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The Effect of Changes in Space Shuttle Parameters on the NASA/MSFC Multilayer Diffusion Model Predictions of Surface HCl Concentrations

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CONTENTS

TABLES

FIGURES

Figure | Page

SUMMARY

The effect of changes in Space Shuttle launch parameters (e.g., changes in design, information about physical processes, or mission definition) on the values predicted by the NASA Multilayer Diffusion Model (stabilization height of the ground launch cloud and surface concentrations and dosages of hydrogen chloride) was investigated. A method for formulating these changes into the model input parameters using a preprocessor program run on a programed data processor was implemented. The results indicate that any changes in the input parameters are small enough to be negligible in comparison to meteorological inputs and the limitations of the model and that such changes will not substantially increase the number of meteorological cases for which the model will predict surface hydrogen chloride concentrations exceeding public safety levels.

INTRODUCTION

In this report, the effect of changes in the Space Shuttle launch parameters on the output values predicted by the Multilayer Diffusion Model (MDM) developed at the NASA George C. Marshall Space Flight Center is discussed. The output values of primary interest are the stabilization height of the ground launch cloud and the surface concentration and dosages of hydrogen chloride (HCl). Factors that may affect the parameters controlling the heat content of the ground launch cloud are also examined. Of particular interest is the added deluge water that will be used for sound damping during the first few seconds of the Space Shuttle launch.

The concern leading to this report is that changes in Space Shuttle launch parameters may result in unacceptably high concentrations of HCl at the surface. Earlier investigations by Glasser and Siler[1] using 1973 Space Shuttle launch parameters (ref. 1), which made no assumptions on afterburning or deluge water effects, indicate that the 10-minute time average concentrations of HCl exceed the short-term public limit (STPL) exposure of 4 parts per million (ppm) only under certain identifiable meteorological conditions and that the particular set of conditions has a low probability of occurrence. It is of interest, then, to document and clarify the more recently suggested values for the Space Shuttle launch parameters and their attendant assumptions and to test their effect on the MDM predictions for cloud stabilization height and surface HCl concentrations.

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[1] Glasser, M. E.; and Siler, R. K.: Diffusion Estimates for Space Shuttle Launches From KSC. Rep. JSC-12507, Feb. 1977.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

SYMBOLS

a,b,c	rise time coefficients defined in equation (1)
c	constant defined in equation (4)
c_p	specific heat at constant pressure
$F = \frac{3gQ}{4c_p T\pi\ell}$	initial buoyancy term
g	acceleration due to gravity
H	equivalent fuel heat content
ℓ	ambient air density
$Q = HWt\{Z_m\}$	total heat release
$s = \frac{\partial\Phi}{\partial z}$	gradient of ambient virtual potential temperature Φ with height z
$\bar{s}$	s averaged over height z
T	ambient air temperature
t	rocket rise time, seconds
W	mass flow rate from solid rocket booster
X	mass
Z_m	stabilization height of launch cloud
z	altitude, meters
γ	entrainment coefficient, $\gamma = 0.64$
γ_p	depletion parameter
Δ	incremental change
Φ	ambient virtual potential temperature
χ_{av}	average cloud concentration of HCl

χ_c	maximum centerline concentration of HCl
χ_{10}	maximum 10-minute average concentration of HCl
$\overline{}$	average over 20 cases except when used with s

MODEL PARAMETERS

AA = a	rise time coefficient
BB = b	rise time coefficient
CC = c	rise time coefficient
DPDZ = $\bar{s}$	average virtual potential temperature gradient between surface and cloud stabilization height
FRQ	mass fraction of HCl in exit plume
HEATN = H	equivalent fuel heat content
Q	total heat release
QC = W	mass flow rate from solid rocket booster
s	stability parameter
t	rocket rise time
Z_m	stabilization height of launch cloud
z	altitude, meters
$\gamma = 0.64$	entrainment parameter
γ_p	depletion parameter
χ_{av}	average cloud concentration of HCl
χ_c	maximum centerline concentration of HCl
χ_{10}	maximum 10-minute average concentration of HCl

MULTILAYER DIFFUSION MODEL INPUT PARAMETERS

Changes in the Space Shuttle launch parameters may occur because of three different factors.

1. Design changes, such as the addition of more deluge water for sound damping

2. Changes in information about physical processes, such as new knowledge on the extent of afterburning of carbon monoxide (CO)

3. Mission changes, such as those related to redefined trajectories

These changes can be formulated into the input parameters of the MDM by a preprocessor program that contains the cloud rise portion of the model and establishes the source strengths and meteorological characteristics for each layer of the diffusion model. The factors affecting a normal Space Shuttle launch and the corresponding MDM input parameters that will be affected are summarized in table I. Table I shows that besides the meteorological input, five parameters are accessible for change without basic modifications in the MDM. Table I also shows that the HEATN parameter relates to several factors that could change the cloud rise and HCl concentrations. It is therefore important that the assumptions concerning these factors be clear whenever a new value for the HEATN or for other Space Shuttle parameters is introduced.

The primary tool used to obtain data was model 4, version 5, of the MDM, which was developed by the H. E. Cramer Co. and is documented in reference 1. For part of the work, the MDM was used in its original form with the original parameters and run on a Univac 1110 computer. The remaining results were obtained from a reprogramed version of the MDM prepared by Joe Yoder at the NASA Lyndon B. Johnson Space Center (JSC) to run on a programed data processor (PDP 11/45), operating under multiprograming system RSX-110, version 6B. This latter form, using Fortran four-plus language, was convenient to use when changes were made in the input parameters.

The meteorological data used in this work were taken from the baseline meteorological soundings at the NASA John F. Kennedy Space Center (KSC) and at Vandenberg Air Force Base (VAFB) compiled by Susko and Stephens (ref. 2), with the exception of case 37. Case 37 was taken from hand-plotted soundings for the date shown for KSC and was used because it has been demonstrated to produce large surface concentrations of HCl.[1] A listing of the 20 cases used is given in table II.

Changes of the input parameters for the Space Shuttle were introduced into the model individually and then all together to determine both their individual and their combined effects. The range of values tested for the solid rocker booster (SRB) mass flow rate (QC), equivalent fuel heat content (HEATN), and other parameters was chosen to encompass the different possible assumptions concerning them. The effect of these changes on cloud stabilization height Z_m was tested on all cases because the computer and peripheral output time was short, about 2 minutes per case. The cloud stabilization is computed by the preprocessor of the MDM. Only selected cases were tested for

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[1] Glasser, M. E.; and Siler, R. K.: Diffusion Estimates for Space Shuttle Launches From KSC. Rep. JSC-12507, Feb. 1977.

the effects on HCl concentrations since computational and peripheral requirements range from 30 to 60 minutes on the PDP 11/45, depending on the number of levels in the input meteorology. In addition, some intermittent hardware problems made it difficult to run as many cases with the MDM as had been originally intended.

RISE PARAMETERS

The rise parameters AA and BB are used to determine the rate of rocket ascent. Their importance is that they determine the amount of source material and indirectly the amount of heat injected into the planetary boundary layer (PBL). Two of the values for these parameters found in the literature and the diffusion predictions obtained from the MDM for case 37 using the two different sets of parameters are cited in table III. All the other parameters are unchanged from those used in reference 1. The rise parameters cited in reference 3 include CC = 5 seconds, so that the rise time is given by the expression

$$t = az^{b} + c \qquad (1)$$

where a = AA
b = BB
c = CC
z = altitude, meters
t = rise time, seconds

The parameter CC was not used in the preprocessor for the computation given in table II, because there was no provision for it in the program. A check of the fit of these parameters against the rise time from the 1976 design data from the NASA Jet Propulsion Laboratory (JPL) indicates that the agreement is better if CC is omitted (ref. 4). Table IV consists of data adapted from reference 4. Columns 3, 4, 5, and 8 have been added to the table for purposes of this report. Column 4 gives the rise time using the altitude in column 3 and the rise parameters from reference 3 without c. Column 5 gives the rise time using the parameters from reference 1. The latter parameters give the better fit over the entire range of primary interest, exceeding the 0.5-second difference only after a rise time of 22 seconds. The data in this table are for mission 3A, which results in slightly more material injection into the PBL than for mission 2. The mass flow of the SRB for different mission types is shown in figure 1 for the 1973 (ref. 5) and 1976 (ref. 4) JPL Space Shuttle design studies.

The general conclusion that can be drawn from table III is that the effect of rise parameter changes on the maximum centerline concentration χ_c, on the maximum 10-minute average concentration χ_{10}, and on the maximum dosage is small; i.e., -1, 7, and 3 percent, respectively. The difference in MDM predictions in using these two sets of rise parameters is, therefore, small enough to be insignificant in comparison to other uncertainties of the MDM and its predictions.

MASS FRACTION PARAMETER

Table V illustrates the effect of changes in the fraction of HCl in the nozzle exit plane of the SRB's on the surface concentrations of HCl predicted by the MDM. All other parameters are the same as in the original version 5 of the MDM (ref. 1). A 5-percent increase in the FRQ parameter produces the same increase (5 percent) in all the concentration and dosage predictions. In conclusion, it can be seen that the changes in this parameter result in small and predictable changes that are negligible in comparison to other uncertainties affecting the MDM predictions.

MASS FLOW RATE PARAMETER

The Shuttle parameter for the mass flow rate, QC, of the SRB is an important parameter affecting the MDM predictions. The values for QC found in the literature are summarized in table VI. Table IV, as has been noted, provides the 1976 design data from JPL (ref. 4) for the mass flow rate as a function of time and altitude for the SRB. Figure 1 is a graphical presentation of the mass flow as a function of time for different types of missions using 1973 (ref. 5) and 1976 JPL design data (ref. 4).

The effect of the QC parameter on the cloud rise portion of the MDM (i.e., the preprocessor) is twofold. First, it establishes the source strength of HCl gas that will subsequently be acted on by the diffusion part of the MDM. Second, it determines the major portion of the heat added to the launch cloud and thereby affects the height of launch cloud stabilization Z_m. An additional amount of heat is introduced into the launch cloud by the liquid-fuel motors and by afterburning processes. These effects, however, can be introduced in the parameter representing the specific heat of the fuel (i.e., HEATN), which is discussed in the next section.

To evaluate the effect of changes in the QC parameter on cloud rise and on the surface concentration predictions, a range of values from 9×10^6 to 15×10^6 g/sec was used. This range corresponds roughly to the range of values found in the literature. (See table VI.)

Effect of Changes in QC on Cloud Stabilization Height

An increase in QC would be expected to increase the cloud stabilization height Z_m because the thermal buoyancy of the cloud would be increased. That this is the case can be seen in figure 2, in which the stabilization height is given as a function of the mass flow rate, QC, for all of the cases listed in table II. The average change in Z_m for an increase in QC from 9×10^6 to 12×10^6 g/sec is 106 m (348 ft). The range of changes in Z_m (i.e., ΔZ_m) is from 73 m (240 ft) for case Ex to 186 m (610 ft) for case 1. A further increase in QC from 12×10^6 to 15×10^6 g/sec gives a slightly reduced average increase in the stabilization height of 87 m (285 ft), with a range from 51 m (167 ft) for case 51 to 117 m (384 ft) for case 46. These results are summarized in table VII.

In conclusion, the overall effect of changes in QC = W of 6 x 10^6 g/sec is to produce a change in cloud stabilization height of 193 m (633 ft). This means that for an increase in the SRB mass flow of 1 x 10^6 g/sec, the cloud stabilizes 32 m (105 ft) higher; i.e.,

$$\frac{\overline{\Delta Z_m}}{\overline{\Delta W}} = 32 \text{ m per } 10^6 \text{ g/sec} \tag{2}$$

Table VII also indicates that a 33-percent increase in W produces an average 8.1-percent increase in Z_m, whereas a further 25-percent increase in W results in a 6.1-percent increase in Z_m.

