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FURTHER STUDIES OF JET CONTRAIL NUCLEATION AND VISIBILITY CHARACTERISTICS

by

Philip Cole

and

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Leasco Systems & Research Corporation
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135 West 50th Street
New York, New York 10020)

Contract No. F19628-67-C-0283
Project No. 8679
Task No. 867902
Work Unit No. 86790201

FINAL REPORT

June 1967 through May 1968

June 15, 1968

Contract Monitor: Seymour J. Birstein
Meteorology Laboratory

Prepared for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
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FURTHER STUDIES OF JET CONTRAIL NUCLEATION AND VISIBILITY CHARACTERISTICS

Abstract

This report is a continuation of the final report for contract AF19(628)-5193. The assumptions and assertions of that report are examined, and estimates made of how these may affect the worth and accuracy of numerical predictions of contrail properties. A special type of analytic-experimental analysis is proposed to ferret out nonthermodynamic variables, and is applied to flight test data. Following the analysis, further computer simulation is explored. Additional data lead to bounds on the values of heretofore unspecifiable parameters. Further experimental study is indicated. The data is presented in terms of the dependence of contrail formation on ambient temperature and relative humidity.

Participating Scientists

Philip Cole

and

Theodore M. Jungreis

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I. Introduction

The current study has been done in fulfillment of Air Force Contract F19628-67-C-0283. Its purpose is the formulation and study in depth, using computer simulation techniques, of mathematical models to describe heterogeneous water nucleation in jet exhaust contrails. In particular, general equations for contrail properties are sought as a function of system variables. Information provided in the final report for contract AF19(628)-5193[1][1] is the base for which this report is a continuation.

For this work, the authors took the approach of developing:

(a) an analysis of the assumptions and assertions of contract AF19(628)-5193,

(b) a set of experimental and statistical, rather than purely theoretical, techniques for quantitative prediction of contrail characteristics, and

(c) a further theoretical treatment involving contrail simulation by computer including the effects of relative humidity and ambient temperature.

Sections II, III, and IV of this report deal with parts (a), (b), and (c) above, respectively. Conclusions are presented in Section V.

Typical fuels used by jets contain large amounts of hydrogen (C_nH_{2n}). The exhaust gases of jets under certain conditions tend to be super-saturated with respect to water vapor, and cooling of the gases produces water droplets known as contrails. Under normal circumstances, water vapor condenses only on foreign particles, and the fuel exhaust usually contains enough such particles for condensation to take place.

The reason for adding SO_3 to the fuel is the addition to the exhaust of much larger numbers of extremely small hygroscopic nuclei than are normally present. The water vapor formed by the burning of a hydrocarbon fuel will then preferentially condense on these nuclei rather than on the fewer, larger, and less hygroscopic nuclei normally produced in the combustion process. The droplets formed will thus be smaller than those formed in normal contrail formation.

The objective of this study is the determination of those amounts of additive which produce an invisible contrail for a given set of ambient conditions and engine characteristics. Such a contrail contains a large number of particles sufficiently small that the total cannot be seen.

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[1] Numbers in square brackets refer to similarly numbered items in the bibliography.

It is an observed fact that contrail visibility requires a minimum desity (in space) of particles whose radius exceeds one - quarter micron. Calling such a particle a "large particle", the objective may then be restated as: Under given conditions, find an additive - fuel combination that produces a contrail in which the density (in space) of large particles is less than the critical density.

II. Review of Previous Research

After investigating possible chemical combinations in the jet exhaust due to oxidation of additive, the authors in their final report for contract AF19(628)-5193, describe the formation of droplets. Thermodynamic considerations, involving ambient conditions as parameters, predict the size and rate of formation of droplets, and knowledge of the physical chemistry of additive end products leads to specific numerical results.

Of course, the worth and accuracy of numerical predictions of a complicated physical simulation are no more valid than the worth and accuracy of the many assumptions involved. In AF19(628)-5193, assumption fall naturally into categories associated with properties of the exhaust wake, the exhaust products, the nucleation process, and the contrail itself.

Description of the exhaust wake has meaning only to the extent that turbulence has not completely dissipated the central core of the wake. Photographs [2] of actual jet flights at altitude 40,000 ft. indicate a distance behind the jet of about 100 to 150 ft. before contrail formation (the range decreases at higher altitudes), with maintainance of the general shape for several hundred additional feet.

Forstall and Shapiro [3] have measured and analytically described the wake temperature distribution over an interval of several hundred feet, but the measurements were taken at ground level; as a result, temperature distribution is not verifiably stated for high altitudes, although the ground-level description is probably adequate after some mathematical adjustments. Accordingly, changes reflecting altitude were made in two parameters of the temperature distribution function employed in the simulation:

(1) an exponent in the temperature - dispersal relation (increasing which has the numerical effect of increasing turbulence), and
(2) the distance over which the authors' estimate of exhaust temperature off the centerline remains in effect.

Computation of virtually every property of the contrail process requires knowlege of the temperature distribution, and it can not be overstressed that only crude estimates of it are available. Therefore, in order to provide results in which more confidence might be placed, numerous trial simulations were performed where the two parameters were varied over wide ranges. The results showed almost no dependence of contrail visibility on these parmeters. The values 1.0 and 300 ft. for the respective parameters were then used during all other runs, with the exception of an occasional run which "tested" other values. The results however, did not change.

Specification of the exhaust end products and their properties for a given fuel additive provided some problems. Information regarding the exact form of the vapor products and the forms into which the gases condense is incomplete. For both sulfur-type and phosphorus-type additives, information is available about the weight percent of acid (sulfuric or phosphoric) present in the condensate formed in a binary water vapor and SO_3 (or P_2O_5) system, but pressures of one atmosphere are presumed. Further, data on surface tension and density are not at hand for all substances assumed to appear in the condensate, although they are usually available for closely allied compounds; e.g., surface tension is presented for liquid P_2O_5 but not for phosphoric acid by weight percent P_2O_5.

Working assumptions were then:

(1) P_2O_5 and SO_3 are the only oxidation states at the high temperatures involved,

(2) all acids presumed in the condensate at one atmosphere actually appear in the contrail,

(3) condensate data available applies at high altitudes, and

(4) physical properties of closely related substance suffice.

There would be considerable difficulty in assessing the extent to which these assumptions affect the results were it not for the fact that independent studies of phosphorus-type and sulfur-type additives produced almost identical results with respect to visibility. It would appear then that knowledge of the exact form of the exhaust end products is not crucial, provided that nucleation definitely occurs and reasonable estimates of condensate properties are available.

The third set of assumptions involves the nucleation process itself. Critical radius size and rate of formation of critical size nuclei are described by formulas derived from thermodynamic considerations, and have been experimentally verified. These formulas, however, require a knowledge of partial pressure of water vapor for each instance of nucleation (at discrete intervals in the simulation), and this, in turn, requires knowledge of how much water has already condensed. Due to the complexity of the problem, described more fully in [1] on pages 17-19, the assumption was made that all nucleation has terminated before condensation begins. This is not unreasonable, considering the small mass of acid relative to condensing water vapor.

The fourth and last group of assumptions, summarized on pages 20-21 of [1], is concerned with formation of the contrail itself from the nucleated particles and excess water vapor. Initial particles grow as they collide and stick, grow as water condenses on them, diminish as they collide and split, and perhaps diminish due to evaporation. Eventually, the collection of particles becomes statistically stable; i. e., during a relatively lengthy time interval, the number of particles of any given size is roughly constant.

For the sake of simplicity, prior research has assumed that the size frequency distribution of particles in an observed contrail was of the type f(radius) = constant ·(radius) $^{-n}$, but this obviously need not be the case. In fact, just as there is a critical radius size in the nucleation process, there may be one in the condensation - collision process. However, even if the mode of such a distribution were 20 times the minimum radius, this would produce a change over only a few percent of the total size range (extending to at least 450 times the minimum). It is reasonable then to assume that the model f(radius) = constant ·(radius) $^{-n}$ is qualitatively correct.

While neither the exponent "n" of the distribution nor the maximum size is known with certainty, ranges for each can be established which almost surely include the "correct" values. Tables of visibility (discussed further in Section IV) using these two parameters as variables show a very wide range, so that here is a set of parameters in which small variations can produce major changes in visibility.

Visibility is also substantially affected by relative humidity and ambient temperature. This result of the simulation (supported, of course, by empirical evidence) implies a need to monitor these parameters if dynamic control is to be achieved. However it may be possible to avoid this non-trivial problem if acceptable design values can be established which suppress visibility within normal ranges of these parameters.

III. Experimental Analysis

Much experimental work has been done in attempting to isolate the factors affecting contrail visibility. Among others a series of in-flight trials using a sulphur additive has been instituted at Holloman Air Force Base in New Mexico, data from which (Appendix A, table 1) has been made available. Regardless of the method of SO_3 addition all analyses of the data are based on the use of a hypothetical additive having the formula $C_5H_{11}SO_3$. The analyses conducted had as their purpose the determination of the two particle size distribution parameters of the theoretical description according to the following process.

Using the thermodynamic variables recorded for each trial, the computer simulation results in a numerical relation between assumed exponent "n" of the size frequency distribution and the corresponding predicted visible fraction of the contrail. Let us assume now that the "actual" value of n in one contrail is the same as that in any other, that it is in fact "universal" over all contrails. While its value is unknown, an estimate can be made and the implications examined to possibly verify or reject the estimate.

Some value of n is now selected, and for each flight trial, a visible fraction of contrail is computed. The difference between this estimate and the observed visible fraction is presumably due to the effects of the non - thermodynamic set of variables; a regression is accordingly performed on each of the two flight - trial sets of differences by the remaining variables. If the value selected for n was truly the "actual" value, then the two regressions would be substantially similar, since they are each fitting the same varables to their true effects. If the selected value is not close to the "actual" value, the regressions will be estimating biased effects and are extremely unlikely to agree substantially. The "actual" value of n can then be best estimated by executing the above process for each n in a range covering the true value, and looking for rough equivalence of two (linear) equations, the accuracy of the result probably depending on the degree of equivalence.

Unfortunately, the above rather elegant scheme requires elimination of several possible shortcomings in the given data, before confidence can be placed in results;

(a) lack of accurate and repeatable recording of observed visible fraction of contrail,
(b) distribution exponent probably varies with total mass,
(c) lack of information on accuracy of readings (of dials, gauges, etc.),
(d) data unavailable for some variables,
(e) every potential variable is not included in the data.

It should be clear at this point that analysis of the Holloman data was undertaken with a particular goal in mind, even though the conclusions of the analysis are open to question.

The data in Appendix A consist of 30 observations of in-flight trials. Values of nine variables are recorded with each value of the response (estimated percent of suppression). The entire set was subjected to extensive regression - correlation analysis with virtually no significant prediction capability resulting.

Among the difficulties was the absence of recorded values for additive flow rate (variable nine) when suppression was not 100%. This means that for the recorded cases of variable nine the response had no variation.

Variables 1, 3, 4 and 8 are statistically equivalent, with correlations of over 99% between any pair. Variables 6 and 7 correlate over 99% also. The immediate result is a reduction in the number of available variables to four: variables 1, 2, 5 and 6. These four, it must be noted, do not exhibit correlations near 99% between any two, but are hardly independent nonetheless. Correlations in the group run from 68% (2 and 6) to 90% (5 and 6), and 1 and 5 together correlate 6 by 94%.

The best regression estimate would, therefore, involve variables 1, 2 and 5, and these three variables and their squares were fitted to the thirty observations of percent of contrail suppression. The squares of the three variables contributed nothing to the fit after the variables themselves were used, and were thereafter ignored.

Sixty percent of the variation in the response can be accounted for by variables 1, 2 and 5, using the equation:
(Percent Suppression) = 4048 (Mach Number) + 1.126 (Exhaust Temp) - 2.916 (Altitude) - 3406.

The variance remaining in the "best fit", after using the measured variables and parameters is sufficient to preclude use of the method outlined above for determining the exponent in the contrail particle size distribution. In fact, further analysis of data of this type is unlikely to prove of value until problems (a), (c), (d) and (e) listed above are adequately resolved, and methods to account for (b) are defined. It thus became necessary to seek some other means of estimating the distribution exponent.

IV. Further Simulation Studies

At this point, when the experimental analysis clearly could go no further, two additional facts were brought out. [5]

(1) At altitude 60,500 feet, using an additive flow rate of 35 pounds per hour, the contrail formed could be described as having impending visibility; that is, the contrail was at the borderline of the visible and invisible regions.

