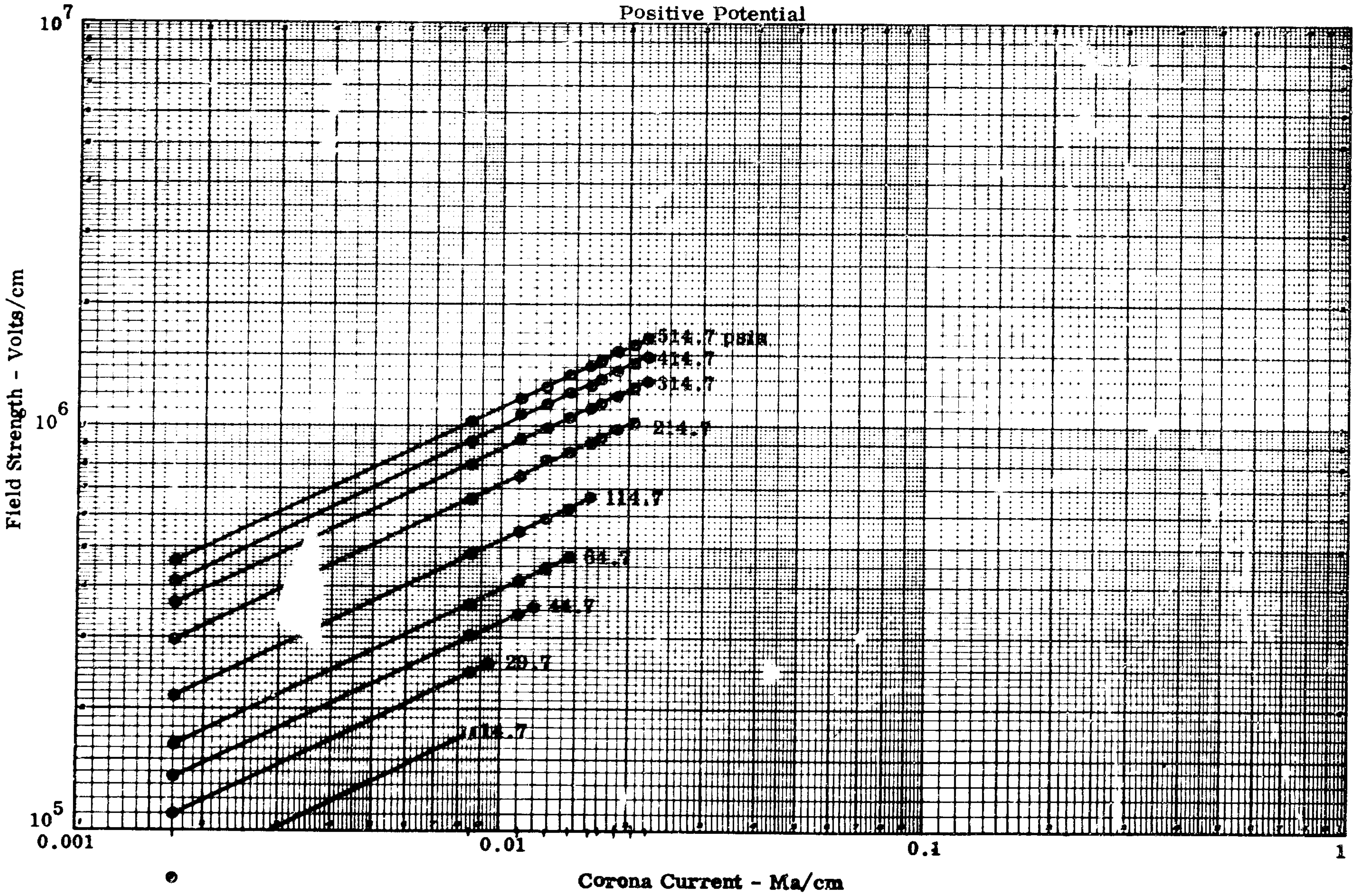

Figure 17. Field Strength vs Corona Current. Helium and Oxygen (PO_2 = 160 mm Hg).

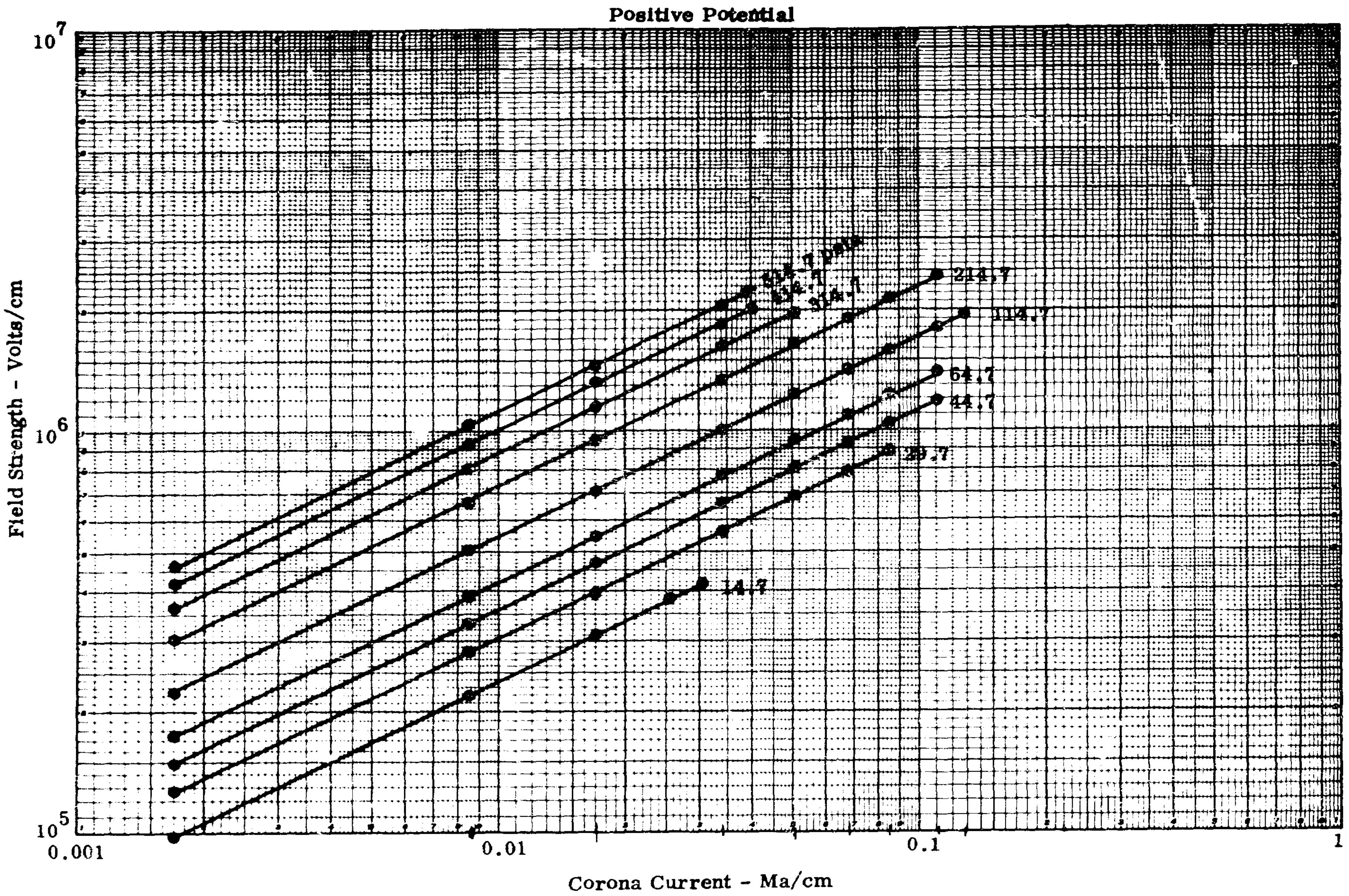

Figure 18. Field Strength vs Corona Current. Helium and Oxygen (PO_2 = 160 mm Hg)

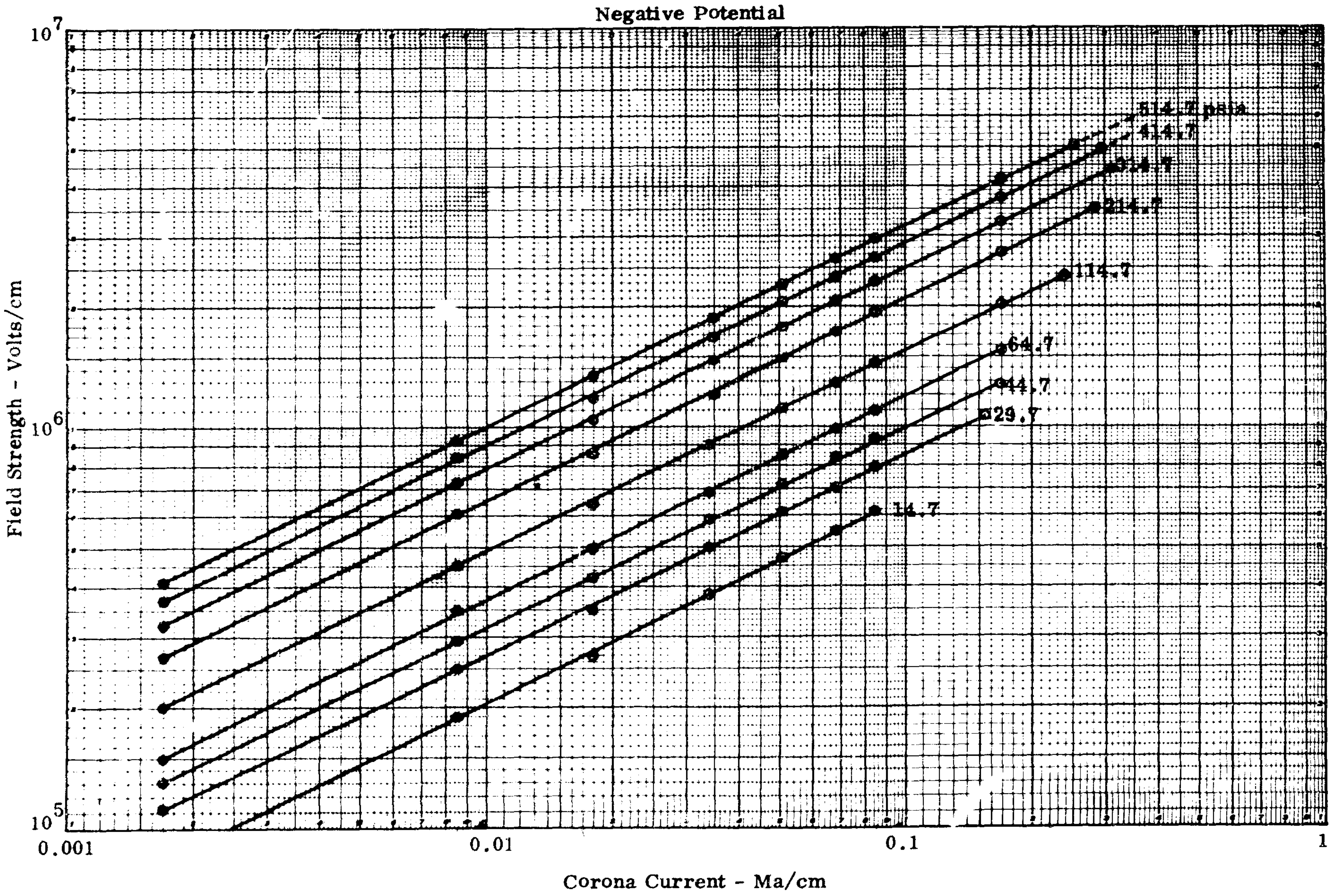

Table 10. Precipitator Experiment Results. Field Strength at Collecting Electrode (1.906 cm. id.) vs Current at Various Pressures.