Part of the reason for the increase in Z_m is immediately apparent from examination of the Briggs formula (ref. 7) used in the preprocessor (ref. 1) to calculate cloud stabilization height. From this relation, the maximum cloud rise for an instantaneous source in a stable atmosphere is given by

$$Z_m = \left(8F/\gamma^3 s\right)^{1/4} \tag{3}$$

where F = $(3gQ)/(4c_p T\pi \ell)$, the initial buoyancy term
g = acceleration due to gravity
c_p = specific heat at constant pressure
T = ambient air temperature
ℓ = ambient air density
Q = $HWt\{Z_m\}$, total heat release
H = heat content of fuel (HEATN)
W = mass flow rate (QC)
t = rise time
γ = 0.64, entrainment coefficient
s = $\partial\Phi/\partial z$, the gradient of the ambient virtual potential temperature Φ with height z

The relation of Z_m to Q,

$$Z_m = cQ^{1/4} \tag{4}$$

where c is a constant, has led Hwang and Gould (ref. 8) to conclude in their evaluation of the effects of the cooling caused by deluge water that a given percentage change in Q will result in one-fourth the percentage change in Z_m; i.e.,

$$\frac{\Delta Z_m}{Z_m} = 0.25 \frac{\Delta Q}{Q} \qquad (5)$$

However, this interpretation is incorrect for two reasons. First, it assumes that neither Q nor any other factor in equation (3) is a function of Z_m. This plainly is not the case: Q itself is a function of Z_m through the rise time; i.e., $t = t(Z_m)$. For example, if deluge water cools the launch cloud, the stabilization height is reduced as well as the rise time, which acts to reduce Q which further reduces Z_m. Even though this is positive feedback, the effect soon damps out and is allowed by the manner in which equation (3) is calculated. The calculation of Z_m is by an iterative procedure that makes a first guess at Z_m and then keeps increasing or decreasing Z_m by 10-m (33 ft) intervals until equation (3) becomes self-consistent.

Second, equation (5) is incorrect because the gradient of the virtual potential temperature s is also a function of Z_m (i.e., $Z_m \propto (\bar{s})^{-1/4}$), so that an additional term $-1/4(\Delta\bar{s}/\bar{s})$, where $\bar{s}$ is s averaged over height z, must be added to equation (5) to consider the effect of stability changes with height. Figure 2 and the results cited in table VII clearly show that a given change in W affects the cases differently; therefore, the usefulness of equation (2) as a criterion to judge the effect of mass flow changes on Z_m is reduced. The reason for concern here with changes in cloud stabilization height is that they in turn have considerable influence on surface concentrations of HCl.

Effect of Changes in QC on Surface HCl Concentrations

The primary interest here is in the effect of changes in the Space Shuttle parameter QC on surface concentrations of HCl. To determine this effect, the MDM must be programed and run with successive changes in the parameter QC for a given case or cases. Because of the limitation in time for this study, it was necessary to select one case. Case 37 was chosen because its meteorology (i.e., a high-level inversion) is capable of producing large surface concentrations of HCl.[1]

Figure 3 shows the maximum values for the centerline concentration χ_c; the 10-minute time average concentration χ_{10}; dose; and the average cloud concentration χ_{av} as a function of changes in QC. The other parameters used

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[1] Glasser, M. E.; and Siler, R. K.: Diffusion Estimates for Space Shuttle Launches From KSC. Rep. JSC-12507, Feb. 1977.

in the MDM are listed in the figure. The value of HEATN used, 5636 J/g (1347 cal/g), is smaller than the recommended value and has the effect of boosting the concentration levels above the STPL of 4 ppm. The concentration and dosage values for the original Space Shuttle parameters are also noted in figure 3. These values were high in comparison to other cases tested in a previous study[1] but are well below the critical level. Figure 3 provides the graphical results and table VIII the data for the effect of changes in the Space Shuttle parameter QC on the MDM concentration predictions. The conclusions that can be drawn from this information are as follows.

1. There is an increase in χ_c, χ_{10}, and dose with the increase in mass flow rate, QC. This indicates that the tendency to increase concentrations caused by the added pollution source strength outweighs the tendency to reduce concentration caused by the higher cloud stabilization.

2. The amount of change in HCl concentrations is small and nearly linear over the range of QC = W tested; i.e.,

   a. $\Delta\chi_c/\Delta W = 0.2$ ppm/10^6 g/sec, or 2.2 percent.

   b. $\Delta\chi_{10}/\Delta W = 0.31$ ppm/10^6 g/sec, or 6.8 percent.

   c. $\Delta\text{dose}/\Delta W = 179$ ppm-sec/10^6 g/sec, or 8.8 percent.

3. There is some inconsistency in the preprocessor program which allows the maximum average cloud concentration χ_{av} to exceed χ_c, which is not possible. The concentration χ_{av} is obtained by dividing the dose by the time of cloud passage. This computation is self-consistent in the results, an indication that some other problem remains. No attempt has been made to identify this problem, which has shown up only when large concentrations are involved.

4. A general conclusion from these results is that even a wide range in values for the parameter QC has only a small effect on the MDM concentration predictions. A 55-percent increase in QC resulted in a 34-percent increase in χ_{10} and only an 11-percent increase in χ_c for case 37. If the increases for case 37 are relatively large in comparison to other cases (as is expected), then changes in this parameter alone will not cause HCl concentrations to exceed the STPL unless they are already very close to 4 ppm.

5. The most reasonable value to use for the Space Shuttle parameter QC in the MDM would be near 10.8 x 10^6 g/sec determined from the JPL 1976 Space Shuttle design data in reference 4.

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[1] Glasser, M. E.; and Siler, R. K.: Diffusion Estimates for Space Shuttle Launches From KSC. Rep. JSC-12507, Feb. 1977.

EFFECTIVE HEAT CONTENT PARAMETER

The HEATN = H parameter, which introduces the heat content of the fuel in joules per gram (calories per gram), is the most complex parameter to discuss because other factors, as shown in table I, must be considered. The important factors to affect HEATN are the cooling effect of the deluge water, particularly with the added water for the acoustic water sound system (AWSS); the heat added because of afterburning; entrainment of outside air into the plume; and perhaps radiation losses.

Some of the values for this parameter cited in the literature and their related assumptions are listed in table IX. In order to ascertain the effect these assumptions may have on HCl predictions, the sensitivity of the MDM to changes in the HEATN parameter will be presented.

Effect of Changes in HEATN on Cloud Stabilization Height

The effects on cloud stabilization height of doubling the HEATN parameter from 4184 to 8368 J/g (1000 to 2000 cal/g) at 2092-J/g (500 cal/g) intervals are illustrated in figure 4 and summarized in table X. The average change in Z_m, ΔZ_m, for an increase of HEATN from 4184 to 6276 J/g (1000 to 1500 cal/g) for the 20 cases in table II is 122 m (400 ft). The range in ΔZ_m is from 30 m (98 ft) for case 51 to 278 m (912 ft) for case 44. A further increase in HEATN from 6276 to 8368 J/g (1500 to 2000 cal/g) gives a slightly reduced increase in ΔZ_m of 98 m (322 ft), with a range from 43 m (141 ft) for case 43 to 156 m (511 ft) for case 1. The overall change in the average cloud stabilization height was 220 m (722 ft) for the 4184-J/g (1000 cal/g) change in HEATN. This means that for every 418-J/g (100 cal/g) increase in the heat content (HEATN), an average increase of 22 m (72 ft) occurred in Z_m; i.e.,

$$\overline{\left(\Delta Z_m/\Delta H\right)} = 26\ \mathrm{m}/500\ \mathrm{J/g}\ (22\ \mathrm{m}/100\ \mathrm{cal/g}) \qquad (6)$$

In conclusion, table X shows that for a given change in HEATN, ΔH, the change in Z_m, ΔZ_m, is strongly dependent on the meteorological case. A 50-percent change in H causes changes in Z_m ranging from 3 to 23 percent. This result adds further evidence that the conclusion of a fixed change in Z_m for a given change in heat content of the cloud as that implied by equation (3) cannot be correct.

Effect of Changes in HEATN on Surface HCl Concentrations

Figure 5 illustrates the effect of changes in HEATN by increments of 1046 J/g (250 cal/g) on the concentrations and dosages of HCl for cases 37 and 51. Table XI summarizes some data for these two cases. The range of values tested for HEATN is as large as the range summarized in table IX but would have been more representative if it had been extended from 6276 to 10 460 J/g (1500 to 2500 cal/g) rather than from 4184 to 8368 J/g (1000 to 2000 cal/g).

However, it is doubtful that the conclusions reached here would be altered by this difference. The conclusions reached from examining figure 5 and table XI are as follows.

1. There is a decrease in χ_c and χ_{10} with the increase in HEATN = H, indicating that the increase in cloud stabilization height reduces the surface concentrations as expected.

2. The amount of decrease in concentrations is small and nearly linear over the range tested and yields the following changes:

   a. For case 37, $\Delta\chi_c/\Delta H = -0.57$ ppm/500 J/g (-0.48 ppm/100 cal/g, or 4.1 percent). For case 51, $\Delta\chi_c/\Delta H = -0.12$ ppm/500 J/g (-0.10 ppm/100 cal/g, or 3.0 percent).

   b. For case 37, $\Delta\chi_{10}/\Delta H = -0.13$ ppm/500 J/g (-0.11 ppm/100 cal/g, or 2.1 percent). For case 51, $\Delta\chi_{10}/\Delta H = -0.05$ ppm/500 J/g (-0.04 ppm/100 cal/g, or 2.5 percent).

Doubling the HEATN parameter from 4184 to 8368 J/g (1000 to 2000 cal/g) produces a tenfold increase in the percentages listed here.

3. The dosage also decreases, as follows.

   a. For case 37, $\Delta\text{dose}/\Delta H = 75$ ppm-sec/500 J/g (63 ppm-sec/100 cal/g, or 2.1 percent).

   b. For case 51, $\Delta\text{dose}/\Delta H = 29$ ppm-sec/500 J/g (24 ppm-sec/100 cal/g, or 2.5 percent).

The percentage changes are the same as those for the 10-minute time average concentration χ_{10}.

4. The average cloud concentration χ_{av} is again incorrect in case 37, although it appears that it will drop below χ_c as it should if H is increased beyond 8368 J/g (2000 cal/g). The value of χ_{av} appears to behave normally in case 51.

In the preceding sections, the Space Shuttle parameters have been related to both cloud stabilization changes and surface concentration changes. These ratios can also be used to relate changes in cloud stabilization height to changes in surface concentration. The results of doing this are as follows.

In case 37, for QC, $\Delta Z_m/\Delta W = 38$ m/10^6 g/sec and $\Delta\chi_{10}/\Delta W = 0.30$ ppm/10^6 g/sec; hence, $\Delta\chi_{10}/\Delta Z_m = 0.79$ ppm/100 m. For HEATN, $\Delta Z_m/\Delta H = 31$ m/500 J/g (26 m/100 cal/g) and $\Delta\chi_{10}/\Delta H = -0.13$ ppm/500 J/g (-0.11 ppm/100 cal/g); hence, $\Delta\chi_{10}/\Delta Z_m = -0.42$ ppm/100 m. In case 51, for HEATN, $\Delta Z_m/\Delta H = 10.8$ m/500 J/g (9 m/100 cal/g) and $\Delta\chi_{10}/\Delta H = -0.048$ ppm/500 J/g (-0.04 ppm/100 cal/g); hence, $\Delta\chi_{10}/\Delta Z_m = -0.44$ ppm/100 m.

The usefulness of these values for extrapolation to other situations is limited, as discussed earlier, because the stability parameter s changes rapidly with height and from case to case. However, since these ratios will be large compared to ratios in other situations, these values could be useful in defining the results expected in the more extreme cases. With these limitations in mind, it is possible to draw the following conclusions.

