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ENVIRONMENTAL HAZARDS STUDY

Prepared under Contract No. NAS 8-11450 by
Glenn R. Hilst

THE TRAVELERS RESEARCH CENTER, INC.

For

NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER
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(Report dated May 1966)

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PREFACE

In July of 1964 The Travelers Research Center, Inc., initiated a study for the National Aeronautics and Space Administration's Marshall Space Flight Center (MSFC/NASA), under Contract NAS8-11450, to "...[study] low level atmospheric diffusion of exhaust gases from vehicle tests at MSFC/NASA, Huntsville, Alabama." This initial study was restricted by the statement of Scope of Work to an analysis of the mechanics of atmospheric dispersion of rocket exhausts from static firings and of airborne materials emanating from inadvertent spills of fuel additives, as these pertained to the Marshall Space Flight Center operations. From this analysis, and the synthesis of known features of atmospheric dispersion, it was expected that preliminary estimates of potential environmental hazards could be made. But, more importantly, this initial effort was to provide the basis for the design of an explicit experimental and analytical program that would provide useful operating criteria for toxic fuel handling and testing at MSFC.

Following a preliminary assessment of the problem, in-depth discussions of fuel handling practices and the probable modes of operation for static firing were held with personnel at MSFC. Fuel consumption or spill rates, exhaust temperatures, jet configurations, duration of firings, and like information was supplied by MSFC. In addition, extensive and detailed records of vertical wind and temperature profiles and less complete information on surface wind patterns in and around MSFC were also provided.

With these input data in hand, an extensive search of the literature was conducted and personal discussions were held to define the state of knowledge regarding the behavior of hot plumes emitted under ultra-sonic jet conditions and involving very large quantities of combustion products. Various empirical and semi-theoretical approaches to the problems of jet effects and buoyant rise were compared, but it was quickly discovered that no clearly adequate formulation of the solution was available for the problem of combined jet- and buoyant-rise of rocket exhausts.

The second phase of the study involved an adaptation of accepted mathematical models of the lateral and vertical diffusion of airborne exhaust or spill materials after these had come into density and kinetic equilibrium with the atmosphere.

Modelling of the cold surface-spill problem posed no serious difficulties, but the hot exhaust and hot spill products required the recognition of variations in wind velocity and vertical and lateral diffusion rates through the lowest few thousand feet of the atmosphere. The model was adapted to account for vertical wind direction shear, but time and resources did not permit incorporation of systematic variations of diffusion rates with height.

Finally, since the fuel additive of greatest concern, F_2, may be highly toxic in large concentrations which persist for only a few minutes, a first approximation to the time-rate of exposure was incorporated in the mathematical model.

The entire model, including estimates of the height of rise of hot materials and the atmospheric transport and diffusion processes, was programmed for the electronic computer and input variables deemed appropriate to various operational and meteorological conditions at Huntsville were specified. Solutions of the model were then calculated for various conditions and presented as maps and time-series presentations of the ground level dosage and exposure rate (concentration).

At this time TRC was requested to extend the analysis to the possible launch modes which might be encountered at Kennedy Space Center (KSC/NASA) and negotiations for an extension of Contract NAS8-11450 were undertaken. Input parameters for KSC were chosen and calculations of exposure rates and dosages for that site were completed.

The work under NAS8-11450 to this point has been documented in the first Final Report [Hage and Bowne, 1965]. Preliminary plans for experimental verification and refinement of the models were submitted, but at this point TRC was requested to expand the range of operational interests to those included in the charge to the NASA Atmospheric Diffusion Sub-group of the NASA Fuorine Hazards Working Group. This involved participation in the activities of the sub-group and an extension of the environmental hazards analyses to all possible modes of release of toxic materials in a wide range of topographical and environmental conditions.

In addition to this broader problem scope, the extension of NAS8-11450 required further attempts to analyze and refine those processes which were uncertain in the initial model, especially the jet- and buoyant-rise problem and the vertical stratification of atmospheric dispersion processes. Finally, TRC was requested to prepare a plan of action, against all this preliminary work, for the preparation of a comprehensive Handbook suitable for the control of toxic fuel usage against any untoward environmental hazards these materials and operations might pose.

This Final Report details the consideration of the further refinement of the atmospheric dispersion models appropriate to NASA operations (Part I) and presents a combined experimental and analytic program required to consolidate and refine all pertinent knowledge of rocket engine operational modes, atmospheric dispersion processes, and receptor sensitivities to toxic fuel exhaust products into a reliable and versatile Environmental Hazards Handbook (Part II). No attempt has been made to synthesize a second-generation comprehensive mathematical model since the findings of this phase point clearly to the need for sophisticated experimental measurements of the buoyant-rise and vertical diffusion rates before any more reliable model can be constructed. The experimental designs for these measurements are included in this report as a part of the work necessary to produce a reliable basis for the Environmental Hazards Handbook.

This report must, therefore, be considered as an interim statement rather than as a comprehensive and completed work. However, the perspective which this broad and deep involvement in the considerations of the potential environmental problems associated with toxic rocket fuel additives provides serves the very useful purpose of defining clearly what must be done if this avenue for improved thrust/fuel-weight ratio is to be exploited without undue risk. Within the context of present and anticipated operational configurations, these problems are unique and beyond reliable extrapolation from other situations. They have now been defined and the method of their solution has been identified. But reliable and comprehensive solutions remain to be achieved.

This work under Contract NAS8-11450 was directed by Mr. John W. Kaufman, Chief, Environmental Applications Branch, Aero-Space Environment Division, Aero-Astrodynamics Department, MSFC/NASA, Huntsville, Alabama.

TABLE OF CONTENTS

PART I

TABLE OF CONTENTS

PART II

LIST OF ILLUSTRATIONS

PART I

PART II

PART I

MODEL REFINEMENTS AND

BACKGROUND RESEARCH

1.0 INTRODUCTION

The general problems associated with the prediction of environmental dosages resulting from operational uses of exotic fuels in rocket engines (and other potential modes of exposure that may arise in fuel handling) were defined and assessed in the Final Report for the first increment of work under this contract (Hage and Bowne [4]). Documented in that report was the initial attempt to synthesize the source and atmospheric processes and properties into a mathematical model whose output was the mode and magnitude of exposure to exhaust products up to 15 km from the source. Solutions of this model by EDPM under realistic, but restricted, estimates of the multiple parameters provided the first estimate of the level of exposure (and thereby the degree of risk) insofar as potential environmental and receptor damage was concerned.

Useful as this first approximation may have been, it was clearly recognized that there were major deficiencies in the component parts of the model. First, the known methods for estimating the height of rise of very hot gases, emitted in large quantities during static firing, and launch and vehicle destruction operations, were at best qualitative; at worst, these methods completely failed to predict the distribution with height of exhaust products when they came into density equilibrium with the atmosphere. Second, it was evident that quantitative specification of the vertical diffusion rate for exhaust products after they had come into density equilibrium with the atmosphere was virtually impossible except under the unlikely condition of uniform vertical exchange at all heights of interest. These two problems—equilibrium height distributions at the end of the so-called buoyancy phase, and the rate of mixing from equilibrium height back to ground level—were identified as the most sensitive factors in the prediction of ground-level exposures.

Less difficult, but no less important, refinements of the model were also identified. In particular, it was deemed desirable to extend the model to cover: (a) a wider range of vertical wind-shear conditions, including those associated with sea breezes, and; (b) more appropriate choices of lateral mixing rates particularly concerning cloud-like, rather than continuous, plume emissions.

With the obvious successes of the initial model, which synthesized the unusual as well as the classic features of environmental processes associated with rocket engine operations, it was considered highly desirable to attempt a substantial refinement of the physical rationale involved in estimating the height of rise and the subsequent diffusion of initially very-hot exhaust products. Having pursued these topics as far as current knowledge permitted, we were requested to design a field experiment program that would provide the information necessary to compile a handbook of operational criteria appropriate to the safe usage of toxic fuel additives under foreseeable geographic and operational conditions.

This report emphasizes the progress made in selected approaches to the problems of buoyant rise of hot clouds and plumes, and the first results of an attempt to simulate vertical diffusion rates in the presence of non-uniform vertical exchange rates in the lower atmosphere. Neither of these problems has been satisfactorily solved, but because of the progress that has been made, it is possible to define clearly and to design the experimental program upon which further progress depends. The complete plan for an experimental program is included in this report.

2.0 THE BUOYANCY PHASE OF ROCKET EXHAUSTS

It was indicated in the previous report (Hage and Bowne, [4]) that, while the diffusion of a mass of toxic gas in the atmosphere can be modeled with a certain amount of confidence on the basis of existing information, the "effective" height due to initial buoyancy and momentum of individual sections of an exhaust plume can only be estimated with the aid of some ad-hoc empirical formulas and speculative theoretical results. Consequently, relatively little confidence could be placed on any predicted ground-level concentration patterns. In this report, the question of upward bodily movement of a mass of hot gas due to its buoyancy and initial momentum is examined in somewhat greater detail on the basis of published experimental and theoretical investigations. While the final conclusion remains unchanged, namely that the existing information is inadequate to provide a basis for predicting the behavior of hot exhaust gases in rocket firings, it is hoped that the present report firmly establishes the need for some fairly extensive experimental work on this problem.

2.1 Qualitative Description of the Behavior of Hot Rocket Exhaust

On the basis of the photographic evidence both on static firings and on a number of regular and abortive launches, it is possible to describe the overall features of the dynamic behavior of hot rocket exhaust. The first major distinction that must be made is between an orderly firing (static or launch) and an explosion near ground level.

When a rocket explodes near ground level, it generates a "fireball" of considerable buoyancy into which most of the gases generated in the explosion are sucked upward. There is, however, a "stem" left behind the fireball which extends to ground level, and sundry burning debris also generates profuse quantities of incompletely burnt gases on the ground. The net outcome is that a residual non-buoyant cloud of substantial size is left behind at ground level. Without some further observational evidence, no estimate seems possible for the total amount of noxious gases in this left-over cloud.

Somewhat more conclusive results may be obtained for cases of static firings and orderly launches. Three phases of the dynamic behavior of rocket exhaust may be clearly distinguished: the "jet," "plume," and "thermal" phases. The jet phase is characterized by velocities large compared to wind speed, so that the jet's initial momentum dominates its behavior. This is followed by a plume phase in which buoyancy is dominant while the shape of the diffusing cloud is long and narrow owing to continuous release over a period of a minute or so. Then, a sufficiently long time after release, the cloud appears to behave as if it were generated instantaneously; this is the thermal phase, still dominated by buoyancy.

A complication of this picture is that the end of a static firing characteristically shows intermittent combustion, while for most of the release period individual sections of the plume follow much the same path and eventually merge into a thermal. Presumably, combustion becomes incomplete after the first loss of ignition. A dark, apparently non-buoyant cloud is generated during the last three or four seconds of a firing. This "tail-puff" becomes separated from the body of the plume and forms a second cloud travelling along with the wind in close vicinity of the ground.

In the last few seconds of the firing, the rate of heat release is thus certainly less than at the beginning. This raises the question whether the rate of heat release is otherwise constant or whether there is a gradual change from start to finish. In the literature, existing information on the behavior of hot plumes refers to a continuous, constant rate of heat release. Another point is that while the length of the cloud is rather larger than its diameter in the plume phase, the portion at the front is subject to edge-effects and behaves somewhat differently than the bulk of the plume.

Although some work has been done on the problem of the so-called "starting plume," it is inconclusive and is not to be used in the calculations below. Although it is not certain that the heat release rate is completely steady, the data supplied by the Marshall Space Flight Center (MSFC) would imply this. Also, a number of films on static firings have been viewed and in none of them is there a suggestion that the plume breaks up into several fragments of differing buoyancy, with the exception of the tail-puff already described. Rather, the whole plume forms a single unit, individual sections of which appear to have much the same history. Thus, in the following it will be convenient to discuss the behavior of the "main plume," which comprises the jet phase, plume phase, and thermal phase, and to treat separately the behavior of the tail-puff.

2.2 The Jet Phase

During a static firing, the exhaust gases impinge on a deflector having its axis at 30° from the horizontal. A considerable amount of cooling water is pumped onto the deflector, most of which evaporates to more than double the mass flow in the jet, according to data received from MSFC.

This increase in mass flow, together with the entrainment of air and friction on the ramp, may be expected to reduce the jet velocity to a value of the order of 3000 ft sec^{-1} on leaving the deflector ramp (from an estimated 9300 ft sec^{-1} before impinging on the ramp). The temperature at this point is apparently uncertain, depending on the degree of after-burning that has taken place, and may range from 1100°R to 3050°R. The uncertainty in the value of the heat flux is thus considerable. Much of the heat flux is in the form of latent heat; according to the data received, at 50% after-burning the heat flux carried by the stream is 8.67×10^8 Btu min^{-1}, against 1.94×10^8 Btu min^{-1} carried by the other gaseous constituents. The diameter of the jet at this point should only be 2 or 3 times rocket diameter.

Judging by the photographic evidence, on leaving the deflector the jet behaves much as any other free jet in the laboratory. Hinze [6, pp. 420—431] has summarized the experimental evidence available. According to his summary, the center-line velocity U_c of a free jet behaves as

$$\frac{U_c}{U_j} = 6.4 \frac{d}{x + 0.6\,d} \tag{2-1}$$

where U_j = jet exhaust velocity, d = jet diameter, and x = distance from nozzle exit. If a tracer gas is present in the jet, the center-line concentration χ_c decays according to a very similar law:

$$\frac{\chi_c}{\chi_j} = 5.27 \frac{d}{x + 0.8\,d} \tag{2-2}$$

where χ_j = jet exhaust concentration. Both the concentration and the velocity are distributed along the radius according to a Gaussian law, but the spread of the concentration is greater. The "half value radius" (at which half the center velocity or concentration is measured) is about 0.08x for velocity, 0.11x for concentration. The jet radius thus grows linearly with distance from the nozzle. Excess temperature behaves almost exactly as concentration of an admixture.

The above data are valid for jets of constant density and issuing into a medium of equal density, that is, provided the excess temperature or the concentration of any light or heavy constituent is small. Where the density differences are considerable, the jet behaves very much as if it had the "equivalent" initial diameter:

$$d_e = d\left(\frac{\rho_{jet}}{\rho_{ambient}}\right)^{1/2} \tag{2-3}$$

The justification for this formula is that a jet of this diameter and with constant density fluid would produce the same momentum flux as the actual jet with the different fluid.

When the temperature of the jet is very high (excess temperature more than 500° F), more rapid cooling is observed than would be given by Eqs. (2-2) and (2-3) (replacing concentration by excess temperature), presumably because of radiative losses.

Turning now to the specific problem of the exhaust gas jet, it is reasonable to assume that the jet phase comes to an end when the center-line velocity decays to a magnitude comparable to wind speed and to the vertical speed the plume would have due to its buoyancy alone. Both of these are of the order of 30 ft sec^{-1}, so that the jet phase may be regarded as that portion of the total path of the exhaust gases wherein the velocity drops from approximately 3000 ft sec^{-1} at the end of the deflector to approximately 30 ft sec^{-1}, a velocity ratio of 100.

By using the above data and relationships, and ignoring radiative losses and heat release by condensation, the following conditions may be estimated for the beginning and the end of the jet phase (50% after-combustion):

Condition	Beginning	End of jet phase
Distance from ramp (unit d_r = rocket diameter)	0	860 d_r
Height above ground	0	430 d_r
Center velocity, feet sec^{-1}	3000	30
Center concentration of gaseous constituents other than air and vapor	0.33	2.73×10^{-3}
Center temperature (ambient: 530°R)	2000°R	542°R
Half-value radius for concentration or temperature	1.5 d_r	95 d_r

While no quantitative checks could be made from the photographic evidence, these values appear to be qualitatively correct.

It should be noted that, according to the data supplied by MSFC, the tail-puff is formed at the engine "cut off" when only 600 lb min^{-1} of fuel leaves in the form of smoke and scatters approximately 30 ft above ground. This rate of fuel flow is little more than 10% of the normal firing rate, and the evidence seems to indicate that it remains almost completely unburnt. If a significant amount of energy release did take place, the initial momentum would carry the tail-puff much higher than 30 ft.