(2) A new set of in-flight data had been made available, (Appendix A Table 2).

The additive in this case was 70% chlorosulfonic acid (CSA), $HClSO_3$, and 30% sulfur trioxide, SO_3, by weight, and was injected through a small nozzle at the tailpipe.

Whereas previous theoretical results included a mathematical relationship between extent of visibility, range of particle size, and distribution exponent, the additional fact (1) removes "extent of visibility" from the relationship, and provides a simple method for determining the remaining two parameters.

The given flow (35 pounds per hour) and mix of additive produces 27.334 pounds of SO_3 per hour, which is equivalent (in SO_3 production) to a flow rate of 51.622 pounds per hour of sulphur additive ($C_5H_{11}SO_3$).

A computer program was then written to implement the formula at the top of page 23 in [1]. For that formula, the values for m and Rc were found by running the simulation program for altitude 60,500 feet and 23.36% additive, m_{vis} is 0.018 gms/m^3, and R_1 is one-quarter micron. The value "23.36" for percent additive is a result of knowing the total fuel flow (221.0 pounds per hour) and the above sulphur additive flow rate (51.622 pounds per hour). Given any value of the distribution exponent, n, a corresponding value of the ratio, M, of largest to smallest particle size can be computed, and pairs of such values satisfying the "impending visibility" criterion are graphed in Appendix B, Figure 1.

The value of fuel flow rate at 60,500 feet is not necessarily that at 60,000 feet (221.0 pounds per hour) but the difference was assumed to be insignificant. Parameters in the simulation may also be affected by using the sulphur additive instead of CSA-SO_3 (such as exhaust temperature or total H_2O mass), but these effects are expected to be quite minor.

Figure 1 of Appendix B, notwithstanding a degree of freedom in the M-n relationship, does indicate a narrow range in which the "true" value of n lies.

The ratio of largest to smallest particle size must be at least as large as the ratio of minimum visible size to typical initial size, (0.25 micron)/(6Å) = 417, and could certainly go as high as twice that. If the "probable" range is taken from 450 to 800 (at 417 itself, visibility is precluded), the corresponding range for n is from 4.00 to 4.52. Note that the vicinity of n = 4.69 is a singularity, where M takes on all large values, qualitatively indicating that values of n near 4.69 should be eliminated.

Because the simulation run of the impending visibility case took into account an altitude of 60,500 feet, and all runs for [1] were based on 60,000 feet, the decision was made to study the effect of altitude on the contrail. Sixty simulations were run, for altitudes 45,000, 55,000, and 65,000 feet, for ambient temperatures 217°K and 207°K, and for 10, 15, 20, 25, and 30 percent sulphur additive.

Various results are presented in Table 1 and Figures 2 and 3 of Appendix B, but before conclusions are drawn, it should be noted that engine and ambient conditions (except temperature and pressure) were not changed from their values at 60,000 feet. Resulting inaccuracies should be more pronounced at 45,000 feet than at the other values.

The most obvious conclusion, on examination of the computer output, is that the fraction of SO_3 which does not decompose to SO_2 before nucleation is almost completely a function of altitude. This conclusion, it may be noted, is statistical only, appearing because pressure (the true controlling variable) is an approximately linear function of altitude within the ranges encountered. Figure 2 in Appendix B shows the mean value (over altitude) of the non-decomposing fractions plotted as a function of altitude; the fractions themselves are within 0.1% of the mean in almost all cases.

The next obvious conclusion is that, for a fixed set of exhaust wake temperature distribution parameters, the value of Rc (the critical radius) is almost invariant to altitude and relative humidity changes (see Tables 1 and 2 in Appendix B) Even when one of those parameters, ambient temperature, was varied for part of the set of 60 runs, no significant changes appeared.

A third conclusion is evident after examination of Figure 3 in Appendix B. The graphs show (for a constant value of n) that, as the altitude increases, the effect on visibility of increasing the percentage of additive in the fuel tends to diminish so that at relatively high altitudes, near 60,000 feet, percent additive is not as effective a factor in controlling contrail formation as at lower altitudes. Of course, this result depends somewhat on the assumption of a fixed acid fraction in each nucleated acid-water droplet, but the inaccuracy is trivial unless the additive fraction decreases to below 10%. This conclusion is borne out by both experimental and theoretical studies on contrail formation which show that a contrail is more unstable and more difficult to form at these high altitudes.

The second set of experimental data (Appendix A, Table 2) is possibly but not necessarily characterized by impending visibility. Information is not recorded as to how "visible" each contrail is, and as a first guess, it was assumed that "impending" would describe the visibility of the contrail formed by an agent flow rate five pounds per hour less than that recorded [5].

On Figure 3 in Appendix B the point Q represents observed data (see statement (1), beginning of this section). The data points of Appendix A, Table 2 are each associated with a percent additive and an altitude which, if the above assumption were valid, should produce a cluster of points around Q on the line "large-particle density=0.018 gm/m^3", when plotted on Figure 3. An alternative way of exploring the problem is the plotting of Q and data from Table 2 on a graph of percent additive versus altitude; the shape of the curve in the latter case is not known a priori, but should approximate a simple curve, and should pass through Q.

The latter plot is shown in Appendix B, Figure 4; the curve is neither simple nor coincident with Q.

Figure 4 indicates clearly that the assumption of impending visibility for the data in Table 2 is invalid. The five pounds per hour decrement in flow rate serves only to shift the curve in Figure 4 to the left, and in no way affects the shape.

The result is that the data set in Table 2 can not be used as it stands to expand our knowledge of the two parameters, distribution exponent and ratio of largest to smallest size.

The effects of relative humidity on visible particle concentration are shown in Appendix B. Figure 5. Relatively low values of the size distribution exponent are seen to increase the sensitivity of the model to changes in relative humidity. Higher values of relative humidity produce the expected increase in visibility.

V. Conclusions

Each of sections II, III and IV includes its own results and conclusions, and those will not be repeated here. Instead, a summary of the kind of results found in those sections is presented, and a final experimental-theoretical technique is suggested.

The basic conclusion is that those parameters which determine contrail visibility are the parameters "distribution exponent" and "size range ratio" of the contrail particle size frequency along with relative humidity and ambient temperature. A corollary conclusion, unfortunately, is that the variables included in the experimental analyses and in the thermodynamic description can only indicate a probable range for the size distribution parameters. A description of the model used in this study is contained in Appendix C. This description is of sufficient level of detail to indicate the method of generating data without being encumbered with non-essential details. A final technique is now suggested whose results may determine the two significant parameters of the particle size distribution.

Figure 1 of Appendix B indicates the locus of pairs of values of the two parameters subject to condition (1) of section IV. If similar sets of data relating additive flow rates to altitude (at impending visibility) are recorded, graphs similar to Figure 1 can be constructed for each such set. As a result, if

(a) the two particle size distribution parameters are truly constant,
(b) information is accurately recorded, and
(c) the assumed monotonic particle size distribution closely fits the physical distribution,

then all of the graphs should intersect at the true values of the two parameters. If they do not intersect at exactly one point, the spread should indicate how the parameters vary with respect to those variables with recorded values.

In either event, further analysis is reasonable and justified, and study in the indicated direction will probably prove to be the only method leading to predictions of contrail visibility as quantitative functions of system variables.

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[3] Forstall, W., and Shapiro, A., "Momentum and Mass Transfer in Coaxial Gas Jets", Journal of Applied Mechanics, December 1950, pp. 399 - 407.

[4] Handbook of Chemistry and Physics, 46th Edition, p. F114.

[5] Personal communications with S. J. Birstein of Air Force Cambridge Research Laboratories, Bedford, Massachusetts.

APPENDIX A (Table 1)

If an entry is blank, use the value above it

Run	Flight Number	Altitude (x1000) Var. 1	Mach No. Var. 2	Air Speed (Knots) Var. 3	Tailpipe Pres(InHg) Var. 4	Exhaust Gas Temp(-°c) Var. 5	Gauge Temp(-°c) Var. 6	Outside Air Temp(-°c) Var. 7	Saturation Temp(-°c) Var. 8	Additive Flow Rate Var. 9	Percent Suppres.
5	1B	50.0	.715	169	11.3	634	60.7	80.0	60.2	45	70
	1B		.707	167		632	61.2			45	70
	2B	58.4	.716	139	7.7	662	45.6	66.0	63.7	40	100
	2B				7.5	664	45.5			40	100
	3B	62.5	.725	128	6.4	691	41.4	62.5	65.2	40	100
	3B		.720	127		688	41.9			40	100
	4B	61.5	.717	129	6.6	685	43.0	64.0	65.0	38	100
	4B		.721	130	6.7	684	44.9	66.0		38	100
	5B	60.5	.721	133	7.0	683	44.9	66.0	64.9	38	100
	5B		.726	134		679	42.1	64.0		38	100
	6B	60.5	.721	133	6.9	670	44.4	66.0	64.9	44	100
	6B		.726	134	7.0		45.1			44	100
7	1A	58.4	.716	139	7.8	650	52.4	72.5	63.9	N/A	0
	1A					648	53.4	73.5		N/A	0
	2A	60.5	.716	132	6.7	648	50.3	71.0	64.6	N/A	0
	2A						49.8	70.0		N/A	0
8	1A	58.4	.720	140	7.8	644	54.5	75.0	63.9	44	100
	1A					643	53.4	74.0		44	100
	2A	60.5	.721	133	6.8	648	47.0	68.0	64.6	43	100
	2A						46.7	67.5		43	100
	3A	61.5	.721	130	6.5	650	48.0	69.5	65.4	37	100
	3A						46.1	67.0		37	100
	4A	58.3	.721	147	8.5	632	58.2	78.0	62.9	N/A	40
	4A						57.1	77.0		N/A	40
	5A	54.2	.706	151	9.1	622	54.5	74.0	62.0	N/A	0
	5A									N/A	0
	6A	52.2	.708	159	10.0	620	59.2	78.5	61.1	N/A	0
	6A						58.9	78.0		N/A	0
	7A	50.0	.711	168	11.0	618	58.9	78.0	60.2	N/A	0
	7A						58.4	77.5		N/A	0

APPENDIX A (Table 2)

(100 Percent Contrail Suppression in All Cases)

Altitude (x1000 ft)	Engine Rpm (Percent)	Outside Air Temp. (-°c)	Pressure (millibars)	Additive Flow (pounds/hour)
63.3	100.0	67.5	60.3	30
61.5	100.0	66.0	66.7	30
61.5	100.0	67.0	66.7	30
58.0	100.1	75.0	77.4	44
60.5	100.0	68.0	70.0	43
61.5	99.7	69.5	66.7	37
60.5	100.0	66.5	70.0	45
60.5	100.0	66.5	70.0	40
62.6	99.0	68.0	63.3	35
62.6	99.0	68.5	63.3	40
64.6	99.0	69.0	57.5	35
64.6	99.0	69.0	57.5	42
65.5	99.0	68.0	55.1	39
65.5	99.0	68.0	55.1	41

APPENDIX B (Table 1)

Ambient Temperature 217°K

Altitude (Feet)	45,000		55,000		65,000	
Additive Fraction	Rc	%	Rc	%	Rc	%
10%	6.42	21.2	6.29	17.5	6.16	14.3
15%	6.34	21.3	6.20	17.6	6.03	14.4
20%	6.19	21.4	6.08	17.6	5.99	14.4
25%	6.17	21.5	6.05	17.7	5.95	14.5
30%	6.14	21.6	6.02	17.8	5.91	14.5

Ambient Temperature 207°K

Altitude (Feet)	45,000		55,000		65,000	
Additive Fraction	Rc	%	Rc	%	Rc	%
10%	6.31	21.2	6.27	17.5	6.14	14.3
15%	6.27	21.3	6.10	17.6	6.03	14.4
20%	6.22	21.4	6.07	17.6	5.95	14.4
25%	6.18	21.5	6.04	17.7	5.91	14.5
30%	6.14	21.6	6.00	17.8	5.88	14.5

The left number of each pair is critical radius, in angstroms (10^{-8} cm.)
The right number of each pair is the percent of SO_3 not decomposing.
Rc has a mean value of 6.12, and standard deviation of 0.14 (2% of mean).