1. For a 100-m (328 ft) change in stabilization height, the magnitude of the HCl concentration change is twice as large if it results from changes in the Space Shuttle parameter QC than if it results from changes in HEATN.

2. Despite significant differences in concentration exhibited in figure 5, the change in concentration with cloud stabilization height is remarkably similar (-0.42 and -0.44 ppm/100 m for cases 37 and 51, respectively) because of the similarity of their stability profiles, both of which contain an upper level inversion.

Changes in Cloud Stabilization Height and Average Stability

As noted previously, changes in cloud stabilization height cannot be inferred from equation (5), primarily because of the effect of changes in stability s. When the stability characteristics are similar (as in cases 37 and 51), the changes in concentration predicted by the MDM are remarkably similar for a given change in Z_m. Figure 6 shows the relation between stability and cloud rise in more detail.

Figure 6 ranks the 20 cases in table II according to their initial cloud stabilization height (i.e., Z_m is shown by the solid line) for the Space Shuttle parameter HEATN = 4184 J/g (1000 cal/g). The average virtual potential temperature gradient between surface and cloud stabilization height, DPDZ = $\bar{s}$, is represented for the cases by a dashed line. The change in Z_m, ΔZ_m, produced by increasing the Space Shuttle parameter HEATN to 8368 J/g (2000 cal/g), is represented by the bar on the left just above the case number. The corresponding change in $\bar{s}$ is represented by the bar on the right. (Decreases are represented by shaded bars.) The ΔZ_m and $\bar{s}$ are not given for case 44, because the parameter HEATN = 8368 J/g (2000 cal/g) caused the cloud to stabilize above the highest level of meteorological data given.

Conclusions derived from figure 6 are the following.

1. The inverse relationship expected from equation (3), $Z_m \propto \bar{s}^{-1/4}$, is apparent. Over the range of cases tested here, $\bar{s}$ decreases by a factor of 15 and Z_m by a factor of 2.

2. All the cases (cases 37, 50, 31, 19, 1, 32, 52, 47, 48, 18, and 46) for which ΔZ_m is greater than 200 m (656 ft) have either negative or very small changes in $\bar{s}$ (less than 0.04×10^{-2} K/m). Case 50 is an exception to this rule. This behavior is reasonable when one considers that a decrease or small change in $\bar{s}$ means that the stability of the atmosphere is decreasing with height or remaining relatively constant. Thus, cloud rise in this region is not inhibited as it would be in the case of large increases in $\bar{s}$.

3. Increases in $\bar{s}$ mean that atmospheric stability is increasing as it would when the cloud enters an inversion region. Cases 51 and 43 best exemplify this condition, in which the change in the average $\bar{s}$, $\Delta\bar{s}$, is greater than 0.1 x 10^{-2} K/m and the change in cloud rise is less than 100 m (328 ft). Case 50 is again an exception.

4. The contributions to the fractional changes in Z_m, $\Delta Z_m/Z_m$, between changes in the Space Shuttle parameter HEATN and the average stability $\bar{s}$, $\Delta\bar{s}/\bar{s}$, for some selected cases are summarized in table XII. The data indicate that changes in stability with height may contribute to the change in cloud stabilization height up to one-half or more of that caused by changes in the Space Shuttle parameter HEATN.

COMBINED EFFECT OF CHANGING ALL SPACE SHUTTLE PARAMETERS

The first part of table XIII summarizes the Space Shuttle parameter changes and their effects on the MDM predictions of surface HCl concentrations. The values are all for case 37. The last part of the table provides the MDM predictions of χ_{10} for cases 37 and 51 using the original parameters (ref. 1) and all the Space Shuttle parameters that maximize MDM predictions of HCl. Note that to obtain the largest concentrations, one must choose the largest value used for the parameter QC but the smallest from that used for HEATN. The combined effect of these changes on χ_{10} is 47 percent for case 37 and 56 percent for case 51.

Table XIV summarizes the MDM predictions, using the original Space Shuttle parameters, for maximum surface concentrations for 19 of the 20 cases studied. It is clear from examining the values of χ_{10} in this table that increases on the order of 50 percent will not cause the majority of cases to approach the 4-ppm STPL for HCl. Only cases similar to 37, which has a type of meteorology that has been shown to have a low probability of occurrence,[1] are likely to exceed this limit.

CONCLUSIONS

The conclusions relating to surface concentrations of HCl reached in this study are derived primarily from case 37, a meteorological case known to produce relatively large surface concentrations. An additional 19 cases were used with studies on cloud stabilization height changes.

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[1] Glasser, M. E.; and Siler, R. K.: Diffusion Estimates for Space Shuttle Launches From KSC. Rep. JSC-12507, Feb. 1977.

Cloud Rise Parameters

The conclusions relating to cloud rise parameters (AA, BB, CC) are as follows.

1. The difference in values predicted by the MDM using different rise parameters for the Space Shuttle for the maximum 10-minute surface concentration of HCl was 7 percent. This change is small enough to be negligible in comparison to other uncertainties in MDM predictions.

2. If one assumes the 1976 JPL design data with mission 3A for the rise time, the rise parameters AA and BB given in version 5 of the MDM yield the better fit.

Mass Fraction of HCl in the Plume

The conclusions as to mass fraction of HCl in the plume (FRQ) are as follows.

1. A 5-percent change in the mass fraction parameter for HCl (FRQ) produced a 5-percent change in all the surface concentration and dosage predictions of the MDM.

2. If one uses the 1976 JPL design data, the FRQ parameter for the Space Shuttle should be 0.209 instead of the original value of 0.207.

Mass Flow Rate

The following conclusions were reached with regard to mass flow rate (QC).

1. An increase in the mass flow rate parameter for the Space Shuttle (QC) has the expected effect of increasing the cloud stabilization height because of the added thermal buoyancy of the ground launch cloud.

2. An average increase in cloud stabilization height of 32 m (105 ft) for every 10^6-g/sec increase in the Space Shuttle parameter QC was obtained for the 20 cases tested.

3. Error analyses suggesting that any fractional change in the total heat content of the launch cloud will produce a fractional change of one-fourth that amount in the stabilization height are shown to be incorrect both in theory and in practice. They are incorrect because other factors, primarily the stability factor (i.e., the gradient of virtual potential temperature), also vary with height.

4. Increases in the Space Shuttle parameter QC increase the maximum 10-minute time average concentration χ_{10} by 0.3 ppm for each 10^6-g/sec change in mass flow rate. This result indicates that the tendency to increase concentrations because of the added pollution source strength

outweighs the tendency to reduce concentrations because of the higher cloud stabilization.

5. If one uses JPL 1976 design data and assumes a mission type 3A, a reasonable value for the Space Shuttle parameter QC is 10.8×10^6 g/sec.

6. The increases in HCl concentrations predicted by the MDM are nearly linear and reasonably small and should not increase predictions above the short-term public limit for public safety, unless the concentrations predicted with the original MDM parameters are already close to these levels. A 55-percent increase in QC results in a 34-percent increase in χ_{10}.

Fuel Heat Content

The conclusions relating to fuel heat content (HEATN) are as follows.

1. Increases in the HEATN parameter, which accounts for the effective heat content of the Space Shuttle fuel, produce an average increase of 22 m (72 ft) in cloud stabilization height for each 418.4-J/g (100 cal/g) change.

2. The change in concentrations predicted by the MDM for changes in HEATN is nearly linear.

3. A 100-percent increase in HEATN produces a 21-percent increase in χ_{10} for case 37 and a 25-percent increase in χ_{10} for case 51.

4. Increasing the cloud stabilization height 100 m by increasing QC results in increasing χ_{10} by 0.79 ppm. However, increasing the cloud stabilization height 100 m by increasing HEATN results in decreasing χ_{10} by 0.44 ppm.

Atmospheric Stability Parameter

With regard to the atmospheric stability parameter $\bar{s}$, Z_m increases by 200 m (656 ft) or more in cases for which the average stability change for the layer below cloud stabilization is negative or nearly zero. However, the change in Z_m will be less than 100 m for the same Space Shuttle parameter when $\Delta\bar{s}$ is greater than 0.1×10^{-2} K/m.

Deluge Water

The following conclusions were reached with regard to deluge water.

1. The evaluation of assumptions important in affecting the value for the HEATN parameter as given by Hwang and Gould will reduce the heat content of the launch cloud by about 20 percent, or an equivalent of 2406 J/g (575 cal/g), resulting in a value of HEATN = 9623 J/g (2300 cal/g).

2. A reduction of HEATN of 2406 J/g (575 cal/g) would

a. Decrease the cloud height by about 2406 J/g x 26 m/500 J/g (575 cal/g x 22 m/100 cal/g), or 126 m (413 ft) for the average case.

b. Increase the maximum 10-minute average concentration χ_{10} by 126 m x 0.44 ppm/100 m, or 0.55 ppm for case 37 and about the same for case 51.

Overall, the following conclusions apply.

1. Any likely changes that will occur in the rise time and HCl mass fraction parameters will have a negligible effect on MDM concentration predictions.

2. The largest change in MDM predictions for χ_{10} values in the literature for HEATN and QC parameters is likely to be 25 and 34 percent, respectively, and about 50 percent for their combined effect.

3. Any changes in the MDM predictions of HCl because of changes in the Space Shuttle input parameters considered here are small enough as to be negligible in comparison to the other uncertainties such as meteorological inputs and the limitation of the model itself.

4. Any likely changes in the Space Shuttle launch parameters, including the deluge water for the acoustic water sound system, will not substantially increase the number of meteorological cases for which the MDM will predict surface HCl concentrations exceeding public safety levels.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, July 26, 1978
953-36-00-00-72

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TABLE I.- FACTORS AFFECTING A NORMAL SPACE SHUTTLE LAUNCH AND THE CORRESPONDING MDM INPUT PARAMETERS

Factor	Comments	MDM input parameter affected
	Meteorological parameters	
Windspeed Wind direction Temperature Pressure Relative humidity	These factors are entered as a function of altitude as obtained from rawinsonde data.	
Surface density		
Standard deviation of horizontal wind direction		
Precipitation		
	Space Shuttle parameters	
Rate of mass flow for the solid rocket booster (SRB)		QC
Rate of mass flow for the main engine		HEATN
Heat content of fuel for the SRB		HEATN
Heat content of fuel for the main engine		HEATN
Rise parameters	Time = a $(\text{altitude})^b$ + c	
a b c	The coefficients a, b, and c are determined from a least-squares fit for the rise time.	AA BB CC
Fractional content of HCl in SRB fuel	This is the mass X fraction at nozzle exit plane of the gaseous HCl.	FRQ
Mission type	The main differences expected here are in trajectory types.	AA, BB, CC

TABLE I.- Concluded

Factor	Comments	MDM input parameter affected
	External factors	
Deluge water	New design considerations use additional deluge water for an acoustic water sound system (AWSS).	HEATN
Afterburning	CO is of primary interest.	HEATN
Entrainment	Entrainment allows expansion of the launch cloud because of mixing of air into it by turbulence.	γ
Radiation		HEATN
Species interaction	HCl combines with aerosols and with aluminum particles. The amount of their interaction is not well known.	FRQ
Surface interaction of HCl	The present version of the MDM assumes HCl to be totally reflected at the top and bottom of the planetary boundary layers. A more realistic approach would allow for a depletion parameter, γ_p.	γ_p

TABLE II.- CASES USED AS METEOROLOGICAL INPUT INTO THE PREPROCESSOR OF VERSION 5 OF THE MDM[a]

Case no.	Comment	Date
1	Titan lift-off	May 30, 1974
17	Average fall at KSC	
18	Average spring at KSC	
19	Average sea breeze at KSC	
31	Cold front north of KSC	Oct. 19, 1972
32	Cold front near KSC	Oct. 20, 1972
[b]37	KSC	Nov. 25, 1965
39	Stationary front south of KSC	
40	Fair weather, high pressure at KSC	
43	Cold front south of KSC	Nov. 26, 1972
44	Titan III lift-off at KSC	Dec. 13, 1973
45	Titan III lift-off at KSC	Feb. 11, 1974
46	Titan III lift-off at KSC	May 20, 1975
47	Titan III lift-off at KSC	Aug. 20, 1975
48	Titan III lift-off at KSC	Sept. 9, 1975
49	Average morning at VAFB	
50	Average sea breeze, low inversion at VAFB	
51	Average sea breeze, high inversion at VAFB	
52	Stationary upper level trough west of VAFB	Oct. 10, 1972
Ex	Example, cold front south of KSC	Oct. 21, 1972

[a] Except as noted, all data in the baseline meteorological soundings are taken from reference 2.