Positive Applied Voltage - Helium

volts/cm

psia	.1709-02	.8550-02	.1111-01	.1282-01	.1453-01	Ma/cm
14.7	.7794+04	.1740+05				
29.7	.1106+05	.2472+05	.2592+05*			
44.7	.1358+05	.3033+05	.3458+05	.3589+05*		
64.7	.1634+05	.3650+05	.4160+05	.4469+05	.4757+05	
114.7	.2178+05	.4861+05	.5540+05	.5951+05	.6335+05	
214.7	.2983+05	.6652+05	.7581+05	.8143+05	.8668+05	
314.7	.3620+05	.8056+05	.9181+05	.9860+05	.1050+06	
414.7	.4157+05	.9250+05	.1054+06	.1132+06	.1205+06	
514.7	.4632+05	.1031+06	.1174+06	.1261+06	.1343+06	

psia	.1624-01	.1709-01	.1880-01	.02051	.02222	Ma/cm
14.7						
29.7						
44.7						
64.7						
114.7	.6698+05					
214.7	.9164+05	.9400+05	.9859+05	.1030+06		
314.7	.1110+06	.1138+06	.1194+06	.1247+06	.1298+06	
414.7	.1274+06	.1307+06	.1371+06	.1431+06	.1490+06	
514.7	.1419+06	.1456+06	.1527+06	.1595+06	.1660+06	

Positive Applied Voltage - Helium + O_2 (160 mm Hg)

psia	.1709-02	.8547-02	.1709-01	.3419-01	.5128-01	Ma/cm
14.7	.9970+04	.2211+05	.3122+05	.3822+05*	.4186+05*	
29.7	.1270+05	.2825+05	.3991+05	.5640+05	.6906+05	
44.7	.1495+05	.3327+05	.4701+05	.6645+05	.8137+05	
64.7	.1753+05	.3898+05	.5508+05	.7786+05	.9534+05	
114.7	.2268+05	.5049+05	.7136+05	.1009+06	.1235+06	
214.7	.3051+05	.6791+05	.9598+05	.1357+06	.1661+06	
314.7	.3676+05	.8172+05	.1155+06	.1632+06	.1999+06	
414.7	.4205+05	.9348+05	.1321+06	.1868+06	.2024+06*	
514.7	.4678+05	.1040+06	.1469+06	.2076+06	.2227+06*	

psia	.6838-01	.8547-01	.1111+00	.1282+00		Ma/cm
14.7						
29.7	.7974+05	.8914+05				
44.7	.9394+05	.1050+06	.1197+06			
64.7	.1101+06	.1231+06	.1403+06			
114.7	.1426+06	.1595+06	.1618+06	.1953+06		
214.7	.1918+06	.2145+06	.2445+06			
314.7						
414.7						
514.7						

Table 10. Continued

Negative Applied Voltage - Helium + O_2 (160 mm Hg)

psia	.1709-02	.8547-02	.1709-01	.3419-01	.5128-01	Ma/cm
14.7	.8722+04	.1939+05	.2736+05	.3865+05	.4731+05	
29.7	.1123+05	.2500+05	.3531+05	.4991+05	.6111+05	
44.7	.1331+05	.2958+05	.4178+05	.5906+05	.7232+05	
64.7	.1562+05	.3475+05	.4910+05	.6941+05	.8499+05	
114.7	.2034+05	.4518+05	.6384+05	.9024+05	.1105+06	
214.7	.2740+05	.6089+05	.8604+05	.1216+06	.1489+06	
314.7	.3296+05	.7334+05	.1036+06	.1465+06	.1793+06	
414.7	.3768+05	.8394+05	.1186+06	.1676+06	.2053+06	
514.7	.4195+05	.9335+05	.1319+06	.1864+06	.2283+06	

psia	.6838-01	.8547-01	.1709+00			Ma/cm
14.7	.5462+05	.6107+05			.6107+05*	
29.7	.7055+05	.7887+05			.1059+06*	
44.7	.8349+05	.9334+05			.1287+06*	
64.7	.9813+05	.1097+06	.1551+06		.1551+06*	
114.7	.1276+06	.1426+06	.2017+06	.2255+06*	.2366+06*	
214.7	.1720+06	.1923+06	.2719+06	.3329+06*	.3492+06*	
314.7	.2071+06	.2315+06	.3273+06	.4009+06*	.4391+06*	
414.7	.2370+06	.2650+06	.374[illegible]+06	.4588+06*	.4885+06*	
514.7	.2636+06	.2947+06	.4167+06	.5103+06*		

* - indicates that the E_o value given does not correspond to the column heading value for current. See tabulations of voltages (V') vs current for appropriate values.

gradients, and currents were achieved but the trends are similar for increasing pressure.

7.4 ELECTRIFICATION CONCLUSIONS

The theoretical material preceding the experimental rediscussion is essentially a summary of currently available theory on this subject and does permit the aerosol charge calculations necessary to establish the required field gradient for a given aerosol removal system. This experiment has established the possibility of the existence of stable coronas under static conditions, in the environments to be expected in deep submergence vehicles. The potential gradient curves have been calculated from the current voltage relationships using the physical dimensions of the experimental apparatus. However, there is no reason why the potential gradient cannot be calculated for other design sizes by normalizing out the dimensions of the experimental precipitator. This data then should be useful for a first approximation for large scale precipitator designs. Lacking only at this point for the evolution of a hypothetical precipitator design are actual data on aerosol species and size distributions existing within a vessel.

SECTION 8.0: PULMONARY DEPOSITION

When aerosols are inhaled into the lung, they are deposited or not deposited, according to many complex but predictable functions. The amount and location of deposition depends on the aerosol properties (size, shape, density); flow dynamics (velocity, gas density), and physiological parameters (breathing rate, residence time caliber of airway) The sites of deposition for portions of the size distribution spectrum vary, for a given aerosol, with breathing rate, i.e., with the activity or work rate of the breathing organism. Numerous deposition studies have been carried out over the years; the results of many of these studies have been somewhat codified by the Task Group on Lung Dynamics - ICRP.(28)

In the simplest terms, the findings show that the larger particles deposit in the upper airways and the finest in the lower. Deposition is also very high, being almost complete, for particles 10 microns and larger and decreases steadily to about one micron. For smaller sizes, deposition again increases to some unknown but high value approaching 70 or greater. This description of the variability of deposition with particle size is approximate for spherical particles (P = 1) and varies considerably with other aerosol properties.

Throughout this study it has been demonstrated that the composition and pressure of the atmosphere to be used for deep submergence systems will cause definite and measurable changes in the motions of the aerosol particles.

Therefore it is logical to consider how pulmonary deposition and the sites of deposition might be affected by this special atmosphere. Models for predicting pulmonary deposition are available in the literature and may be analyzed for the affects of the helium-oxygen atmosphere on deposition.

The first model was developed in 1935 by Findiesen(29) and considers deposition in the lung due to three factors. The three factors, already considered and discussed in this report, are sedimentation, impaction, and diffusion. Based on increased knowledge of the structure of the lung, Landahl published a revised and improved deposition model in 1950.(30) Landahl revised this model in 1963;(31) further work of Landahl's was published by Hatch in 1964.(32) Beeckmans(33) also published a model that takes into account the same basic parameters but uses a slightly different mathematical approach. For the purposes of this study, we have adopted a detailed published lung structure according to Landahl as presented by Hatch,(32) which is reproduced in Table 11. Also, since Landahl's 1950 publication(30) gives the most detailed description of his model, it was adopted for this consideration. All the authors reviewed adopted more or less typical equations for the quantity of deposition due to each mechanism. The equations quoted below are basically according to Landahl, although they have been arranged so that the parameters affected by the specific environment in question can be directly inserted.

Before presenting the equations, we must describe the sub- and superscript nomenclature utilized.

Region (a)	Number	Volume, cm³	Relative volume (V)	Diameter (2R), cm	Length, cm	Cross-sectional area, cm²	Velocity, cm/second	Passage time (t′), second	Fraction passing
Mouth (1)	1	20	0.04	2	7	3	100	0.07	1.00
Pharynx (2)	1	20	0.04	3	3	7	45[b]	0.07	0.96
Trachea (3)	1	24	0.06	1.6	11	2	150	0.07	0.92
Prim. bronchi (4)	2	10	0.02	1.0	6.5	1.6	190	0.03	0.86
Sec. bronchi (5)	12	4	0.01	0.4	3	1.5	200	0.015	0.84
Ter. bronchi (6)	100	5	0.01	0.2	1.5	3.1	100	0.015	0.83
Quart. bronchi (7)	770	7	0.015	0.15	0.5	14	22	0.02	0.82
Terminal bronchioles (8)	5.4×10^4	45	0.10	0.06	0.3	170	2	0.15	0.81
Resp. bronchi (9)	1.1×10^5	33	0.07	0.05	0.15	300	1.4	0.10	0.72
Alveolar ducts (10)	2.6×10^7	(160)[c]	(0.63)	(0.02)[c]	0.02	8000			0.65
Alveolar sacs (11)	5.2×10^7	(730)[c]		(0.03)[c]	(0.03)[c]				

[a] According to Landahl. Revised, 1962, from original

[b] Glottis velocity = 150.

[c] Values as estimated. These values are corrected to 2.5 liters at end of expiration.

Table 11. Schematic Representation of the Respiratory Tract. (after Hatch, Ref. 32)

Superscripts:

i = inhalation

e = exhalation

h = breath holding or pause

Subscripts

α = region in question. Refer to Figure 11. Regions are numbered in descending order. viz., $\alpha = 1$ is the mouth.

8.1: INERTIAL DEPOSITION

The probability of inertial deposition in the lung is defined as:(30, 32)

$$I_\alpha = \frac{P_i}{1 + P_i} \; ,$$

where

P_i = impaction parameter

$= v\, V \sin\, \theta / g\, R \quad , \qquad (57)$

v = sedimentation velocity of particle - (value used is from Table 5 and includes slip correction factor),

V = air stream velocity,

g = gravitational acceleration,

R = radius of airway, and

sin θ = angular branching of airway.

The probability of deposition due to sedimentation in the lung is defined as:(30, 32)

$$S_{\alpha} = 1 - \exp\left[- (0.8\ v\ t \cos \psi\ 1R)\right] \qquad (58)$$

where

t = time of travel along a tube, and

cos ψ = angle of tube inclination.

The probability of deposition due to diffusion in the lung is defined as:(30, 32, 33)

$$D_{\alpha} = \frac{4}{R} \sqrt{\frac{Dt}{\pi}} \qquad (59)$$

where

D = diffusion coefficient - (value used is from Figure 7 and includes the slip correction factor).

Numerous minor assumptions are made by the various authors(29, 30, 31, 33) in calculating the probabilities for i, e, and h. The combined probabilities are given as:(30)

$$P^{i}_{\alpha} = D^{i} + I^{i}_{\alpha} + S^{i}_{\alpha} - D^{i}_{\alpha} I^{i}_{\alpha} - D^{i}_{\alpha} S^{i}_{\alpha} - I^{i}_{\alpha} S^{i}_{\alpha} + D^{i}_{\alpha} I^{i}_{\alpha} S^{i}_{\alpha} \qquad (60)$$

$$P^{e}_{\alpha} = D^{i}_{\alpha} + I^{e}_{\alpha} + S^{i}_{\alpha} - D^{i}_{\alpha} I^{e}_{\alpha} - D^{i}_{\alpha} S^{i}_{\alpha} - I^{e}_{\alpha} S^{i}_{\alpha} + D^{i}_{\alpha} I^{e}_{\alpha} S^{i}_{\alpha} \qquad (61)$$

$$P^{h}_{\alpha} = D^{h}_{\alpha} + S^{h}_{\alpha} - D^{h}_{\alpha} S^{h}_{\alpha} \qquad (62)$$

The balance of the calculation to arrive at a specific deposition figure for a region is complex and, since it is neither special nor specific to the understanding of the model, we have omitted it.(30)

We must emphatically point out that the preceding relationships do not allow for differences in the physiologic breathing patterns that might be expected to occur in the helium-oxygen atmosphere. That such differences exist has already been demonstrated,(34) but available information is not directly applicable to this study. The detailed changes in percentages of breathing mixture traversing the various airways is not available nor are the inhalation, exhalation, holding times, or airway velocities apparent. Therefore, this consideration involves only a determination of the effects of the breathing mixture on the aerosol while the physiological behavior of the organism is still behaving as if it were breathing air. This is a limiting assumption and renders these considerations valid only as a very first approximation.