A somewhat different problem is presented by the orderly launch in which the high-velocity exhaust gases of a rocket are directed nearly vertically to the ground, in an axially symmetric arrangement. The induced flow pattern is similar to stagnation point flow as illustrated in Fig. 2-1. As the streamlines straighten out along the ground, the hot fluid is distributed in a horizontal layer of relatively small, more-or-less constant, depth. With surfaces of constant density nearly horizontal, the fluid is close to being in static equilibrium, albeit an unstable one. As a consequence, buoyancy exercises no immediate direct accelerating effect in the vertical. Under these circumstances, the hot fluid is likely to flow out to a considerable radius before the

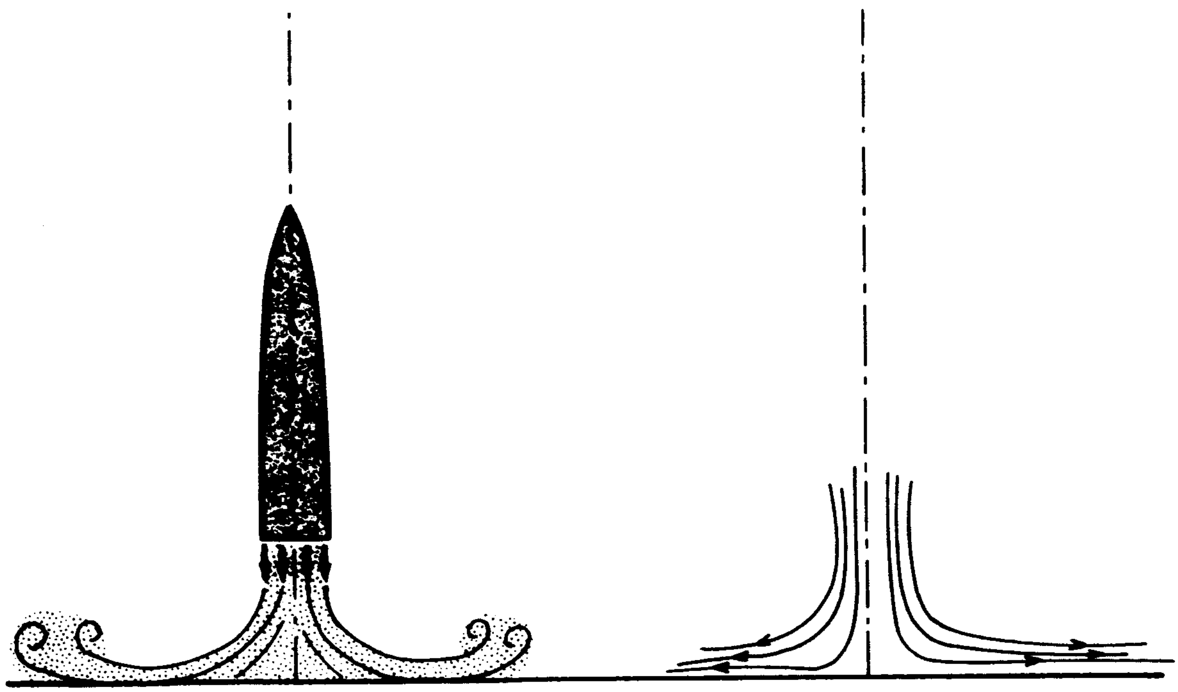

Fig. 2-1. Rocket exhaust and idealized induced flow pattern.

instability of the arrangement establishes an updraft. The net effect is presumably similar to the distribution of the initial buoyancy (less any radiation losses) over a circular area of relatively large radius R_0.

While this "wall-jet" problem is different from the circular jet discussed above, the ratio of jet exhaust velocity to characteristic buoyant velocity is again of the order 10^2, so that the wall-jet has to slow down by this factor before it merges into a plume. Thus, it is reasonable to assume that the "effective radius" R_0 at the beginning of the plume phase is a factor of order 10^2 times rocket radius, much as at the end of the free jet's expansion. Some more-detailed calculations similar to those carried out above for the free jet could conceivably be made at this point, but would require a fairly extensive literature search because wall-jet data are not widely available. However, in order to be useful in practical hazard predictions, such calculations would have to be checked against systematic field observations.

2.3 The Plume Phase

If the steady firing rate is maintained for a long enough period, the exhaust "jet" merges into a continuous "plume," resembling a smoke plume in appearance. Physically, the important point is that the upward movement in this phase is determined mainly by the total buoyancy rather than by momentum, as in the jet phase.

In an industrial smoke plume, two characteristic regions may be distinguished: close to the source, the self-generated turbulence of the buoyant motion is the main diffusion mechanism for heat, matter, and momentum; considerably further downstream, the environmental turbulence becomes the main spreading agent and produces a different plume behavior (Priestley [9], Csanady [2, 3], Briggs [1], Slawson [11]). Because the entire plume phase for rocket exhaust gases is relatively short, the second region of plume behavior is irrelevant in the present context; the plume effectively becomes a "thermal" before reaching that regime.

The first regime of plume behavior is relatively well known. Atmospheric variables (including temperature gradient, provided it is not too far removed from neutral) are not particularly important in determining the mean position of the plume at a given distance from the source. Excluding the immediate neighborhood of a source such as an industrial chimney (where the effects of the conditions of release, gas velocity and chimney radius are felt), the mean path of a smoke plume is well described by

$$\frac{z}{\ell} = 2.2 \left(\frac{x}{\ell}\right)^{2/3} \tag{2-4}$$

where z = height above chimney top, x = horizontal distance from it, and ℓ = the length-scale of buoyant movements:

$$\ell = \frac{F}{U^3} \tag{2-5}$$

where F = "flux of buoyancy," i.e., volume flow rate times buoyant acceleration at the source:

$$F = \frac{\Delta\rho}{\rho} g\, w_0 \pi R_0^2 \tag{2-6}$$

Here, ρ = density, $\Delta\rho$ = density deficiency, g = acceleration due to gravity, w_0 = gas efflux velocity, and R_0 = chimney diameter. The symbol U in Eq. (2-5) stands for horizontal wind speed. Equation (2-4) holds to about x/ℓ = 1800, which is well beyond the range of interest for rocket exhaust.

If one wishes to investigate the effect of initial conditions on plume rise, the approach of Morton, Taylor and Turner [7] may be adopted. As before, the turbulence is assumed to be due entirely to the plume's motion. Self-similarity of the velocity and temperature profiles at different levels is assumed, while the rate of influx is represented by the plausible hypothesis that, if v is the influx velocity and w is the bodily upward velocity of the plume,

$$v = \alpha w \tag{2-7}$$

where α is the "entrainment constant." The rate of entrainment is equal to influx velocity times the circumference of the plume.

Conditions at a cross section of an inclined plume are illustrated in Fig. 2-2. With the coordinate ξ measured along the arc, the conservation laws may be written for a neutral atmosphere:

(matter) $$\frac{d}{d\xi}(R^2 V) = 2\,Rv \qquad (2\text{-}8)$$

(momentum) $$\frac{d}{d\xi}(R^2 w V) = R^2 g \frac{\Delta\rho}{\rho} \qquad (2\text{-}9)$$

(energy) $$R^2 V g \frac{\Delta\rho}{\rho} = F = \text{constant} \qquad (2\text{-}10)$$

where R is the radius of the plume element and V is its resultant velocity.

This assumes a constant wind speed U with height so that

$$V^2 = U^2 + w^2 \qquad (2\text{-}11)$$

The basic hypothesis is that of self-similarity of the profiles, which may not be very accurate in strongly curved portions of the plume. The formulation is valid for a neutral atmosphere; in a non-neutral one, Eq. (2-10) has to be changed. Given the values of F and U and an initial value of R and w, with known α, Eqs. (2-7) to (2-11) may be solved numerically.

A computer program has been compiled and calculations made to simulate the behavior of plumes observed by Stewart, Gale, and Crooks [12] and Csanady [2]. With a sensible choice of α (0.1 to 0.2), a virtually perfect agreement between theory

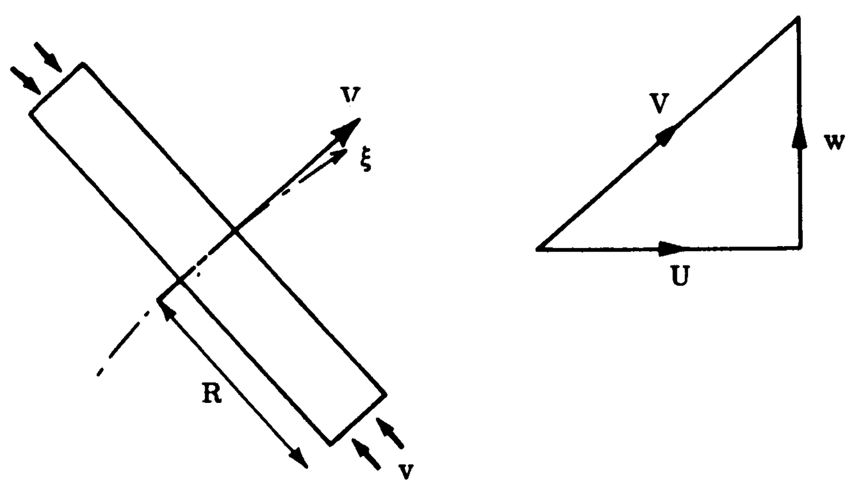

Fig. 2-2. Cross section of an inclined plume.

and experiments was obtained. The calculations also showed that the effect of initial conditions (R_0, w_0) is very quickly lost (within a distance of $x = 2\ R_0$ or $3\ R_0$) and the plume approaches a form given by Eq. (2-4).

It should be noted here that both Eq. (2-4) and the numerical calculation give the mean path of a plume, while in reality the position of any section of the plume fluctuates about this mean. Particularly under superadiabatic conditions, these fluctuations may be serious if the mean plume height above ground is not too great. In the special case of rocket exhaust on static firings, however, both calculations and visual evidence indicate that the mean position of the cloud is too high above ground for vertical velocity fluctuations to be a serious factor.

It may be estimated from data supplied by MSFC that the flux of sensible heat during steady combustion is $Q = 7.5 \times 10^6$ Btu sec^{-1}. The flux of buoyancy is related to heat flux by

$$F = \frac{gQ}{\pi \rho c_p T_a} \tag{2-12}$$

For the plume phase, the initial conditions are those calculated at the end of the jet phase in the previous section. Here the excess temperature is already small (12°F), most of the gas in the plume being atmospheric air. It is therefore appropriate to substitute density and specific heat of air into Eq. (2-12). The resulting flux of buoyancy is then 7.5×10^6 ft^4 sec^{-3}, which is some 2 orders of magnitude larger than that characteristic of large power station chimneys.

Taking an average case, let the wind speed be $U = 20$ ft sec^{-1}; for the length scale of buoyant movements, this gives $\ell = F/U^3 = 937$ ft. From the mass flow and material properties, the rocket diameter is calculated to be $d_r = 8.8$ ft. Thus, at the beginning of the plume phase, the plume is $430\ d_r = 3780$ ft above the ground and has a half-value radius of concentration or excess temperature of $R_0 = 835$ ft. In order to fit Eq. (2-4) to these initial conditions, it is necessary to define a "virtual origin" of the plume, as discussed by Priestley and Ball [10]. At the beginning of the plume phase, the plume is deemed to be a distance z_0 above this virtual origin, which is calculated from

$$R_0 = 0.10\ z_0 \tag{2-13}$$

Thus, z_0 = 8350 ft; Eq. (2-4) now gives x_0 = 7580 ft, which, for all practical purposes, is identical with the distance from the beginning of the jet phase, $x = 860 d_r$ = 7560 ft. The vertical origin is vertically below the real source at a distance of 4570 ft. This combination of the jet phase and the plume phase is illustrated in Fig. 2-3, which shows clearly that the transition cannot be abrupt; a conjectured actual plume outline is also drawn in.

If the plume phase exists for approximately the same distance as the jet phase (which appears to be the case from the photographic evidence), then at the end of it, or at a distance of 3 miles from the source, the plume will be at a height of 9000 ft above the ground (in a 20 ft sec^{-1} wind, it should be recalled) and its half-radius should be of the order of 1500 ft. The windward extension of the entire released mass of gas is, if the firing lasts for 100 sec, originally 2000 ft, and rather longer at 3 miles downwind due to diffusion of the edges. Nevertheless, the length-to-depth ratio of this entire mass is now no more than 2:1, and it is appropriately regarded a thermal.

2.4 The Thermal Phase

The initial conditions for the thermal phase are those just calculated to characterize the end of the plume phase. In view of the large size of the cloud and the large height over the ground already attained, it is to be expected that the thermal will exhibit the typical features of regular atmospheric thermals. Thus, the temperature gradient will now be of crucial importance, while the high moisture content may lead to the formation of a cumulus cloud, given the appropriate atmospheric conditions. Cloud formation may, in fact, be observed in the film records of some static-firing clouds.

From the point of view of ground-level pollution, the thermal phase may generally be ignored, although it is of some meteorological interest as an experiment in cloud formation. Any downward diffusion from such high levels will generally be insignificant in comparison with materials left at lower altitude.

2.5 Ground-level Concentrations due to Main Plume and to Tail-puff

According to the data supplied, at engine cut-off some 600 lb sec^{-1} of fuel is discharged for a short period. From the film records, the maximum duration of this tail-puff generating time may be estimated to be 4 sec. Thus, a total of some 2400 lb

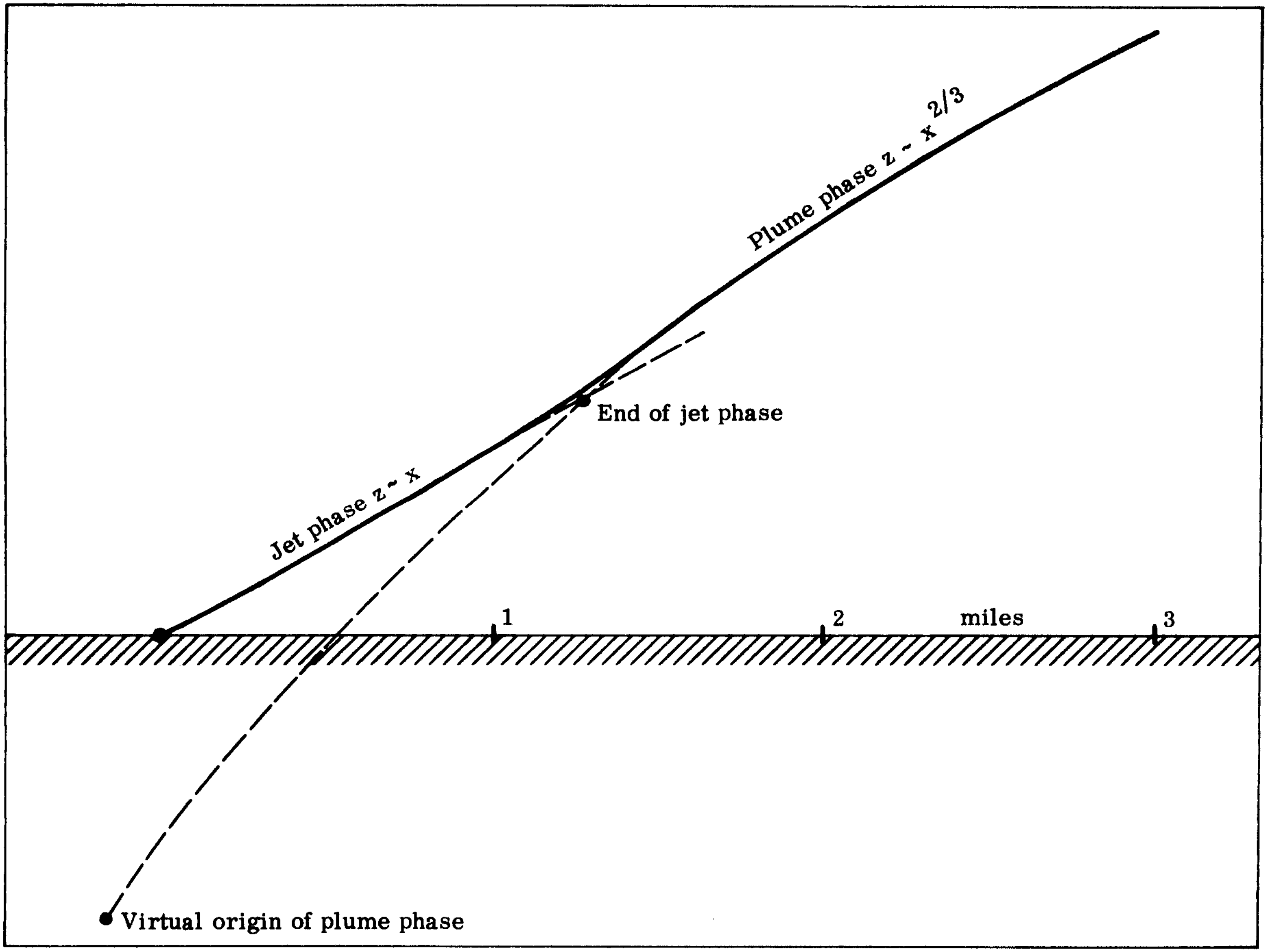

Fig. 2-3. Mean path of exhaust gases (wind parallel to jet).

of fuel may be released in an essentially unburnt form. This is of the order of 1% of the total fuel burnt, so that the "source strength" for the tail-puff is of order 10^{-2} times the source strength for the main plume.