[b] This case is taken from hand-plotted soundings for 12:00 Greenwich mean time.

TABLE III.- EFFECT OF CHANGES IN RISE PARAMETERS ON MDM CONCENTRATIONS FOR CASE 37

(a) Rise parameters

Reference	AA	BB
1	0.663552	0.485477
3	.652213	.518422

(b) HCl predictions by the MDM

Parameter	From		Percent change
	Ref. 1	Ref. 3	
X_c, ppm	5.60	5.53	-1
X_{10}, ppm	3.29	3.52	7
Dose, ppm-sec	1972	2126	3

TABLE IV.- RISE TIME, ALTITUDE, AND MASS FLOW DATA FROM SRB OF SPACE SHUTTLE USING 1976 JPL DESIGN DATA

[Adapted from reference 4, p. A-101]

Rise time, sec	Altitude z, km	z − 0.056 km, km	Rise time, sec		SRB mass flow, kg/sec (lb/sec)	Total mass exhausted, kg (lb)		Average mass flow, g/sec (lb/sec) (a)	
			From ref. 3	From ref. 1					
0	0.056	0			7 005 (15 411)				
2	.062	0.006			10 332 (22 730)	$17.84\text{x}10^{3}$	($39.25\text{x}10^{3}$)	$8.920\text{x}10^{6}$	($19.66\text{x}10^{3}$)
4	.088	.032			10 569 (23 252)	38.75	(85.25)	9.688	(21.36)
6	.136	.080	6.3	5.7	10 800 (23 760)	60.13	(132.29)	10.022	(22.09)
8	.208	.152	8.8	7.6	10 924 (24 033)	81.85	(180.07)	10.231	(22.56)
10	.305	.249	11.4	10.5	11 004 (24 209)	103.78	(228.32)	10.378	(22.88)
12	.429	.373	14.0	11.8	11 078 (24 372)	125.87	(276.91)	10.489	(23.12)
14	.580	.524	16.8	13.9	11 152 (24 534)	148.10	(325.82)	10.579	(23.32)
16	.760	.704	19.5	16.0	11 224 (24 693)	170.48	(375.06)	10.655	(23.49)
18	.969	.913	22.3	18.2	11 289 (24 836)	192.99	(425.58)	10.722	(23.64)
20	1.209	1.153	25.0	20.3	11 313 (24 889)	215.59	(474.30)	10.780	(23.77)
22	1.480	1.424	28.1	22.5	11 037 (24 281)	237.95	(523.49)	10.816	(23.84)
24	1.781	1.725			10 490 (23 078)	259.47	(570.83)	10.811	(23.83)
26	2.110	2.054			10 195 (22 429)	280.15	(616.33)	10.775	(23.75)
28	2.465	2.409			9 938 (21 864)	300.28	(660.62)	10.724	(23.64)
30	2.845	2.789			9 704 (21 349)	319.92	(703.82)	10.664	(23.51)

[a] Total mass exhausted divided by rise time.

TABLE V.- EFFECT OF CHANGES IN THE HCl MASS FRACTION PARAMETER ON THE MDM CONCENTRATION PREDICTIONS FOR CASE 37

(a) Concentration and dosage predictions

Reference	Fraction by weight at nozzle exit plane (FRQ)	HCl predictions by MDM		
		χ_c, ppm	χ_{10}, ppm	Dose, ppm-sec
3	0.197	5.33	3.13	1877
1	.207	5.60	3.29	1972
4 and 5	.209	--	--	--

(b) Percent increase

[From ref. 1]

Parameter	Percent increase
FRQ	5
χ_c	5
χ_{10}	5
Dose	5

TABLE VI.- QC VALUES FOR THE SRB's

QC, g/sec (lb/sec)		Reference (a)	Comment
9.315×10^6	(20.54×10^3)	5	[b]Mission 3B
9.385	(20.69)	1	Original parameters in MDM version 5, 1975
9.451	(20.84)	5	[c]Mission 2
10.352	(22.82)	4	[d]Mission 1
10.8	(23.81)	4	[d]Mission 3A
13.766	(30.35)	6	Workshop on May 17 to 18, 1976
15.219	(33.55)	[e]7	Used in low-altitude plume program

[a] The references cited in this table do not necessarily represent the first use of the particular mass flow value, nor do they represent the only reference in which these values appear.

[b] This comment is from table I of reference 5 (i.e., for mission 3B), which indicates that the flow rate is constant at 9315.15 kg/sec (20 536.41 lb/sec) flow launch for the first 28 seconds.

[c] This comment is from table I of reference 5 (i.e., for mission 2), which indicates that the flow is between 9443.59 kg/sec (20 819.57 lb/sec) at 0 second and 9458.63 kg/sec (20 852.73 lb/sec) at 27.6 seconds. The value presented assumes a constant rate of 9451.11 kg/sec (20 836.15 lb/sec) averaged between the two values.

[d] These values represent the time average flow rate over the first 22 seconds after firing. The values were obtained by dividing the total time elapsed into the total mass emitted. (See table IV for mission 3A.)

[e] This rate was also used by Hans Rudolph (private communication, July 1977.)

TABLE VII.- EFFECT OF CHANGES IN SRB MASS FLOW RATE W ON PREDICTIONS OF CLOUD STABILIZATION HEIGHT Z_m FOR 20 CASES[a]

Parameter	Average		Range	
	First increment	Second increment	First increment	Second increment
SRB mass flow rate, g/sec (lb/sec)				
W_1	12×10^6 (26.46×10^3)	15×10^6 (33.07×10^3)	--	--
W_0	9×10^6 (19.84×10^3)	12×10^6 (26.46×10^3)	--	--
[b]ΔW	3×10^6 (6.61×10^3)	3×10^6 (6.61×10^3)	--	--
$\Delta W / W_0 \times 100$, percent	33	25	--	--
Cloud stabilization height, m (ft)				
Z_{m1}	1420 (4658)	1507 (4943)	--	--
Z_{m0}	1314 (4310)	1420 (4658)	--	--
[c]ΔZ_m	106 (348)	87 (285)	[d]186 (610) to [e]73 (239)	[f]117 (384) to [g]51 (167)
$\Delta Z_m / Z_{m0} \times 100$, percent . . .	8.1	6.1	--	--
$\Delta Z_m / Z_m \times 100$, percent . . .	--	--	[d]15 to [e]4.1	[f]6.4 to [g]4.7

[a] See figure 2.
[b] $\Delta W = W_1 - W_0$.
[c] $\Delta Z_m = Z_{m1} - Z_{m0}$.
[d] Case 1.
[e] Case Ex.
[f] Case 46.
[g] Case 51.

TABLE VIII.- EFFECT OF CHANGES IN SRB MASS FLOW RATE W ON MDM PREDICTIONS OF MAXIMUM SURFACE CONCENTRATIONS AND DOSAGES OF HCl FOR CASE 37[a]

Parameter	Average	
	First increment	Second increment
SRB mass flow rate, g/sec (lb/sec)		
W_1	12×10^6 (26.46×10^3)	15×10^6 (33.07×10^3)
W_0	9×10^6 (19.84×10^3)	12×10^6 (26.46×10^3)
[b]ΔW	3×10^6 (6.61×10^3)	3×10^6 (6.61×10^3)
$\Delta W/W_0 \times 100$, percent	33	25
Max. centerline HCl concentration, ppm		
χ_{c1}	10.03	10.26
χ_{c0}	9.22	10.03
[c]$\Delta\chi_c$	0.81	0.23
$\Delta\chi_c/\chi_{c0} \times 100$, percent	8.8	2.3
Max. 10-min average HCl concentration, ppm		
$\chi_{10(1)}$	5.45	5.94
$\chi_{10(0)}$	4.44	5.45
[d]$\Delta\chi_{10}$	1.01	0.49
$\Delta\chi_{10}/\chi_{10(0)} \times 100$, percent	23	9
Max. dosage, ppm-sec		
Dose_1	3272	3561
Dose_0	2666	3272
[e]Δdose	606	289
$\Delta\text{dose}/\text{dose}_0 \times 100$, percent	23	8.8

[a] See figure 3.

[b] $\Delta W = W_1 - W_0$.

[c] $\Delta\chi_c = \chi_{c1} - \chi_{c0}$.

[d] $\Delta\chi_{10} = \chi_{10(1)} - \chi_{10(0)}$.

[e] $\Delta\text{dose} = \text{dose}_1 - \text{dose}_0$.

TABLE IX.- SUMMARY OF VALUES FROM LITERATURE FOR THE SPACE SHUTTLE FUEL EQUIVALENT HEAT CONTENT (HEATN = H) AND THE ATTENDANT ASSUMPTIONS ON AFTERBURNING, AWSS, AND RADIATION LOSS

HEATN, J/g (cal/g)		Afterburning	AWSS	Radiation	Reference	Comment
Effective (total)	Actual (SRB main engine)					
6 191.1 (1479.7)	--	Yes	Yes	Yes	(a)	AWSS one-half evaporated; one-half raised to boiling point.
8 889.7 (2124.7)	--	Yes	No	--	6	--
9 623.2 (2300)	11 911.8 (2847)	Yes	Yes	Yes	8	Radiation loss negligible; AWSS, complete evaporation.
10 803.1 (2582)	10 460.0 (2500)	No	No	No	1	Although 2092 J/g (500 cal/g) is discussed in ref. 1, a value equivalent to 2887 J/g (690 cal/g) is actually used.

[a] Hans Rudolph, private communication, July 1977.

TABLE X.- EFFECT OF CHANGES IN EQUIVALENT FUEL HEAT CONTENT H ON PREDICTIONS OF CLOUD STABILIZATION HEIGHT Z_m FOR 20 CASES[a]

Parameter	Average		Range	
	First increment	Second increment	First increment	Second increment
Equivalent fuel heat content, J/g (cal/g)				
H_1	6276 (1500)	8368 (2000)	--	--
H_0	4184 (1000)	6276 (1500)	--	--
[b]ΔH	2092 (500)	2092 (500)	--	--
$\Delta H/H_0$ x 100, percent	50	33	--	--
Cloud stabilization height, m (ft)				
Z_{m1}	1271 (4169)	1369 (4490)	--	--
Z_{m0}	1149 (3769)	1271 (4169)	--	--
[c]ΔZ_m	122 (400)	98 (322)	[d]278 (912) to [e]30 (98)	[f]156 (511) to [g]43 (141)
$\Delta Z_m/Z_{m0}$ x 100, percent	10.6	7.7	--	--
$\Delta Z_m/Z_m$ x 100, percent	--	--	[d]23 to [e]3	[f]13 to [g]4

[a] See figure 4.

[b] $\Delta H = H_1 - H_0$.

[c] $\Delta Z_m = Z_{m1} - Z_{m0}$.

[d] Case 44.

[e] Case 51.

[f] Case 1.

[g] Case 43.