A further difficulty with the model selected is that, while it was the most detailed model available, it was not possible to discern all the assumptions that had been made in performing the calculations. This difficulty was particularly evident during the consideration of the alveolar ducts and alveolar sacs, for which it should be noted that the information given in Table 11 is incomplete and a time factor could not be determined. Personal conversations with the author of the model were unfruitful, since the work was performed many years ago and the original notes were not available to him at the time of our inquiry. To complete this study, then, several simplifying assumptions were made for each of the particle sizes considered in the calculations (20, 6, 2, 0.6 and 0.2 microns) for the alveolar ducts and alveolar sacs. These assumptions are based on physical and physiological considerations and should be reasonably correct for this approximation:

1) There is no deposition of 20-micron particles in the alveolar region.
2) If 6-micron particles deposit in the alveolar region, it is by sedimentation only.
3) If 2-micron particles deposit in the alveolar region, it is by sedimentation only.
4) If 0.6-micron particles deposit in the alveolar region, it is by diffusion only.
5) If 0.2-micron particles deposit in the alveolar region, it is by diffusion only.

By restricting the deposition in the alveolar regions to one mechanism only, it is possible then to calculate back from Landahl's results the necessary time parameters, so that the model can be completed and the calculations for the helium-oxygen atmosphere carried out. Landahl's results, as quoted by [illegible]ch for five sizes and four breathing rates, are presented in Table 12. Our calculations for a model as described above at several pressures are given in Table 13.

Because so many pressure ranges are considered, Table 13 results in an extremely long tabulation of values. For this reason, the findings observed

Region	(a)[c]	300 cm^3/sec, 4-sec cycle 450 cm^3 tidal air					300 cm^3/sec, 8-sec cycle 900 cm^3 tidal air					300 cm^3/sec, 12-sec cycle 1350 cm^3 tidal air					1000 cm^3/sec, 4-sec cycle 1500 cm^3 tidal air				
		20	6	2	0.6	0.2	20	6	2	0.6	0.2	20	6	2	0.6	0.2	20	6	2	0.6	0.2
M	1	15	0	0	0	0	14	1	0	0	0	14	1	0	0	0	18	1	0	0	0
P	2	8	0	0	0	0	8	1	0	0	0	8	1	0	0	0	10	1	0	0	0
T	3	10	1	0	0	0	11	1	0	0	0	11	1	0	0	0	19	3	0	0	0
PB	4	12	2	0	0	0	13	2	0	0	0	13	1	0	0	0	20	5	1	0	0
SB	5	19	4	1	0	0	17	4	1	0	0	18	5	1	0	0	21	12	2	0	0
TB	6	17	9	2	0	0	20	9	2	0	1	21	10	2	0	0	9	20	5	0	0
QB	7	6	7	2	1	1	8	7	1	1	1	8	7	1	0	1	1	10	3	1	1
T.B.	8	6	19	6	4	6	6	24	7	4	6	6	24	8	4	6	1	9	3	2	4
R.B.	9	0	11	5	3	4	0	10	7	6	6	0	12	11	3	5	0	3	2	2	4
A.D.	10	0	25	25	8	11	0	27	44	17	23	0	27	48	22	25	0	13	26	10	13
A.S.	11	0	5	0	0	0	0	5	4	2	3	0	5	11	9	10	0	18	17	6	7
Totals		93	83	41	16	22	97	91	66	30	40	99	94	82	38	47	99	95	59	21	29

• According to Landahl. Revised calculations from original values

Table 12. Retention in Various Regions of the Respiratory Tract for Air at Ambient Pressure. Particulate Density = 1. (after Hatch, Ref. 32).

PRESSURE = 10 PSIA

Region	300 cm^3/sec, 4-sec cycle 450 cm^3 tidal air					300 cm^3/sec, 8-sec cycle 900 cm^3 tidal air					300 cm^3/sec, 12-sec cycle 1350 cm^3 tidal air					1000 cm^3/sec, 4-sec cycle 1500 cm^3 tidal air				
dia - μ →	20	6	2	.6	.2	20	6	2	.6	.2	20	6	2	.6	.2	20	6	2	.6	.2
1	14	2	0	1	2	13	2	0	1	2	13	2	0	1	2	18	2	0	0	1
2	8	1	0	0	1	8	1	0	0	1	8	1	0	0	1	11	2	0	0	1
3	9	1	0	0	1	110	1	0	0	1	10	1	0	0	1	19	4	0	0	0
4	12	2	0	1	2	13	2	1	1	2	14	2	1	1	2	19	5	1	0	1
5	19	5	1	1	2	21	6	1	1	3	22	6	1	1	3	20	14	3	1	2
6	17	9	2	2	4	19	10	2	2	5	19	10	2	2	5	8	20	5	2	3
7	6	6	2	3	6	7	7	2	3	7	7	7	2	3	8	2	11	3	2	5
8	6	21	10	16	30	6	24	11	18	34	6	26	12	19	36	0	10	7	11	26
9	0	9	7	10	15	0	12	8	13	17	0	13	9	14	18	0	4	4	9	17
10	0	23	32	25	16	0	25	48	39	19	0	25	51	43	19	0	13	36	37	31
11	0	0	0	0	0	0	1	1	0	0	0	2	4	0	0	0	10	13	0	0

PRESSURE = 14.7 PSIA

	20	6	2	.6	.2	20	6	2	.6	.2	20	6	2	.6	.2	20	6	2	.6	.2
1	14	2	0	1	2	13	2	0	1	2	13	2	0	1	2	18	2	0	0	1
2	8	1	0	0	1	8	1	0	0	1	8	1	0	0	1	11	1	0	0	1
3	9	1	0	0	1	10	1	0	0	1	10	1	0	0	1	19	3	0	0	0
4	12	2	0	1	1	13	2	0	1	1	14	2	0	1	2	19	5	1	0	1
5	19	5	1	1	2	21	5	1	1	2	22	5	1	1	2	20	13	2	1	1
6	17	9	2	2	4	19	10	2	2	4	19	10	2	2	5	8	20	5	2	3
7	6	6	2	2	5	7	7	2	3	6	7	7	2	3	7	2	10	3	2	4
8	6	21	9	14	28	6	24	11	16	32	6	25	11	17	33	0	10	6	10	23
9	0	10	6	10	15	0	12	8	12	17	0	13	8	13	18	0	4	4	8	16
10	0	24	31	25	19	0	26	47	39	23	0	26	51	44	23	0	14	35	36	33
11	0	0	0	0	0	0	1	2	0	0	0	2	5	0	0	0	11	14	1	0

Table 13. Retention in Various Regions of the Respiratory Tract for He-O_2 (PO_2 = 160 mm Hg) at Various Pressures. Particulate Density = 1.

```
PRESSURE = 20 PSIA

     20  6  2 .6 .2    20  6  2 .6 .2    20  6  2 .6 .2    20  6  2 .6 .2

 1   14  2  0  1  1    13  2  0  1  1    13  2  0  1  1    19  2  0  0  1
 2    8  1  0  0  1     8  1  0  0  1     8  1  0  0  1    11  1  0  0  1
 3    9  1  0  0  0    10  1  0  0  0    10  1  0  0  0    19  3  0  0  0
 4   12  2  0  0  1    13  2  0  0  1    14  2  0  1  1    19  5  1  0  1
 5   20  5  1  1  2    21  5  1  1  2    22  5  1  1  2    20 13  2  1  1
 6   17  9  2  1  3    19 10  2  2  4    19 10  2  2  4     8 20  4  1  3
 7    6  6  2  2  5     7  7  2  2  6     7  7  2  2  6     1 10  3  2  4
 8    5 21  9 13 26     6 24 10 14 29     6 25 10 15 31     0 10  6  9 21
 9    0 10  6  9 14     0 12  7 11 17     0 13  8 12 18     0  4  4  8 15
10    0 24 30 24 21     0 26 46 39 27     0 26 50 44 27     0 14 34 34 35
11    0  0  0  0  0     0  1  2  0  0     0  2  6  1  0     0 11 15  1  0


PRESSURE -30 PSIA

     20  6  2 .6 .2    20  6  2 .6 .2    20  6  2 .6 .2    20  6  2 .6 .2

 1   14  2  0  0  1    13  2  0  0  1    13  2  0  0  1    19  2  0  0  1
 2    8  1  0  0  1     8  1  0  0  1     8  1  0  0  1    11  1  0  0  0
 3    9  1  0  0  0    10  1  0  0  0    10  1  0  0  0    19  3  0  0  0
 4   12  2  0  0  1    13  2  0  0  1    14  2  0  0  1     9  5  1  0  1
 5   20  5  1  1  1    21  5  1  1  2    22  5  1  1  2    20 13  2  1  1
 6   17  9  2  1  3    19 10  2  1  3    19 10  2  1  4     8 20  4  1  2
 7    6  6  2  2  4     7  7  2  2  5     7  7  2  2  5     1 10  3  1  3
 8    5 21  8 11 24     6 24  9 13 27     6 25 10 13 28     0 10  5  8 19
 9    0 10  5  8 14     0 12  7 10 17     0 12  7 11 18     0  4  4  7 14
10    0 24 29 23 23     0 26 46 38 31     0 26 50 43 31     0 13 33 32 35
11    0  0  0  0  0     0  1  2  0  0     0  2  7  1  0     0 11 15  2  0


PRESSURE = 40 PSIA

     20  6  2 .6 .2    20  6  2 .6 .2    20  6  2 .6 .2    20  6  2 .6 .2

 1   14  2  0  0  1    13  2  0  0  1    13  2  0  0  1    19  2  0  0  1
 2    8  1  0  0  1     8  1  0  0  1     8  1  0  0  1    11  1  0  0  0
 3    9  1  0  0  0    10  1  0  0  0    10  1  0  0  0    19  3  0  0  0
 4   12  2  0  0  1    13  2  0  0  1    14  2  0  0  1    19  5  1  0  1
 5   20  5  1  1  1    21  5  1  1  1    22  5  1  1  2    20 13  2  1  1
 6   17  9  2  1  2    19 10  2  1  3    19 10  2  1  3     8 20  4  1  2
 7    6  6  2  2  4     7  7  2  2  4     7  7  2  2  5     1 10  3  1  3
 8    5 21  8 10 22     6 24  9 11 24     6 25  9 12 26     0 10  5  7 17
 9    0 10 [illegible]  7 13     0 12  6  9 16     0 12  7 10 17     0  4  3  6 13
10    0 25 28 21 24     0 26 46 37 34     0 26 49 42 34     0 13 32 29 35
11    0  0  0  0  0     0  1  3  0  0     0  2  8  2  0     0 11 16  3  0
```