Although the diffusion mechanisms in a high-speed jet and in a puff of gas are different, the order of magnitude of the peak mean concentrations reached is the same, if the source strength is the same. Thus, in our case the peak concentrations at the center of the tail-puff are of order 10^{-2} times the peak concentration at the center-line of the jet at the same distance from the source, at least until longitudinal diffusion in the tail-puff further reduces peak concentration in the latter.

In the jet phase of the main plume, the half-value radius grows as 0.11 x; thus, the standard deviation is $\sigma_z = 0.0935\,x$. Ground level is 30° from jet axis, and is therefore closest along a line at 5.35 standard deviations. The concentration between the centerline of the jet and 5.35 standard deviation reduces by a factor of $\exp[-(1/2)\,5.35^2] = 0.617 \times 10^{-6}$. Consequently, concentrations due to the main plume are of order 10^{-4} times those due to the tail-puff. The very firm conclusion emerges that the main problem, as far as toxic effects are concerned, is the tail-puff. This fact is apparently known to MSFC personnel.

It should be emphasized here that the reason why the main plume on a static firing is relatively innocuous is the 30° angle of the jet, an excellent engineering measure.

In conclusion, for further work on the problem, the following points may be made:

(a) Apart from the immediate vicinity of the firing ramp, the most serious pollution hazard arises from the tail-puff of a static firing which is released at engine cut-off and consists of apparently non-buoyant, black smoke.

(b) While it could not be detected from the photographic evidence, a similar relatively cold puff may be released at the beginning of the firing.

(c) It is uncertain what quantity of gases are contained in the tail-puff, and whether they are entirely non-buoyant or are effectively distributed over a layer of some depth over the ground.

(d) The thermal generated by an orderly launch probably causes a pollution problem intermediate in severity between the tail-puff and the main jet-plume of a static firing. The cloud is highly buoyant, but it does not possess a high vertical momentum as does the jet. Further theoretical work on the orderly launch problem would probably lead to a good estimate of pollution hazards, provided that some detailed release data and some good film records could be made available.

In order to avoid creating the misleading impression that the above calculations are quantitatively reliable, it is perhaps appropriate to enumerate their weaknesses:

(a) The Mach number of the jet prior to reaching the deflector is 3.0. Little information is available on the spread of such highly supersonic jets; the calculations above are gross extrapolations.

(b) The jet is initially very hot; its behavior is likely to be somewhat unorthodox.

(c) The separation into jet, plume,and thermal phases is somewhat arbitrary; transition regimes, in particular, behave in an unknown way.

(d) The plume rise formula Eq. (2-4) was established at values of F two orders of magnitude smaller; its use here is an extrapolation requiring experimental confirmation.

(e) The data on which the calculations were based are crude or unreliable; the 50% after-combustion is a guess, so that the heat flux is quite uncertain. The evaporation rate on the ramp appears to be an assumption.

(f) Condensation after jet formation has been neglected, even though it visibly occurs, and even though the heat flux in the form of latent heat is very high.

One may say that the calculations are only of qualitative value and that, for detailed practical predictions, a good deal of experimental evidence is required. The design of such experiments is presented in part II of this report.

3.0 A SIMULATION APPROACH TO VERTICAL DIFFUSION RATES IN NON-UNIFORMLY STRATIFIED ATMOSPHERES

The practical problem of predicting cumulative concentrations or dosages at a fixed point, given an arbitrary distribution of the sources of airborne pollutants, has been generally restricted to sources arranged in a horizontal plane. Individual point sources, arbitrarily-oriented horizontal line sources, and finite or semi-infinite area sources have been treated mathematically and experimentally. The most fundamental assumptions employed are (a) homogeneous and steady atmospheric diffusion, and (b) independent dispersion of each source contribution. Under these assumptions, the total cumulative dosage at a fixed point is the sum of the contributions from each individual source, or source element; these contributions may be estimated separately on the basis of the uniform dispersion rates and the relative geometry of the source and the fixed point.

In the initial approach to the modeling of very hot plumes and fireballs, which give rise to large buoyancy-induced vertical displacements of the hot gases, and forced, heated jets, these assumptions were extended to the vertical dimension. In particular, it was assumed, in the absence of more definitive information, that the vertical exchange rate for gases which had come into density equilibrium with the atmosphere, was a constant, regardless of the height at which this equilibrium was achieved. It was clearly recognized even then that this was a gross simplification of reality, and that, in many situations, variations of static stability and wind shear in the lowest few thousand feet of the atmosphere produce pronounced variations in the vertical exchange rate within relatively short vertical distances. The method of incorporation of non-uniform stratification of the atmosphere into the models was not obvious, however.

The most basic approach to non-uniform vertical exchange rates has been the classic diffusion equation for non-settling gases, which may be written as follows (for the vertical dimension only):

$$\frac{\partial \chi}{\partial t} = \frac{\partial}{\partial z}\left[k(z)\,\frac{\partial \chi}{\partial z}\right] \qquad (3\text{-}1)$$

where χ is the local concentration, z is the vertical coordinate, k(z) is the exchange coefficient as a function of height, and t is time. Given suitable boundary conditions and a prior knowledge of k(z), Eq. (3-1) may be solved for the appropriate local concentration history. This approach has been highly developed for the prediction of vertical profiles of moisture, momentum, and gases or aerosols, but attempts to relate $k(z)$ explicitly to stability, wind shear, and the spectral properties of the vertical component of turbulent motions (and it is the latter which control vertical exchange rates) have not been particularly fruitful. Frequently, Eq. (3-1) has been treated as the definition of k, and empirical values derived from one situation have been transferred to analogous situations for the prediction of χ.

In an attempt to go more directly to the problem of the relationships between non-uniform structure of turbulence in the vertical dimension, and the resultant vertical exchange rates for gaseous or fine aerosol materials, a wholly new simulation model has been constructed and tested. The model and the initial results are described in the following sections of this report. It should be noted at the outset, however, that heartening as these results are (and they come amazingly close to simulating reality), this work has been carried only to the point of clear identification of atmospheric motion and stability parameters and accompanying diffusion processes, necessary for a comprehensive experimental program. Only fragmentary measurements of vertical diffusion through non-uniformly stratified atmospheres are now available for testing these models against reality. In a very real sense, we are "playing games" with these models until comprehensive measurements are available.

3.1 The Lagrangian History of Turbulent Motions

The most fundamental feature of turbulent diffusion is the trajectory of an individual particle or molecule of a gas; we shall assume for the purposes of this model that such a particle assumes the motion of the air in its vicinity at all times. The basic problem then is the derivation of the atmospheric motion in this Lagrangian frame of reference. If w is the vertical component of this motion, we wish to know w(t), where t is real time. Let us assume that $\overline{w}$, the mean motion over some large time interval, is zero and therefore w(t) is always a turbulent, i.e., non-steady, motion.

We recognize almost intuitively that the generation of a turbulent element of atmospheric motions in the vicinity of a particle is a stochastic process. Without inquiring at this point as to the causes of turbulence generation, we shall assume that there is a finite probability that an impulsive motion w_0 is generated in the immediate vicinity of the particle at time ξ. However, once this turbulent motion has been generated, we shall assume its subsequent history [i.e., $w(t - \xi)$] is subject to a specific law of motion. With the further stipulation that the generation of a turbulent component at time ξ is independent of the history of turbulence generation prior to time ξ, these arguments permit us to combine the probabilistic and deterministic aspects of turbulent motions. In particular, we must specify the probabilities

$p(w_0^+)$ = probability of a positive initial motion w_0

$p(w_0^-)$ = probability of a negative initial motion w_0, and

$p(w_0 = 0)$ = probability of no turbulence generated.

We expect, but do not require, that $p(w_0^+) = p(w_0^-)$, and require that.

$$p(w_0^+) + p(w_0^-) + p(w_0 = 0) \equiv 1 . \tag{3-2}$$

In general, w_0 is chosen from a distribution of possible values.

Given the probability of the generation of a turbulent element at time ξ, we recognize the random nature of this event by choosing which of these three possible events occurs in any time interval by reference to random number generation. The criteria for choice must satisfy the components of the left-hand side of Eq. (3-2) only over a large number of time intervals.

The selection of the equation of motion for an individual turbulent element is the next step. Based largely on the work of Priestley [8], the following law has been adopted:

$$w_i(t - \xi) = w_{0_i} \exp [- \lambda_i (t - \xi_i)] \cos \beta_i (t - \xi_i) \tag{3-3}$$

where the subscript i identifies the component of motion generated at time ξ_i. Equation (3-3) is only one of a wide number of choices which could be made, but for the purposes of our present "game playing," it incorporates the major features of the decay of turbulent motions in the simplest form. We note in particular that for $\beta \equiv 0$, the motion is continuously accelerated if $\lambda < 0$, but w decays to zero if $\lambda > 0$. Both of these cases are admissible, but the former cannot persist. For the more likely case of $\lambda > 0$, the trajectory of the particle due to this single component of turbulence is an assymptotic approach to a new equilibrium level.

For $\lambda > 0$ and $\beta \neq 0$, the trajectory of the particle is characterized by an overshoot and then by a damped oscillation about a new equilibrium level. Priestley identifies this situation with hydrostatically-stable, stratified atmospheres.

The three parameters of the motion as defined by Eq. (3-3) are w_0, λ, and β, each of which may assume any of a range of values, and each of which may vary as a function of the height, z. (w_0 is, of course, a function of z and ξ, the place and time of generation of the turbulent element. λ and β characterize the motion at subsequent locations and are therefore only a function of z.)

The major purpose of this exercise is to devise an analogue to the salient features of turbulence generation and subsequent decay of turbulent motions in a Lagrangian framework. The foregoing construction permits simulation of the following major properties of turbulent motions:

(a) They are randomly generated.

(b) They decay to zero in time.

(c) The magnitude and character of the motions are properties of the fluid which may vary in space and time.

Without any claim of rigor, so far as real fluid simulation is concerned, these component parts may be programmed for computer synthesis and study of the major sensitivities of simulated motions and dispersion properties to variations of the statistical and dynamic properties of the model.

3.2 The Model

The component parts of the model described above have been assembled into a first-generation computer program that performs the following operations:

(a) At time $t = \xi = 0$, generate a random number and compare this number with a look-up table. From such comparison, assign zero or non-zero values for w_0, λ, and β.

(b) If (a) is non-zero, calculate w and Δz for the first time step. If (a) is zero, proceed to second time step.

(c) Repeat (a) for second time step. Add resulting motions from first and second perturbations and calculate w and Δz for this time step.

(d) Repeat (a) for third time step and calculate w and Δz.

(e) Continue this cycle to time step n; store total displacement of particle from initial height and the value of w for the nth time step.

(f) Continue this cycle to second, third, etc., reference time.

(g) Discontinue calculations at time step N.

By this process, the motion of the particle at time t is the residual of all motions which have been produced prior to time t. (Any individual perturbation's contribution was dropped when it had decayed to 0.1% of its initial value.)

Having established the history of motion and position for a single particle during the time $0 < t < N$, the entire calculation is repeated for M individual particles. The following information is accumulated from these calculations:

(a) The frequency distribution of the displacement of the particles from injection height at various times up to time period N.

(b) The mean, variance, skewness, and kurtosis of the frequency distribution defined in (a).

(c) The mean and variance of the motions at discrete time intervals and heights (displacement distances).

(d) The Lagrangian correlation function for w, $R(\tau)$.

(e) The scale length, $L = \int_0^\infty R(\tau)\, d\tau$.

This model has been programmed for the IBM-7094 computer. As presently constructed, it accepts inputs at one level only; thus, the simulation is for a continuous point source. Running time for N = 500, M = 500 is approximately 20 minutes.

3.3 Results

3.3.1 Uniform Stratification

In order to test the model against classic results, the initial runs assumed single values for $|w_0|$, λ, and β. The probabilities $p(w_0^+)$, $p(w_0^-)$ and $p(w_0 = 0)$ were assigned the value 1/3. Under these conditions, the particle distribution should be Gaussian, centered about the height of injection, and its variance should increase initially as the time of flight squared, and then as the first power of this time.

The parameters chosen for four initial calculations are shown in Table 3-1.

TABLE 3-1
PARAMETERS FOR UNIFORM
STRATIFICATION CALCULATIONS

Parameter	Run number			
	01	02	10	11
$\lvert w_0 \rvert$ cm sec^{-1}	10	50	10	50
λ sec^{-1}	0.10	0.05	0.10	0.05
β sec^{-1}	0	0	0.10	0.10

The frequency distributions calculated for each of these was indeed Gaussian within experimental error.

The primary results for these test cases are shown in Figs. 3-1 and 3-2, where the Lagrangian correlation function, the scale length L, the intensity of turbulence $\overline{w^2}$, and the variance of the displacement distributions are shown. Two major features emerge immediately: (a) the growth rate of the "plume," as measured by σ_z^2, is increased by four orders of magnitude when the initial perturbation value is increased by a factor of 5 and the decay coefficient (λ) is decreased by a factor of 1/2 (the model is evidently quite sensitive to these choices), and (b) with equal values of $\lvert w_0 \rvert$ and λ, the growth of the "plume" is dramatically reduced when a non-zero value of β is introduced.

This latter point is of considerable importance, as we attach non-zero values of β to stably-stratified atmospheres. To see the effect of this oscillatory term more clearly, the first 100 time steps of run No. 10 are plotted in greater detail in Fig. 3-3. The initial second-power dependence of σ_z^2 on T and the inflection of this curve are clearly evident. The appropriateness of this result is evident when it is compared with direct measurements of σ_z^2 made in stably-stratified atmospheres at Hanford (Hilst and Simpson [5]). Further measurements are required, but it would appear that the model, primitive as it is, has clearly reproduced a real situation!

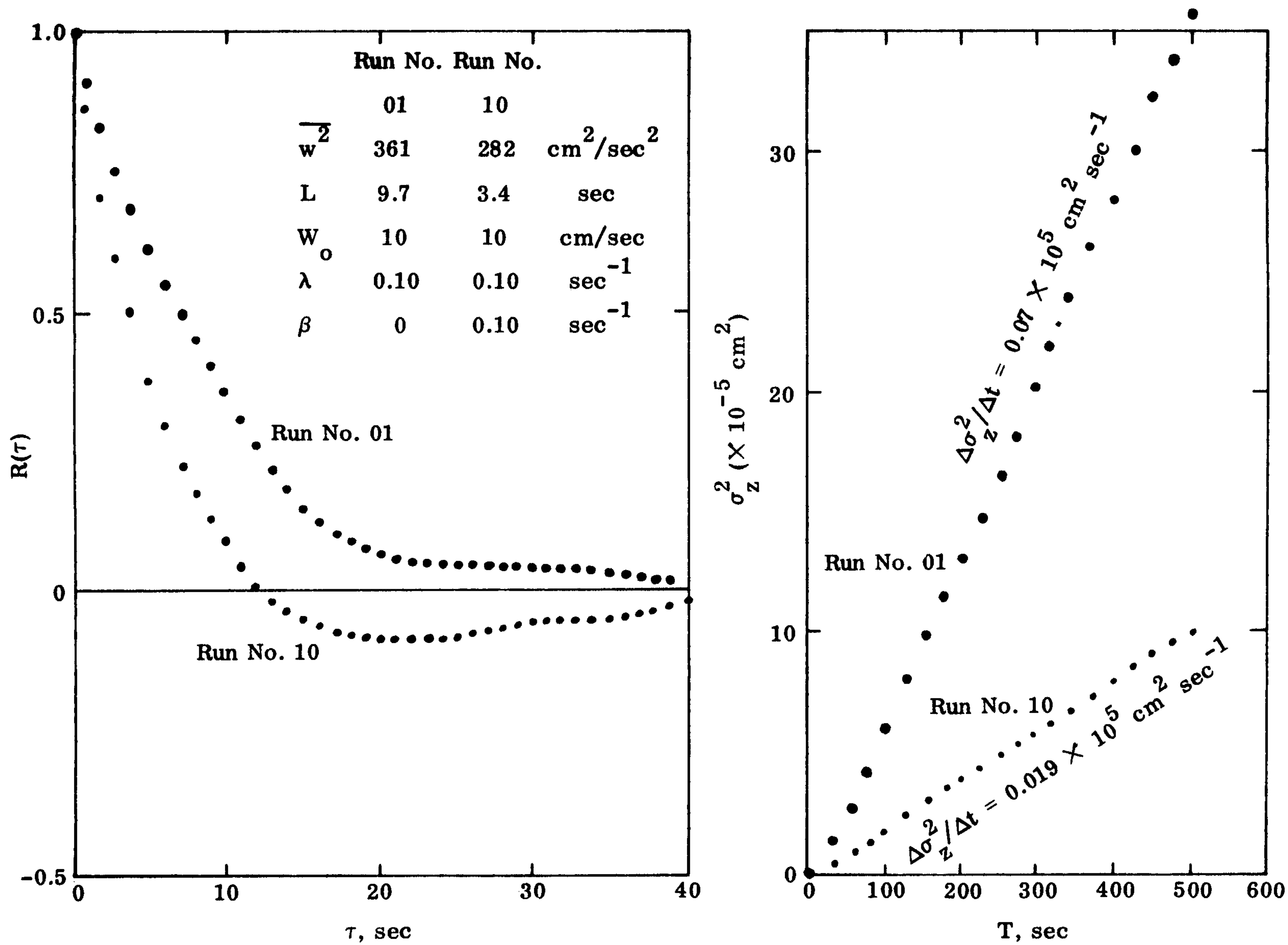

Fig. 3-1. Lagrangian correlation function and variance of particle concentration for situations simulating neutral or unstable (No. 01) and stable (No. 10) atmospheric diffusion.