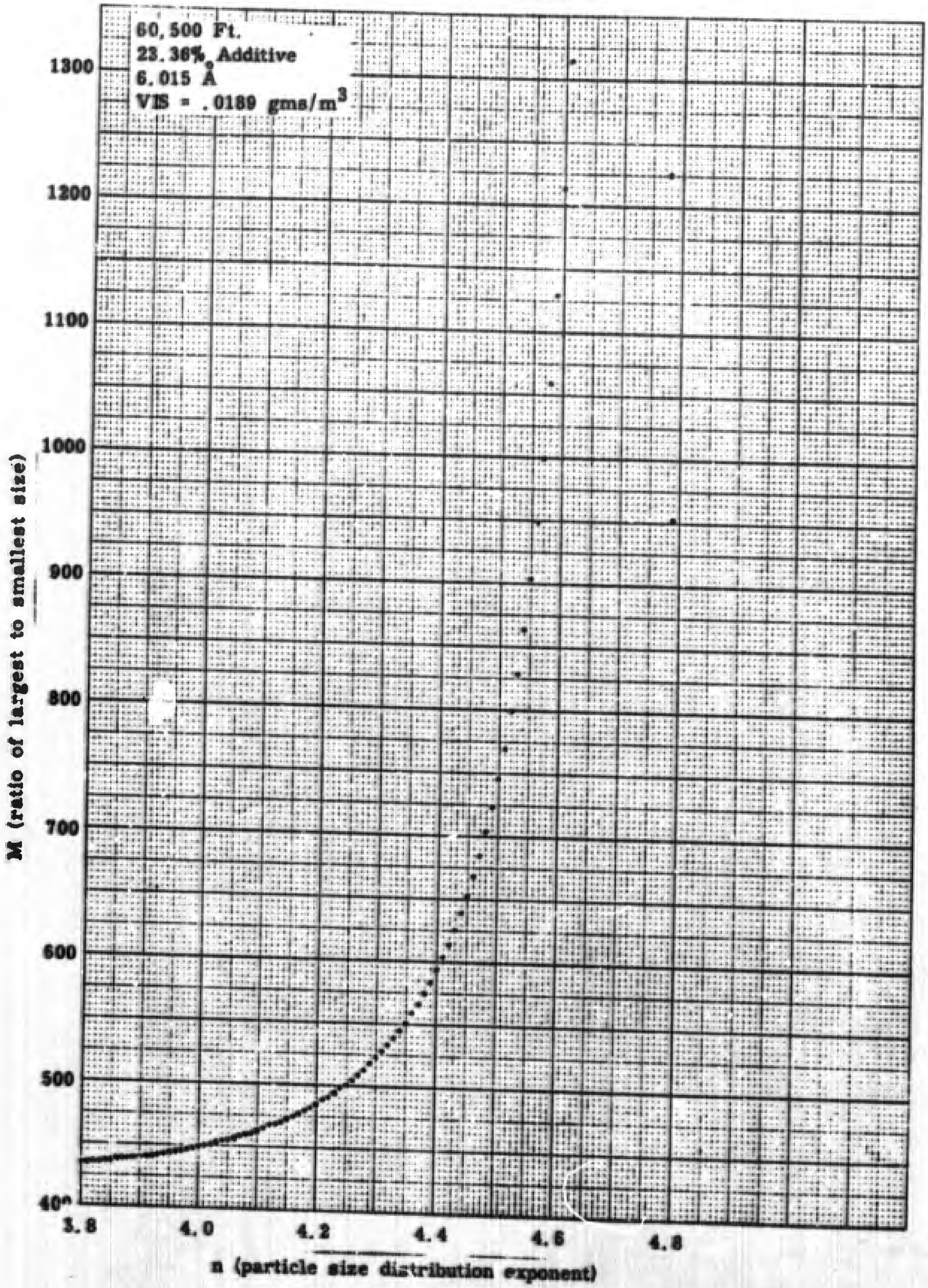
APPENDIX B (Table 2)

Relative Humidity (%)	Ambient Temperature (^oK)		
	198	212	217
	Rc	Rc	Rc
0	$.4776x10^{-7}$	$.4762x10^{-7}$	$.4763x10^{-7}$
10	$.4836x10^{-7}$	$.4836x10^{-7}$	$.4896x10^{-7}$
20	$.4892x10^{-7}$	$.4892x10^{-7}$	$.4989x10^{-7}$
30	$.4943x10^{-7}$	$.4943x10^{-7}$	$.5053x10^{-7}$
40	$.4981x10^{-7}$	$.4981x10^{-7}$	$.5106x10^{-7}$
50	$.5016x10^{-7}$	$.5016x10^{-7}$	$.5135x10^{-7}$
60	$.5048x10^{-7}$	$.5048x10^{-7}$	$.5166x10^{-7}$
70	$.5075x10^{-7}$	$.5075x10^{-7}$	$.5204x10^{-7}$
80	$.5087x10^{-7}$	$.5087x10^{-7}$	$.5237x10^{-7}$
90	$.5108x10^{-7}$	$.5108x10^{-7}$	$.5257x10^{-7}$
100	$.5124x10^{-7}$	$.5124x10^{-7}$	$.5287x10^{-7}$

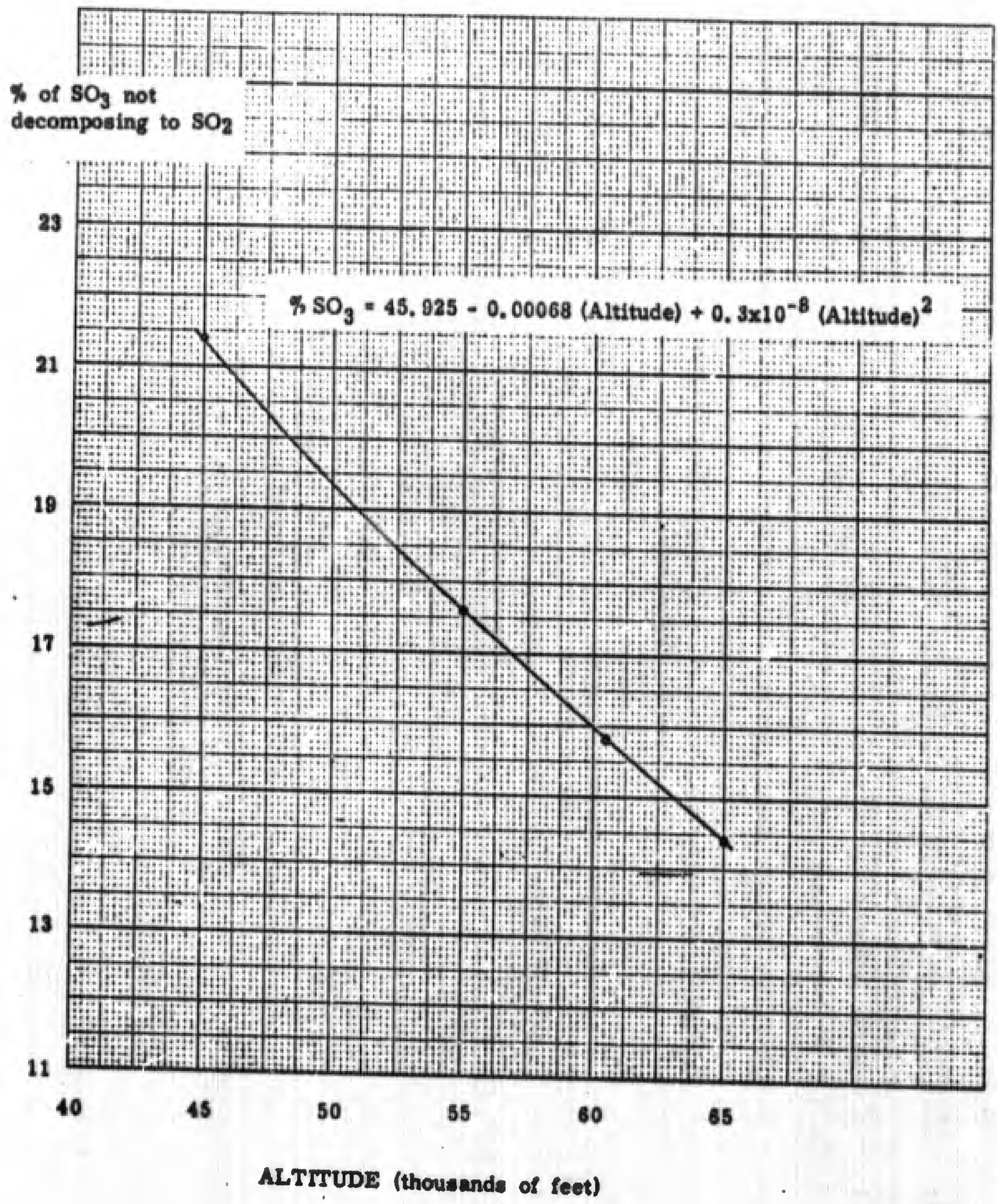
Table of critical radius Rc (cm) vs. relative humidity