Table 13. Continued

```
 PRESSURE =50 PSIA

      20   6   2 .6 .2    20   6   2 .6 .2    20   6   2 .6 .2    20   6   2 .6 .2

  1   14   2   0   0   1   13   2   0   0   1   13   2   0   0   1   19   2   0   0   1
  2    8   1   0   0   1    8   1   0   0   1    8   1   0   0   1   11   1   0   0   0
  3    9   1   0   0   0   10   1   0   0   0   10   1   0   0   0   19   3   0   0   0
  4   12   2   0   0   1   13   2   0   0   1   14   2   0   0   1   19   5   1   0   1
  5   20   5   1   1   1   21   5   1   1   1   22   5   9   1   1   20  13   2   1   1
  6   17   9   1   1   2   19  10   2   1   3   19  10   2   1   3    8  20   4   1   2
  7    6   6   1   1   3    7   7   2   2   4    7   7   2   2   4    1  10   3   1   3
  8    5  21   7  10  20    6  24   8  11  23    6  25   9  11  24    0  10   5   7  16
  9    0  10   5   7  13    0  12   6   8  15    0  12   7   9  17    0   4   3   6  12
 10    0  25  28  21  24    0  26  45  36  35    0  26  49  42  36    0  13  31  29  35
 11    0   0   0   0   0    0   1   3   0   0    0   2   8   2   0    0  11  16   3   0


 PRESSURE = 100 PSIA

      20   6   2 .6 .2    20   6   2 .6 .2    20   6   2 .6 .2    20   6   2 .6 .2

  1   14   2   0   0   1   13   2   0   0   1   13   2   0   0   1   19   2   0   0   0
  2    8   1   0   0   0    8   1   0   0   0    8   1   0   0   0   11   1   0   0   0
  3    9   1   0   0   0   10   1   0   0   0   10   1   0   0   0   19   3   0   0   0
  4   12   2   0   0   1   13   2   0   0   1   14   2   0   0   1   19   5   1   0   0
  5   20   5   1   0   1   21   5   1   0   1   22   5   1   0   1   20  13   2   0   1
  6   17   9   1   1   2   19  10   2   1   2   19  10   2   1   2    8  20   4   1   1
  7    6   6   1   1   3    7   7   2   1   3    7   7   2   1   3    1  10   3   1   2
  8    5  21   7   8  17    6  24   8   9  19    6  25   9   9  20    0  10   5   5  12
  9    0  10   5   6  11    0  12   6   7  13    0  12   7   8  14    0   4   3   5  10
 10    0  25  28  19  25    0  26  45  34  39    0  26  49  39  39    0  13  31  25  33
 11    0   0   0   0   0    0   1   3   0   0    0   2   8   4   0    0  12  16   4   0


 PRESSURE = 200 PSIA

      20   6   2 .6 .2    20   6   2 .6 .2    20   6   2 .6 .2    20   6   2 .6 .2

  1   14   1   0   0   1   13   1   0   0   1   13   1   0   0   1   19   2   0   0   0
  2    8   1   0   0   0    8   1   0   0   0    8   1   0   0   0   11   1   0   0   0
  3    9   1   0   0   0   10   1   0   0   0   10   1   0   0   0   19   3   0   0   0
  4   12   2   0   0   0   13   2   0   0   1   14   2   0   0   1   19   5   1   0   0
  5   20   4   1   0   1   21   5   1   0   1   22   5   1   0   1   20  13   2   0   0
  6   17   8   1   1   1   19   9   2   1   2   19   9   2   1   2    8  19   4   1   1
  7    6   6   1   1   2    7   6   1   1   2    7   7   1   1   3    1  10   3   1   2
  8    5  20   7   7  13    6  23   8   8  15    6  24   8   8  16    0  10   4   5  10
  9    0  10   5   5   9    0  12   6   6  11    0  12   6   7  12    0   4   3   4   8
 10    0  26  27  17  23    0  28  44  31  39    0  28  48  37  40    0  14  30  23  29
 11    0   0   0   0   0    0   2   4   1   0    0   3   9   5   1    0  13  16   5   1
```

Table 13. Continued

PRESSURE = 300 PSIA

	20	6	2	.6	.2	20	6	2	.6	.2	20	6	2	.6	.2	20	6	2	.6	.2
1	14	1	0	0	0	13	1	0	0	0	13	1	0	0	0	19	2	0	0	0
2	8	1	0	0	0	8	1	0	0	0	8	1	0	0	0	11	1	0	0	0
3	9	1	0	0	0	10	1	0	0	0	10	1	0	0	0	19	3	0	0	0
4	12	2	0	0	0	13	2	0	0	0	14	2	0	0	0	19	5	1	0	0
5	20	4	1	0	1	21	5	1	0	1	22	5	1	0	1	20	13	2	0	0
6	17	8	1	1	1	19	9	2	1	1	19	9	2	1	1	8	19	4	1	1
7	6	6	1	1	2	7	6	1	1	2	7	7	1	1	2	1	10	3	1	1
8	5	20	7	6	12	6	23	8	7	13	6	24	8	8	14	0	10	4	4	9
9	0	10	5	5	9	0	12	6	6	10	0	12	6	6	11	0	4	3	4	7
10	0	26	27	16	22	0	28	44	30	38	0	28	48	36	39	0	14	30	22	28
11	0	0	0	0	0	0	2	4	1	0	0	3	9	5	2	0	13	16	5	2

PRESSURE = 400 PSIA

	20	6	2	.6	.2	20	6	2	.6	.2	20	6	2	.6	.2	20	6	2	.6	.2
1	14	1	0	0	0	13	1	0	0	0	13	1	0	0	0	19	2	0	0	0
2	8	1	0	0	0	8	1	0	0	0	8	1	0	0	0	11	1	0	0	0
3	9	1	0	0	0	10	1	0	0	0	10	1	0	0	0	19	3	0	0	0
4	12	2	0	0	0	13	2	0	0	0	14	2	0	0	0	19	5	1	0	0
5	20	4	1	0	1	21	5	1	0	1	22	5	1	0	1	20	13	2	0	0
6	17	8	1	1	1	19	9	2	1	1	19	9	2	1	1	8	19	4	1	1
7	6	6	1	1	2	7	6	1	1	2	7	7	1	1	2	1	10	3	1	1
8	5	20	7	6	11	6	23	8	7	13	6	24	8	7	13	0	10	4	4	8
9	0	10	5	5	8	0	12	6	6	10	0	12	6	6	11	0	4	3	4	7
10	0	26	27	16	22	0	28	44	30	38	0	28	48	35	39	0	14	30	21	27
11	0	0	0	0	0	0	2	4	1	0	0	3	9	6	2	0	13	16	5	2

PRESSURE = 500 PSIA

	20	6	2	.6	.2	20	6	2	.6	.2	20	6	2	.6	.2	20	6	2	.6	.2
1	14	1	0	0	0	13	1	0	0	0	13	1	0	0	0	18	2	0	0	0
2	8	1	0	0	0	8	1	0	0	0	8	1	0	0	0	11	1	0	0	0
3	9	1	0	0	0	10	1	0	0	0	10	1	0	0	0	19	3	0	0	0
4	12	2	0	0	0	13	2	0	0	0	14	2	0	0	0	19	5	1	0	0
5	19	4	1	0	1	21	5	1	0	1	22	5	1	0	1	20	13	2	0	0
6	17	8	1	1	1	19	9	1	1	1	19	9	2	1	1	8	19	4	1	1
7	6	6	1	1	2	7	6	1	1	2	7	7	1	1	2	2	10	3	1	1
8	6	20	7	6	11	6	23	8	7	12	6	24	8	7	13	0	10	4	4	8
9	0	10	5	5	8	0	12	6	6	9	0	12	6	6	10	0	4	3	4	7
10	0	26	27	16	21	0	28	44	29	37	0	28	48	35	38	0	14	29	21	26
11	0	0	0	0	0	0	2	4	1	0	0	3	10	6	3	0	13	16	5	3

Table 13. Continued

upon inspection of Table 13 and a comparison with Landahl's model presented in Table 12 are presented in columnar form.

1) For all cycle times and flow rates, there are only small changes observed in the deposition pattern of the larger particles.

2) For the lower pressures in helium-oxygen mixtures, there is a remarkable increase in lower pulmonary deposition of fine particles for all cycle times and flow rates. As the environmental pressure increases, the upper respiratory deposition of the fine particles decreases but the lower respiratory deposition is maintained at the new higher rate being almost double that for air.

3) The middle particle sizes (about 2 microns) show increases in deposition for all areas when changing from air to helium-oxygen at the low pressures. This increase maintains itself at a fairly uniform level as pressure is increased.

The preceding conclusions are briefly stated and are based upon an inspectional analysis of the data· the implications are very strong in considering toxicological hazards due to aerosols in a high pressure environment. Deposition is increased, the pattern is changed, and lower pulmonary deposition of fine sizes is remarkably increased. The model used is a refined one that has been proven and tested in air; it does not take into account altered breathing patterns that have been demonstrated to exist in the helium-oxygen environment at pressure. Clearly, this information needs to be developed and a second exercizing of the model undergone.

SECTION 9.0: SUMMARY AND CONCLUSIONS

This section restates the progress that has been made on this study and the conclusions that can be drawn at this time, without the surrounding welter of supporting technical detail. It is specifically intended that this section facilitate a comparison between the goals and attainments of the past year and prepare the ground for an appreciation of proposed future recommendations.

Although the literature survey can claim to be fairly extensive by virtue of the number of citations, it was, in fact, unsuccessful in uncovering information related to aerosol behavior in high-pressure environments. The fact that literature in this area has not been uncovered is a significant finding in itself and is indicative of the investigative efforts that may be required here. The literature treated in the annotated bibliography deals mostly with nuclear submarine literature and the search has served to further the education of the investigator in this area. It is further hoped that the annotated bibliography will serve as a ready source for others interested in nuclear submarine environment problems.

The physical properties of a specific gaseous mixture usable for saturation dives to 500 ft have been tabulated. These include calculations and, in some cases, approximations regarding composition, density, viscosity, and mean free path of the molecules of the mixture. Most of these computations and virtually all other considerations made in this report were done by computer and could therefore be extended with little additional effort. The results of these computations are all presented in as much detail as was considered necessary to provide a handbook for other investigators.

The studies on aerosol mechanics have followed what might be termed classical lines, in that extrapolations were made for the atmosphere under considerations of the slip correction factor, sedimentation, diffusion, agglomeration, and any combination. The slip correction factor, also referred to as the Cunningham correction deals with the necessity for accounting for the increased mobility of particles as the dimensions become comparable with the mean free path of the gas molecules. This factor is important for submicron particles, expecially since there are some strong indications (at least for nuclear submarines) that the majority of the particles found are in the submicron range. The classical Cunningham correction is not at all amenable to considerations in atmospheres other than air. However, there is a more modern model, attributable to Fuchs and Stechkina, that is useful under any conditions if a measure of the diffuse reflectivity of gas molecules from an aerosol particle is available. Unfortunately, a source was not found for these measurements over the range of pressures and compositions required. However, assuming total diffuse reflection, the slip correction problem is one that decreases rapidly with increasing pressure and, while measurements should be made, the necessity for them is not high. Nothing was discovered regarding sedimentation, diffusion, or agglomeration that is directly indicative of the need for further research. The relationshios for each of these mechanisms are all apparently calculable and have been extrapolated insofar as possible. It should be noted, however, that we are referring to the classical relationships and as much difficulty will be encountered in applying these equations to the real situation in a deep submergence vehicle as in applying them to the real situation in air or a room of a particular configuration, chemical process container, etc. A preview of the complexity of simultaneously considering all these problems is presented in the discussion on the combined effects of sedimentation, diffusion, agglomeration. It is certainly a worthy problem and capable of solution but again not of primary importance to the goals of this study.

Although filtration theory has many [illegible] areas, some very recent reviews have put available knowledge of this subject into a very uniform and searching format. It is possible at this point to carry out meaningful calculations on the effectiveness of filtration, given some initial information regarding the aerosols to be encountered. Based on a consideration of the review, it is expected that there will be little degradation of the effectiveness of filtration mechanisms due to pressures and composition involved; the overall conclusion is that effective filtration is entirely possible. We recommend that the starting point for a series of verifying experiments and calculations would be the "absolute" type filter configuration commonly in use for all types of environmental problems. Such experiments would be of a verifying nature and are prime candidates for further studies relative to the protection of personnel.