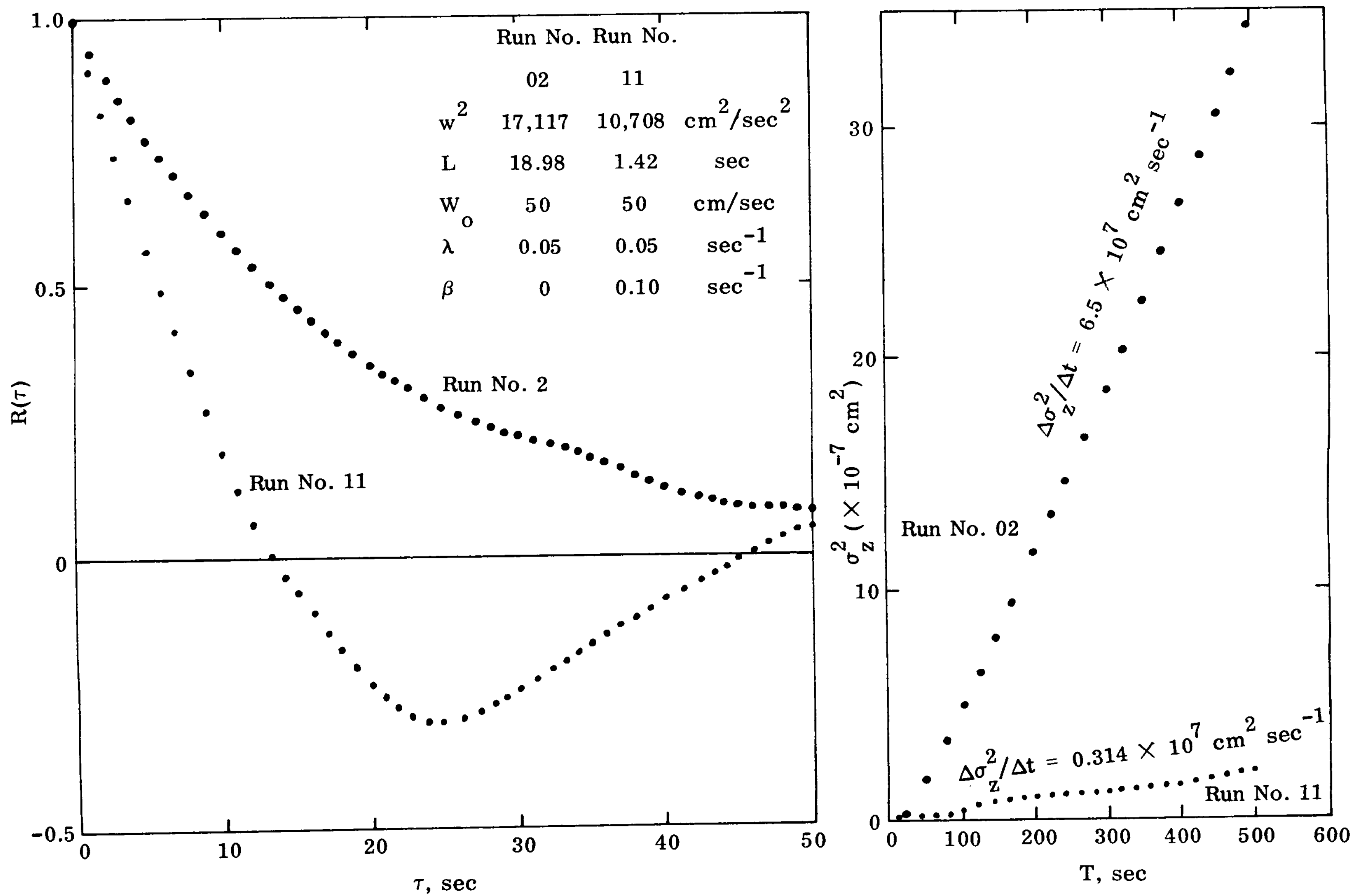

Fig. 3-2. Same as Fig. 3-1, but with increased magnitude of initial turbulent motion and slower decay of turbulence.

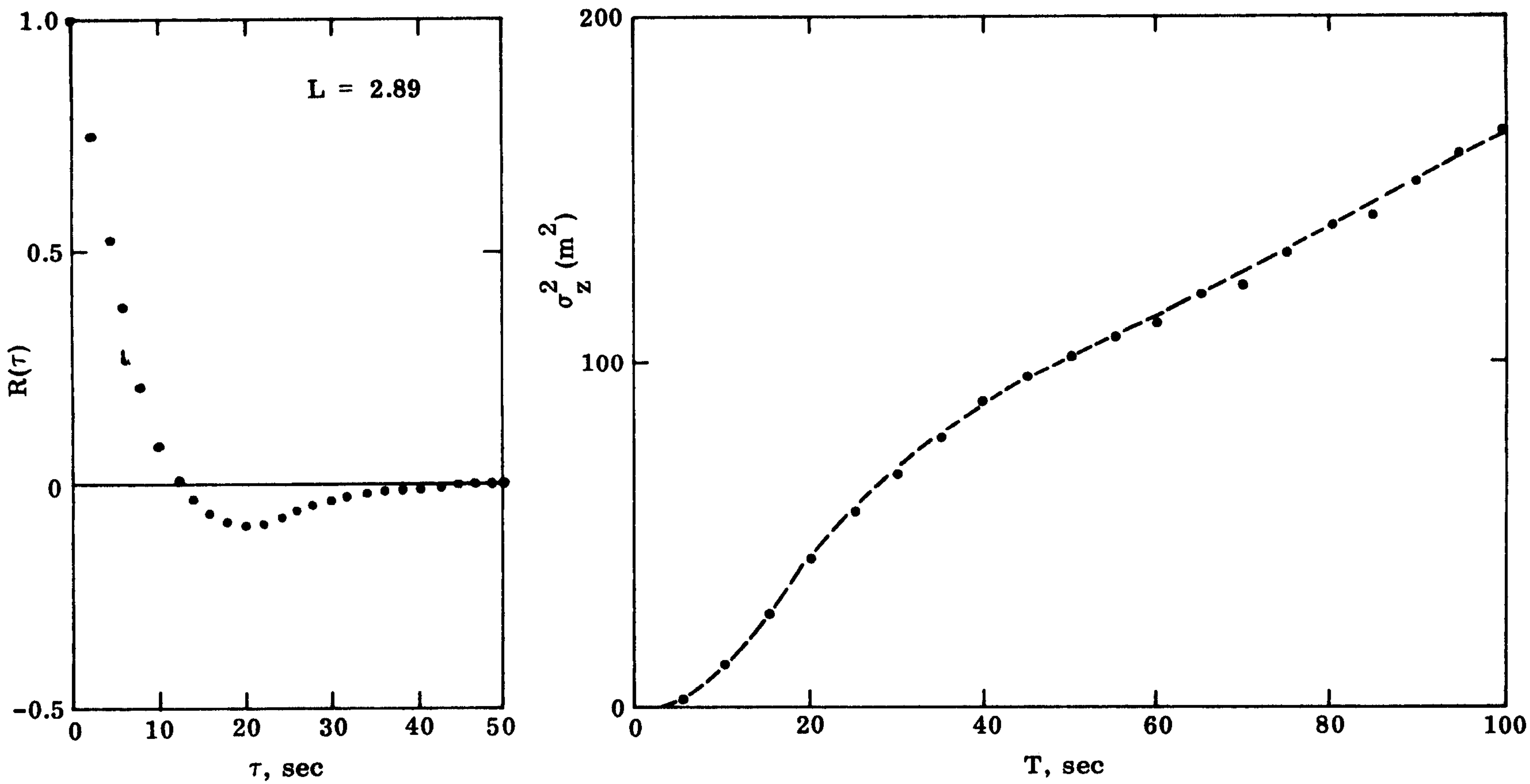

Fig. 3-3. Diffusion results for first 100 sec of stable atmospheric diffusion showing effects of non-zero β values.

3.3.2 Non-uniform Stratification

On the basis of these results, we can now proceed to a simulation of non-uniformly stratified atmospheres by assuming that stably-stratified layers will be characterized by non-zero values of β, and neutral stratification by $\beta = 0$. Intuitive choices of $|w_0|$ can be made, but for these initial calculations we have held this parameter constant at 10 cm sec^{-1}.

Three cases have been chosen for this initial presentation; all of the pertinent information for each is shown in Figs. 3-4, 3-5, and 3-6. While it is easily recognized that these are results of the model, and not the atmosphere, they are identified here according to their atmospheric analogue.

3.3.2.1 An Inversion Cap (Figure 3-4)

For this example, the particles were introduced into an unstably-stratified layer which was capped by a stably-stratified layer. The values of β and λ chosen to simulate these conditions, and the resulting vertical distribution of $\overline{w^2}$ are shown in the upper left-hand frame.

The resulting frequency distribution of particle displacement at times T = 25, 100, and 200 sec are shown in the next three frames. The values of the coefficients of skewness and kurtosis are shown in the lower left-hand frame, the Lagrangian correlation function in the next, and the increase of the variance of the particle displacement as a function of travel time in the last.

The increasing assymmetry of the particle displacement distribution is the key feature of the results. Rapid downward diffusion and a distinct capping of the vertical growth is very clear. These are reflected in the behavior of the skewness and kurtosis coefficients, but are most clearly associated with the vertical distribution of $\overline{w^2}$, to which, of course, they are related. An unexpected feature was the displacement of the height of maximum concentration to the transition zone between neutral and stable stratification. This may be due to the inability of a one-dimensional model to account for mass continuity. The "layering" of smoke and haze at an inversion is commonly observed, however, so this result may be real.

Rotating the stratification parameters 180 degrees about the height of injection causes a similar rotation of the displacement frequency distribution, but does not

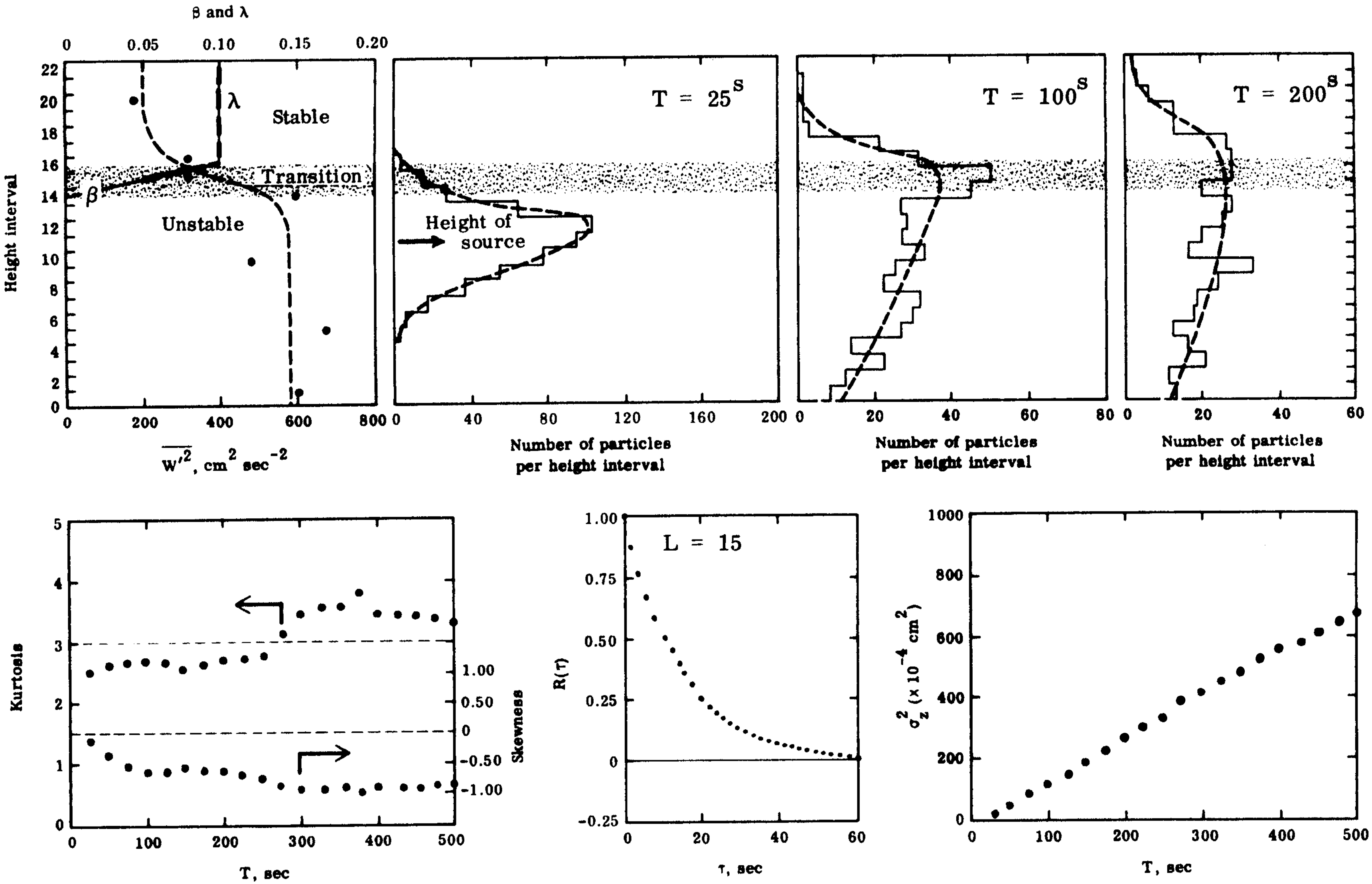

Fig. 3-4. Diffusion statistics and results for the case of particle injection into an unstable layer capped above by a stable layer.

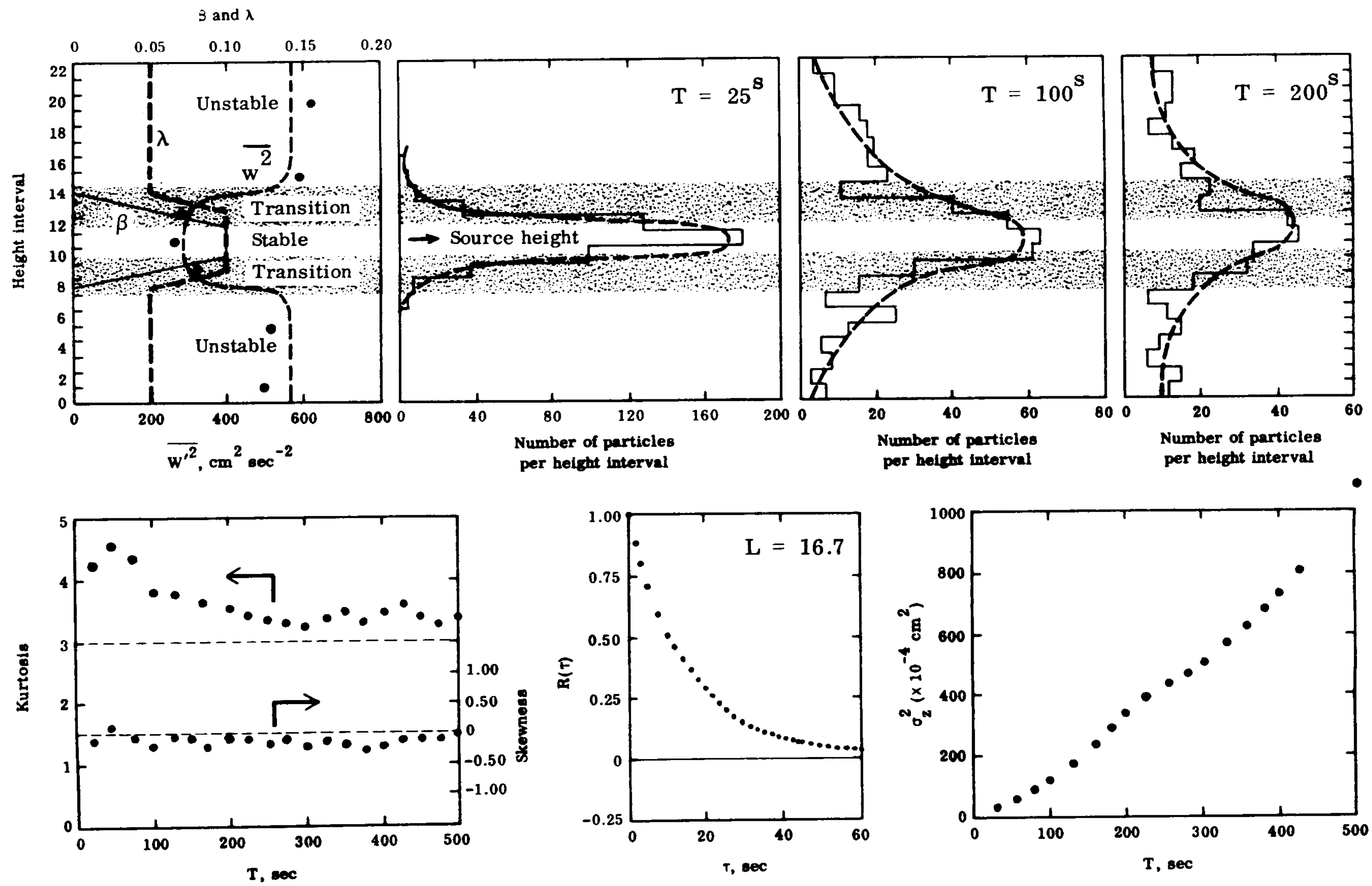

Fig. 3-5. Diffusion statistics and results for the case of particle injection into a stable layer capped above and below by unstable layers.