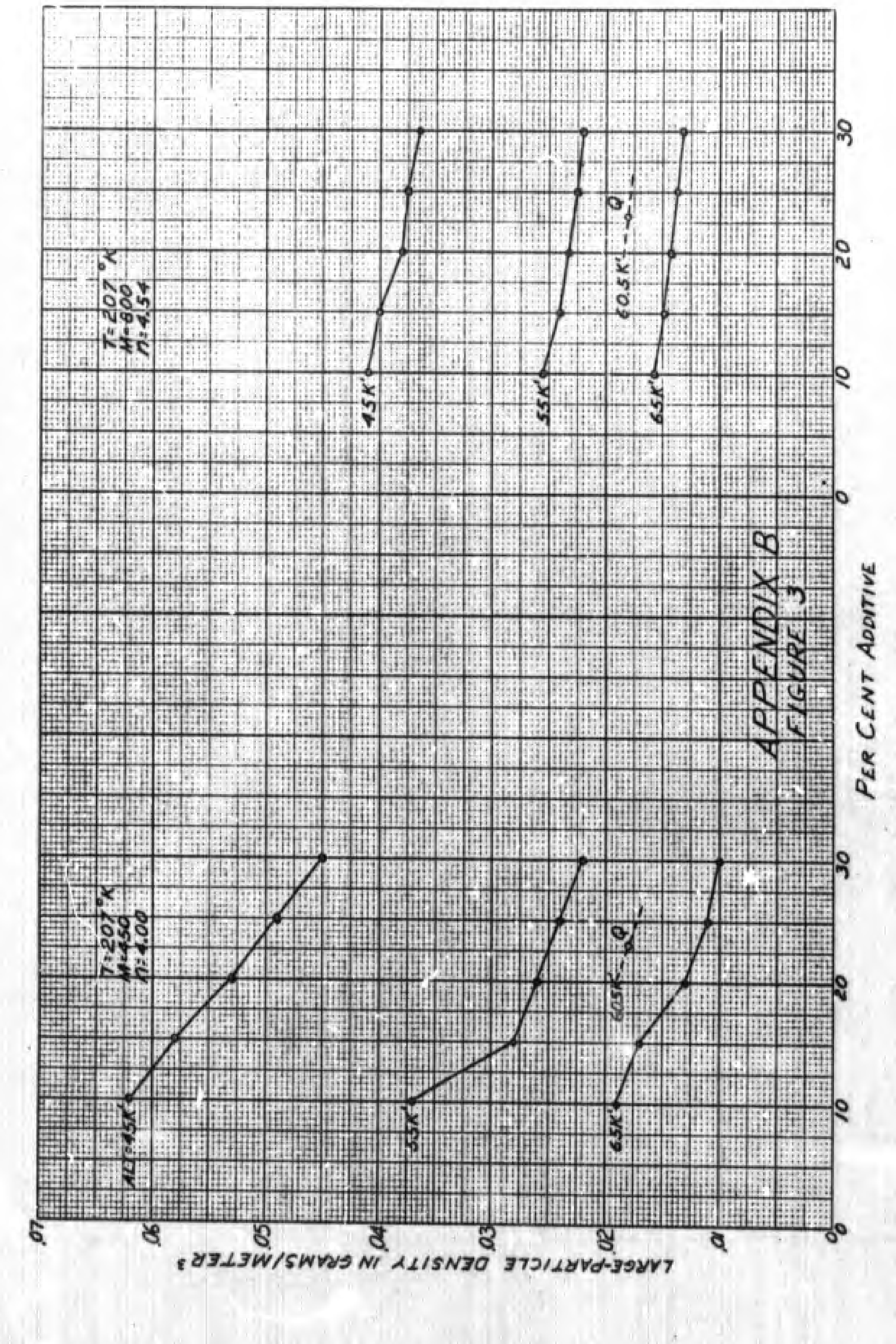
At various ambient temperatures

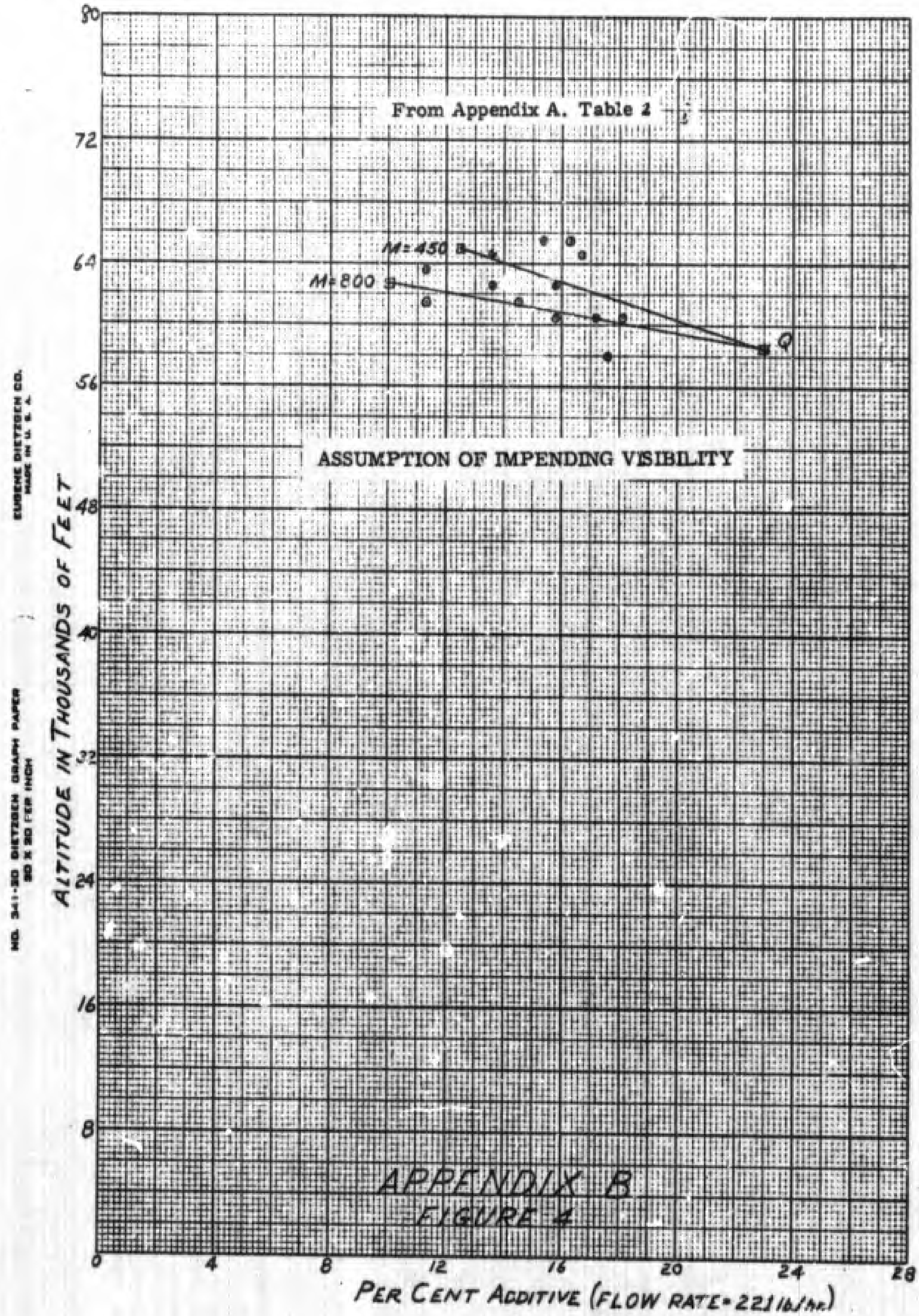
APPENDIX B FIGURE 1



APPENDIX B FIGURE 2

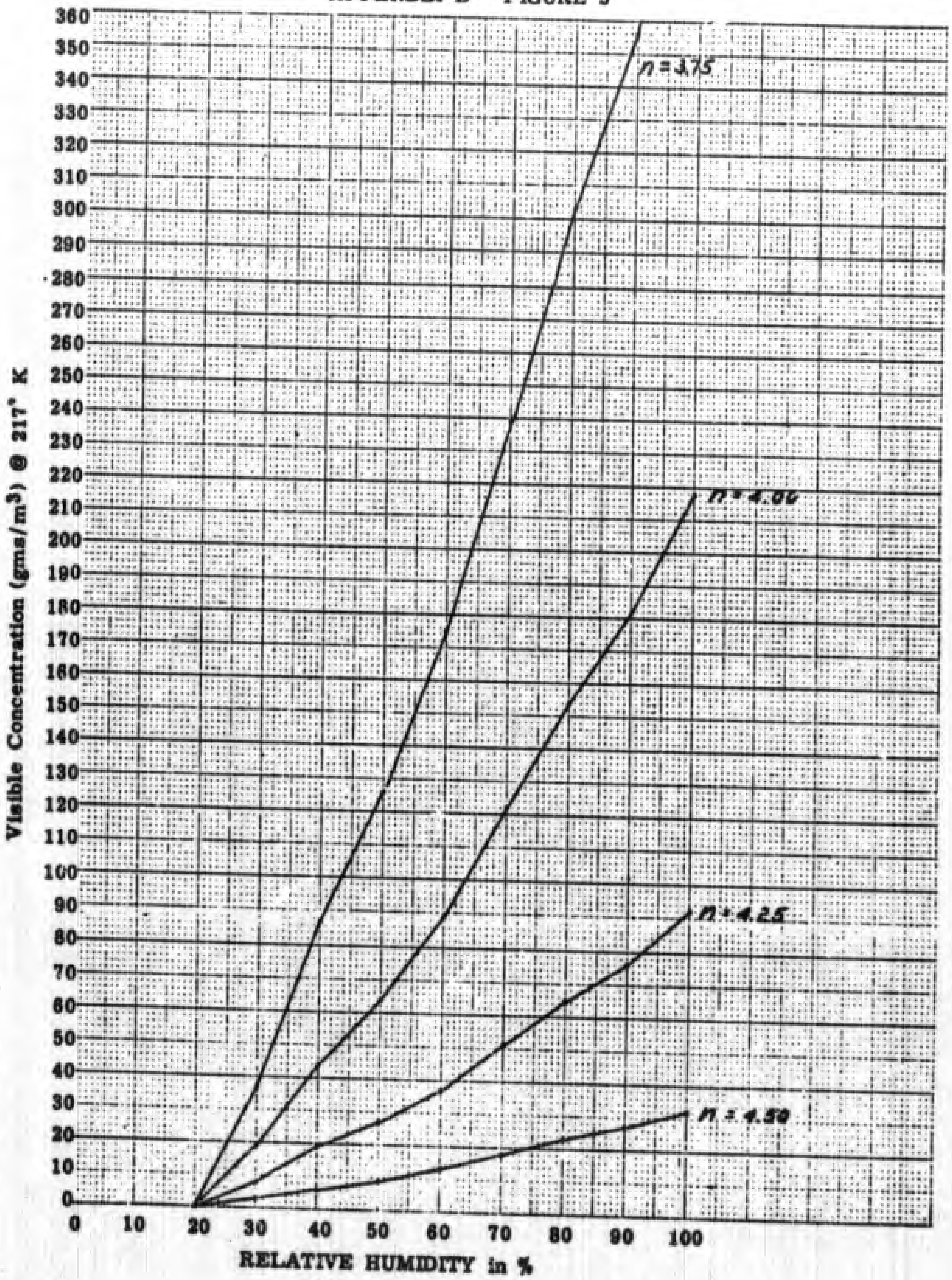



APPENDIX B
FIGURE 3
PER CENT ADDITIVE
LARGE-PARTICLE DENSITY IN GRAMS/METER³
T=207°K
M=450
n=4.00
T=207°K
M=800
n=4.54
AD=4.5K'
5.5K'
6.5K'
6.0.5K' Q
4.5K'
5.5K'
6.5K'
6.0.5K' Q
.07
.06
.05
.04
.03
.02
.01
00
10
20
30
0
10
20
30