A series of calculations have been performed to detail the effects of the given atmosphere and pressure upon droplet lifetimes and the evaporation-condensation rate of water vapor. The equations for these mechanisms are reasonably well developed. However, many of the parameters in the equations are not readily available and must be calculated from other relationships that contain varying factors of uncertainty. The general conclusions that can be drawn for water vapor and possibly other liquids is that the propensity of aerosol to grow by condensation processes is retarded with increasing pressure but that, once formed, aerosols will have increased lifetimes as the pressure increases. Without picking a specific problem, the generalization may certainly be made that the distribution structure and mean sizes of aerosols formed by the evaporation-condensation process will be "different". There is a good possibility that there will be a preponderance of fine sizes with a consequent shift in pulmonary deposition based on size parameters alone. There is a possibility that materials handled in nuclear submarines by the vapor removal system will become aerosol problems. The existence of potential toxicological hazards indicate clearly that further consideration must be made of the liquid-aerosol formation process.

The electrification and electrostatic precipitation of aerosols proved a fruitful area of consideration for two reasons. First, the mobility of ions is reduced in direct proportion to the increased pressure, so that strong effects are observable. Second, there are statements in the literature that corona discharges are not possible in pure helium atmospheres. Due to the low percentages of oxygen present at the higher pressures (34 atmospheres), we felt that this statement should be experimentally verified because of the precipitator's current application in nuclear submarine environments. The findings of the static experiment performed are that sustained corona discharges are entirely possible and that the 160 mm Hg partial oxygen pressure is more than sufficient for the corona discharge at all pressures up to 34 atmospheres. The data tabulated and presented should be useful for precipitator design considerations bearing in mind that this was a non-flow test without the presence of particles and thus merely elucidated the possibility of corona discharge.

The calculations of pulmonary deposition patterns within the lung, in the high pressure environment, showed remarkable differences in the sites of deposition and that there is an overall increase in deposition. The model did not take into account altered breathing patterns because of the lack of available data. However, the conclusion is certainly justified that further efforts on gathering the necessary breathing pattern information and a second run of the model with this information is definitely indicated. It may be that the different breathing patterns will negate the seemingly increased deposition and this is certainly to be hoped for. However, the indication of increased potential toxic effects cannot be disregarded at this time.

SECTION 10.0: FUTURE STUDIES

Several areas for further work can readily be defined from the preceding conclusions. Two areas of research that have been inferred throughout the entire project must now be brought into sharper focus and a balance maintained. The first is studies pertaining to the toxicological significance of aerosols in the environment; the second is methods of removing aerosols from the environment. With regard to the toxicological importance of the aerosols, we feel at this point that the primary aerosol experiment should be designed to determine how the size of liquid aerosol particles generated in the high pressure environment differs from the size of the particles generated by exactly the same mechanism at ambient pressures. Consideration should also be given to determining the possibility that materials existing as aerosols in a high-pressure environment are vapors at ambient conditions. Such experiments will have direct potential toxicological significance in that the existence of a compound in a particle size range other than that usually expected might lead to pulmonary deposition at different sites within the lung. Pulmonary penetrations may well be deeper, to sites that are more adsorptive and where clearance proceeds at a slower rate. The possibility of vapors existing as aerosols is a cause for even more concern, as there will be changes from simple adsorption/desorption to direct deposition of the bulk material within the lung.

With regard to the removal aerosols from the environment, we initially felt, as the theoretical portion of the work progressed, that electrostatic precipitation was of doubtful value and that efforts should be made to verify filtration mechanisms. While the electrification experiments indicate that precipitators may be usable in deep submersible vehicles, the effort required to perform the necessary experimentation and evolve filtration system designs may be accomplished far more rapidly and result in a more reliable system than might be the case with a precipitator. Further, there seems to be some probability that an economic evaluation might favor a filtration package rather than a precipitation system for this type of vehicle. The aerosol formation experiments contemplated will lend themselves completely to filtration tests and a multiple use of the same equipment is anticipated.

In considering the two basic lines of research there is a primary task to be performed that impinges upon both of them. While many assumptions can be made, experiments performed, and useful data evolved, there is at the present time virtually no information available on the aerosol content of a deep submersible environment. Much data needs to be developed on weight and number concentrations, size distribution, charge spectrum, and chemical composition. This information can only be obtained during an actual or simulated dive and we stress that provisions for obtaining this information be made at the earliest possible time.

While the preceding proposals for future work have tentatively been accepted, the results of the pulmonary deposition evaluation are being made known for the first time in this report, and have not been programmed into future work.

It is recommended at this time that efforts be made to further the available knowledge of breathing patterns within the high pressure environment. Once this information has been made available we should reconsider the model. In view of the large number of <u>inapparent</u> assumptions made by the authors of the various models, it is further recommended that our work be done in collaboration with one of the model originators.

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ACKNOWLEDGEMENTS

We wish to gratefully acknowledge the assistance of Miss Eileen Ahern for her efforts throughout the entire project in performing the necessary computer programs. Her work is particularly in evidence and appreciated in the section on Pulmonary Deposition, in which she undertook a major role in constructing and utilizing the pulmonary model. K.L. Chandiramani lent his aid throughout the project on several of the mathematical developments. R.C. Wanta has endeavored to guide and inspire the efforts of this project in all its phases and has materially aided in clarifying its goals and purpose.

APPENDIX I: ANNOTATED BIBLIOGRAPHY

The goal of this literature search was to determine the extent of existing knowledge of aerosols in high pressure environments. While nothing specific was uncovered the sources that were examined and bear some relation to the overall project are detailed below.

ARNEST, Richard T.: Atmosphere Control in a Closed Space Environment (Submarine). U.S. Naval Medical Research Lab Rpt. #367, Bureau of Medicine & Surgery, Navy Dept., Vol. 20, No. 21, 14 Dec 1961.

Abstract: The material presented in this report is a summation of class lectures on submarine medicine. The various aspects of atmospheric control within the submarine is discussed in great detail from a medical point of view. Particularly useful is a listing of more than 25 atmospheric contaminants, their sources and maximum allowable concentrations. Additional information includes symptoms, long term effects, measurement techniques, and methods of control and removal.

BECK, E.J.: Environment Control in Pressurized Underwater Habitats. U.S. Naval Civil Engineering Lab., Port Hueneme, Calif., Tech Rpt. R496, Nov. 1966. AD #642 835

Abstract: A study was made to identify those environmental factors which would have to be controlled in order that man could live and work beneath the sea. The state-of-the-art of undersea habitation is described, limitations and areas of possible major improvements are listed, and possible approaches to improvement are outlined. The developmental routes suggested are aimed at reducing cost and complexity, establishing more normal environments, and above all, reducing the hazards of working in the ocean.

Environmental factors considered are atmosphere, sanitation, food storage and preparation, heating, and the effects of special atmospheres on voice communication. The peculiar requirements for providing a tolerable atmosphere at any but the shallowest depths have, by known approaches, produced major changes in all other areas. (Author's abstract)

BOND, George F.: New Developments in High Pressure Living. Archives of Environ. Health, Vol. 9, p. 310, Sept. 1964.

Abstract: Six years of experimentation were carried out to develop the proper synthetic breathing mixtures of helium nitrogen and oxygen to permit continuous submergency at 200 ft depth. The percentage of oxygen was usually such as to be equivalent to the atmospheric partial pressure of O_2 i.e. about 160 millimeters Hg. Small amounts of nitrogen were also used. There are indications that these artificial atmospheres are superior to the ones man commonly breathes. However, at the writing of this paper the problems of body temperature control and voice communication have not been solved.

BROWN, Ivan W. and Barbara G. Cox (editors): Compression and Decompression Problems. Nat'l. Aca. of Science, Nat'l Research Council, Washington, D.C. (Rpt. 1404). Proceedings of the Thind Internat'l. Conf. on Hyperbaric Medicine, Duke Univ., Durham, No. Carolina, Nov. 17-20, 1965.

Abstract: Generalized discussion and guidelines regarding decompression sickness, air embolism, oxygen toxicity, nitrogen narcosis air problems, vertigo migraine, etc.

CARHART, Homer W.: The Maintenance of a Habitable Atmosphere. U.S. Naval Research Lab., Washington, D.C. (presented at the Underwater Tech. Conf., New London, Conn., May 5-7, 1965.

Abstract: An updated review of the various aerosol and gaseous contaminant control devices used in nuclear submarines is presented. Additionally a brief section is presented outlining the problems in high pressure environments using helium and possibly hydrogen as the diluent gas. However, the problems outlined deal with the absorption and removal of carbon monoxide, dioxide, etc. Aerosols are not specifically treated. There is an implication that virtually the total nuclear submarine aerosol problem is related to cigarette smoking and since this is impossible in the high pressure atmosphere the problem will not be important.

CARPENTER, E.P.: NOTS Participation in Sealab II Project. U.S. Naval Ordnance Test Station, Rpt. #NOTS TP 4130, China Lake, Calif., Sept. 1966.

Detail discussion is presented for mechanical logistical problems in siting and removing the Sealab II project. The various systems are discussed but useful detail on atmospheric control is not specifically presented.

COUSTEAU, Cap. Jacques-Yves: Working for Weeks on the Sea Floor. Nat'l. Geographic, April 1966.

Abstract: Detailed and highly illustrated description on Conshelf III experiment. Approximately 3 weeks were spent on the ocean floor at a depth of 328 ft and a pressure of 11 atmospheres. This was a saturation dive with the breatning mixture being helium and oxygen. The divers lived within the environment and regularly left it using diving gear and breathing the special mixture to perform simulated work projects.

EBERSOLE, Lt. Comm. John H.: New Dimensions of Submarine Medicine. Submarine Medicine, Vol 262, No. 12, p. 599, 24 Mar. 1960.

Detailed discussions of the various problems involved in maintaining the atmosphere during long periods of submergence. The methods of scrubbing carbon dioxide as well as the additional toxicological problems encountered with the monoethanolamine solution are discussed. Average flow rates are given for the up-take of oxygen per man and per hour. While insufficient oxygen can be stored in high pressure flasks the details of the current system are stated to be classified at the time of this paper's presentation. Carbon monoxide is eliminated by the catalytic "burning" technique. This method oxidizes the carbon monoxide to carbon dioxide which is then handled by the CO_2 scrubbing system. This system also serves to oxidize other atmospheric contaminants particularly the volatile hydrocarbons. However, there is also the problem that some hydrocarbons are not completely oxidized and toxic and irritating intermediates are formed. Freon is extensively used in submarines and while of itseif is a relatively non-toxic substance it is readily decomposed to hydrocloric acid etc. in the presence of open flames. Several sources of hydrocarbons are indicated such as paints, waxes, cleaning fluids, etc. The most effective control technique is a rigorous substitution program. The chief source of aerosol concentrations are tobacco smoke and electrostatic precipitators are suggested for abatement purposes. Ozone has been found to be generated by various electric devices but the rates and concentrations are sufficiently low so that increased ventilation can be utilized as an abatement technique. The balance of the paper deals with reports of the first long dives of Skate and Seawolf.

EBERSOLE, Lt. Comm. John H.: Submarine Medicine on U.S.S. Nautilus and U.S.S. Seawolf. Proc. of the Royal Society of Medicine, Vol. 51, p. 63

Abstract: The initial evaluation of the medical problems on the nuclear submarines Nautilus and Seawolf are presented. The paper deals mainly with radiation exposures and the safety of the environment. Other comments refer to the ventilation system and CO and CO_2 removal facilities.

KINSEY, Jack L.: Some Toxicological Hazards in Submarines. Federal Proc. 19, No. 3, Part II: Problems in Toxicology, p. 36, 1962.