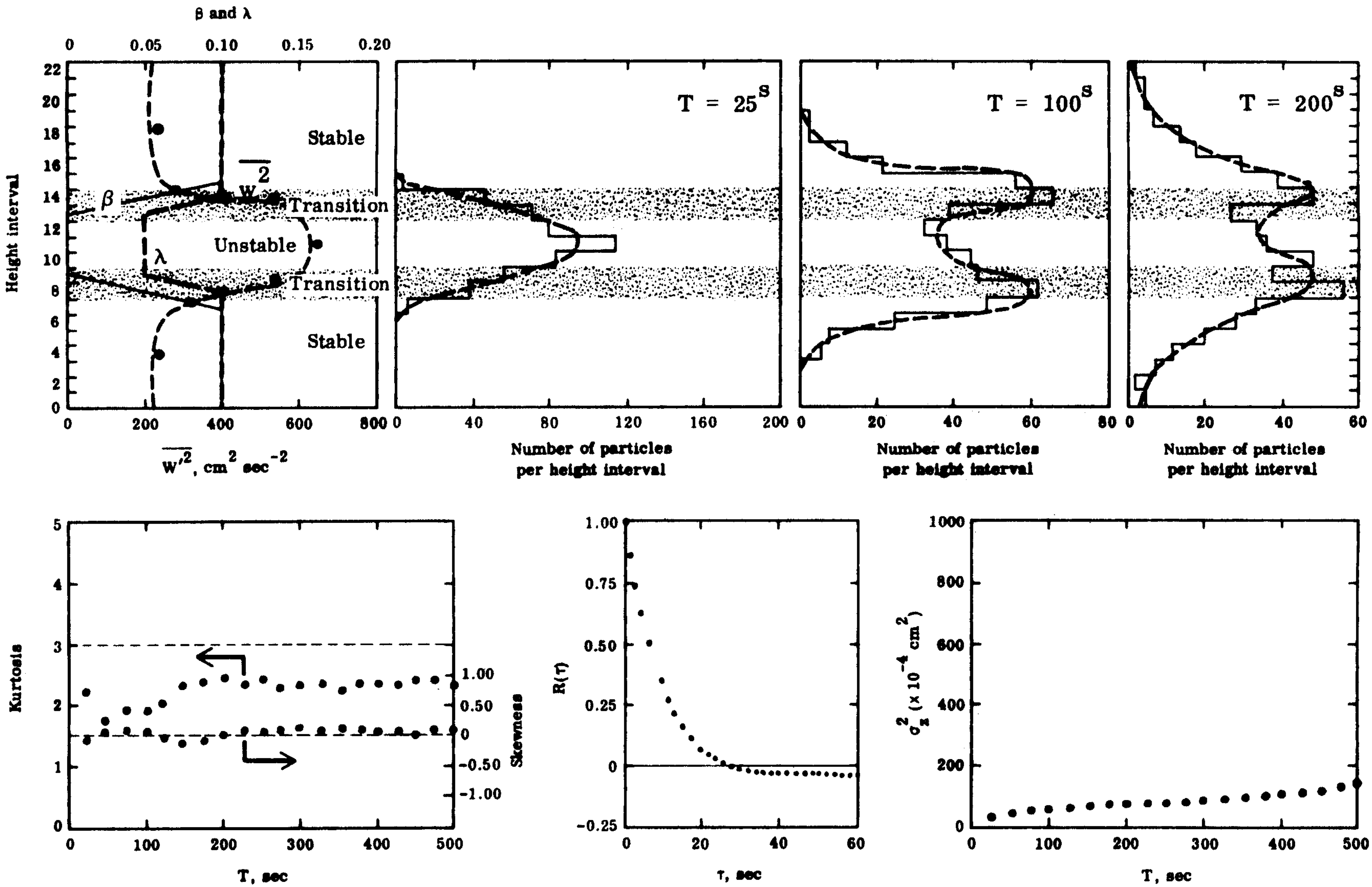

Fig. 3-6. Diffusion statistics and results for the case of particle injection into an unstable layer capped above and below by stable layers.

alter other results. Therefore, this case also represents injection into an unstable layer capped below by an inversion.

Also of interest are the orders of magnitude of σ_z^2. These are directly comparable to σ_z^2 values observed in the atmosphere for similar travel times. This result would suggest that the parameters chosen are essentially of the right orders of magnitude.

3.3.2.2 Injection into a Finite Inversion Layer Bounded Top and Bottom by Unstable Layers (Figure 3-5)

The method of presentation here is identical to the previous case. Because of the symmetry of stability stratification, the particle distributions are also symmetrical (skewness = 0), but the slow rate of growth within the inversion layer, followed by more rapid dispersion of those particles that find their way into the unstable layers, produces a modest degree of kurtosis. The variance of the displacement distributions is again well behaved and of the right order of magnitude.

3.3.2.3 Injection into a Finite Unstable Layer Bounded Top and Bottom by Stable Layers (Figure 3-6)

The results of this run are the inverse of the previous example. Once again the shift of the height of maximum concentration to the transition zones is noted. The primary result, however, is the very slow growth of σ_z^2, reflecting the dominant constraint of slow exchange in the stable layers. At 500 sec, the distribution within the unstable layer was quite uniform, but definite gradients of concentration were still evident in the stable layers.

4.0 CONCLUSIONS

The reality of the results obtained from these first calculations suggests that a significant part of the analogous atmospheric processes have been simulated. Further development and use of the model for sensitivity checks is in order, but the greater requirement is for definitive measurements of atmospheric stability and motion, and accompanying diffusion measurements in the vertical dimension. The tools for such measurements are now available.

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PART II

A PLAN FOR THE DEVELOPMENT OF AN ENVIRONMENTAL HAZARDS HANDBOOK FOR THE SAFE USAGE OF HAZARDOUS FUELS—NASA

1.0 INTRODUCTION

As the need for greater payload capacity in space vehicles increases, more and more attention is being turned to the use of fuel additives capable of improving markedly the thrust/fuel weight ratio. A prime candidate for this role, although not the only one, is liquid fluorine.

The design and engineering of rocket engine and vehicle systems capable of using highly reactive cryogenic oxidants appears to be progressing to a state of satisfactory reliability. However, one further major problem has not been satisfactorily resolved. This is the complex problem of safe handling and usage of toxic fuel additives in terms of potential environmental exposures of man, animals, plants and objects to these fuels or compounds formed in reaction and combustion processes. The potential for such exposures during earth-bound phases of fuel production, transportation and vehicle fueling operations are subject to the controls and precautions developed for producing and handling dangerous materials. However, during scheduled operations of static firing and launch (with attendant probabilities of abort destruction of the vehicle) these materials are unavoidably introduced into the earth's atmosphere.

The primary problems which arise from either deliberate or inadvertent release of quantities of F_2 and HF to the atmosphere are, of course, dependent upon the effects these materials have on humans, animals, plants and inanimate objects. Direct exposure of any or all of these and indirect exposure via ecological chains must both be considered. A major problem which is not well resolved now is the dependence of measureable effects upon both the level and the duration of exposure.

Figure 1-1 represents an attempt to synthesize various tolerance levels of receptors for direct and indirect exposures to airborne F_2 and HF. The types of damage as well as the receptors are shown, and uncertainty limits or, in several cases, total ignorance are also indicated. Quite clearly better definition of short-term effects is required in each of these categories of effects and receptors if reliable control measures for such exposures are to be developed and employed. The work and results necessary to delimit these cause-and-effect criteria for the purposes of NASA's operational control are discussed in Section 3.4.

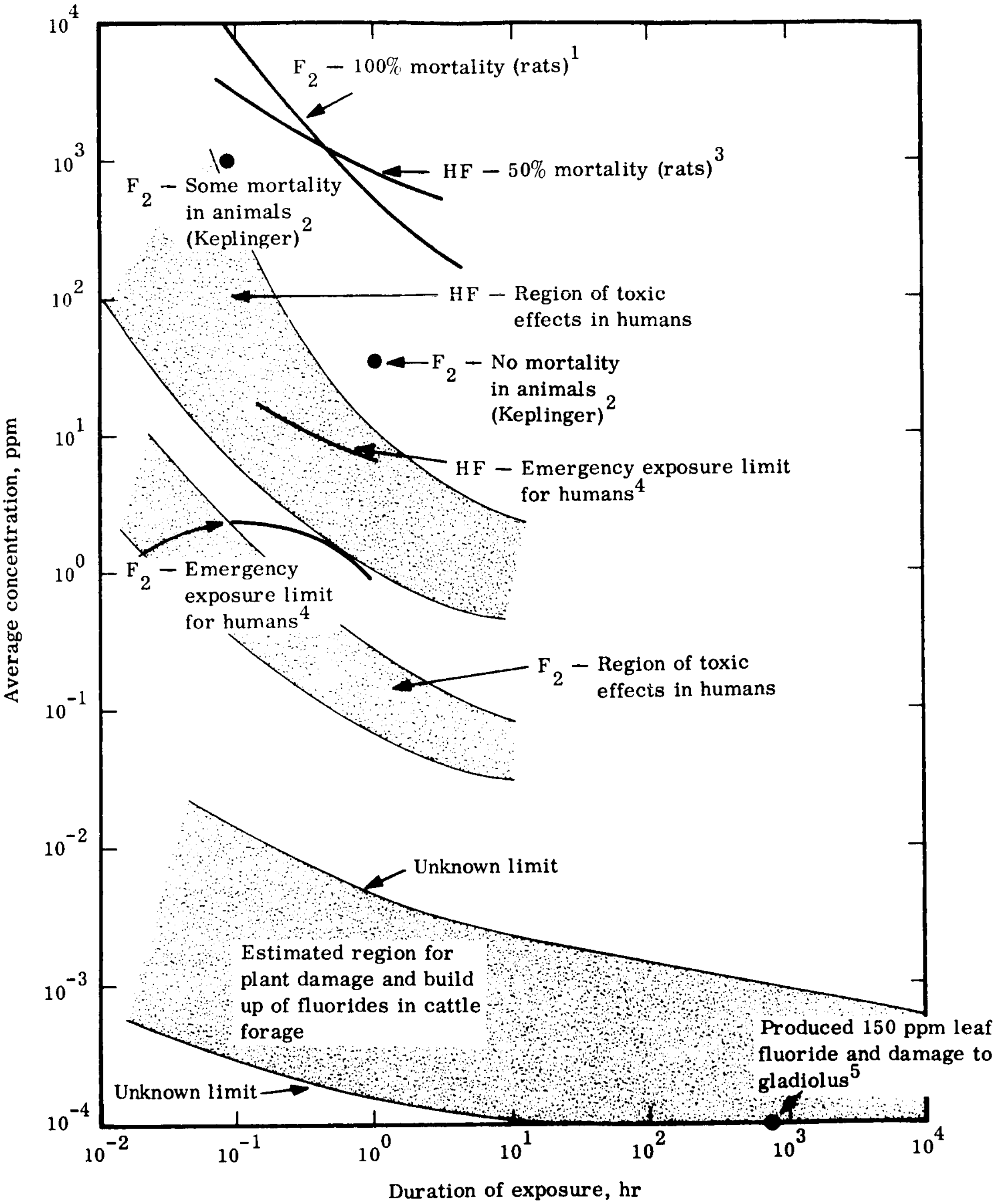

Fig. 1-1. Time-concentration relationships for effects of F_2 and HF.

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Beyond this definition of safe and unsafe conditions, or tolerable and intolerable risks, the major problem which must be solved is the specification of expected airborne concentrations near ground level, given the variety of terrain, meteorological and source conditions under which NASA may wish to employ toxic fuel additives. The various combinations that must be considered are discussed in Section 2.1, but for the present discussion it is important to note that one particular source type, the so-called cold spill, can be clearly identified as the most hazardous in terms of potential maximum exposures in the immediate vicinity of the spill site. Exposure rates of the order of 10^2 to 10^5 ppm for periods of minutes and to distances of the order of 1 to 3 miles can be expected if several hundreds or thousands of pounds of F_2 are spilled on clean surfaces. These exposure rates are clearly in excess of tolerance limits which can be reliably defined from the data presented in Fig. 1-1.

Unless the probability of inadvertent spills of F_2 can be reduced to acceptable risk levels, or the amount spilled in any one incident can be controlled to less than a few hundred pounds, this potential source sets the limit on routine operational use of F_2 as a fuel additive. Operational use is not precluded, but the exclusion and control area which must be set up to assure safe usage (i.e., no damage to non-NASA personnel and property) dictates government owned property well removed from cities and active farms.

Given a satisfactory resolution of this cold-spill problem, other activites using F_2 pose lesser but still critical potentials for environmental exposures. These are discussed in Section 2.2, but it can be noted now that within reasonable operational limits, hot spills, conflagrations, static firings, and normal launch operations pose environmental exposure rates in the range from 10^{-3} to 10 ppm. These are in the noticeable but lesser effects categories illustrated in Fig. 1-1.

We must immediately emphasize and re-emphasize that both the tolerance limits estimates and the expected exposure rate estimates are subject to an intolerable uncertainty now. We simply do not know the expected exposure rates for the less than 1-minute to five-minute exposure period to within one order of magnitude; and the uncertainty on the estimate of effects levels is probably greater than one order of magnitude.

However, preliminary estimates of all these components of the environmental hazards problems suggest that with adequate control on fuel handling and reasonable flexibility for choice of operational times and places, F_2 can be used safely and effectively. The exact extent of limitations that must be imposed to realize the benefits of substantial thrust increases without penalizing fuel weight load, and all without over-riding costs of environmental damages or control, cannot be estimated precisely until the program planned here has proceeded toward completion. With this qualification, and recognizing the degree of conjecture involved, we can note the following general expectations:

(a) Cold spills in amounts greater than a few hundred pounds will present high risk exposure conditions up to several miles from the spill area in all meteorological and terrain conditions.

(b) Hot spills and conflagrations involving very large amounts of F_2 will cause intolerable environmental exposures only in the immediate vicinity of the conflagration.

(c) Static firing operations involving between 10^4 and 10^6 pounds of fuel pose a complicated choice of meteorological and source conditions (due to combined effects of buoyancy and source strength) but can generally be conducted safely at least half of the time.

(d) Normal launch operations also involving 10^4 to 10^6 pounds of fuel pose a marginal exposure problem to a presently indeterminate distance from the launch site, but probably to no more than a few miles.

All of these and other more specific operational limitations must be made more reliable by a program of experimentation and analysis. The component parts of such a program, culminating in the preparation of a comprehensive Environmental Hazards Handbook, are described and planned in the present document.

In at least one major aspect, NASA's environmental problem goes well beyond the classes of problems studied in previous investigations. This can be identified as the very large amount of heat generated in hot sources and its impact on the vertical motions of exhaust or combustion products. Studies have failed to provide reliable methods for estimating height of rise and resultant vertical distributions of exhaust products when they come into density equilibrium with the ambient atmosphere. As a result, it has been necessary to design an experimental system of multi-color (or other distinguishable property) tracers for experimental determination of this buoyant contribution to ground level exposure levels. In order to implement this part of the planned program it will be necessary to develop a multi-tracer system. The prospects and problems are discussed in Section 3.2, but it is our considered opinion that an intensive development program will provide this necessary experimental tool.