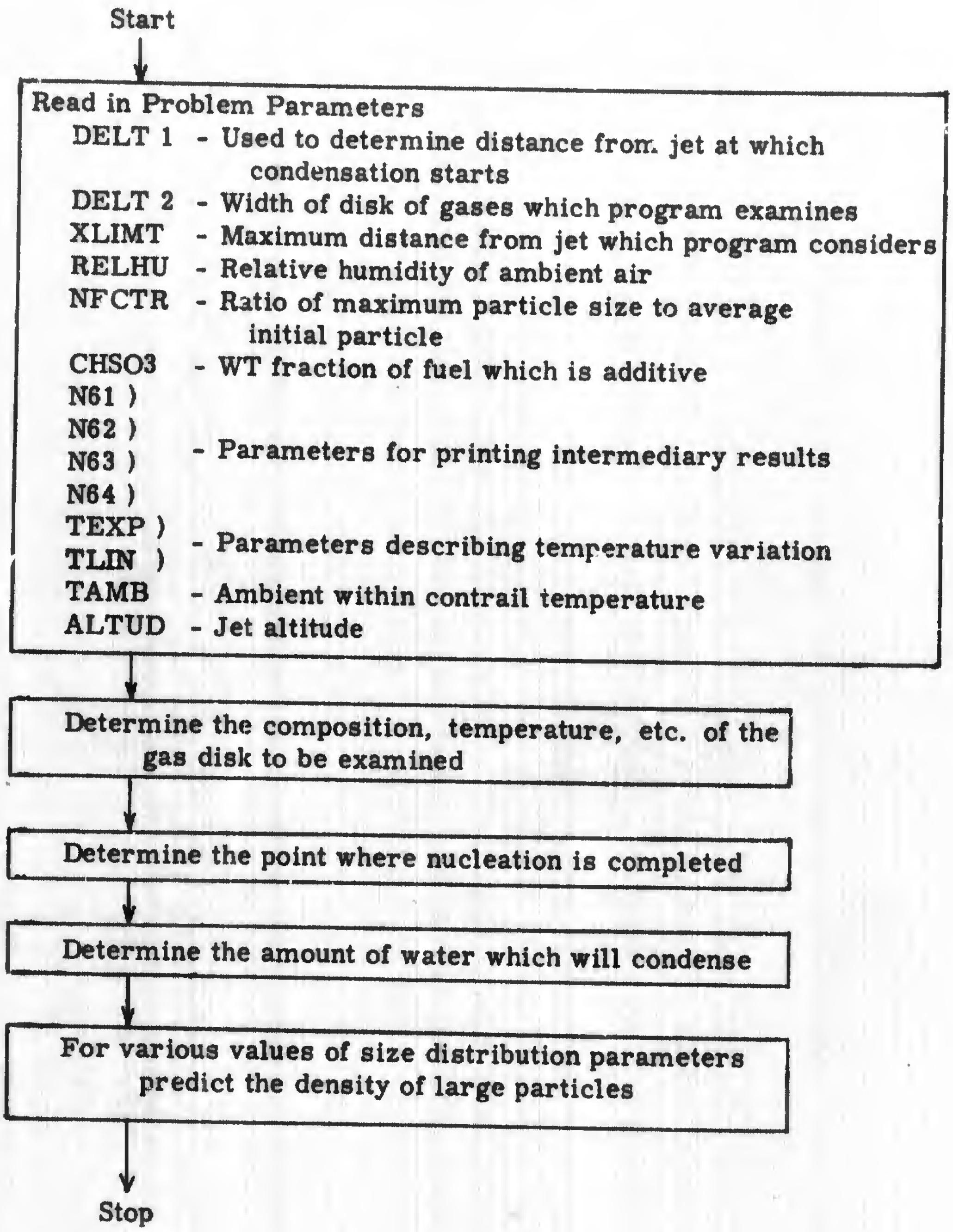
APPENDIX B
FIGURE 4

APPENDIX B FIGURE 5



APPENDIX C FIGURE 1

Simplified Block Diagram of Computer Model



P COLE TRAJECTORY

```
$ID     5196   P COLE       TRAJECTORY                                  0C0054
$IBJOB
$IBFTC TRAJ
C      THIS PROGRAM DETERMINES THE SSD FOR C5H11SO3 ADDITIVE.
C
C
C      THE ORDER OF INPUT TO THIS PROGRAM IS
C             CARD1 CONTAINS DELT1(F4.1), 1X, DELT2(F4.1), 1X, XLIMT(F6.1)
C  ****************************************************************
C  ****************************************************************
C  ****************************************************************
C      CARD 1B CONTAINS RELHU,F5.1) WHICH IS THE RELATIVE HUMIDITY OF
C              THE AMBIENT AIR IN PERCENT.
C  ****************************************************************
C  ****************************************************************
C  ****************************************************************
C             CARD2 CONTAINS FACTR (I4)
C             CARD3 CONTAINS CHSO3(F7.4),53X,N61,N62,N63,N64(ALL A1)
C             CARD4 CONTAINS TEXP (F6.3), 2X, TLINR (F5.1)
C             CARD5 CONTAINS TAMB (F7.2), 2X, ALTUD (F5.0)
C     FOR FURTHER COMPUTATION, REPEAT CARDS TWO THRU FIVE(CARD1 IMPLIED)
C
C
      0REAL   MW1, MW2, MW3, MW4, MW5, MW6, MW7, MOLS, MOLS1, MOLS2,
      1       MOLS3, MOLS4, MOLS5, MOLS6, MASS2, MASS3, MPV2, MPV3,
      2       MWBAR, I, L, N, K, LB2GM, MWAVE
      0COMMON SAVE(10,10), SO,XMIN,XMAX,UZPCT,UZOVR,AVLBL,AVLBR,CONC1,
      1 DENSE,TOT1,R1BAR,R2BAR,SURFC,R3BAR,VOLM,RMAX,NFCTR,SHMRG,MOLS2
C ... TEMPX  IS IN DEGREES KELVIN
      TEMPX(X)= TAMB+(TPIPE-TAMB)*(L*(DPIPE/12.0)/(X+0.5*DELT2))**TEXP
C
C ... THE PROGRAM 'FOLLOWS' A FIXED-MASS FIXED-WIDTH VARIABLE-VOLUME
C ... DISC OF EXHAUST GAS AS IT COOLS,NUCLEATES,AND RECEDES FROM THE JET
C
C ...        CONSTANT VALUES ARE CODED AS SUCH, ALTHOUGH
C ...        FUTURE VERSIONS WILL READ THEM IN AS PARAMETERS
      PI     = 3.1415927
C ... R       IS THE GAS CONSTANT (ERGS PER DEGREE KELVIN PER GRAM-MOLE)
      R      = 8.3143 E 7
C ... N       IS THE AVOGADRO CONSTANT IN THE CGS SYSTEM
      N      = 6.0225 E23
C ... K       IS THE BOLTZMANN CONSTANT IN CGS SYSTEM
      K      = 1.3805 E-16
      LB2GM  = 453.59237
      FT2CC  = 28316.847
C ... CGSAT  CONVERTS DYNES PER CENTIMETER-SQUARED TO ATMOSPHERES
      CGSAT  = 9.86923E-7
C
C ... MW(N) IS THE MOLECULAR WEIGHT OF AIR,WATER,SO3,SO2,H2SO4,C5H11SO3
C ... MW7     IS THE MOLECULAR WEIGHT OF JP-4 (C-100 H-197)
      MW1    = 28.96
      MWAVE  = MW1
      MW2    = 18.0153
      MW3    = 80.0622
      MW4    = 64.0628
```

```
               TRAJ       P COLE        TRAJECTORY
          TRAJ          -   EFN   SOURCE STATEMENT   -   IFN(S)   -

      MW5    = 98.0775
      MW6    = 151.2057
      MW7    = 1399.685
C
C ... IF THE DISC IN ITS CURRENT POSITION (DISTANCE FROM JET = X ) DOES
C ...    NOT PRODUCE DROPLETS, X IS AUTOMATICALLY INCREMENTED BY DELT1
C ... DELT2  IS THE WIDTH OF THE DISC OF EXHAUST EXAMINED BY THE PROGRAM
C ... THE PROGRAM IS ALWAYS TERMINATED IF THE VALUE OF X REACHES XLIMT
C
      READ (5,1232) DELT1, DELT2, XLIMT
1232  FORMAT ( F4.1, 1X, F4.1, 1X, F6.1 )
1     CONTINUE
C   ************************************************************
C   ************************************************************
C   ************************************************************
      READ (5,15) RELHU
   15 FORMAT (F5.1)
      WRITE (6,25) RELHU
   25 FORMAT (26H1 THE RELATIVE HUMIDITY IS, F6.1, 10H PER-CENT.)
      RELHU = RELHU/100.
C   ************************************************************
C   ************************************************************
C   ************************************************************
C ... FACTR  IS THE FACTOR BY WHICH THE LARGEST PARTICLE'S RADIUS IS
C ...                  ASSUMED GREATER THAN THE AVERAGE INITIAL RADIUS
      READ (5,12321) NFCTR
12321 FORMAT ( I4 )
      FACTR = NFCTR
C
C ... CHSO3  IS THE WEIGHT FRACTION OF FUEL WHICH IS C5H11SO3
C
C ... COLUMNS 61 AND 62 OF THE CHSO3-VALUE CARD ARE EQUAL (PRESUMABLY
C ... TO 'BLANK') IF PRINTING OF DATA POINT BY POINT IS TO BE SUPPRESSED
C ... PRINTING WILL OCCUR IF COLUMNS 61-2 DIFFER (ONE MAY BE LEFT BLANK)
C
C     COLUMNS 63 AND 64 ARE EQUAL IF PRINTING OF COEFFICIENTS AND ROOTS
C     OF THE EQUILIBRIUM-RELATED CUBIC EQUATION IS TO BE SUPPRESSED
      READ (5,12325) CHSO3, N61, N62, N63, N64
12325 FORMAT( F7.4, 53X, 4A1 )
C
C ... TEXP IS THE EXPONENT OF THE FRACTION DEFINING TEMPERATURE WHICH
C ...   MORE OR LESS DESCRIBES THE MIXING AND VOLUME CHANGE (TURBULENCE)
C     TLINR  IS THE DISTANCE, IN FEET, OVER WHICH THE MEAN DISC
C          ABS TEMPERATURE IS ASSUMED TO VARY LINEARLY WITH DISTANCE
C        FROM TPIPE AT (L*DPIPE/12) TO (T-CENTERLINE + TAMB)/2 AT TLINR
C          BEYOND TLINR THE MEAN IS TAKEN AS (T-CENTERLINE+TAMB)/2
      READ (5,1233) TEXP, TLINR
1233  FORMAT( F6.3, 2X, F5.1 )
C ... TAMB   IS THE ATMOSPHERIC (AMBIENT) TEMPERATURE AT 60,000 FT
C ... ALTUD  IS JET ALTITUDE IN FEET
C     IF NO ALTITUDE IS SPECIFIED, 60,000 FT WILL BE ASSUMED.
      READ (5,12341) TAMB , ALTUD
12341  FORMAT ( F7.2, 2X, F5.0 )
      IF ( ALTUD ) 6000, 6000, 6010
6000  ALTUD = 60000.0
6010  CONTINUE
```

```
C
C ... AIRIN  IS THE AIR INTAKE IN LBS/SEC (NOT INCLUDING 0.06 FOR FUEL )
      AIRIN = 3.05
C ... TPIPE  IN DEGREES KELVIN
      TPIPE = 934.0
C ... PPIPE  IN ATMOSPHERES (EXIT PRESSURE)
      PPIPE = 0.25
C
C ... DPIPE  IS THE TAILPIPE DIAMETER IN INCHES
      DPIPE = 11.0
C ... VPIPE  IS IN FEET PER SECOND
     OVPIPE = R * TPIPE * AIRIN *LB2GM  * 576.0 /
     1         ( MW1 * (PPIPE*1.01325E 6) * PI * DPIPE**2 *FT2CC  )
C ... XTIME  IS THE TIME REQUIRED FOR THE FORMATION OF THE DISC
      XTIME = DELT2 / VPIPE
C     THRST IS THE JET THRUST IN POUNDS .
      THRST = 170.0
C ... FUEL   IS THE WEIGHT OF FUEL BURNED PER HOUR PER POUND OF THRUST
      FUEL  = 1.3
C ... TEMP   IS THE NUMBER OF GRAMS OF FUEL BURNED DURING DISC FORMATION
      TEMP  = FUEL * THRST * LB2GM * XTIME / 3600.0
C
C ... PAMB   IS AMBIENT PRESSURE IN ATMOSPHERES, ALTITUDE IN FEET
      PAMB  =10.0**(-0.64528-0.68133*(-1.10191+ALT00/32808.3))*0.986923
C
C ... MOLS1  IS MOLES OF AIR IN THE DISC
C ... MOLS2  IS MOLES OF H2O IN THE DISC
C ... MOLS3  IS MOLES OF SO3 IN THE DISC
C ... MOLS4  IS MOLES OF SO2 IN THE DISC
C ... MOLS5  IS MOLES OF O-2 IN THE DISC
C ... MOLS6  IS TOTAL INERT MOLES IN THE DISC (CO2 PLUS INERT AIR)
      MOLS1 = AIRIN*LB2GM * XTIME / MW1
      MOLS2 = TEMP * (CHSO3 * 5.5 / MW6  +  (1.0-CHSO3) * 98.5 / MW7 )
C   **************************************************************
C   **************************************************************
C   **************************************************************
C ... VPSAT IS VAPOR PRESSURE (IN MILLIBARS) AT SATURATION.
C ...      (A MILLIBAR IS 1,000 DYNES PER SQUARE CM.)
      VPSAT= 10.**(-7.90298*(373.16/TAMB-1.0)+5.02808*ALOG10( 373.16/TAM
     1B)-(-1.3816E-7)*(10.**(11.344*(1.0-TAMB/373.16))-1.0)+(8.1328E-3)*
     2(10.**( -3.49149*(373.16/TAMB-1.0))-1.0)+ALOG10(1013.246))
C ... ABSHU IS ABSOLUTE HUMIDITY AT SATURATION IN GRAMS PER CC
      ABSHU=VPSAT*MW2*1000.0/(R*TAMB)
C ... SATHU IS NO. OF GRAMS OF WATER PER GRAM OF AIR AT SATURATION.
      SATHU = ABSHU*R*TAMB*CGSAT/(PAMB*MW1)
      SHAMB = SATHU
      MOLS1 = MOLS1 -LB2GM*AIRIN*RELHU*SATHU*XTIME/MW2
      MOLS2 = MOLS2 +LB2GM*AIRIN*RELHU*SATHU*XTIME/MW2
C   **************************************************************
C   **************************************************************
C   **************************************************************
      MOLS3 = TEMP * CHSO3 / MW6
      MOLS4 = 0.0
     OMOLS5 = 0.13957*MOLS1  -  149.25*TEMP*(1.0-CHSO3)/MW7
     1                       -  7.75*TEMP*CHSO3/MW6
     OMOLS6 = 0.813*MOLS1  +  TEMP*(1.0-CHSO3)*100.0/MW7
```

```
                TRAJ      P COLE       TRAJECTORY
        TRAJ          -   EFN   SOURCE STATEMENT  -  IFN(S)  -

      1                    +  TEMP*CHSC3*5.0/MW6
C ... MOLS   IS TOTAL MOLES IN DISC (MOLS1 INDIRECTLY INCL IN MOLS5,6)
C