Abstract: The paper describes seven systems used in nuclear submarines to control pollutants generated therein. Briefly described are the specific control methods for carbon dioxide and carbon monoxide. Aerosol concentrations within the craft are found to stabilize at about 400 micrograms per cubic meter consisting of approximately 80% organic substances. One of the chief sources of aerosol production is found to be cigarette smoking. Air ions also tend to reach stable concentrations averaging about 450 positive and 240 negative ions.

The fact that higher concentrations are not found is attributed to their binding with the high aerosol concentrations. The excess of positive ions is attributed to their slightly lower mobility. Monitoring is carried out with the Mk 3 analyzer designed by NRL. It consists of five analytical channels for oxygen, carbon monoxide, carbon dioxide, hydrogen and Freon.

KRUEGER, Alpert P. and Richard F. Smith: The Physiological Significance of Positive and Negative Ionization of the Atmosphere. Man's Dependence on the Earthly Atmosphere, Karl Schaeffer, (ed.), The Macmillian Co., New York. Proc. of the First Internat'l. Symposium on Submarine & Space Medicine, U.C. Submarine Base, New London, Conn., Sept. 8-12, 1958.

Abstract: The histroy of atmospheric electricity is briefly cataloged together with methods of generating and measuring ions in air. Detailed are natural and artificial sources of ions and the observed physiologic effects of positive and negative ions on both extripated tissues and intact animals. As a generality negative ions seem to have beneficial effects and promote feelings of wellbeing while the positive ions have the opposite effect.

KRUEGER, Albert P. and Richard F. Smith: The Effects of Air Ions on the Living Mammalian Trachea. J. of General Physiology, Vol. 42, No. 1, p. 69-82, Sept. 20, 1958.

The paper discusses the effects of air ions on the rate of ciliary action. Generally positive ions tend to decrease the beat, the negative ions tend to increase it.

LEARY, Frank: Vehicles for Deep Submergence. Space/Aeronautics, Vol. 49, No. 4, p. 52, Apr. 1968.

A generalized description of all the current and recently past submergence projects is presented. Emphasis is placed upon the mission capabilities of the vessels with very little mention being made of life-support systems. No differentiation is pointed out between saturation dive vessels and normal pressure types.

Man's Extension into the Sea: Marine Technology Society - transactions of the Joint Symposium, 11-12 Jan 1966, Washington, D.C.

This is a report of a symposium whose purpose was to disseminate knowledge gained from the Sealab II experiments. A great deal of engineering detail is presented on the Sealab II experiments and items discussed cover: design and construction, logistics, crew selection and training, proplusive efficiency of divers in the sea, ocean engineering, underwater photography problems, human physiology, underwater weather station, measurement of human performance, value of saturation diving, salvage operations, flexible structures and unusual engineering problems are all discussed.

MAVOR, James W., et al: Alvin, 6000 Ft. Submergence Research Vehicle. The Soc. of Naval Architects and Marine Engineers, No. 3, p. 1-32, (1966).

Alvin, a deep-submergence oceanographic research submarine was commissioned on June 5, 1964, reached her designed operating depth of 6000 feet during trials in July, 1965, and maintained a deep-diving schedule in February and March 1966. The vehicle, displacing 30,000 lb on an overall length of 22 ft, carries a payload of 1400 lb and a complement of one pilot and one or two observers. Five plexiglas windows and a mechanical arm permit observation, collection, and manipulative tasks. The design of Alvin is described in some detail and the lessons learned from operations over a two-year period are presented and discussed. The logistic support used with Alvin operation is described, including a seagoing catamaran built for the task. (Author's Abstract)

McCONNAUGHEY, W.E.: Atmosphere Control of Confined Spaces from Man's Dependence on the Earthly Atmosphere, Karl Schaefer (ed.), The Macmillian Co., New York. (Presented at the Proc of the First International Symposium on Submarine & Space Medicine, U.S. Submarine Base, New London, Conn., Sept. 8-12, 1958.

The technical considerations for choosing between a non-regenerative lithium hydroxide CO_2 absorption system and a regenerative MEA scrubber system are presented for nuclear submarines and submergence times in excess of ten days, the heavier, bulker, MEA system is utilized. Descriptions are also presented for the CO burner and electrostatic precipitator used for the removal of aerosols.

McCONNAUGHEY, W.E.: Atmosphere Control on Submarines. BuShips Journal, p. 11, May 1960.

See paper by same author "Atmosphere Control of Confined Spaces".

DEPT. of the NAVY, Office of Naval Research & Bureau of Medicine & Surgery, Washington, D.C.: A Bibliographical Sourcebook of Compressed Air, Diving and Submarine Medicine. Vol 1 - Hoff, E.C., Feb. 1948. Vol II - Hoff, E.C. and L.J. Greenbaum, Nov. 1954. Vol III - Greenbaum, L.J. and E.C. Hoff, Dec. 1966.

These three volumes cover all aspects of the problems of compressed air diving, medical, physiological, etc. The volumes have been developed over a period of years and in each case emphasis is shifted and changed to fully explain new and important developments. In addition to this specific bibliographic material and annotation there are long summaries on each subtopic.

U.S. NAVAL Research Lab., Washington, D.C.: The Present Status of Chemical Research in Atmosphere Purification and Control on Nuclear-Powered Submarines.
Miller, R.R. and Piatt, V.R., NRL Rpt. No. 5465, 21 Apr 1960
Piatt, V.R., et al, NRL Rpt. No. 5630, 14 July 1961
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Carhart, H.W. and Piatt, V.R., NRL Rpt. No. 6053, 31 Dec. 1963
Lockhart, L.B., Jr. and V.R. Piatt, NRL Rpt. No. 6251, 23 Mar 1965
Alexander, A., et al, NRL Rpt. No. 6491, 11 Jan 1967

This series of reports represents continuing discussions of the detailed progress and research results of various projects intended to continuously improve the habitability of submarine atmospheres and discern long range problems. The subjects covered deal with aerosols, gases, and vapors, their sources, instruments and techniques for detection and control methods. Control is generally effected by collection devices or substitution techniques. Significant details are presented for all phases of the research and it is possible to continuously follow the statement of a problem, development of a technique and ultimate solution, in the reports of several successive years.

NONHEBEL, G. (ed.): Purification of the Atmosphere in Nuclear-Powered Submarines from Gas Purification Processes, George Newnes Ltd., London, Pt. 3, p. 799, 1964.

This chapter is contained in a general book on gas purification and briefly outlines the gaseous and aerosol problems in nuclear submarines. Tables are given for compounds which have been identified in submarine atmospheres, the concentrations normally found, and acceptable concentrations. Flow charts are also given for the purification chain and detailed descriptions are presented for the various gas purification systems.

PAULI, D.C. and G.P. Clapper (eds.): An Experimental 45-Day Undersea Saturation Dive at 205 Feet. Office of Naval Research, Dept. of the Navy, Washington, D.C. ONR Rpt. No. ACR-124, March 8, 1967

This document of over 400 pages represents a complete description of the Sealab II experiment. All phases and aspects of the dive have been covered in considerable detail. With specific relation to atmosphere control there is no mention of aerosols whatsoever. Carbon dioxide was controlled with lithium-hydroxide canisters. Hydrocarbons and odors were controlled by the use of large filters of activated charcoal.

RAMSKILL, Eugene A.: Providing Better Air for Bottled Up Men. SAE Journal, Paper 352D, June 1961

The complete atmospheric control system for nuclear submarines is detailed in outline form. Components include an electrostatic precipitator, catalytic combustor, particulate filter, cooling coil, activated charcoal and CO_2 remover. Inputs are the submarine atmosphere itself and an oxygen generator. An atmosphere analyzer (undescribed) has the ability to sample the system at several points in the cycle. A table is also presented on the various constituents of nuclear submarine atmospheres and representative concentrations found therein.

SAKHALOV, I.N.: Undersea Research Vehicles. Dept. of the Navy, Office of the Chief of Naval Operations, Office of Naval Intelligence, Translation Section, ONI Translation No. 2092, August 1965, AD No. 633 826.

A brief discussion is given on two proposed undersea research vehicles. Details are given as to their range, mobility and facilities. However no details are available on atmospheric systems. Stated usage for these vehicles is for research for the fishing industry.

SAUNDERS, Raymond A.: A New Hazard in Closed Environmental Atmospheres. Arch. Environ. Health, Vol. 14, p. 380, Mar 1967.

A government contractor recently evaluated a completely integrated life support system in an experiment which involved maintaining five men for 30 days in a hermetically sealed environmental chamber. Undesirable contaminants developed in the chamber and persisted in spite of the contaminant control system. The atmosphere acquired an odor which became increasingly disagreeable. The crew developed anorexia, became nauseated, suffered severe vomiting, and developed headaches and odd facial sensations. These symptoms together with other difficulties prompted test termination after four days. Preliminary efforts to pin-point the cause of the sickness were unsuccessful.

Later analysis of the chamber atmosphere at the Naval Research Laboratory identified 23 volatile compounds. Among these were monochloroacetylene and dichloroacetylene. The latter compound is known to produce symptoms identical to those experienced by the chamber crew. Dichloroacetylene has since been found at low concentration in a submarine atmosphere also.

A few chlorinated hydrocarbons customarily have been tolerated in most closed environmental atmospheres because of their general usefulness and relatively low toxicity. Such was the case in both these instances. The toxicant was produced through the action of an improperly operating element of the environmental control system on one of these compounds. (Author's Abstract)

SAUNDERS, R.A. and R.H. Gammon: The Sealab II Trace-Contaminant Profile. Naval Research Laboratory, Rpt. No. 6636, Washington, D.C., Dec. 4, 1967.

Adsorption of contaminants on activated charcoal was one of the methods used to sample the atmosphere of Sealab II. The contaminant material was later recovered by slowly heating the charcoal in an evacuated system and retaining the desorbate in liquid-nitrogen-cooled traps. The desorbate mixture was resolved with a vapor-phase chromatograph. The eluted components were passed directly into a rapid-scanning mass spectrometer for positive identification. Components were also collected from the effluent of the chromatograph and identified by means of their infrared spectra. Over 30 different compounds were identified in the charcoal desorbate. Added to those already known, the total number of atmospheric contaminants which have been identified in Sealab II now amounts to 40. These include refrigerants, saturated and unsaturated aliphatic hydrocarbons, cyclin aliphatic hydrocarbons, chlorinated hydrocarbons, and aromatic hydrocarbons. The characteristic feature of the Sealab II contaminant profile, like that of Sealab I, was a predominance of hydrocarbon contaminants. Some of the more prominent contaminants in the Sealab II atmosphere were cyclic aliphatic hydrocarbons which are not generally encountered as dominant trace contaminants in closed environmental atmospheres. (Author's Abstract)

SCHAEFER, Karl E.: Basic Physiological Problems in Submarine Medicine from Man's Dependence on the Earthly Atmosphere, Karl Schaefer (ed.) The Macmillian Co., New York. Presented at the Proc. of the First International Symposium on Submarine & Space Medicine, U.S. Submarine Base, New London, Conn., Sept. 8-12, 1958.

The very basic requirements of man the "open system" living in a submarin "closed system" are presented. Discussed in detail are questions of adapta to various gas and contaminant concentrations and the relationship between natural and artificial time cycles.

SCHAEFER, Karl E.: Airborne Condensation Droplets, Ions May be Major Health Factors in Habitability of Closed Spaces. Heating, Piping & Air Conditioning, p. 101-105, May 1959; p. 123-125, June 1959 and p. 139-140, July 1959

Three components of the submarine atmosphere which previously have escap major attention are discussed. These included (1) trace substances, (2) condensation droplets (nuclei) and (3) positive or negative ions. The biological effects of ions are discussed with a general indication that negative ions are beneficial and positive ones are not. During submergence there are found to be marked increases in both positive and negative and ions and condensation nuclei. The increase of ions in fleet type submarines is thought to be due to radioactive dials. In modern nuclear-powered submarines there is a consta source of radiation which contributes to the ion formation. The increase in condensation nuclei and condensation droplets are possibly due to temperatur extremes found within the vessel which give rise to supersaturated condition and the condensation of moisture on the ions. It was also found that higher temperatures generally decrease the number of ions and that humidity and io content have an inverse relationship. It was also noted that the number of positive ions increased more than the negative ones. The general conclusio is that the production of the ions in a submarine is from radiation sources.