The plan presented here, when carried through, will result in a comprehensive handbook which specifies operational constraints dictated by environmental constraints. The scheduling and time-phasing of the work required have been set to produce such results within three years of the initiation of the program. Partial results will be forthcoming within this three-year period, but this schedule has not been adjusted to accommodate a specific engine or vehicle development schedule. The largest uncertainty in costs is in the availability of facilities that can simulate the heat sources generated by medium to large rocket engines (tens-of-thousands to millions of pounds of fuel per minute) and in the development costs of more sophisticated tracer systems for atmospheric transport and diffusion measurements.

2.0 THE PROBLEMS

2.1 NASA Operational Configurations and Sites

An analysis of the fuel handling and engine test and launch configurations that NASA may wish to employ shows five major source types:

(a) A cold spill (inadvertent)

(b) A hot spill (inadvertent)

(c) Vehicle or test stand destruct with conflagration (inadvertent)

(d) A normal static firing (scheduled)

(e) A normal vehicle launch (scheduled)

Of these eventualities, the first two are associated with fuel handling operations and could therefore occur at any time and place where such operations are conducted. The latter three possibilities are associated with scheduled engine and vehicle operations and are generally subject to controlled scheduling at the few sites capable of conducting these operations.

A general analysis of the dependence of subsequent environmental exposure levels upon the mode and magnitude of the source and the meteorological variables has been presented by Hage and Bowne [1]. Because of the sensitivity of the source-atmosphere system to the range and variability of atmospheric stability, wind velocity, and surface conditions (such as roughness, vegetation and locally induced flow patterns), consideration must also be given to major variations in geographical conditions.

The combinations of sources, atmospheric variabilities, and terrain conditions that must be included for comprehensive coverage of NASA's operational requirements are summarized in Table 2-1. This analysis reveals 30 presently definite operational configurations and an additional 15 configurations that may be required in the future. A comprehensive operational handbook must be applicable to all 45 combinations unless some can be ruled out on other criteria (e.g., normal launch in mountainous terrain, adverse effects of sound propagation).

2.2 Environmental Hazards Posed by Different Sources

As part of the analysis and synthesis of NASA's operational problems in the context of environmental hazards, models of source configurations and atmospheric processes were constructed and solved for the flat terrain (Plain) case [1]. These

TABLE 2-1
COMBINATION OF SOURCES, ATMOSPHERIC VARIABILITIES, AND TERRAIN CONDITIONS

Terrain Type	Plain			Mountainous			Coastal		
Atmospheric Stability*	S	U	Loc	S	U	Loc	S	U	Loc
Source Type									
Cold Spill	x†	x	x	x	x	x	x	x	x
Hot Spill	x	x	x	x	x	x	x	x	x
Static Firing	?	x	x	?	x	x	?	x	x
Normal Launch	?	?	?	?	?	?	x	x	x
Launch Abort	?	?	?	?	?	?	x	x	x

* S = stable, low diffusion capacity
U = unstable, high diffusion capacity
Loc = local circulations (e.g., sea breeze, marine inversion)
† x = present definite requirement
? = possible future requirement

models and their solutions are for the most part useful only in defining first order sensitivities of environmental exposures to the many source-atmosphere variables involved. THE RESULTS ARE CLEARLY UNRELIABLE FOR OPERATIONAL CONTROL NOW. However, the results also point clearly to the areas of uncertainty and ignorance that must be clarified before reliable guidelines can be established.

2.2.1 The Cold Spill

Of all the configurations that must be considered, the cold spill is by far the simplest and most amenable to solution from previous work. The source of toxic material is generated by evaporation from an exposed surface. The resultant gases are essentially in density equilibrium with the atmosphere and travel and diffuse at or near the surface of the earth.

Figure 2-1 shows the expected ground level concentration as a function of distance from the source. Recent work by Lewis Research Center-NASA [3] and by General Dynamics [4] show that the evaporation rate for F_2 spilled on clean surfaces rises rapidly to a maximum and then decreases with time after spill. This modification can be included in the models. The primary requirement for refinement in this

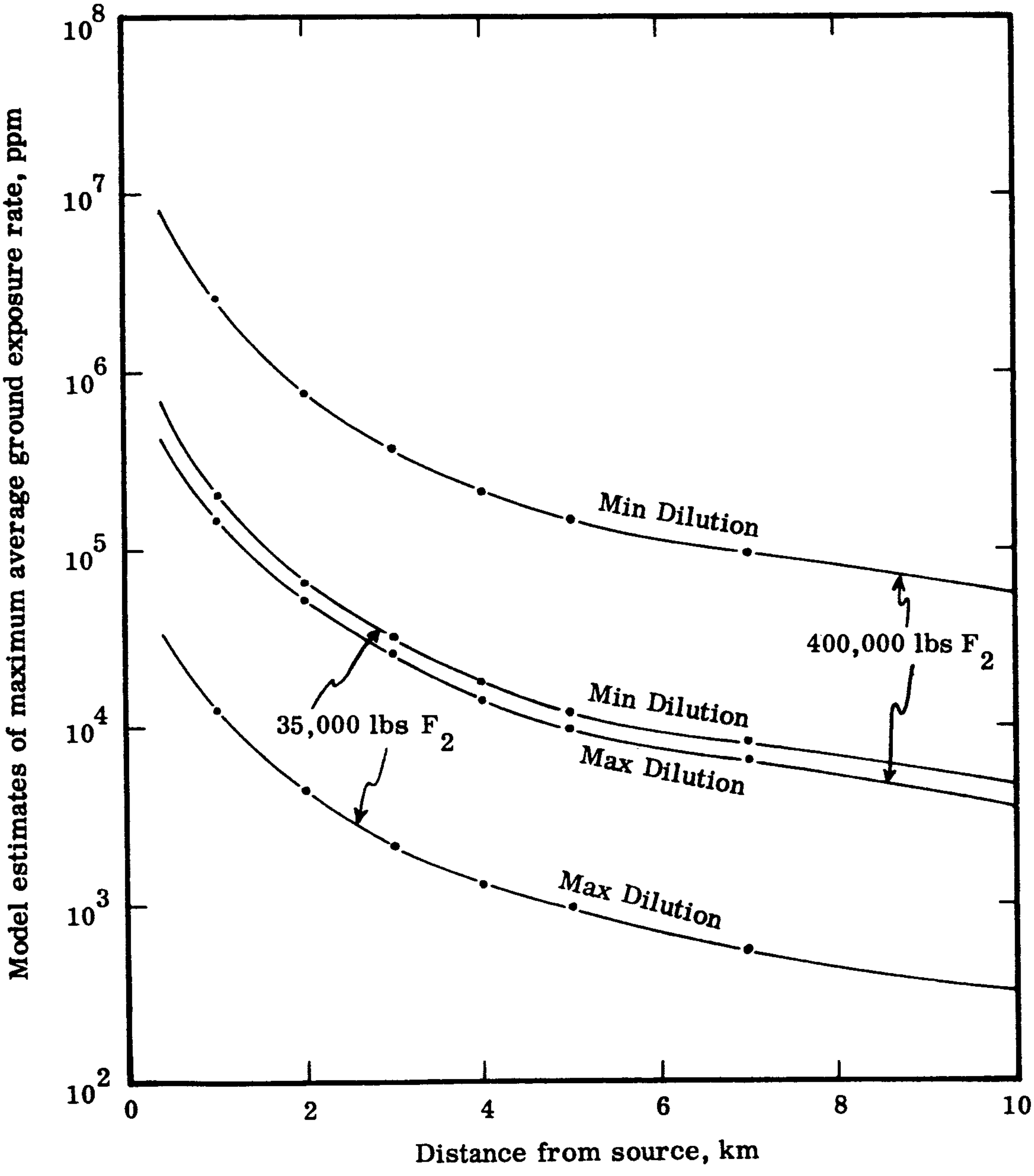

Fig. 2-1. Cold spill

Estimates of ground level concentrations at various distances from site of a cold spill of F_2 as a function of atmospheric dispersion. Numbers derived from model reported by Hage and Bowne [1]. Duration of exposure is approximately one-half hour.

particular mode of release is incorporation of more accurate coefficients of diffusion rates at specific sites. These should be obtainable with a minimum measurements program at each site.

2.2.2 The Hot Spill and Engine Exhaust Cases

The case of the hot spill (and all remaining source configurations) involves consideration of large heat releases (and, frequently, forced jets) at the source. In these cases a large buoyancy force causes the source material to rise above the surface, where, eventually, it comes into density equilibrium with the atmosphere and is transported and mixed downward and laterally by turbulent motions. The ground level exposure pattern depends critically upon the height to which the source material rises and the rate at which it is mixed downward by atmospheric turbulence. The airborne concentrations also depend upon the amount of material injected at the source and, since there is a relation between the amount of material released and the heat generated (buoyance), there is a tendency to cancel the advantage of height gained by buoyancy. It is also generally true that the position of the maximum ground level exposure moves downwind as the source strength is increased.

These features are illustrated clearly (and, again, within the limitations of the models employed) in Fig. 2-2 where the maximum average ground level concentrations and the distance to the maxima are plotted versus source strength for the cases of hot spill, static firing, normal launch and launch abort near the earth's surface. In the normal launch situation, the maxima are observed at the launch site. (Hot spill and launch abort are combined in Fig. 2-2 because the source simulation was the same.) It is also significant to note that the values of the maximum average ground level concentrations produced by the model are within or close to the emergency human exposure limits established by the National Research Council for HF (e.g., 30 ppm for 5 min , 8 ppm for 60 min) [5].

These results provide the first guidance to optimum operational decisions. For example, static firing tests of engines burning between 5×10^4 to 5×10^5 pounds of fuel per two minutes should be scheduled for times when atmospheric dilution is a minimum (generally at night time, under stable conditions) since the maximum exposure is one to two orders of magnitude less than exposures predicted for neutral and unstable

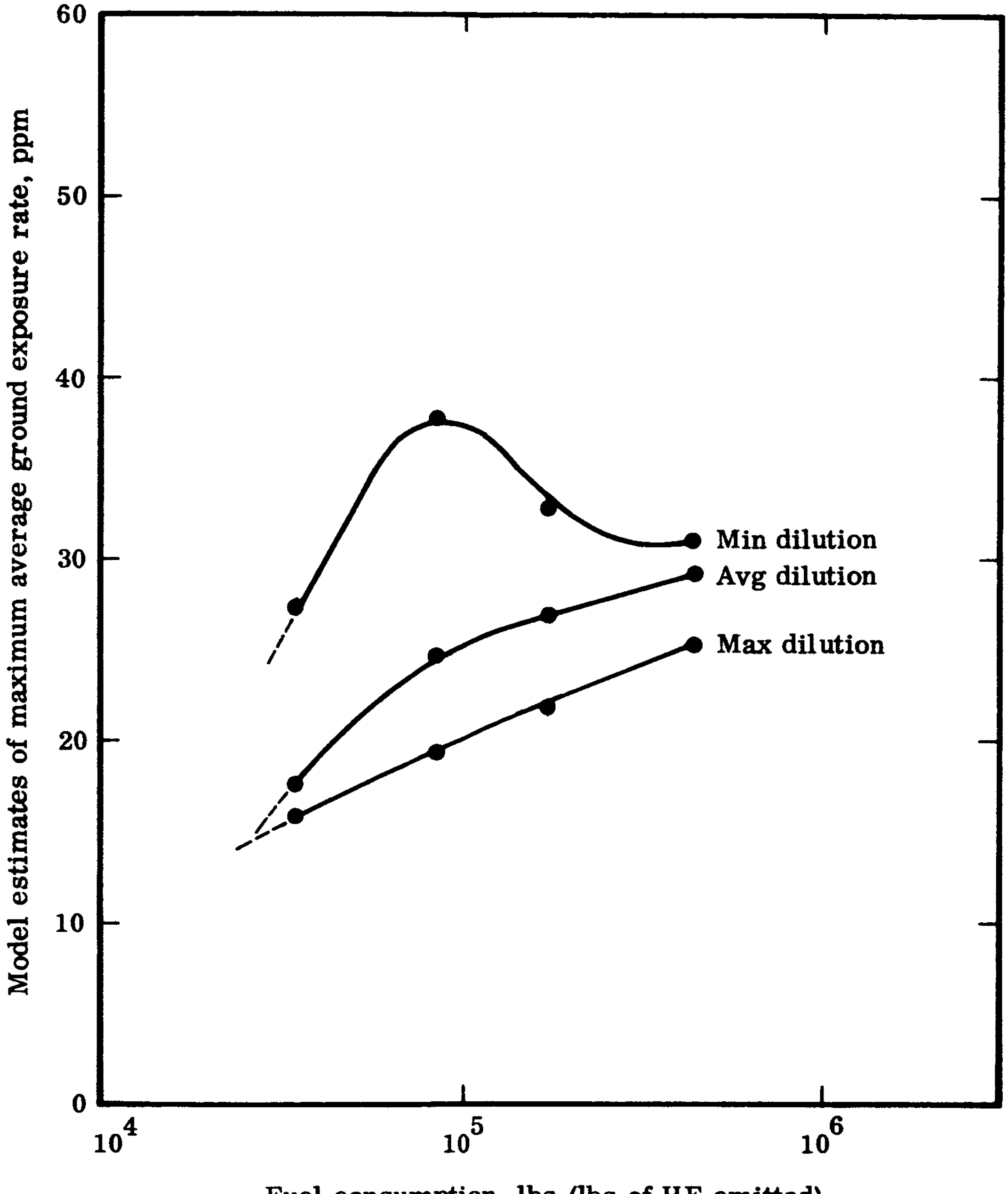

Fig. 2-2a. Launch cases

Estimates of maximum ground level concentrations of HF for normal launch of various size engines and vehicles (Hage and Bowne [1]. Duration of exposure is approximately 5-10 min.

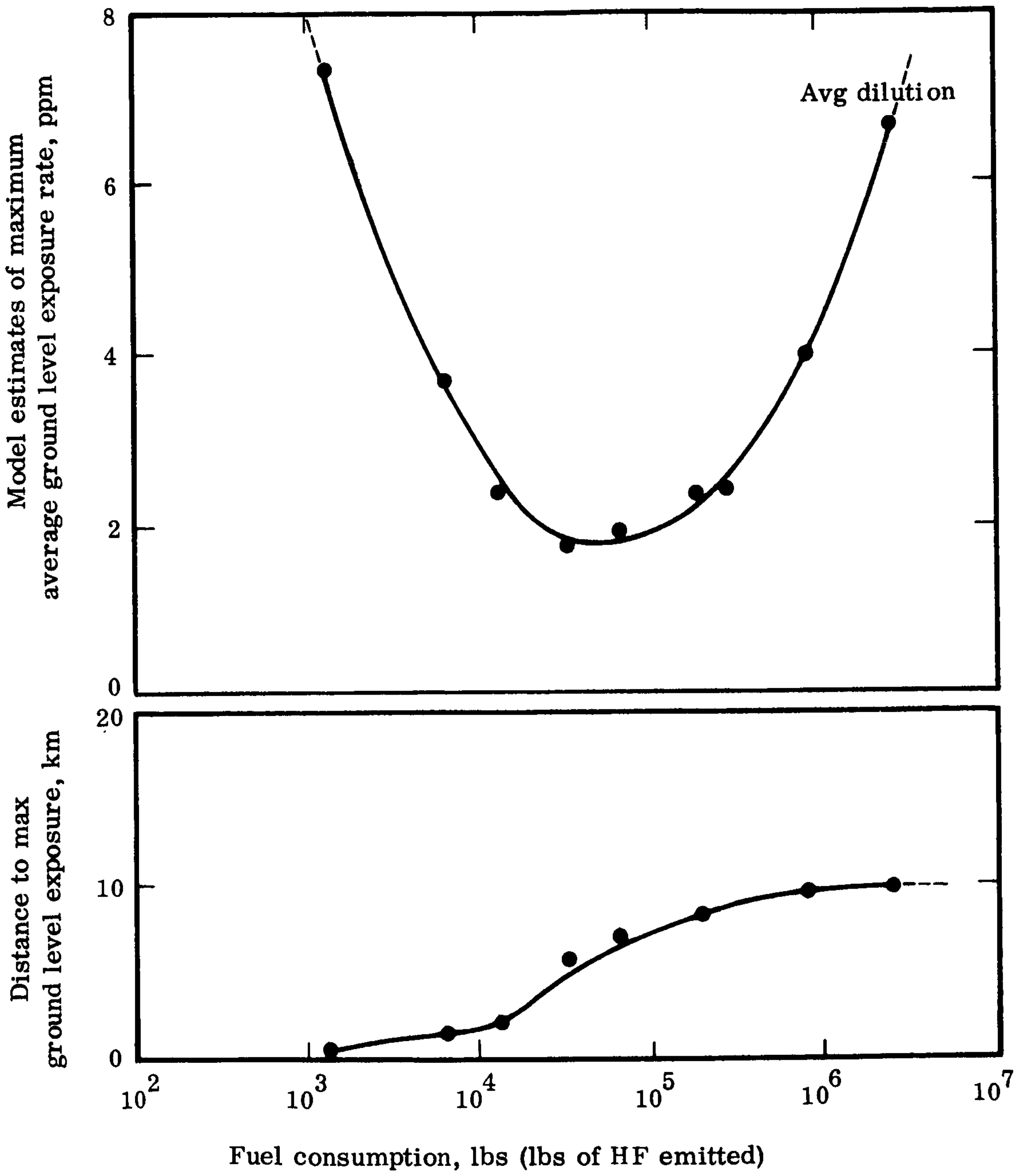

Fig. 2-2b. Conflagration

Estimates of ground level concentrations for hot spills and surface conflagrations for various size engines and vehicles or spill amounts, and estimates of distance of maximum exposure from conflagration. Duration of exposure is 2-5 min.