      MOLS  = MOLS2 + MOLS3 + MOLS4 + MOLS5 + MOLS6
C
C ... FRCT3, FRCT4, AND FRCT5 ARE THE FRACTIONS OF THE TOTAL MOLES WHICH
C         ARE SO3, SO2, AND O-2, RESPECTIVELY.
      FRCT3 = MOLS3 / MOLS
      FRCT4 = MOLS4 / MOLS
      FRCT5 = MOLS5 / MOLS
      APROX = 0.5 * FRCT3
C
C ... AVLBW IS THE INITIAL NO. OF MOLES OF H2O AVAILABLE FOR NUCLEATION
      AVLBW = MOLS2
C     AVLBL IS THE NO. OF MOLES OF SO3 AVAILABLE FOR NUCLEATION OR DECAY
      AVLBL = MOLS3
C     AVLBR  IS THE NUMBER OF MOLES AVAILABLE FOR NUCLEATION AFTER DECAY
      AVLBR = AVLBL
C ... VAMB   IS FORWARD VELOCITY OF JET IN KNOTS
      VAMB  = 515.0
      L      = 4.0 + 12.0 * 1.6878099 * VAMB / VPIPE
C ... THIS VALUE OF X IS WHERE THE CALCULATIONS START (X IN FEET)
      START = L * DPIPE / 12.0
      X      = START
C
      WRITE (6,12342) TAMB, ALTUD
12342 FORMAT (340TAMB = ,F7.2, 18H AT AN ALTITUDE OF, F7.0)
      WRITE (6,12343) DELT1, DELT2, XLIMT
12343 FORMAT (9H0DELT1 = ,F4.1,10H  DELT2 = ,F4.1,12H  X-LIMIT = ,F6.1)
      WRITE (6,12345) TEXP, TLINR
12345 FORMAT (25H TEMPERATURE EXPONENT IS ,F6.3,/,68H DISTANCE OVER WHIC
     1H THE TEMPERATURE FUNCTION IS LINEAR IN T-AMB IS ,F6.1)
C ... DIAM2 AND DIAM3 ARE THE DIAMETERS OF H2O AND SO3 MOLECULES IN CMS
C ...    DIAMETERS ARE BASED ON LIQUID VOLUMES.  SPEC GRV OF SO3 IS 1.95
      DIAM2 = 3.3314E-8
      DIAM3 = 5.0684E-8
C ... MASS2 AND MASS3 ARE THE MASSES, IN GRAMS, OF H2O AND SO3 MOLECULES
      MASS2 = 0.299133E-22
      MASS3 = 1.329400E-22
C ... VOLMO  IS INITIAL VOLUME IN CUBIC FEET
      VOLMO = DELT2 * PI * (DPIPE/24.0)**2
      WRITE (6,12350)
12350 FORMAT(107H                        TEMP             MOLES H2O        MOLE
     1S SO3          VPIPE                  L             PAMB    )
      WRITE (6,12352) CHSO3, TEMP, MOLS2, MOLS3, VPIPE, L, PAMB
12352 FORMAT (9H CHSO3 = ,F7.4,6E16.7)
      WRITE (6,12354)
12354 FORMAT (121H0   EXIT  TIME    TOTAL  MOLES   SO3 FRACTION   SO2 FR
     1ACTION   O-2 FRACTION    INITIAL  X   INITIAL VOLUME  EXIT TEMP (K
     2))
      WRITE (6,12355) XTIME, MOLS, FRCT3, FRCT4, FRCT5, X, VOLMO, TPIPE
12355 FORMAT (1H ,7E15.8,F11.2)
      IF ( N61 - N62 ) 6030, 6035, 6030
6030  WRITE (6,12356)
12356 FORMAT (110H)                       TEMPERATURE     VOLUME          Z
     1        P-ZERO         ALPHA              TEMP4            MWBAR)
```

```
C ... J      IS THE INDEX OF THE LATEST POINT OF SIGNIFICANT NUCLEATION
6035  J      = 1
C ... SAVE(J,1) IS THE DISTANCE X OF POINT J FROM THE TAILPIPE, IN FEET
C ... SAVE(J,2) IS THE AVERAGE MOLECULAR WEIGHT OF THE NUCLEATED DROPLET
C ... SAVE(J,3) IS THE NUCLEATION RATE AT DISTANCE X
C ... SAVE(J,4) IS THE CRITICAL RADIUS
C ... SAVE(J,5) IS THE NUMBER OF NEW NUCLEI CREATED AT DISTANCE X
C ... SAVE(J,6) IS THE TEMPERATURE AT DISTANCE X
C ... SAVE(J,7) IS MOLES OF H2O  AVAILABLE WHEN THE DISC REACHES POINT X
C ... SAVE(J,8) IS MOLES OF P2O5 AVAILABLE WHEN THE DISC REACHES POINT X
C ... SAVE(J,9) IS THE DENSITY OF THE NUCLEATED DROPLET
C ... TOT1 IS THE TOTAL NUMBER OF PARTICLES NUCLEATED FROM XMIN TO XMAX
C ... TOT2   IS THE SUM OF THE RADII OF ALL PARTICLES NUCLEATED
C ... TOT3   IS THE SUM OF THE RADIUS-SQUARED OF ALL NUCLEATED PARTICLES
C ... TOT4   IS THE SUM OF THE RADIUS-CUBED OF ALL PARTICLES NUCLEATED
      TOT1  = 0.0
      TOT2  = 0.0
      TOT3  = 0.0
      TOT4  = 0.0
C     UZPCT = THE PERCENT OF THE ORIGINAL SO3 ALREADY USED IN NUCLEATION
      UZPCT = 0.0
C     DELTX IS IN FEET AND IS DELT1 BEFORE NUCLEATION,DELT2 SUBSEQUENTLY
      DELTX = DELT1
      GO TO 7001
6999  J     = J + 1
7000  X     = X + DELTX
C ... IF X IS GREATER THAN XLIMT  FEET, TERMINATE NUCLEATION PROCESS
7001  IF( X - XLIMT ) 7010, 7010, 7075
C
C     BETWEEN  START  AND  TLINR , THE MEAN DISC TEMPERATURE VARIES
C         LINEARLY FROM TPIPE=T-CENTERLINE AT X = START TO
C        (1/2)*(T-CENTERLINE+TAMB) AT TLINR
7010  IF( X - TLINR ) 7012, 7013,  7013
7012  COEF1 = -0.5 / (TLINR - START)
      COEF2 = (TLINR - 0.5*START) / (TLINR - START)
      COEF3 = COEF1 * X  +  COEF2
      TABS  = COEF3 * (TEMPX(X) - TAMB)  +  TAMB
      GO TO 7014
7013  TABS  = (TEMPX(X) + TAMB) / 2.0
7014  TCENT = TABS - 273.16
C  ************************************************************
C  ************************************************************
C  ************************************************************
      RDISK=1.5 + .0385*X
      VOLME=DELT2*PI*(RDISK**2)
      MWAVE = 1.0/(MOLS2/(VOLME*FT2CC) + .03466098)
      WTAIR=MWAVE*(PAMB*VOLME*FT2CC/(R*TABS*CGSAT)-MOLS)
      MOLS1 = MOLS1 + WTAIR/MWAVE
      MOLS2 = MOLS2 + SHAMB*RELHU*WTAIR/MW2
      MOLS5=MOLS5+.20946*WTAIR/31.9988
      MOLS6=MOLS6+.78084*WTAIR/28.0134+.00033*WTAIR/44.00995+.00934*
     1WTAIR/39.948
      VPSAT= 10.**(-7.90298*(373.16/TABS-1.0)+5.02808*ALOG10( 373.16/TAB
     1S)-(-1.3816E-7)*(10.**(11.344*(1.0-TABS/373.16))-1.0)+(8.1328E-3)*
     2(10.**( -3.49149*(373.16/TABS-1.0))-1.0)+ALOG10(1013.246))
      ABSHU = VPSAT*MW2*1000.0/(R*TABS)
```

```
                TRAJ      P COLE       TRAJECTORY
          TRAJ          -  EFN   SCURCE STATEMENT  -  IFN(S)  -

      SATHU=AB3HU*R*TABS*CGSAT/(PAMB*MWAVE)
      AVLBW = 4JLS2-SATHU*WTAIR/MW2
      IF (AVLBW .LT. 0.) AVLBW = 0.0
C   *************************************************************
C   *************************************************************
C   *************************************************************
C
      MOLS  = 4JLS2 + MOLS3 + MCLS4 + MOLS5 + MOLS6
C     FRCT3, FRCT4, AND FRCT5 ARE THE FRACTIONS OF THE TOTA   L S WHICH
C ...     ARE SO3, SO2, AND O-2, RESPECTIVELY
      FRCT3 = 4JLS3 / MOLS
      FRCT4 = MJLS4 / MOLS
      FRCT5 = MJLS5 / MOLS
C      THE EQUILIBRIUM RELATION LEADS TO A CUBIC EQUATION FOR THE
C        INCREMENT OF MOLES OF SO3 DECAYEC.  GIVEN A FIRST ESTIMATE, THE
C        ROUT MAY BE ACCURATELY FOUND USING NEWTON'S METHOD.  THE FOUR
C        COEFFICIENTS OF THE CUBIC ARE  CUBIC, QUAD1, QJAD2, QUAD3.
C        THE ESTIMATE IN THE FIRST INTERVAL IS 0.5*FRCT3, AND IN ALL
C        SUBSEQUENT INTERVALS IS 0.01*FRCT3. IF THE ROOT IS NOT POSITIVE
C        THE ESTIMATE FOR THE NEXT INTERVAL IS SET TO ZERO.
C
C ... THE EQUILIBRIUM CONSTANT IS EQCCN(TABS) = EXP(4956.0/TABS - 4.678)
C ...    THE CONSTANT RELATES PSO3, PSC2, PO2 (FOR P IN ATMOSPHERES) BY
C ....       EQCON(TABS) = PSO3 / ( PSC2 * SQRT(PO2) )  (AT EQUILIBRIUM)
      EQCON = EXP( 4956.0 / TABS  -  4.678 )
      CONST = PAMB * EQCON * EQCON
      CUBIC = CONST - 1.0
      QUAD1 = 2.0 * ( CONST*(FRCT4*FRCT5) + FRCT3 - 1.0 )
      QUAD2 = CONST * FRCT4 * (4.  FRCT5*FRCT4) - FRCT3 * (FRCT3 - 4.0 )
      QUAD3 = 2.0 * CONST * FRCT   2 * FRCT5  -  2.0 * FRCT3**2
C
      IF( N63 - N64 ) 861, 862, 861
861   CONTINUE
      WRITE (6,12357) APROX, CUBIC, QUAD1, QUAD2,QUAD3
12357 FORMAT (9H0APROX = ,E13.6,20H  CUBIC, QUAD1-3 ARE,4E16.8)
862   CONTINUE
C
      IF( CUBIC ) 5003, 5001, 5003
C     THE COEFFICIENT OF THE CUBIC TERM IS ZERO--DEGENERATE CASE.
5001  ROOT  = 0.0
      CUBIC = QUAD1
      QUAD1 = QUAD2
      QUAD2 = QUAD3
C     WHEN 'CUBIC' IS ZERO, QUAD1 IS ALWAYS NEGATIVE, AND QUAD2 POSITIVE
      IF( N63 - N64 ) 863, 864, 863
863   CONTINUE
      WRITE (6,11177)
11177 FORMAT ( 85H DEGENERATE CUBIC EQUATICN--THE REDUCED QUADRATIC EQUA
     1TION ALWAYS HAS A PORITIVE ROOT.)
864   CONTINUE
      GO TO 5007
C
5003  TEST  =SIGN(1.,CUBIC)+SIGN(1.,QUAD1)+SIGN(1.,QUAD2)+SIGN(1.,QUAD3)
C     IF ALL COEFFICIENTS ARE NON-NEGATIVE, NO POSITIVE ROOT IS POSSIBLE
      IF( TEST - 4.0 ) 5005, 5030, 5030
5005  F     = QUAD3 + APROX * (QUAD2 + APRCX * (QUAD1 + APROX * CUBIC))
```

```
      FPRIM = QUAD2  +  APROX * ( 2.0*QUAD1 + 3.0*CUBIC*APROX )
      ROOT  = APROX  -  F / FPRIM
      IF( N63 - N64 ) 865, 866, 865
865   CONTINUE
      WRITE (6,12358) ROOT
12358 FORMAT (9H  ROOT = ,E13.6)
866   CONTINUE
      IF( ABS( (ROOT-APROX)/ROOT ) - 0.00005 ) 5007, 5006, 5006
5006  APROX = ROOT
      GO TO 5005
5007  QUDR1 = CUBIC
      QUDR2 = QUAD1  +  ROOT * CUBIC
      QUDR3 = QUAD2  +  ROOT * (QUAD1 + ROOT*CUBIC)
C     THE ROOT 'ROOT' IS ALGEBRAICALLY REMOVED FROM THE CUBIC EQUATION
C     DISCR  IS THE DISCRIMINANT OF THE RESULTING QUADRATIC EXPRESSION