SCHAEFER, Karl E.: Experiences with Submarine Atmospheres. J. of Aviation Medicine, Vol. 30, p. 350-359, May 1959.

The problems of submarine atmosphere experienced during long submergence periods are reviewed. [illegible] exchange in the normal apartment and submarine are compared. The role of trace substances and ionization patterns of the atmosphere in confined spaces are discussed. Emphasis is placed on chronic carbon dioxide toxicity which has been in the past a cardinal problem of submarine medicine. Differences in the combined effects of increased CO_2 and low oxygen under accute and chronic conditions are analyzed. (Author's Abstract)

SCHAEFER, Karl E. and James H. Dougherty: Interaction of Aerosols and Air Ions. Bureau of Medicine & Surgery, Rpt. No. 380, Dept. of the Navy, Vol. XXI, No. 11, 29 Mar 1962

An experiment is described wherein variations in ion concentrations of small, medium and large ions were investigated with relation to numbers of condensation nuclei. The nuclei were generated from DOP. Results indicate that the air ions do become attached to aerosol particles and their measurable numbers are decreased. This finding is pointed out as being of importance in physiologic studies of the effect of air ions when the aerosol concentration is unknown.

SCHAEFER, Karl E.: Environmental Physiology of Submarines and Spacecraft. Archives of Environmental Health, Vol. 9, p. 320-331, Sept. 1964.

Description of experiments to check the 1-1/2% TLV used in submarines for carbon dioxide concentrations. The conclusion of the evaluation was that the TLV of 0.5% CO_2 recommended by the ACGIH is supported. The TLV for carbon monoxide in submarines is reduced from 100 ppm to 25 ppm. Additional values are given for 90 days continuous exposure on various other toxic trace substances most of which are below the currently accepted values for 8 hour exposures.

The bulk of the aerosol concentration in submarines is mainly attributed to cigarette smoking. Concentrations of aerosol on a submarine were reduced by 1/3 when smoking was temporarily prohibited during a specific trip. Maximum concentrations of positive and negative ions were found to be approximately 1,000 per cc. Increases in the aerosol concentration caused a decrease in the number of small ions and an increase in the large to medium size ions. Further increases in aerosol concentration lead to a general decrease of small and large ions. Condensation nuclei concentrations in the in the submarine atmosphere increased ten to twenty-fold during periods of submergence. Aerosols are further found to be significant in concentrating trace substances present in the atmosphere.

SCHULTE, John N.: The Medical Aspects of Closed Cabin Atmosphere Control. Military Medicine, p. 40, Jan 1961.

The paper describes some initial studies on the cruise of nuclear submarines. Briefly mentioned are the toxic substances and levels observed, episodes during equipment failure and the results of physiological and hematological studies before, during, and after the trips.

SMITH, W.D., F.J. Woods and M.E Umstead: Submarine Atmosphere Studies Aboard the U.S.S. SCAMP. U.S. Naval Research Lab, Washington, D.C. Oct. 4, 1965. (AD No. 474 373)

An improved model of the original NRL Total Hydrocarbon Analyzer was successfully tested aboard the USS SCAMP. It was demonstrated that the ship's air banks can be used as a source of air for the operation of the Total Hydrocarbon Analyzer, a procedure which will facilitate use of the instrument aborad ship. Detailed analyses were made of the concentrations of methane, Freon-12, and "total hydrocarbons," with particular attention given to the methods of sampling and of sample introduction. A slowly rising level of methane and Freon-12 during submergence was observed, but little variation in contamination level from compartment to compartment was noted. (Author's Abstract)

STARK, James E.: Concepts of Atmosphere Control in Submarines. Archives of Environmental Health, Vol. 9, p. 315, Sept 1964.

The discussion recognizes the need to control carbon monoxide and carbon dioxide as major items but deals in general with the trace substances. Four basic approaches are listed to atmosphere control. The first is screening of materials proposed for entry into the submarine. The second is consideration of the constructional material used in the submarine, such as paints, adhesives and lagging, etc. The third consideration for control is the processes of detection and analysis and the fourth and final consideration is removal systems for conversion or destruction of toxic materials.

The need for further study of an establishment of TLV's for the unusual conditions of submarines is emphasized.

VERZAR, Fritz: Physiological and Toxicological Significance of Atmospheric Condensation Nuclei from Man's Dependence on the Earthly Atmosphere, Karl Schaefer (ed.), The Macmillian Co., New York. Presented at the First International Symposium on Submarine and Space Medicine, U.S. Submarine Base, New London, Conn., Sept. 8-12, 1958.

The number of atmospheric condensation nuclei affects the condition of air in confined spaces. Droplets condensing on nuclei can precipitate toxic substances from the air and raise the concentration to toxic levels. This can occur in the ambient air or in the respiratory tract during normal respiration. Temperature and humidity measurements show that this precipitation takes place mainly on mucous membranes between the nose and the larynx.

Condensation nuclei of atmospheric or human origin (smoking) can be filtered out. Sunrays can produce nuclei in air by photochemical action on trace substances and should, therefore, be prevented from entering the confined space. (Author's Abstract)

WINGET, Clifford, L., et al: A Technical Guide to the Deep Submergence Research Vehicle (DSRV) Alvin for use in Planning Scientific Missions. Woods Hole Oceanographic Institution, Woods Hole, Mass., Dec 1967.

This report is a detailed brochure for scientists who are contemplating the use of Alvin for research purposes. Complete information is presented regarding all the systems available, their capabilities, and details given even down to the types of clothing which should be worn. A form is also presented on which the scientific mission may be outlined for consideration.

APPENDIX II: EVAPORATION CONDENSATION - CALCULATION OF NECESSARY PARAMETERS.

II.1 INTRODUCTION

Because of a lack of the detailed experimental data required for calculation of droplet evaporation rates, the various methods used in calculating the transport and other properties are presented in extension. Note that all the calculations are based upon properties that are themselves deduced from quasi-empirical equations given in the literature stated to be correct within limits ranging from about ±4 to ±20%. Therefore, the results may only be considered rough and indicative of trends.

II.2 MOLECULAR DIFFUSION

In considering the condensation, evaporation, and nucleation of any substance in a given atmosphere, a necessary parameter is the diffusivity of that substance in the atmosphere. Such a determination has been made for water vapor in the helium-oxygen environment at pressures ranging from 10 to 500 psia. Because data for this situation is not apparently available, the calculations were performed using empirical equations. Since these equations will be useful in the future for calculating the diffusivities of substances other than water and because of an error in the most readily available reference source*, the relationships will be presented in detail.

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*Note: The method of calculating diffusivities of mixtures is presented in the 4th Edition of the Chemical Engineers' Handbook (Ref. II-2). However, while it is well discussed, it contains a major numerical error. Therefore, we recommend that the original source by Wilke and Lee (Ref. II-1) be utilized.

The diffusion coefficient of one component through a stagnant multi-component mixture may be calculated from equation (II-1).

$$D_{1(23)} = \frac{1 - Y_1}{(Y_2/D_{12}) + (Y_3/D_{13})} \qquad \text{(II-1)}$$

where Y = mole fraction of each component

D = diffusion coefficient - cm^2/sec

$D_{1(23)}$ = H_2O vapor diffusing through He-O_2

D_{12} = diffusivity of H_2O and O_2

D_{13} = diffusivity of H_2O and He

Thus: 1 refers to H_2O

2 refers to O_2

3 refers to He

The mole fractions of each component was determined from a knowledge of the fact that the oxygen partial pressure is maintained constant at 160 mm mercury and the partial pressure of water vapor at saturation (vapor pressure) should be constant at a value of 23.37 mm of mercury. The diffusivity of water vapor through oxygen and water vapor through helium was calculated according to the equation of Wilke and Lee.(II-1)

$$D_{12} = \frac{B\,T^{3/2}\,\left[(1/M_1) + (1/M_2)\right]^{1/2}}{P\,(r_{12})^2\,I_d}\,, \qquad \text{(II-2)}$$

where

M_1 & M_2 = molecular weights of the respective components,

$B \quad 10.7 - 2.46 \left[(1/M_1) + (1/M_2)\right]^{1/2} \times 10^{-4}$,

T = absolute temperature - °K

$r_{12} = \frac{r_1 + r_2}{2}$ = collision diameter - Å from table of values,(II-2)

I_d = collision integral - from table after calculating force constants also from table(II-2), and

P = absolute pressure - atm.

The results of this series of calculations are shown in Table 7 and Figure A-1. The diffusion coefficient varies from a value of 0.736 at 10 psia to 0.026 to 500 psia. The value for water vapor in air at ambient pressure is about 0.220 cm^2/sec.

II.3 THERMAL CONDUCTIVITY

Thermal conductivity of the gas mixture in which a droplet is evaporating is an important component of the evaporation (condensation) equation that varies with atmospheric composition and pressure. The thermal conductivity (K^o_{123}) may be determined from the following equations:(II-2)

$$K^o_{123} = \frac{Y_1 K^o_1 M_1 + Y_2 K^o_1 M_2 + Y_3 K^o_3 M_3}{Y_1 M_1 + Y_2 M_2 + Y_3 M_3} \quad , \qquad \text{(II-3)}$$