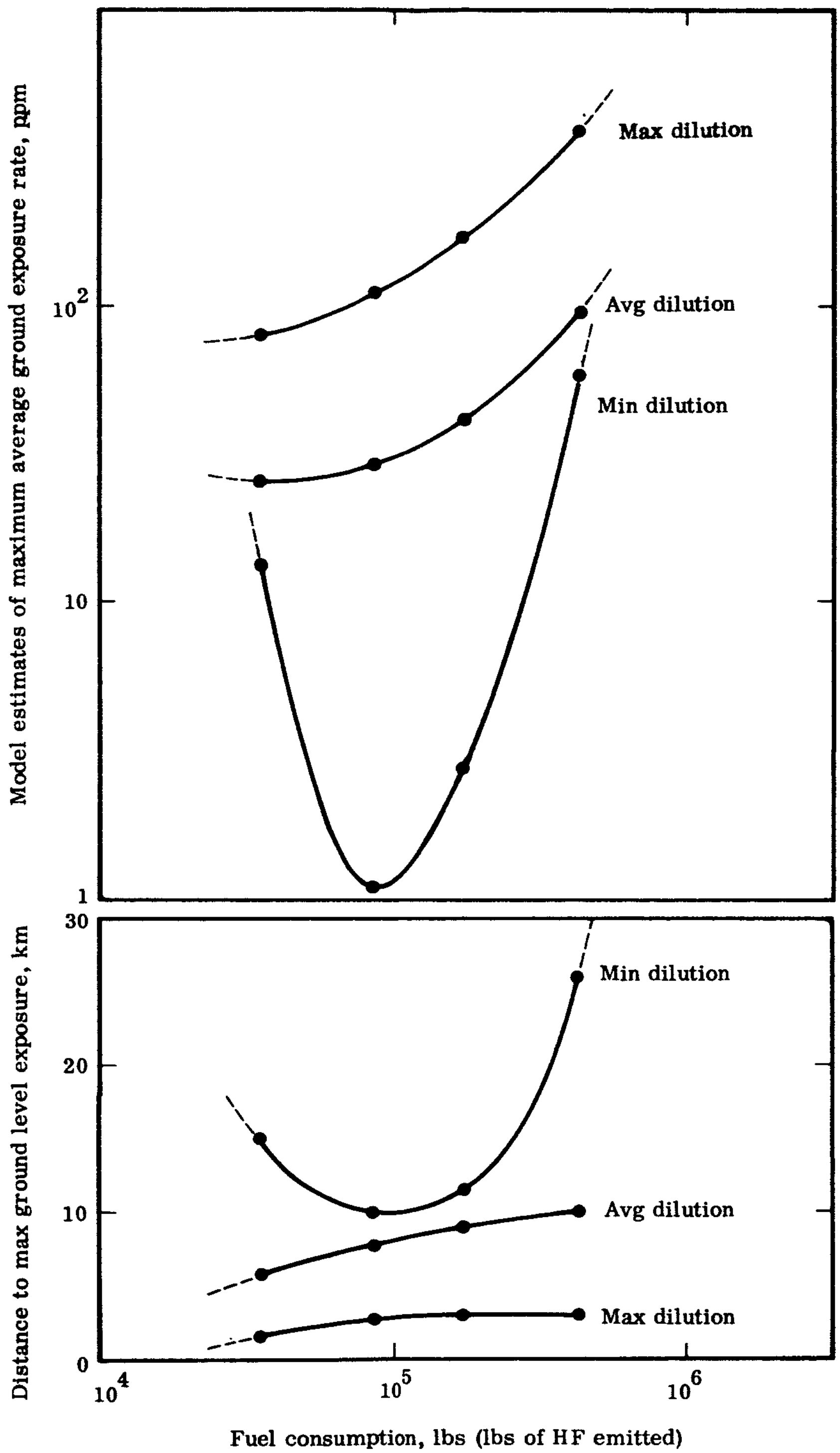

Fig. 2-2c. Static firing

Estimates of maximum ground level concentration and distance to this maximum from normal static firings under various atmospheric dispersion and fuel consumption conditions.

atmospheric conditions. Clearly, however, stable atmospheres should be avoided when fuel expenditure rates exceed 10^6 pounds/2 minutes.

These are the first indications of useful prediction systems, BUT THEY MUST BE VERIFIED AND REFINED BEFORE THEY CAN BE USEFULLY EMPLOYED IN LOCATING AND SCHEDULING THESE OPERATIONS. The bulk of this plan is directed toward this refinement and extension of knowledge and its synthesis into an environmental hazards handbook for NASA operations.

2.3 Source-Atmosphere Problems

An analysis in depth of the source-atmosphere system has shown two major problem areas which must now be defined by full-scale experimental methods.

2.3.1 The Buoyancy-Source Phase

Except for explosive releases of large amounts of energy in nuclear detonations, the heat sources represented by medium to large rocket engines are beyond the range for which reliable scientific and engineering solutions have been developed. Prediction of height of rise, ascent rates and entrainment-detrainment of source material and air during the buoyant phase depend so critically upon atmospheric density stratification, wind shear, and turbulent entrainment or mixing rates that reliable solutions are not available. This problem must now be approaced with full-scale experimental measurements.

In the context of NASA's environmental exposure problem, the critical feature of the buoyancy phase is the determination of the spatial distribution of exhaust or combustion products as they come into density equilibruim with the atmosphere. A suggested experimental method for measuring these distributions from hot spills and static firings has been outlined and is included as Appendix A to this report. The method does depend upon a facility which can generate heat and jet situations that duplicate rocket engines and hot spills. An intensive measurement program should be necessary at only one site, however, if the pertinent meteorological conditions at that site embrace the range to be expected elsewhere.

The distribution of combustion products from launched vehicles can only be measured at launch sites. Inability to fully instrument a launch site and difficulties in injecting compatible tracer material into engine exhausts will dictate a different experimental method to characterize the launch-source plume. A method of direct measurement must be developed.

2.3.2 Vertical Diffusion Rates in the Lower Atmosphere

Despite intensive efforts, both theoretical and experimental, the vertical diffusion of airborne material in the presence of non-uniform density stratifications and wind shears is not well known. These state-of-the-art limitations in the context of NASA's environmental hazards problem have been analyzed by Hage and Bowne [1]. Included in this study are the requirements for experimental data needed to verify and extend existing theories. The meteorologist is now in a position to provide such experimental data, primarily because of recent advances in techniques for measuring the vertical distribution of tracer materials at sequential distances from their sources. The present plan includes an intensive experimental approach to this problem, with experiments undertaken at one site chosen to provide the full range of atmospheric stability and wind shear.

2.4 Receptor Problems

The limits of environmental exposure to potentially harmful materials are inevitably set by the tolerance of the most sensitive receptors that are of value to man. In the case of fluorine compounds, particularly HF, this limit appears to be set by the ability of plants to concentrate this compound in their leafy structure; when eaten by animals, these materials produce fluorosis with attendant rapid tooth decay and eventual starvation. This ecological chain is not well defined for brief but high exposure to airborne fluorine compounds, and must be re-examined from this point of view.

Limits of direct exposure (inhalation and skin reactions) also exist for man and lower animal life forms. Again, however, the tolerance limits for very brief exposures (which are characteristic of most NASA sources) are not well known. Further intensive efforts must be expended on reliable definition of short-term exposure tolerance levels for appropriate fuel products. Until better information is available, conservative limits must be imposed.

3.0 THE EXPERIMENTAL APPROACH

Limitations of existing theory, or of the verification of the theory, require that an experimental approach be employed in attacking the problems outlined in the previous section. To meet these requirements, this development plan embraces facilities in four areas of activity:

(a) A design and analysis group responsible for the definition, coordination and synthesis of all studies and activities and the preparation of the Environmental Hazards Handbook.

(b) A major experimental facility at which all experimental methodology for full-scale simulation of source configurations and meteorological variability can be employed.

(c) Secondary experimental facilities at which partial experiments can be performed. These will be generally chosen for major terrain and vegetation variations.

(d) A toxicology and effects study group to seek improved definition of the effects of toxic and reactive agents, with particular attention to the short-term modes of exposure at relatively high concentration levels.

While the choice of management and administrative systems for this work is a NASA policy decision, a prime requirement is to assure that technical control and integration of the program is vested in a competent design and analysis group of unquestioned objectivity. The development program should be administered by a single agency within NASA which has responsibility for the environmental facets of NASA operations.

3.1 The Design and Analysis Activity

This group is visualized as the technical focal point for the entire program and must include those who will prepare the final handbook. The first task for this group will be to define the program in detail, including final experimental configuration design and operation. During laboratory and field operations these people will continue theoretical developments, monitor quality control of experimental operations, modify experimental designs in light of early returns, and systematize the data handling and analysis operations.

It is estimated that a group of seven professional people, including the technical leader and senior and junior professionals in the fields of source specification, atmospheric dispersion processes, test technology, and toxicology, will be required. In addition, supporting personnel and approximately 500 hours of EDPM time per year will probably be necessary.

3.2 The Primary Experimental Activity

The major effort required to produce reliable operational guides should be concentrated in this activity. Every effort should be expended to simulate the range of operational conditions with which NASA will be required to contend, and to measure all uncontrolled variables with the completeness and precision that will provide understanding of the processes by which environmental exposures are generated.

3.2.1 Objectives

Specific objectives of this program are:

(a) to define the height of rise and the vertical distribution of combustion products for spills, conflagrations, static firing and launch of vehicles or engines whose fuel consumption rates are in the range of 10^4 to 10^6 pounds/minute (solid fuel as well as liquid should be considered);

(b) to define the vertical and lateral mixing of combustion products in the atmosphere with particular emphasis on ground-level exposure rates for very short periods of exposure (a few seconds to five minutes);

(c) to define the contribution of wind velocity variability, including vertical wind direction shear, to the magnitude and distribution of short-period exposure rates at ground level.

3.2.2 Facilities

To achieve these objectives, an unrestricted experimental facility is required. Major installations are:

(a) a comprehensive instrumentation network for the measurements of pertinent meteorological variables throughout the airspace involved in the transport of exhaust material;

(b) a large network of sensors (of the order of 500 to 1000) at the surface and aloft for the collection of air-tracer materials;

(c) assay facilities for the collected samples of air-tracer materials;

(d) source generators to create the equivalent of real sources, with provision for the tagging of the latter sources with tracer materials;

(e) restricted facilities for the exposure of potential receptors to toxic sources associated with proposed fuels.

The experimental facility will need a large site with a number of major features:

(a) relatively flat terrain without major vegetation cover (trees) extending at least ten miles in all directions from a central source point. Access for spot measurements at distances up to twenty miles or more may also be required;

(b) capability for unrestricted flights of tethered balloons, helicopters and other aircraft to 5000 feet above terrain over the primary experimental area. Clearance for flights by small rockets to higher elevations may be required. Fixed tower installations to 500 feet above terrain should also be permissible;

(c) access within the primary area for operation of air sampling and meteorological equipment and for undisturbed soil and vegetation samples;

(d) transportation facilities for heavy equipment and large quantities of fuel.

Several sites have been examined with these requirements in mind. Two possibilities emerge as the strongest candidates, either an inland, semi-arid site in the intermountain or plains states, or a coastal plain site along the Texas Gulf coast. Between these, the greatest meteorological variability and readiest access for experimental control is found at inland sites. However, local circulations induced by land-sea contrasts are found only at coastal sites. Since these local circulations represent a second order effect on trajectories, and these can be measured in a separate experimental effort, the inland site appears more advantageous as the primary experimental facility. Descriptions of available sites are included in Appendix B to this plan.

3.2.3 Required Development

An extension of the present state-of-the-art in tracer systems will be required for a maximum return on expenditures for experimental programs. Presently established methods for the creation, collection, and assay of tracer components in a gaseous material diffusing through the atmosphere will support only a minimum program. Two zinc sulfide fluorescent particulates have been used extensively for air tracer studies but, while inexpensive in themselves, require an expensive visual assay procedure. Their fluorescent colors are yellow-green and green. These are quite adequate to study the evaporative cold-spill or storage leakage problems. An inexpensive material with a color in the orange or orange-red portion of the spectrum could be added for a vertical simulant plume or alternatively, a more expensive vanadate or silicate could be used as a tracer for real-source vertical plumes. This is either currently within, or a minor and predictable extension of, the state-of-the art.

The extension of technology for the fully adequate study of hot spills, static vehicle tests, and vehicle launches is most desirable and will require rapid development along several lines. These are:

(a) the development of a six-tracer system and associated collection and assay techniques consistent with a large scale operation.

There are three plausible approaches:

(1) Select a group of three visually separable fluorescent materials (e.g., the zinc/cadmium sulfides) and another group of three with colors matching the first. The two groups would be discriminated by a non-color technique such as infra-red sensitivity of emission, phosphorescence decay, or even selective solubility. Materials would be inexpensive, but assay would be visual and therefore expensive.

(2) Basically, use the same approach as in (1) except to select from more expensive materials whose fluorescence is contained within restricted and mutually non-interfering spectrum bands. With two distinguishable groups of three spectrally-separable colors, a machine

approach to assay becomes feasible. Material cost would be moderate, but assay cost would be low compared to a visual approach.

(3) Select or develop a group of six narrow-band fluorescent emitting materials (the rare-earth vanadates are examples of such materials) and a machine system for light separation and assay. Development of an array of such materials may be lengthy and expensive. The materials themselves are expensive, but the machine assay costs should be low.

(b) The selection of a compatible tracer which will survive the combustion process.

This is likely to be a rare-earth vanadate.

(c) The development of techniques to inject or include the tracer selected in (b) into combustion products.

There are two circumstances: the hot spill and the static test. Tracer can be added to static-test exhaust products by injecting a tracer-carrier slurry as a high velocity spray into the exhaust plume at the lip of the flame deflector. Addition of tracer material to the products of a spill conflagration depends upon the mode of simulation. One approach would be to mix the tracer material into one of the components of a liquid fuel source, another to include the material in a solid fuel mix.

(d) Develop a combination source—measurement system to define the combustion product plume just after a vehicle launch, if (b) and (c) cannot form the basis of a system.

The addition of particulate tracers to the exhaust of a launched vehicle may pose severe engineering and reliability problems. Instead, one may be restricted to a gaseous material, either a normal product of combustion (e.g., CO_2) or a product (such as SO_2) of a deliberate fuel impurity. An associated airborne system of collection and measurement is also needed, as launch sites would not be instrumented with surface arrays of collectors and a gaseous tracer system does not, in any case, lend itself to such an approach.

(e) The development of a technique for creating a vertical plume of tracer material as a simulant of exhaust products.

Candidate vehicles are rockets, helicopters, drop-generators, and balloon-cable borne generators.

3.2.4 Activation and Scheduling

Approximately nine months will be required to bring the primary experimental facility to complete operation. The experimental requirements of varying meteorological conditions and source types dictate an extensive field operation. Primary experimental efforts would begin during the first year of operation (the tenth through the twenty-first month). A six month period for further experiments of a special nature (as dictated by earlier results and interaction with secondary experiments) will complete this primary experimental activity.

3.3 Secondary Experimental Activities

While the primary measurements of source-atmosphere interactions and processes involved in determining environmental exposure rates are to be completed at the primary experimental site, partial measurements in other terrain and vegetation conditions will be required. These experimental measurements will involve primarily transportable systems for detailed vertical and horizontal wind and temperature structure and tracer releases over a minimum surface air sampling grid. Two sites should be chosen, one in a coastal plain situation with trees and vegetation and the second in a well defined but rugged mountain-valley area. In addition, experimental activities, of a more limited nature, will be required at an existing launch site to define the equilibrium vertical distribution of combustion products from actual vehicle launches.