TABLE XI.- EFFECT OF CHANGES IN EQUIVALENT FUEL HEAT CONTENT H ON MDM PREDICTIONS OF MAXIMUM SURFACE CONCENTRATIONS AND DOSAGES OF HCl FOR TWO CASES[a]

Parameter	Average	
	First increment	Second increment
Case 37		
Equivalent fuel heat content, J/g (cal/g)		
H_1	6276 (1500)	8368 (2000)
H_0	4184 (1000)	6276 (1500)
[b]ΔH	2092 (500)	2092 (500)
$\Delta H/H_0 \times 100$, percent	50	33
Max. centerline HCl concentration, ppm		
χ_{c1}	8.96	6.94
χ_{c0}	11.7	8.96
[c]$\Delta\chi_c$	-2.74	-2.02
$\Delta\chi_c/\chi_{c0} \times 100$, percent	-23	-23
Max. 10-minute average HCl concentration, ppm		
$\chi_{10(1)}$	4.82	4.19
$\chi_{10(0)}$	5.31	4.82
[d]$\Delta\chi_{10}$	-0.49	-0.63
$\Delta\chi_{10}/\chi_{10(0)} \times 100$, percent	-9.2	-13
Max. dosage, ppm-sec		
$Dose_1$	2892	2515
$Dose_0$	3188	2892
[e]$\Delta dose$	-296	-377
$\Delta dose/dose_0 \times 100$, percent	-9.3	-13

[a] See figure 5.
[b] $\Delta H = H_1 - H_0$.
[c] $\Delta\chi_c = \chi_{c1} - \chi_{c0}$.
[d] $\Delta\chi_{10} = \chi_{10(1)} - \chi_{10(0)}$.
[e] $\Delta dose = dose_1 - dose_0$.

TABLE XI.- Concluded[a]

Parameter	Average	
	First increment	Second increment
	Case 51	
Equivalent fuel heat content, J/g (cal/g)		
H_1	6276 (1500)	8368 (2000)
H_0	4184 (1000)	6276 (1500)
[b]ΔH	2092 (500)	2092 (500)
$\Delta H/H_0$ x 100, percent	50	33
Max. centerline HCl concentration, ppm		
χ_{c1}	2.91	2.30
χ_{c0}	3.30	2.91
[c]$\Delta \chi_c$	-0.39	-0.61
$\Delta \chi_c/\chi_{c0}$ x 100, percent	-12	-21
Max. 10-minute average HCl concentration, ppm		
$\chi_{10(1)}$	1.50	1.24
$\chi_{10(0)}$	1.65	1.50
[d]$\Delta \chi_{10}$	-0.15	-0.26
$\Delta \chi_{10}/\chi_{10(0)}$ x 100, percent	-9	-17
Max. dosage, ppm-sec		
Dose_1	912	763
Dose_0	1003	912
[e]Δdose	-91	-149
$\Delta \text{dose}/\text{dose}_0$ x 100, percent	-9	-16

[a] See figure 5.

[b] $\Delta H = H_1 - H_0$.

[c] $\Delta \chi_c = \chi_{c1} - \chi_{c0}$.

[d] $\Delta \chi_{10} = \chi_{10(1)} - \chi_{10(0)}$.

[e] $\Delta \text{dose} = \text{dose}_1 - \text{dose}_0$.

TABLE XII.- CONTRIBUTIONS TO THE FRACTIONAL CHANGES IN Z_m, $\Delta Z_m/Z_m$, BETWEEN CHANGES IN THE SHUTTLE PARAMETER HEATN AND THE AVERAGE STABILITY $\bar{s}$

Case	$\Delta Z_m/Z_m$	$1/4 \Delta W/W$	$1/4 \Delta\bar{s}/\bar{s}$
51	0.09	0.25	-0.13
43	.10	.25	-.11
Ex	.06	.25	-.17
37	.33	.25	-.07

TABLE XIII.- SPACE SHUTTLE PARAMETER CHANGES

(a) Effects of changes on MDM predictions of maximum HCl surface concentrations for case 37

Parameter	Change		Prediction
	From	To	
AA	0.663552	0.652213	--
BB	0.485477	0.518422	--
$\Delta\chi_c$, ppm	--	--	-0.07
$\Delta\chi_c/\chi_c \times 100$, percent	--	--	-1
$\Delta\chi_{10}$, ppm	--	--	0.23
$\Delta\chi_{10}/\chi_{10} \times 100$, percent	--	--	7
Δdose, ppm-sec	--	--	156
Δdose/dose x 100, percent	--	--	3
FRQ	0.197	0.207	--
$\Delta\chi_c$, ppm	--	--	0.27
$\Delta\chi_c/\chi_c \times 100$, percent	--	--	5
$\Delta\chi_{10}$, ppm	--	--	0.16
$\Delta\chi_{10}/\chi_{10} \times 100$, percent	--	--	5
Δdose, ppm-sec	--	--	95
Δdose/dose x 100, percent	--	--	5
QC, g/sec	9×10^6	14×10^6	--
$\Delta\chi_c$, ppm	--	--	1.04
$\Delta\chi_c/\chi_c \times 100$, percent	--	--	11
$\Delta\chi_{10}$, ppm	--	--	1.50
$\Delta\chi_{10}/\chi_{10} \times 100$, percent	--	--	34
Δdose, ppm-sec	--	--	895
Δdose/dose x 100, percent	--	--	34
HEATN, J/g (cal/g)	8368 (2000)	4184 (1000)	--
$\Delta\chi_c$, ppm	--	--	4.76
$\Delta\chi_c/\chi_c \times 100$, percent	--	--	68
$\Delta\chi_{10}$, ppm	--	--	1.12
$\Delta\chi_{10}/\chi_{10} \times 100$, percent	--	--	27
Δdose, ppm-sec	--	--	673
Δdose/dose x 100, percent	--	--	27

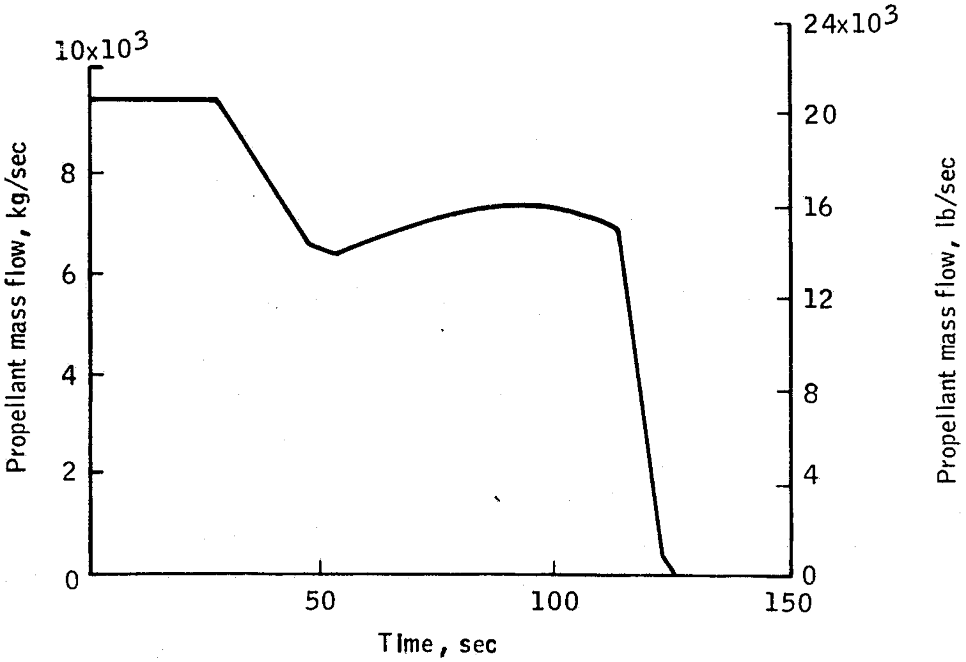
TABLE XIII.- Concluded

(b) Effects of changes from original to worst-case values on MDM predictions of maximum HCl surface concentrations

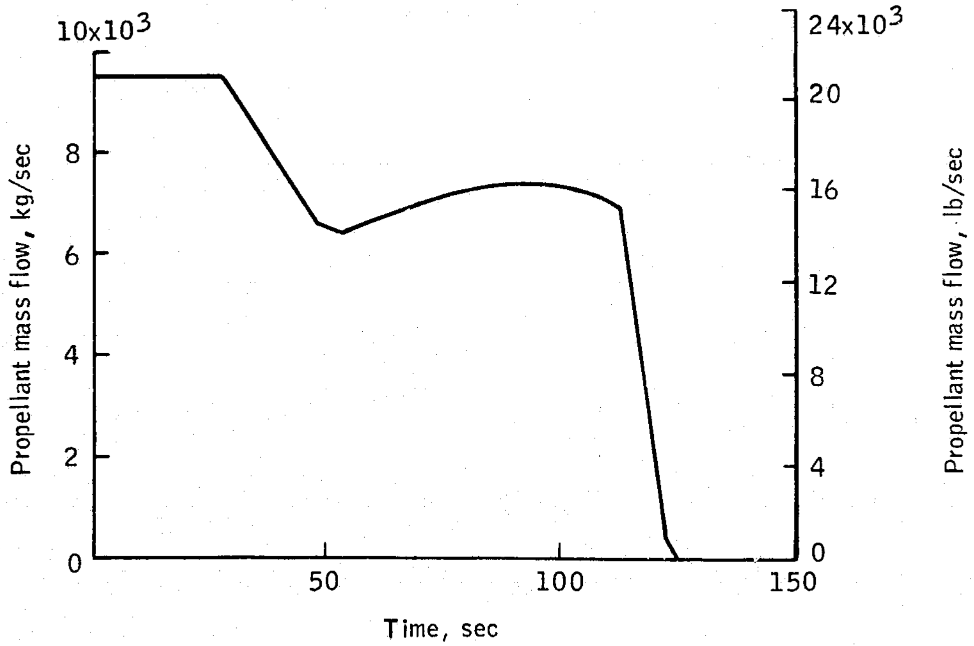
Parameter	Change		Prediction	
	From	To	From	To
AA	0.663552	0.652213	--	--
BB	0.485477	0.468085	--	--
FRQ	0.207	0.207	--	--
QC, g/sec	9.385×10^6	15.219×10^6	--	--
HEATN, J/g (cal/g)	10 803 (2582)	6191.1 (1479.7)	--	--
Case 37 χ_{10}, ppm	--	--	3.29	4.84
Case 37 $\Delta\chi_{10}$, ppm	--	--	--	1.55
Case 37 $\Delta\chi_{10}/\chi_{10} \times 100$, percent	--	--	--	47
Case 51 χ_{10}, ppm	--	--	0.99	1.54
Case 51 $\Delta\chi_{10}$, ppm	--	--	--	0.55
Case 51 $\Delta\chi_{10}/\chi_{10} \times 100$, percent	--	--	--	56

TABLE XIV.- MDM PREDICTIONS OF MAXIMUM SURFACE HCl CONCENTRATIONS FOR 20 CASES LISTED IN TABLE II

Case	Original Space Shuttle parameter		
	Z_m, m	χ_c, ppm	χ_{10}, ppm
1	1090	0.62	0.12
17	1654	.54	.90
18	2099	.21	.08
19	1136	.44	.10
31	1255	.37	.18
32	1619	.23	.04
37	1027	5.60	3.29
39	1530	.69	.54
40	990	.48	.20
43	933	1.48	.26
44	1085	.64	.12
45	1133	.60	.15
46	1406	.32	.23
47	1149	1.53	.91
48	1293	.77	.48
49	782	.99	.21
50	757	.44	.10
51	1040	1.86	.99
52	1430	--	--
Ex	1730	.45	.11

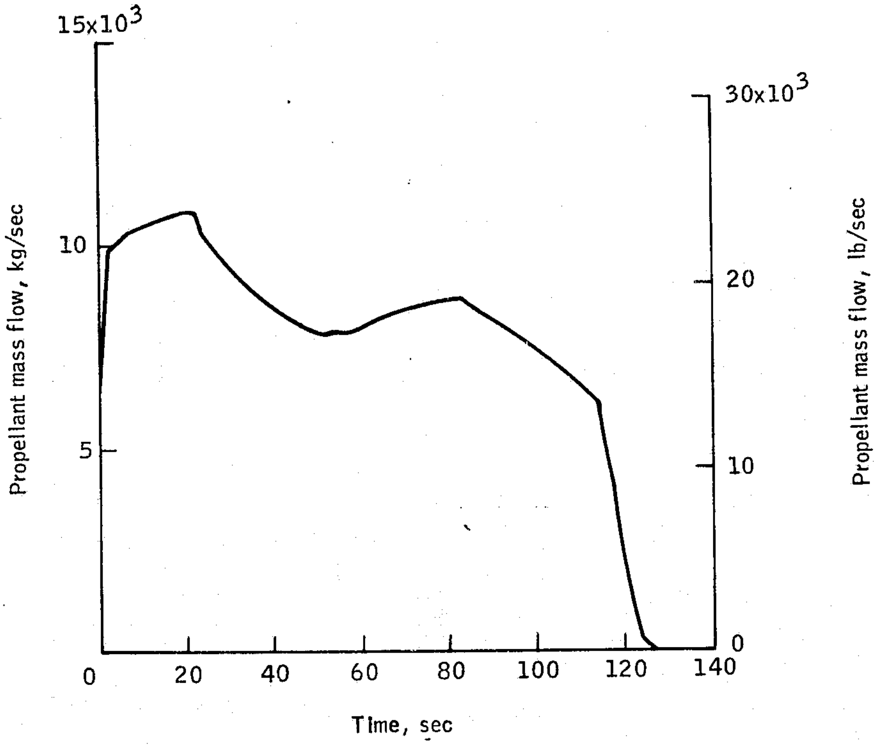


(a) For mission 3B using JPL 1973 Space Shuttle design data (ref. 5).