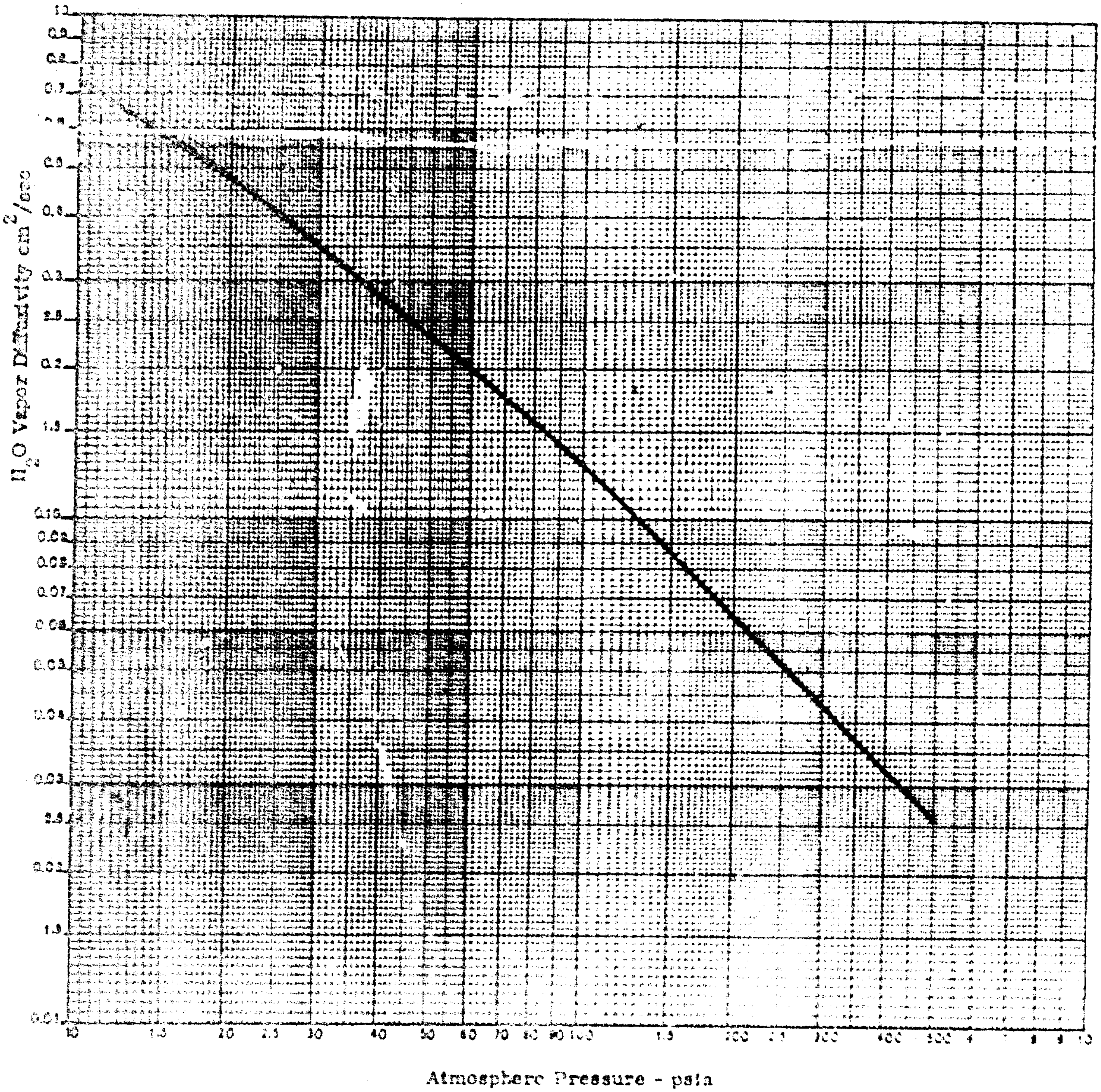


Figure A-1 Water Vapor Diffusivity in the Oxygen-Helium Atmosphere vs Pressure.
(PO_2 = 160 mm Hg; PH_2O = 23.37 mm Hg; T = 20°C)

where

K^o_{123} = thermal conductivity of the mixture at ambient pressure - cal/sec-cm-°K,

K^o_1 = thermal conductivity of H_2O vapor at ambient pressure,

K^o_2 = thermal conductivity of O_2 vapor at ambient pressure, and

K^o_3 = thermal conductivity of He vapor at ambient pressure.

From the above equation, the thermal conductivity may be determined (usually ambient) at the pressure for which tabulated values are quoted. Several solutions of the equation are necessary since, in our case, the mole fractions of the gas are varied with increasing pressure. To determine the thermal conductivity at the pressure of interest (K_{123}) it is first necessary to determine the psuedo critical pressure and temperature of the mixture. This is accomplished according to the mole fraction of each component by the following equations:(II-2)

$$T/T_{pc} = \frac{T}{Y_1 (T_c)_1 + Y_2 (T_c)_2 + Y_3 (T_c)_3} , \qquad \text{(II-4)}$$

where

T = temperature of the gas mixture - °K and

T_c = critical temperature of each component (1, 2, 3) ;

$$P/P_{pc} = \frac{P}{Y_1 (P_c)_1 + Y_2 (P_c)_2 + Y_3 (P_c)_3} , \qquad \text{(II-5)}$$

where

P = absolute pressure of the gas mixture - atm and

P_c = critical pressure of each component (1, 2, 3).

After determination of the critical properties of the mixture, the thermoconductivity at the stated pressure (K_{123}) may be found through the use of Figure A-2 and the following equation.

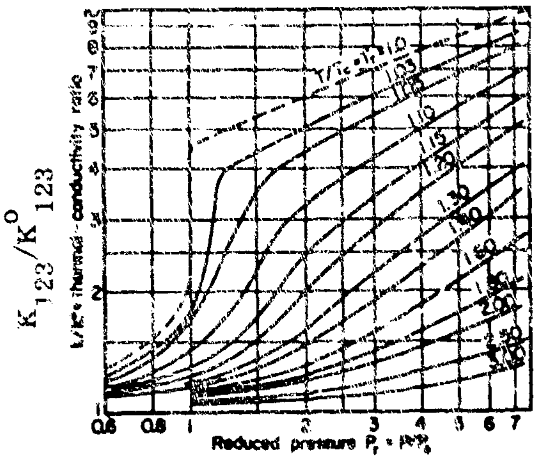
$$K_{123} = K^{o}_{123} \, (K_{123}/K^{o}_{123}) \qquad \text{(II-6)}$$

In the case of the helium-oxygen atmosphere and water vapor up to 500 psia, the psuedo-critical properties of the gas are asympototic to unity in Figure A-2; therefore the values at ambient pressure are suitable for use as combined by the mixture equation. The variation in the tabulated (Table 7) values with increasing pressure is due not to the effects of pressure, but to the fact that the mole fraction of each component varies as the pressure is increased.

II.4 VAPOR PRESSURE

The vapor pressure of liquids tends to increase slightly with increasing pressure. According to Bradley this increase may be determined by the Poynting equation:(II-3)

$$\frac{p'_t}{p_t} = \exp\left(\frac{P' \, V_L}{R \, T}\right) , \qquad \text{(II-7)}$$



$$P_r = P/P_{pc}$$

Figure A-2. Curve for Determining the Thermal Conductivity of a Gas at Pressures Other Than Ambient. (After Perry, R.H. et al (eds.): Chemical Engineers Handbook (4th ed), McGraw-Hill Book Co., New York, 1963).

where

p_t = vapor pressure of the bulk liquid - dynes/cm^2,

p_t' = vapor pressure of the bulk liquid at the pressure of interest (P) dynes/cm^2,

P' = pressure of the environment - dynes/cm^2,

T = temperature of the environment - ^oK,

R = gas constant - 8.317 x 10^7 ergs/^oK-mole, and

V_L = molecular volume - cm^3/g-mole

For water vapor in the helium-oxygen environment at 500 psia, this increase amounts to only 2.5% and has therefore been neglected for the entire series of calculations.

II.5 DROPLET VAPOR PRESSURE

The evaporation or condensation rate of the droplet depends on the vapor pressure of the surrounding vapor (p_t) and the vapor pressure of the droplet (p). Because of the droplet's curved surface, the molecules are less tightly held then they would be in a plain surface that results in a higher vapor pressure over the droplet than for the liquid itself.$^{(II-4)}$ The droplet vapor pressure may be calculated from the classical Gibbs-Thompson relationship:

$$\ln\left(\frac{p}{p_t}\right) = \frac{4\gamma M_l}{R\,\rho_L\,T_d\,d}\,, \qquad \text{(II-8)}$$

where

p = droplet vapor pressure - dynes/cm^2,

ρ_L = liquid density g/cm^3,

d = droplet diameter - cm,

γ = surface tension of the liquid - dynes/cm, and

T_d = droplet temperature - $^\circ$K.

Note: Strictly speaking, the temperature used in this equation is the actual temperature of the evaporating droplet rather than the ambient temperature. This, then, results in an equation with two unknowns: the droplet temperature (T_d) and the vapor pressure of the droplet (p).

The droplet temperature may be calculated from the following relationship:(21)

$$T_d = \frac{L M_1 D_{1(23)}}{K_{123} R T} \left[\frac{\xi p_t - p}{2 D_{1(23)}/d v \alpha + d/d + 2\Delta} \right] , \qquad \text{(II-9)}$$

where

L = latent heat of vaporization of the liquid - cal/g

Δ = vapor shell thickness ≈ λ the molecular mean free path,

$v = (RT/2\pi M_1)^{1/2}$ - cm/sec,

α = evaporation (or condensation) coefficient = 0.04 for pure H_2O(II-6), and

ξ = degree of saturation assumed = 1 (i.e. 100% RH).

This now results in two equations and two unknowns, the solution of which is given in Table 6.

APPENDIX II: LITERATURE CITED

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APPENDIX III: SYMBOLS

A = a numerical factor having a value of approximately unity

A_o = first Cunningham correction coefficient = 1.257

B = second Cunningham correction coefficient = 0.400, mobility of the aerosol particles

C = third Cunningham correction coefficient = 1.10, in filtration, a numerical factor of 0.5 to 0.75

C_D = drag coefficient

D = diffusion coefficient

E = collecting field strength, efficiency of intact filter

E_D = diffusional filtration efficiency

E_G = gravitational filtration efficiency

E_I = inertial filtration efficiency

E_j = filtration efficiency due to all mechanisms (j = ERIGM Qq)

E_M = molecular filtration efficiency

E_o = charging field strength

E_{Qq} = electrostatic filtration efficiency (Also: E_{oq}, only fiber is charged; E_{Qo}, only aerosol is charged.)

E_R = direct interception filtration efficiency

$E\beta_j = E_j$ and includes consideration of the interference effect

F = drag on particle

I_d = collision intergral

K = agglomeration coefficient

$K_{1,2,3}$ = thermal conductivity

M = collection efficiency, molecular weight

N_D = gravational filtration parameter

N_I = inertial filtration parameter

N_M = molecular filtration parameter

N_o = ion concentration

N_{Qq} electrostatic filtration parameter

N_R = direct interception filtration parameter

P = pressure in atmospheres

P_c = critical pressure

P_e = Peclet number

P_{pc} = psuedo critical pressure

R = radius, gas constant

R_1 = radius of discharge electrode

R_2 = radius of collecting electrode

R_e = Reynolds number

S = ratio of particulate sphere of influence to particle radius, saturation

$Stk.$ = Stokes number

T = absolute temperature

T_c = critical temperature

T_d = droplet temperature

T_{pc} = pusedo critical temperature

U_o = velocity of particle (re: mobility, B)

V = gas velocity

V' = applied potential

V_L = molecular volume

Y = mole fraction

Z = electric mobility of ions

Z_2 = electric mobility of O_2 ions

Z_3 = electric mobility of He ions

Z_r = reduced electric mobility of ions

$\bar{c}$ = R.M.S. velocity

d = particle diameter (in filtration as d_p)

d_f = fiber diameter

e = electronic charge

f = fraction

g = gravitational acceleration

h = height

i = current per unit length of electrode

k = Boltzmann's constant

m = ion mass, droplet mass

n = number concentration of particles, number of electronic charges, e

n_o = initial number concentration of particles

n_s = saturation charge

p = a factor (re: electrification), droplet vapor pressure

p_t = liquid vapor pressure

q = charge acquired in time, t

r = radial distance from electrode centerline

r_{12} = collision diameter

s = fraction of molecules reflected diffusely

t = time

u = drift velocity of particles

v = sedimentation velocity

α = evaporation (condensation) coefficient

β = f(s) (re: slip correction), volume fraction of fibers

γ = 0.499 as extracted from the current expression for λ, surface tension

Δ = vapor shell thickness

δ = 1 for specular reflections of the molecule from a particle but generally $\delta = (1 + \pi s/8)$ (re: slip correction), saturation

ϵ = dielectric constant

ϵ_o = dielectric constant of a vacuum. 8.85434×10^{6} amp-sec/volt-cm

η = viscosity of the fluid medium

θ = integer

λ = mean free path of gas molecules

μ = micron

ν = $(RT/2\pi M)$

ρ = particulate density

ρ_L = liquid density

ρ' = gas density

τ = relaxation time

$\chi = \frac{2\lambda}{d}$, the Knudsen number

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The purpose of this study was to elucidate hazards to personnel arising from aerosols in high pressure helium-oxygen atmospheres utilized in deep submergence vessels. Aerosol properties of sedimentation, diffusion, agglomeration, electrification,and the slip correction factor have been extrapolated to pressures of 500 psia. The effects of the atmosphere upon aerosol filtration, electrostatic deposition, condensation and evaporation have been considered. Experiments have been performed to verify the possibility of maintaining a corona discharge in the given atmosphere for both positive and negative applied potentials. Th deposition patterns of aerosols within the lung have been considered via the application of a deposition model to a range of particle sizes and pressures. The possibility of significantly increased respiratory deposition is evident.

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