      DISCR = QUDR2**2  -  4.0 * QUDR1 * QUDR3
      IF( DISCR ) 5008, 5009, 5009
5008  IF( ROOT ) 5030, 5030, 5020
C
5009  ROOT2 = ( -QUDR2 + SQRT( DISCR ) ) / (2.0 * QUDR1)
      ROOT3 = ( -QUDR2 - SQRT( DISCR ) ) / (2.0 * QUDR1)
      IF( N63 - N64 ) 867, 868, 867
867   CONTINUE
      WRITE (6,11188) ROOT2, ROOT3
11188 FORMAT (9H ROOT2 = ,E14.7,11H   ROOT3 = ,E14.7)
868   CONTINUE
C     THE NEXT TEN CARDS FERRET OUT THE SMALLEST POSITIVE ROOT
C     THE TWO REMAINING ROOTS ARE NOT REQUIRED AND ARE IGNORED
      IF( ROOT2 ) 5011, 5011, 5010
5010  IF( ROOT3 ) 5013, 5013, 5014
5011  IF( ROOT3 ) 5020, 5020, 5012
5012  ROOT2 = ROOT3
5013  IF( ROOT )  5019, 5019, 5018
5014  IF( ROOT )  5015, 5015, 5016
5015  ROOT  = ROOT3
5016  IF( ROOT3 - ROOT2 ) 5017, 5018, 5018
5017  ROOT2 = ROOT3
5018  IF( ROOT2 - ROOT ) 5019, 5020, 5020
5019  ROOT  = ROOT2
5020  IF( ROOT - ROOT3 ) 5025, 5025, 5030
C     CHNGE IS THE CHANGE IN MOLES OF SO3 DUE TO DECAY AT THIS STEP
5025  CHNGE = ROOT * MOLS
      MOLS3 = MOLS3  -  CHNGE
      MOLS4 = MOLS4  +  CHNGE
      MOLS5 = MOLS5  +  CHNGE / 2.0
      MOLS  = MOLS  +  CHNGE / 2.0
      AVLBR = AVLBR  -  CHNGE
      GO TO 5035
C
5030  IF( N63 - N64 ) 869, 870, 869
869   CONTINUE
      WRITE (6,12359)
12359 FORMAT (38H NO CHANGE IN EQUILIBRIUM AT THIS STEP)
870   CONTINUE
5035  CONTINUE
      IF( N63 - N64 ) 871, 872, 871
```

```
                TRAJ       P COLE       TRAJECTORY
          TRAJ         -  EFN   SOURCE STATEMENT  -  IFN(S)  -

871   CONTINUE
      WRITE (6,12365) MOLS3, MOLS4, MOLS5, MOLS
12365 FORMAT (35H AFTER TAKING INTO ACCOUNT PREVIOUS NUCLEATION (IF ANY)
     1, AND DECAY THIS STEP (IF ANY),/,21H          MOLES SO3 = ,E14.7,
     215H   MOLES SO2 = ,E14.7,15H   MOLES O-2 = ,E14.7, 17H   TOTAL MOL
     3ES = ,E15.8)
872   CONTINUE
C
C     ****************************************************************
C     ****************************************************************
C     ****************************************************************
      FAKE = TCENT
      IF (TCENT .LT. 0.) TCENT = 0.0
C     ****************************************************************
C     ****************************************************************
C     ****************************************************************
C ... GAMMA  IS SURFACE TENSION IN ERGS / CM SQUARE, KELVIN TEMPERATURE
      GAMMA = 54.022 + 0.4C86*SQRT(TCENT) - 0.059017*TCENT
      TCENT = FAKE
C ... ALPHA  IS THE PERCENT OF THE TOTAL NUMBER OF MOLECULES OF H2O AND
C ...        SO3 IN THE EXHAUST WHICH ARE H2O.  ALPHA IS LESS THAN ONE.
      ALPHA = MOLS2 / (MOLS2 + MOLS3)
      BETA  = 1.0 - ALPHA
C ... VOLME  IS THE VOLUME OF THE DISC AT DISTANCE X FROM THE TAILPIPE
C     VOLME IS DEPENDENT ON THE TOTAL NUMBER OF MOLES AT P-AMB AND T-ABS
      VOLME = MOLS * R * TABS * CGSAT / (PAMB * FT2CC)
C     MPV2 AND MPV3 ARE THE NO. OF MOLECULES OF H2O AND SO3 PER CUBIC CM
      MPV2  = MOLS2 * N / (VOLME*FT2CC)
      MPV3  = MOLS3 * N / (VOLME*FT2CC)
C     Z      IS THE COLLISION FREQUENCY OF WATER AND SO3 MOLECULES
     0Z     = 2.0 * (1.0 + 4.0*ALPHA*BETA) * (ALPHA*DIAM2+BETA*DIAM3)**2
     1             * MPV2**(2.0*ALPHA) * MPV3**(2.0*BETA)
     2             * SQRT( PI * K *       TABS
     3             * ( (ALPHA/MASS2) + (BETA/MASS3) ) )
C
C ... WTPCA  IS THE WEIGHT PERCENT IN SOLUTION OF H2SO4 ACID
      WTPCA = 0.95
      WTPCA = 0.85
      WTPCA = 0.90
C
C ... PZERO  IS THE SATURATION PRESSURE IN ATMOSPHERES AT ABS TEMP TABS
      A      = WTPCA*(0.55490+WTPCA*(-3.14591+WTPCA*3.58243)) + 8.89743
      B      = WTPCA * ( -2361.98 + WTPCA * 3736.88 ) + 2560.87
      PZERO = ( 10.0**( A - B/TABS ) ) / 760.0
C     MWBAR  IS THE AVERAGE MOLECULAR WEIGHT OF THE CONDENSATE
      MWBAR = MW2 * MW5 / ( MW5 - WTPCA * (MW5-MW2) )
C ... CNST1  IS THE FACTOR CHANGING GRAM-MOLES TO PRESSURE (ATMOSPHERES)
      CNST1 = PAMB / MOLS
C     DNSTY  IS THE DENSITY OF THE NEW CONDENSATE, IN GRAMS PER CUBIC CM
      DNSTY = 1.00070 + WTPCA*(0.80185+0.08819*WTPCA) - 0.0006447*TCENT
C ... RC     IS THE MINIMUM RADIUS OF STABLE NUCLEI AT ABS TEMP TABS--CM
     0RC    = 2.0 * GAMMA * MWBAR / ( R * TABS * DNSTY *
     1        ALOG( CNST1*(MOLS2+MOLS3)/PZERO ) )
      VOLNC = 4.1887902 * (    RC     )**3
      TEMP4 = 4.0 * PI * GAMMA * RC*RC / (3.0 * K * TABS)
      IF ( N61 - N62 ) 7016, 7019, 7016
```

```
 7016  IF ( J - 10 ) 7018, 7018, 7019
 7018  WRITE (6,1238) X, TABS, VOLME, Z, PZERO, ALPHA, TEMP4, MWBAR
 1238  FORMAT ( 1H0, 2HX=, 4E13.5, 4E15.7 )
 C ... EXPMN  IS THE MINIMUM EXPONENT OF I AS A POWER OF TEN (G.T. 4)
 7019  EXPMN = 10.)
 C      FOR NUCLEATION TEMP4 SHOULD BE L.T. OR EQUAL TO THE FRACTION BELOW
       IF( TEMP4 - (23.6-EXPMN )/0.434 ) 7020, 7020, 7030
 C ... I        IS THE NUCLEATION RATE IN PARTICLES/CC/SEC AT ABS TEMP TABS
 7020  I      = Z * EXP(-TEMP4)
       IF( J - 1 ) 7021, 7021, 7022
 C     XMIN   IS THE VALUE OF X WHERE SIGNIFICANT NUCLEATION FIRST OCCURS
 7021  XMIN   = X
 7022  CONTINUE
 C
 C ... DELTT  IS THE TIME NEEDED TO TRAVERSE DELTZ  AT CONSTANT VELOCITY
       DELTT = DELTZ   /   (VAMB + L*DPIPE*(VPIPE-VAMB)/(12.0*X))
 C     CNONS  IS THE INCREMENT OF MASS OF CONDENSATE IN DELTZ, IN GRAMS
       CNONS = I * VOLME*FT2CC * DELTT * VOLNC * DNSTY
 C     IN A SOLUTION CONSISTING OF ONLY H2O AND H2SO4, THE WEIGHT PERCENT
 C     OF H2SO4 = THE WEIGHT PERCENT OF SO3 MULTIPLIED BY THE FACTOR
 C     1.225016 = 1 + MW(H2O)/MW(SO3)     THE RECIPROCAL IS 0.8163159
 C     WTPCC  IS THE WEIGHT PERCENT OF SO3 IN THE CONDENSATE
       WTPCC = WTPCA * 0.8163159
 C ... UZDUP  IS THE NUMBER OF  SO3 MOLES NECESSARY IN DELTZ  TO FORM
 C ...        I  PARTICLES PER CC, AT TEMPERATURE T-ABS, OF RADIUS  RC
       UZDUP = CNONS * WTPCC / MW3
 C     IF THE AMOUNT THAT CONDENSES IS MORE THAN THE AMOUNT LEFT,
 C       ALTER THE AMOUNT USED TO REFLECT THIS BUT FORCE A TERMINATION
       IF( UZDUP - MOLS3 ) 7024, 7023, 7023
 7023  DELTT = DELTT * MOLS3 / UZDUP
       CNONS = CNONS * MOLS3 / UZDUP
       UZDUP = MOLS3 * 1.0001
 7024  CONTINUE
       IF ( N61 - N62 ) 7025, 7029, 7025
 7025  IF( J - 10 ) 7027, 7027, 7029
 7027  WRITE (6,1239) CNONS, DELTT, UZDUP
 1239 0FORMAT ( 1H , 11HCONDENSED =, E13.5, 5X, 8HDELTA T=, E13.5,
      1                  5X, 8HUSED UP=, E13.5 )
       IF( J - 10 ) 7029, 7028, 7029
 7028  WRITE (6,12395) CHSO3
 12395 FORMAT (114HJ       X              MWBAR           I             RC
      1  NUMBER       TEMPERATURE     MOLES H2O     MOLES SO3     DENSITY,/,
      221H04H            VOLUME
      3                  ( BEFORE  NUCLEATION ),/, 9H CHSO3 = ,F7.4)
 C
 C ... A POINT IS DESCRIBED AS HAVING NONTRIVIAL NUCLEATION IF IT CAN USE
 C       ONE-TWENTIETH PERCENT OF THE SO3 AVAILABLE IN DELTZ AT CONSTANT I
 7029  IF( UZDUP - 0.0005*AVLBR ) 7048, 7030, 7030
 C ... THE IDEA IS THAT IF A POINT HAS A NUCLEATION RATE THAT IS BOTH
 C ...        ABOVE TEN**EXPMN  AND ENOUGH TO USE 0.05 PERCENT OF THE
 C ...        INITIAL DISTRIBUTION OF  SO3, IT HAS SIGNIFICANT NUCLEATION
 C ... IF THE AMOUNT USED IS LESS THAN 0.05 PERCENT, AND J IS NOT 1,
 C ...        INDICATING PREVIOUS SIGNIFICANT NUCLEATION, NO ERROR EXISTS
 C ... AN UPPER BOUND OF XLIMT FT IS CHOSEN AS A PRECAUTION THAT THE
 C ...        CURRENT CASE WILL HAVE NO SIGNIFICANT NUCLEATION AT ALL
 C
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                 TRAJ       P COLE        TRAJECTORY
         TRAJ          -  EFN   SOURCE STATEMENT  -  IFN(S)  -

 7030  DELTX = DELT2
       DELUZ = UZDUP / AVLBL
       NEWJ  = J - ( (J-1)/10 ) * 10
       SAVE(NEWJ,1)= X
       SAVE(NEWJ,2)= MWBAR
       SAVE(NEWJ,3)= I
       SAVE(NEWJ,4)= RC
       SAVE(NEWJ,5)= I * VOLME*FT2CC * DELTT
       SAVE(NEWJ,6)= TABS
       SAVE(NEWJ,7)= MOLS2
       SAVE(NEWJ,8)= MOLS3
       SAVE(NEWJ,9)= DNSTY
       SAVE(NEWJ,10)= VOLME
       UZPCT = UZPCT + 100.0*DELUZ
       MOLS2 = MOLS2  -  CNDNS * (1.0-WTPCC) / MW2
       MOLS3 = MOLS3  -  UZDUP
       TOT1  = TOT1 + SAVE(NEWJ,5)
       TOT2  = TOT2 + SAVE(NEWJ,5)*RC
       TOT3  = TOT3 + SAVE(NEWJ,5)*RC*RC
       TOT4  = TOT4 + SAVE(NEWJ,5)*RC*RC*RC