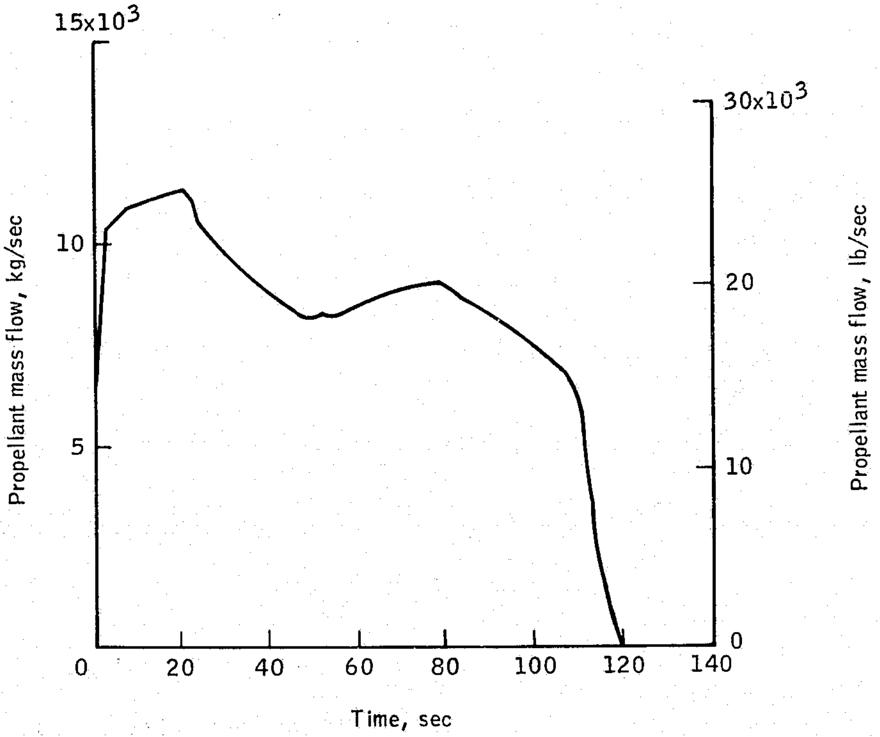


(b) For mission 2 using JPL 1973 Space Shuttle design data (ref. 5).

Figure 1.- Propellant mass flow (SRB's only).

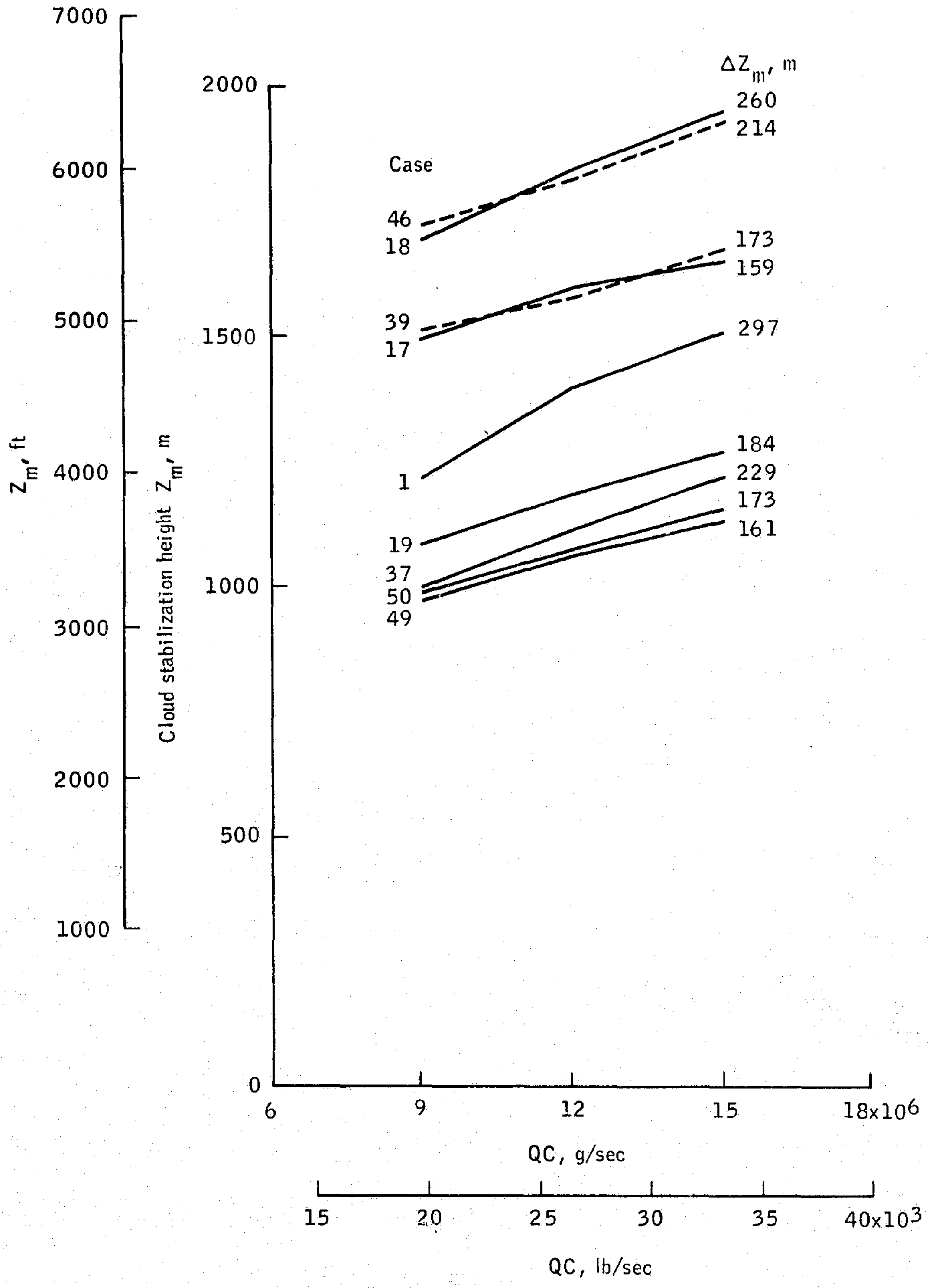


(c) For mission 3A using JPL 1976 Space Shuttle design data (ref. 4).



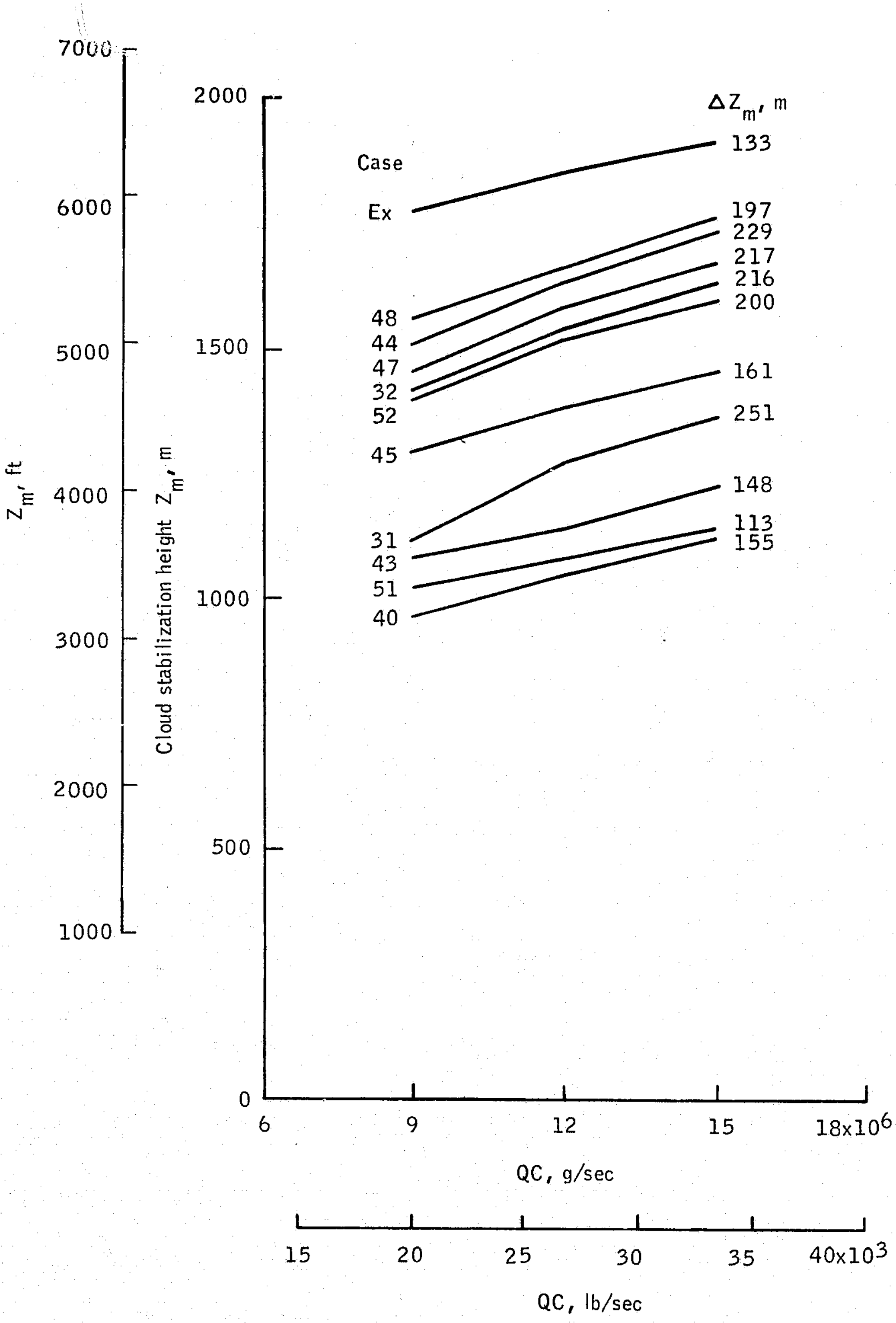
(d) For mission 1 using JPL 1976 Space Shuttle design data (ref. 4).

Figure 1.- Concluded.



(a) For cases 46, 18, 39, 17, 1, 19, 37, 50, and 49.

Figure 2.- Effect of changes in the Space Shuttle parameter QC on the MDM predictions of cloud stabilization height.



(b) For cases Ex, 48, 44, 47, 32, 52, 45, 31, 43, 51, and 40.

Figure 2.- Concluded.

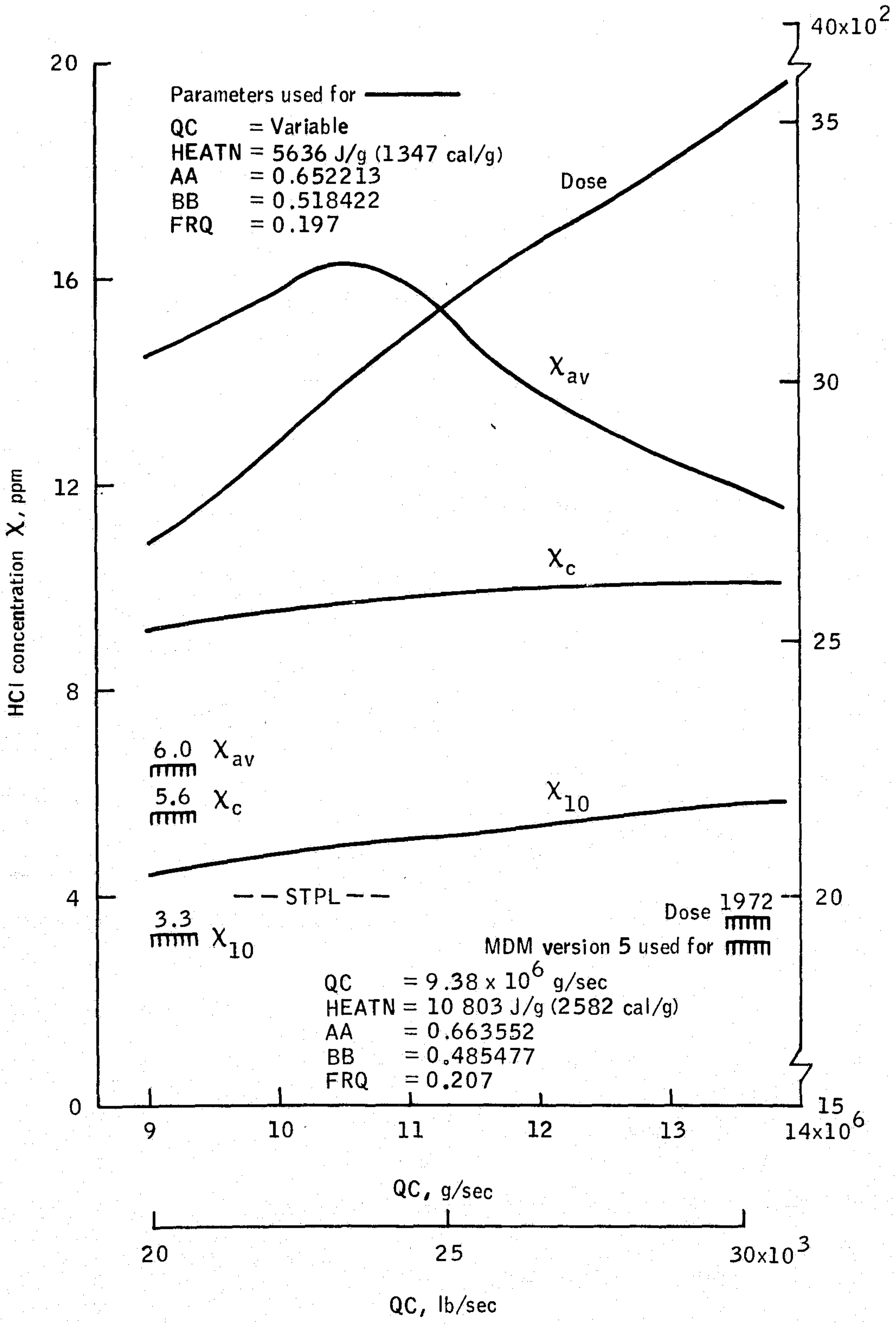
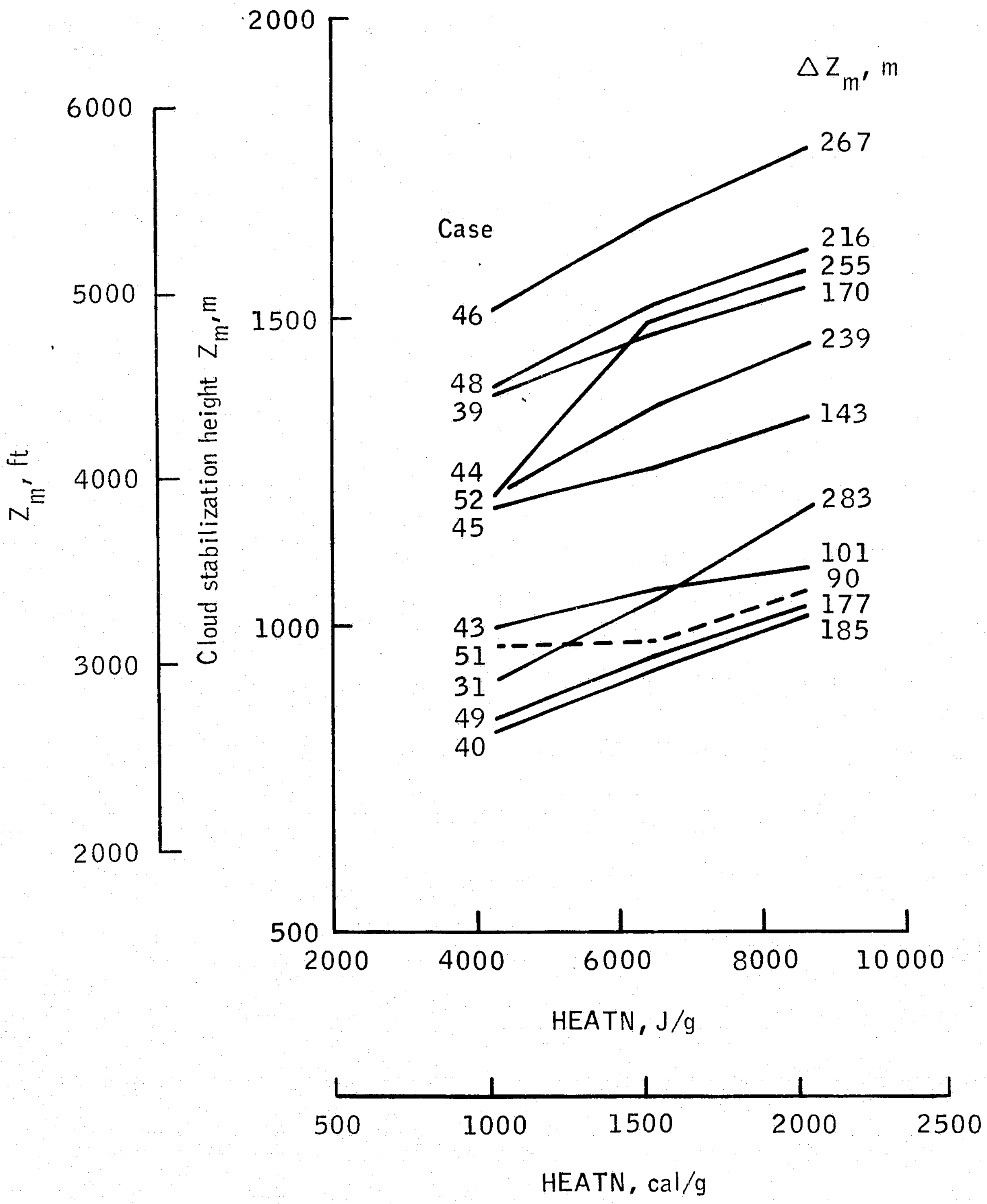
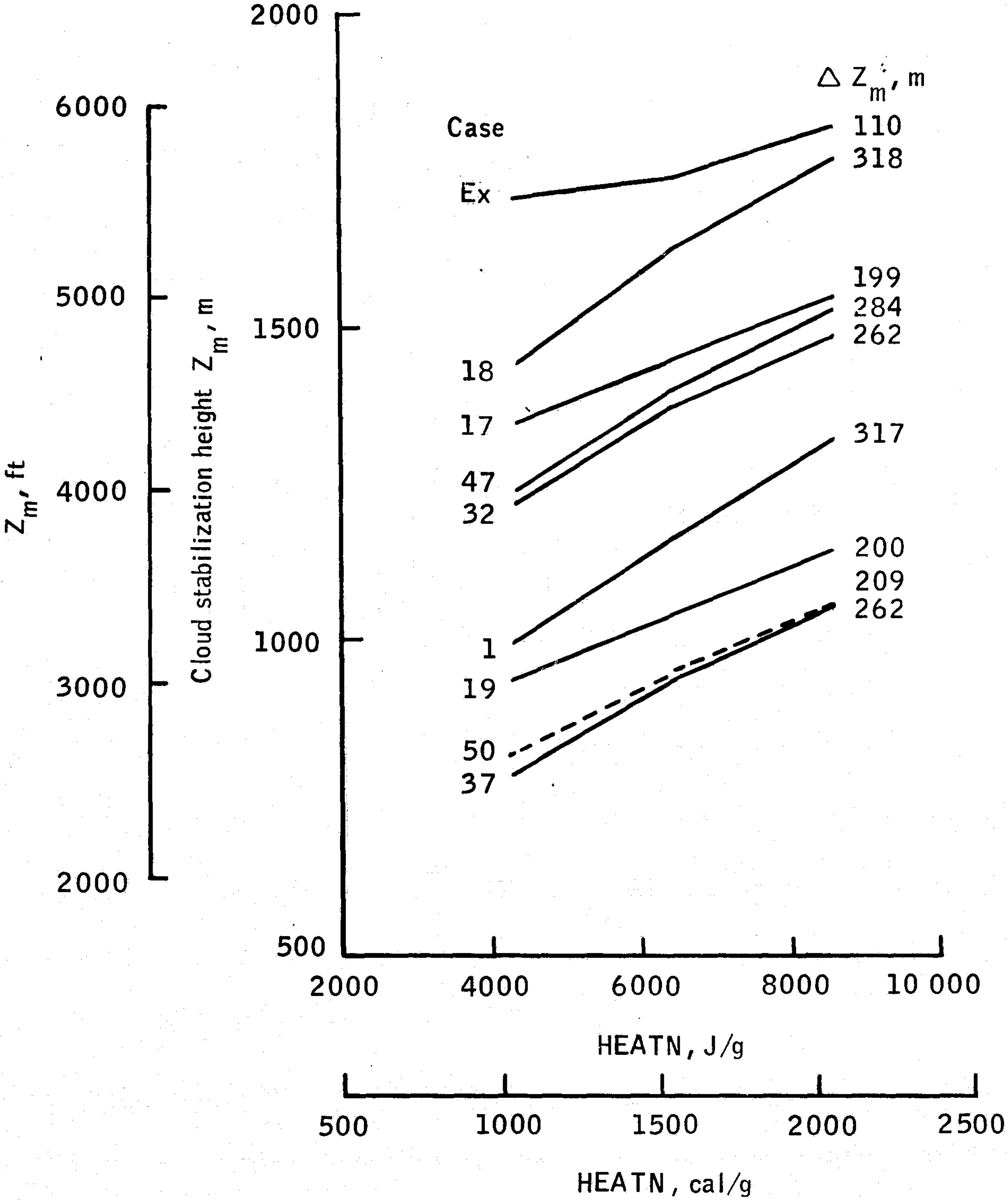


Figure 3.- Effect of QC changes on surface HCl concentrations, case 37.