       IF ( N61 - N62 ) 7031, 7034, 7031
 7031  IF ( NEWJ - 10 ) 7034, 7033, 7034
 7033  WRITE (6,1240) ((SAVE(JL,KL),KL=1,10),JL=1,NEWJ,5)
 1240  FORMAT ( 1H , 9E13.6, /, 7H       , E13.6)
 7034  IF ( MOLS3 ) 7051, 7051, 7035
  7035  IF (MOLS2) 7040, 7040, 7036
  7040 IF (X-XLIMT) 7036, 7051, 7051
 7036  GO TO 5999
 C     IF J IS NOT 1, THE INCREMENT IN PERCENT OF SO3 USED HAS DECREASED
 C        TO LESS THAN .0005 OF INITIAL SO3. IT IS ASSUMED TO REMAIN LESS
 7048  IF ( J - 1 ) 7000, 7000, 7049
 7049  J       = J - 1
       X       = X - DELTX
       IF( N61 - N62 ) 17049, 7051, 17049
 17049 IF( NEWJ - 10 ) 7050, 7051, 7050
 7050  WRITE (6,1240) ((SAVE(JL,KL),KL=1,10),JL=1,NEWJ,5)
 C
 C ... JMAX   IS THE MAXIMUM J WITH SIGNIFICANT NUCLEATION
 7051  JMAX  = J
       XMAX  = X
       SQ    = JMAX
       SQ    = SQ * DELT2
       R1BAR = ( TOT2/TOT1 )
       R2BAR = ( TOT3/TOT1 )**0.5
       R3BAR = ( TOT4/TOT1 )**0.333333
       SURFC = 4.0 * PI * TOT3 / TOT1
       VOLM  = 4.0 * PI * TOT4 / (3.0*TOT1)
 C     THE VISIBILITY CRITERION IS 0.025 GRAMS/CUBIC METER OF
 C         PARTICLES OF RADIUS AT LEAST 1/4 * 10**(-4) CM
 C ... VISBL  IS THE MINIMUM VISIBILITY RADIUS, IN CENTIMETERS
       VISBL = 0.000025
 C ... FACTR  IS THE FACTOR BY WHICH THE LARGEST PARTICLE'S RADIUS IS
 C ...                ASSUMED GREATER THAN THE AVERAGE INITIAL RADIUS
 C ... RMAX   IS THE MAXIMUM ALLOWED RADIUS IN THE SIZE DISTRIBUTION
       RMAX  = FACTR * R1BAR
       SHMRG = FACTR * R1BAR / VISBL
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```
      GREBL =          R1BAR / VISBL
C
C     DENSE  IS THE AVERAGE CONDENSATE DENSITY AFTER ALL REMAINING WATER
C     VAPOR HAS CONDENSED ON THE 'INITIAL' PARTICLES.  THE VOLUME USED
C     TO DETERMINE THE DENSITY IS THE SUM OF THE VOLUME OF THE INITIAL
C     PARTICLES AND THE VOLUME OF THE REMAINING WATER TAKEN AS 1 CC ' GM
C     OF VAPOR, WITH NO PROVISION MADE FOR DECREASE IN VOLUME DUE TO
C     CHEMICAL COMBINATION.  THE MASS IS THE SUM OF THE INITIAL MASSES
C     OF H2O AND SO3 AS COMPUTED FROM EXHAUST VELOCITY AND DISC WIDTH.
      ODENSE = ( MW2 * AVLBW  +  MW3 * AVLBR )  /
     1         ( 4.0*PI*TOT4/3.0  +  MW2 * PCLS2 )
C
C ... CONC1  IS THE CONTRAIL DROPLET MASS CONCENTRATION (GRAMS/CU METER)
      CONC1 = 1000000.0 * (AVLBR*MW3 + AVLBW*MW2) / (VOLME*FT2CC)
C
      WRITE (6,1070)
 1070 FORMAT (14H0* - * - * - *)
      WRITE (6,1071) SQ, XMIN, XMAX, UZPCT
 1071 FORMAT ( 5H0IN A, F6.1, 27H FT INTERVAL EXTENDING FROM, F6.1,
     13H TO, F6.1, 18H FT BEHIND THE JET, F6.1, 39H PERCENT OF THE SO3 M
     2ASS HAS CONDENSED.)
C     UZOVR  IS THE PERCENT OF THE NON-DECAYED SO3 THAT HAS CONDENSED
      UZOVR = UZPCT * AVLBL / AVLBR
      WRITE (6,10712) UZOVR
10712 FORMAT (72H AFTER TAKING INTO ACCOUNT THE DECAYED PORTION OF THE O
     1RIGINAL SO3 MASS,, F6.1, 39H PERCENT OF THE SO3 MASS HAS CONDENSED
     2.)
C
      WRITE (6,10715) CONC1
10715 FORMAT (101H0ASSUMING THAT ALL REMAINING WATER CONDENSES ON THE DR
     1OPLETS, THE MAXIMUM POSSIBLE MASS-CONCENTRATION,/, 69H      OF THE
     2 CONTRAIL, TAKING INTO ACCOUNT PARTICLES OF ALL SIZES, IS, F7.3,
     320H GRAMS / CUBIC METER)
C
      WRITE (6,1072) TOT1
 1072 FORMAT ( 82H0THE TOTAL NUMBER OF PARTICLES NUCLEATED (BEFORE AGGLO
     1MERATION TO LARGER SIZES) IS, E13.6, 1H.)
      WRITE (6,1073) R1BAR, R2BAR, SURFC, R3BAR, VOLM
 1073 FORMAT (33H0FOR THE SET OF INITIAL DROPLETS,, /, 27H      THE AVER
     1AGE RADIUS IS,6X,E12.5,4H CM,,/,33H      THE AVERAGE SURFACE AREA
     2IS,E12.5,36H SQ CM (CORRESPONDING TO A RADIUS OF,E12.5,9H CM), AND
     3,/,27H      THE AVERAGE VOLUME IS,6X,E12.5,36H CC    (CORRESPONDIN
     4G TO A RADIUS OF,E12.5,4H CM))
C
      WRITE (6,1074) R1BAR, RMAX, NFCTR, SHMRG
 1074 FORMAT (103H0FOR THE SET OF DROPLETS RESULTING FROM COLLISION, AGG
     1LOMERATION, AND CONDENSATION (OF WATER VAPOR),, /, 26H      THE RA
     2DII RANGE FROM, E11.4, 6H CM TO, E11.4, 16H CM, A FACTOR OF, I5,
     31H, /, 31H      AND THE MAXIMUM RADIUS IS, F6.2, 25H TIMES THE VIS
     4IBLE LIMIT., /,113H      THE FREQUENCY DISTRIBUTION OF DROPLET RAD
     5IUS IS ASSUMED TO BE OF THE FORM    F(R) = CONSTANT * RADIUS**(-N)
     6)
      IF ( RMAX - VISBL ) 7775, 7775, 7055
 7055 WRITE (6,1079) XMAX, CHSO3
 1079 FORMAT (/,21X, 12HTHE EXPONENT,11X, 7HVISIBLE,13X,  15HFRACTION OF
     1 THE,8X, 13H(EVALUATED AT, F6.1, 15H FT BEHIND JET), /, 21X, 60H
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                TRAJ      P COLE        TRAJECTORY
         TRAJ          -  EFN   SOURCE STATEMENT  -  IFN(S)  -

     2N  OF THE            CONCENTRATION          TOTAL CONCENTRATION, /,
     379H C5H11SO3 FRACTION   DISTRIBUTION          (GM/CU METER)
     4 THAT IS VISIBLE, /,  7H      IS, F7.4)
C
 7057 DO 7073 INDX=1,17,1
      XINDX = INDX
      EXPON = (XINDX-9.0) / 4.0
C     IF EXPONENT IS ZERO, N = 4 SO USE LOGS (SEE DERIVATION)
      IF( EXPON ) 7061, 7060, 7061
7060  FRCTN = ALOG( SHMRG ) / ALOG( FACTR )
      GO TO 7063
7061  TERM  = SHMRG**EXPON
      FRCTN = ( TERM - 1.0 )  /  ( TERM - GREBL**EXPON )
7063  CONC2 = FRCTN * CONC1
      EXPRL = 4.0 - EXPON
      WRITE (6,1085) EXPRL, CONC2, FRCTN
1085  FORMAT ( 23X, F7.4, 12X, F10.6,15X, F8.5)
7073  CONTINUE
C ***
C ***
C ***
      DELTX = 10.0
      X = X + DELTX
      IF (X-XLIMT) 7080, 7080, 1
 7080 IF (X-TLINR) 7082, 7084, 7084
 7082 COEF1 = -.5/(TLINR-START)
      COEF2 = (TLINR-.5*START)/(TLINR-START)
      COEF3 = COEF1*X+COEF2
      TABS = COEF3*(TEMPX(X)-TAMB)+TAMB
      GO TO 7086
 7084 TABS = (TEMPX(X)+TAMB)/2.0
 7086 TCENT = TABS-273.16
      RDISK = 1.5 + .0385*X
      VOLME = DELT2*PI*(RDISK**2)
      MWAVE = 1.0/(MOLS2/(VOLME*FT2CC) + .03466098)
      WTAIR=MWAVE*(PAMB*VOLME*FT2CC/(R*TABS*CGSAT)-MOLS)
      MOLS1 = MOLS1 + WTAIR/MWAVE
      MOLS2 = MOLS2 + SHAMB*RELHU*WTAIR/MW2
      MOLS5=MOLS5+.20946*WTAIR/31.9988
      MOLS6=MOLS6+.78084*WTAIR/28.0134+.00033*WTAIR/44.00995+.00934*
     1WTAIR/39.948
      VPSAT= 10.**(-7.90298*(373.16/TABS-1.0)+5.02808*ALOG10( 373.16/TAB
     1S)-(-1.3816E-7)*(10.**(11.344*(1.0-TABS/373.16))-1.0)+(8.1328E-3)*
     2(10.**( -3.49149*(373.16/TABS-1.0))-1.0)+ALOG10(1013.246))
      ABSHU = VPSAT*MW2*1000.0/(R*TABS)
      SATHU=ABSHU*R*TABS*CGSAT/(PAMB*MWAVE)
      AVLBW = MOLS2-SATHU*WTAIR/MW2
      IF (AVLBW .LT. 0.) AVLBW = 0.0
      MOLS = MOLS2+MOLS3+MOLS4+MOLS5+MOLS6
      CONC1=1000000.*(AVLBR*MW3+AVLBW*MW2)/(VOLME*FT2CC)
      WRITE (6,10700) X,TABS
10700 FORMAT (8H1    X = ,F6.2,13H, AND TABS = ,F6.2)
      WRITE (6,10715) CONC1
      WRITE (6,1079) X,CHSC3
      GO TO 7057
C ***
```

```
C ***
C ***
C ... IF J IS NOW 1, THERE WAS NO NUCLEATION BY XLIMT  FEET--ERROR
 7075  IF( J - 1 ) 7049, 7777, 7049
 7775  WRITE (6,1775)
 1775  FORMAT (121H0THE FACTOR BY WHICH THE LARGEST RADIUS EXCEEDS THE AV
      1ERAGE INITIAL RADIUS IS SMALL ENOUGH THAT THE CONTRAIL IS INVISIBL
      2E)
       GO TO 1
 7777  WRITE (6,1777) CHSO3
 1777  FORMAT ( 53H X GREATER THAN X-LIMIT -- NO NUCLEATION FOR CHSO3 = ,
      1F7.4)
       GO TO 1
       END
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13. ABSTRACT

This report is a continuation of the final report for contract AF19 (628)-5193. The assumptions and assertions of that report are examined, and estimates made of how these may affect the worth and accuracy of numerical predications of contrail properties. A special type of analytic-experimental analysis is proposed to ferret out nonthermodynamic variables, and is applied to flight test data. Following the analysis, further computer simulation is explored. Additional data lead to bounds on the values of heretofore unspecifiable parameters. Further experimental study is indicated. The data is presented in terms of the dependence of contrail formation on ambient temperature and relative humidity.( )

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fuel Additive	1	1				
Jet Exhaust	1, 5	3				
Particle Size Distribution	2	3				
Contrail	2, 8	3				
Visibility	4, 8	3				
Theory	8	2				
Digital Computer	10	1				
Mathematics	10	1				
Thermodynamics	10	1				
Experiment	8	2				

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