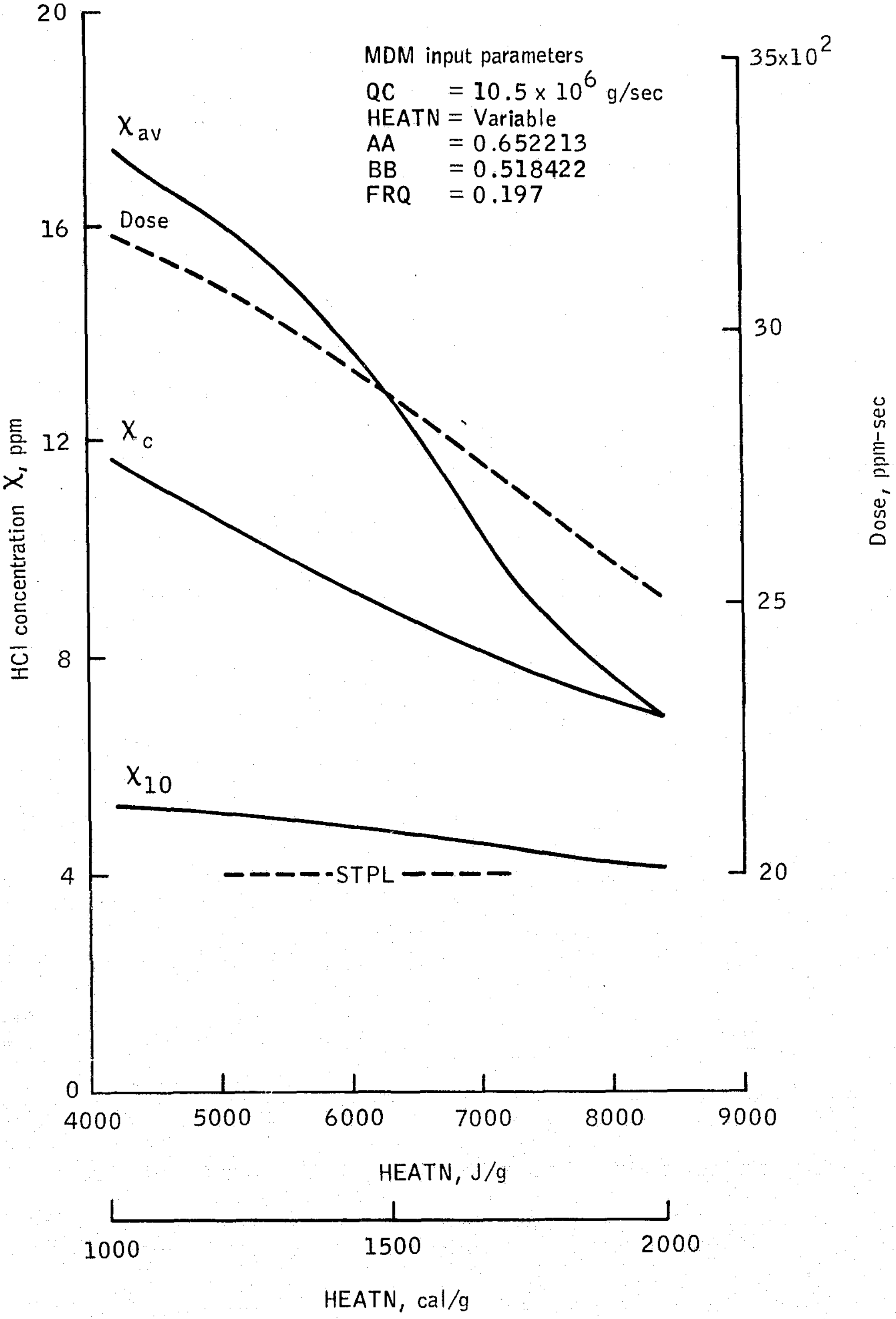
(a) For cases 46, 48, 39, 44, 52, 45, 43, 51, 31, 49, and 40.

Figure 4.- Effect of HEATN changes on the MDM predictions of cloud stabilization height.



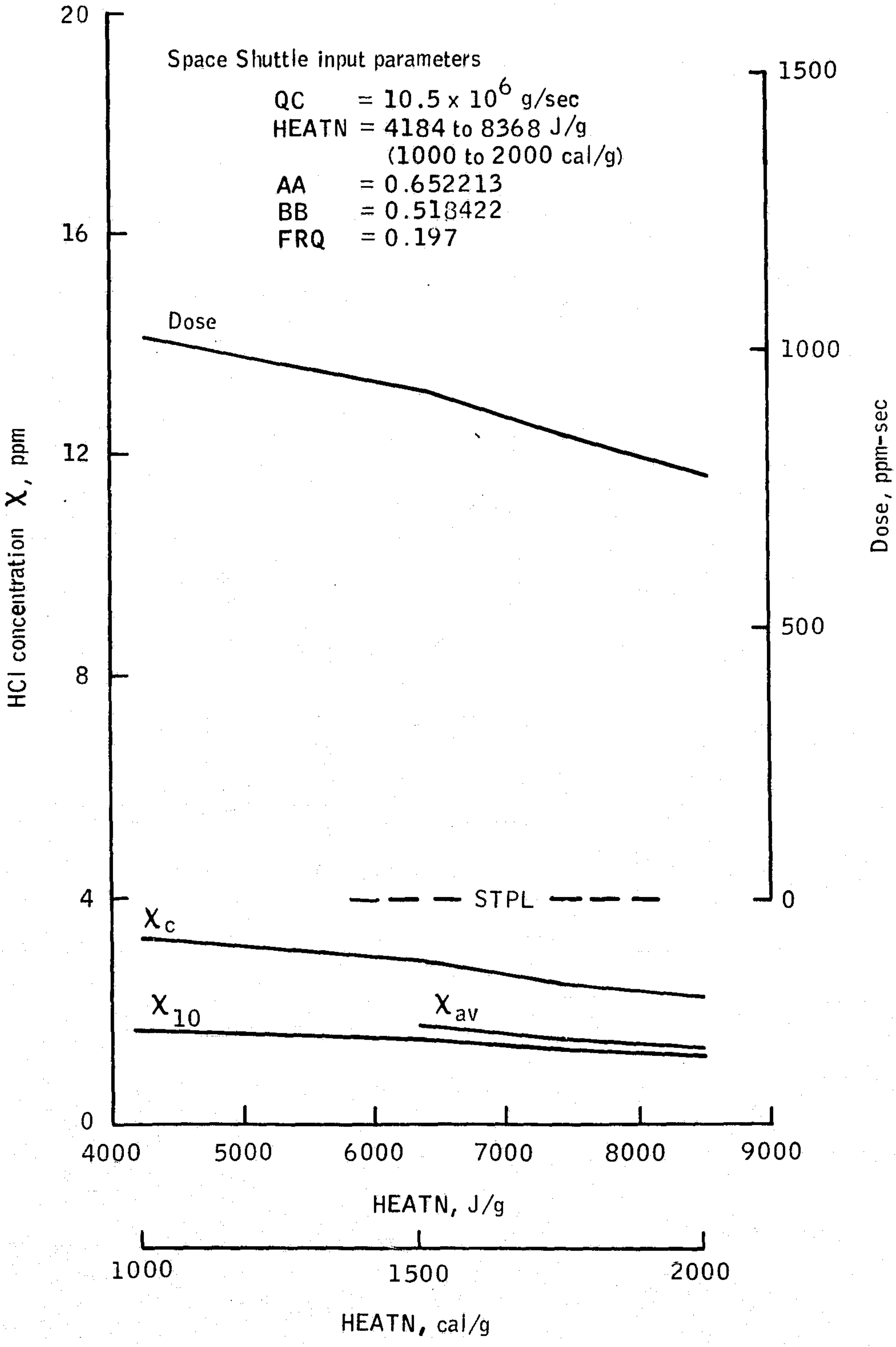
(b) For cases Ex, 18, 17, 47, 32, 1, 19, 50, and 37.

Figure 4.- Concluded.



(a) For case 37.

Figure 5.- Effect of changes in HEATN on surface HCl concentrations.



(b) For case 51.

Figure 5.- Concluded.

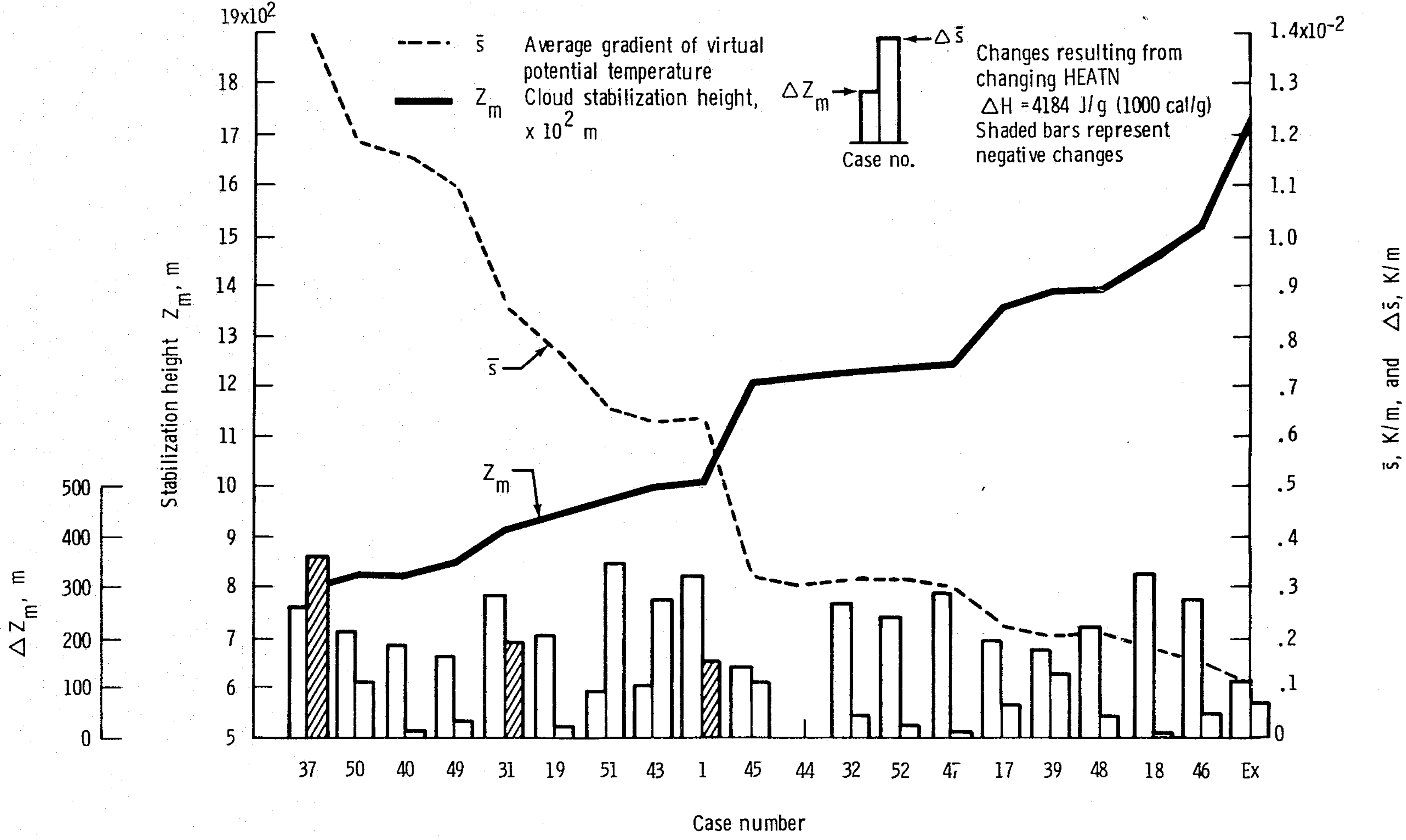


Figure 6.- Relation of changes in cloud stabilization height and average stability.