These sites should be activated after the primary experimental activities are under way, probably in the 15th month, and should be operated for at least six months so as to catch the maximum seasonal variability (winter to summer or vice versa) of locally induced air flow patterns and vegetation changes. The measurements made at these sites will be aimed at defining local atmospheric and surface variables and at verifying environmental exposure predictions derived from the primary experimental results and other studies.

Surrounding test sites should be exposed and observed for signs of damage. Families of time-concentration curves for forage grasses would be developed for various levels of fluoride accumulation. Fluoride accumulates and concentrates in leaf tissue; when leaf concentrations exceed about 45 ppm, cattle eating such vegetation can develop fluorosis. Thus, the effect of a series of short exposures on leaf fluoride accumulation should be investigated.

Effects on Materials

Fluoride levels of concern from industrial sources are usually too low to cause damage to non-viable substances. However, the high concentrations of both HF and F_2 are capable of causing damage to metals, glass and ceramics, and building materials (concrete, wood, paint, etc.). Such damage would result from the acidic nature of HF (in the presence of moisture), the oxidizing ability of F_2, and the reactivity of silica and silicates with both HF and F_2.

Controlled environment chambers should be used to expose representative materials under a wide range of HF, F_2, moisture, temperature, and time regimes to find the most critical combination of materials and exposure conditions.

4.0 DATA ANALYSIS AND PREPARATION OF ENVIRONMENTAL HAZARDS HANDBOOK

Based upon the review and synthesis of previous studies by Hage and Bowne, and additional development work undertaken under this program, an extensive analysis of the meteorological and tracer data will be undertaken to verify, extend, or develop physically meaningful atmospheric diffusion models. The significance of variations in thermal stability, wind speed, turbulence, vertical wind profile, source configurations and strengths, and terrain will be analyzed fully and incorporated, as appropriate, into prediction methods.

From the experimentation and analysis planned in the extension of the toxicology and effects area, improved definition of permissible dosage levels of fluorine compounds and other toxic materials will be available for humans, animals, plants, and objects. Review and approval of these dosage levels by high governmental authority, possibly the National Research Council, will undoubtedly be required. However, this approval action need not hold up preparation of the operational handbook, per se.

The preparation of the comprehensive operational handbook for the safe usage of hazardous fuels by NASA can proceed quite logically given definition of tolerable environmental concentrations and verified methods of predicting the concentrations under various source and meteorological conditions. This task should be undertaken by the design and analysis group.

The bulk of this handbook would consist of a series of charts and tables specifying the exposures to be anticipated:

at varying	operational sites, distances from the source
under varying	operations or accident conditions, meteorological conditions
with various	types and amounts of fuel employed.

Alternative methods of presentation are also envisioned to assure that immediate access to pertinent data is available. For example, the data should be presented to show those operations which can, or cannot, be safely conducted at a given site under given meteorological conditions. Also to be presented is information on the relative occurrence of these given meteorological conditions at each site of interest to NASA, such as KSC, Wallops Island, WSMR, WTR, MSFC, Atlas and Titan Test Sites, etc. Adequate explanatory information would be included relative to the use of the data as well as its limitations and confidence factors.

5.0 RESOURCES AND SCHEDULE

The estimated resources required to implement this plan for the development of operational guidelines for the safe usage of hazardous fuels under various NASA operations should be adequate to encompass the schedule illustrated in Fig. 5-1.

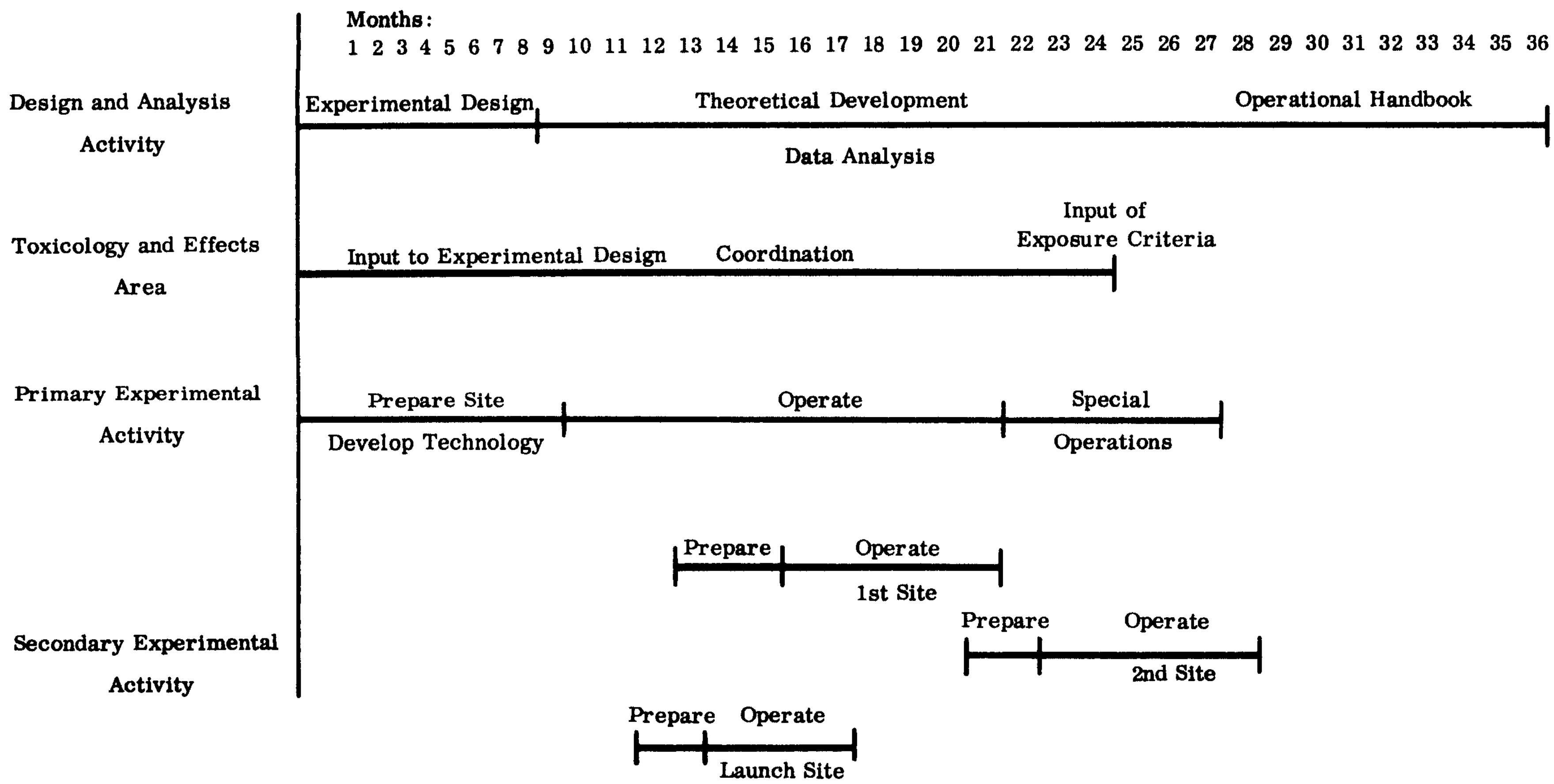

Fig. 5-1. Schedule

6.0 REFERENCES

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3. Personal communication between Harold Schmidt, Lewis Research Center, and Glenn R. Hilst, TRC.

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5. The Boeing Co., November 1965: Fluorine Cloud Characteristics.

APPENDIX A

A SIMPLE EXPERIMENTAL SYSTEM FOR INFERENCE OF DISTRIBUTION AT EQUILIBRIUM

APPENDIX A. A SIMPLE EXPERIMENTAL SYSTEM FOR INFERENCE OF DISTRIBUTION AT EQUILIBRIUM

Arrange for the release of five simultaneous and distinguishable lines of tracer material across wind at five selected elevations above static firing stand or launch pad. Arrange further for the introduction or identification of a sixth tracer material in the vehicle exhaust at the stand or pad.

Arrange an array of ground sampling points so that the integrated crosswind concentration of each of the six tracers can be measured at discrete distances of interest. The desired experimental results are:

(a) $u\ (z)$ the horizontal wind speed

(b) $Q\ (z)$ the tracer source strength

(c) $X_{IC}\ (x,z)$ the integrated crosswind concentration at distance x attributable to the tracer released at height z

(d) $X_{TIC}\ (x)$ the total integrated crosswind concentration of the tracer placed in the vehicle exhaust.

From items (a), (b) and (c) we form the ratio

$$K\ (x,z) = \frac{\bar{u}\ (z)\ X_{IC}\ (x,z)}{Q\ (z)}$$

and map K(x,z). The map should look something like Fig. A-1. From such a map we can interpolate mean values of K(x,1) where 1 is the increment for heights at which the apparent source strengths of the sixth tracer (real plume) are to be estimated.

We now form n independent linear equations

$$X_{TIC}\ (x) = \sum_{j=1}^{n} Q(1_j)\ K(x_i,\ 1_j),$$

$i = 1,\ 2,\ 3,\ \ldots n$, and solve these for $Q(1_j)$.

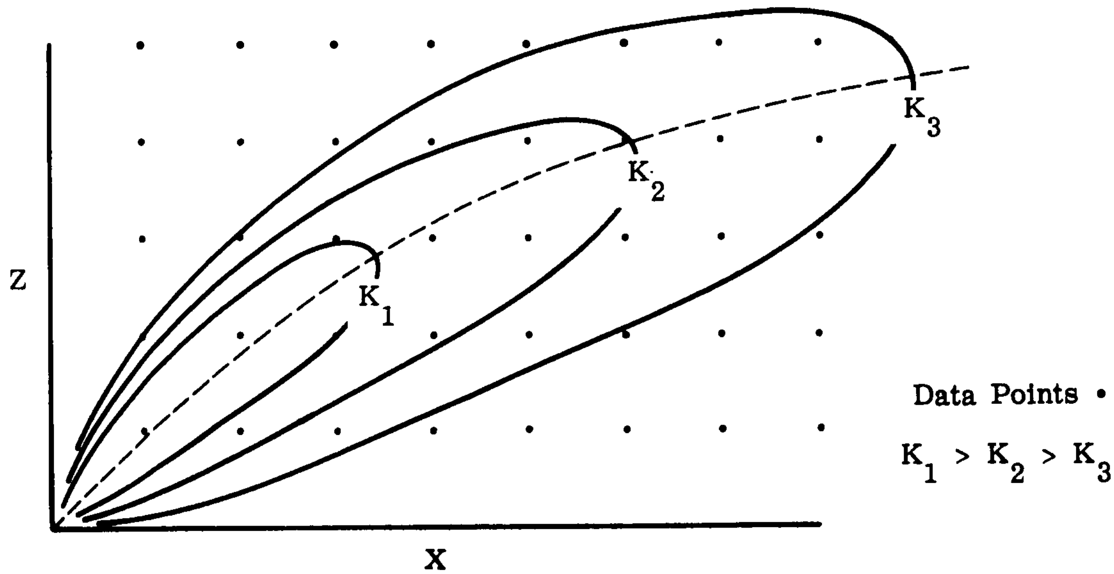

Fig. A-1. Map of K(x, z).

APPENDIX B

POTENTIAL SITES FOR NASA ENVIRONMENTAL HAZARDS EXPERIMENTS

APPENDIX B. POTENTIAL SITES FOR NASA ENVIRONMENTAL HAZARDS EXPERIMENTS

Government Owned Sites:

Several large tracts of land suitable for the experimental work described in this plan are owned by the U. S. Government. The following list is not exhaustive of such facilities, but does provide representive coverage.

Edwards Air Force Base, California

The A. F. Rocket Propulsion Laboratory's atmospheric diffusion test network is situated on the eastern portion of Edwards A. F. Base which is about 50 air miles north of Los Angeles, California. The closest municipality of any size is Lancaster, California which is about 35 miles southwest. The city is served by the Southern Pacific Railway and by a major highway to Los Angeles and is capable of providing the routine supplies and personnel required to conduct an environmental hazards program.

Edwards A. F. Base consists of a desert area of about 20 by 40 miles. The Rocket Propulsion Laboratory, a tenant unit on the base, has a diffusion test grid of 108 degrees with a radial distance of 9600 meters located on the eastern portion of the base. While the government-owned property line is only 5 to 6 miles downwind, the next 10 to 20 miles are relatively uninhabited.Meteorological data are acquired from a 204 ft tower just upwind of the test stand.

Two small horizontal test stands are available and currently in use, one for 400 lb solid rocket motors and one for the 4000 lb size range. An adequately equipped block-house is located adjacent to the network. Also located just off the grid is a quonset shop used for instrument repair and staging.

The prevailing winds at Edwards A. F. Base are southwesterly at 10 knots with winds from the sector SSW through WNW occurring 62% of the time at a mean speed of 11 knots. The frequency of broken or overcast skies below 10,000 feet is 6.4%; visibilities less than 10 miles, 4.1%. Mean monthly precipitation varies between 0.6—0.9 inches in the winter months to 0.1—0.3 inches in the summer. From Hosler (1961), the annual frequency of temperature inversions is approximately 40% of total hours.

National Reactor Test Station, Idaho

The National Reactor Testing Station (NRTS) is an Atomic Energy Commission facility located in southeastern Idaho on the Snake River Plain approximately 42 miles west of Idaho Falls. Idaho Falls is accessible by air and rail.

The site is rectangular, 34 miles wide (east to west) and 29 miles long (north to south) with the northwest corner of the rectangle curtailed because of two mountain ranges. Terrain is predominantly flat and uniformly covered with sagebrush growing to a height of 3 feet. There is a 250-ft meteorological tower at the south end of the site and a 150-ft meteorological tower at the north end of the site. The U. S. Weather Bureau has operated a station at NRTS since 1949. Three comprehensive diffusion programs have been performed at NRTS on a 60 degree, two-mile range in the past 10 years. The Atomic Engergy Commission maintains an excellent chemistry laboratory and instrument shop at the facility.

Wind flow is channeled by the terrain into two predominant directions, northeast and southwest. This is particularly true in summer when winds are southwest in the afternoon and northeast at night about 75 percent of the time. Altitude and dryness create temperature extremes: the average minimum in January is 4°F with a maximum of 28°F, while in July the average minimum is 50°F and the maximum 88°F. Average annual rainfall is 7.69 inches. Inversions occur almost every night, spring being the least frequent season and an inversion occurs on 92% of the nights even then. The percentage of total hours having inversions varies from 37% in the spring to 57% in the fall and the median inversion duration varies from 10 hours in spring and summer to 16 hours in winter.

Dugway Proving Ground, Utah

Dugway Proving Ground is 60 miles southwest of Salt Lake City, Utah. The reservation is controlled by the U. S. Army. The area is accessible only by automobile or light plane from Salt Lake City.

The reservation is some 50 miles square, most of it in the Great Salt Lake Desert. Vegetation is restricted to stunted brushes of the sage variety and a salt marsh grass over the flat portions of the terrain. The Dugway Meteorological Group has a large telemetering wind and temperature array feeding into their central facility computer and regularly conduct diffusion field trials over their test range on the reservation. At least one other group has used the Dugway facilities for diffusion studies; Convair, in 1959, conducted I^{131} diffusion trials.

The climate is much like that of NRTS, exhibiting large extremes of temperature, little rainfall and high frequency of inversions.

White Sands Missile Range, New Mexico

White Sands Missile Test Center is located some forty miles north of El Paso, Texas. The area is accessible by automobile from El Paso, Texas or Alamogordo, New Mexico.

The reservation is 35 miles east to west and approximately 100 miles north to south. It lies in Tularosa Valley at a mean elevation of about 4000 feet bounded on the west by the San Andres Mountains (7000 to 8000 ft.) and on the east by the Sacramento Mountains (8000 to 9000 ft.). The reservation has a meteorology group primarily concerned with the vertical structure of the atmosphere and its effect on rockets and missiles.

The climate is dry; winds are channeled into general north-south directions by the mountains. Nocturnal temperature inversion frequency is expected to vary between 30 and 40 percent of all hours with a minimum in summer and a maximum in winter.

Eglin Air Force Base, Florida

The Eglin reservation is owned by the United States Air Force and is on the shore of the Gulf of Mexico centered about 40 miles east of Pensacola, Florida. The base is served by commercial airlines; automobile travel is required for the reservation.

The total area of the reservation is 957 square miles roughly 50 miles east to west and 20 miles north to south. A rocket launching facility is located on Santa Rosa Island south of the main base. There are 10 auxiliary airfields, but not all are used. The area is predominantly covered with trees growing to a height of 30 to 40 feet in a sandy soil. The terrain is rolling, i.e., many small hills up to 100 feet within 5 miles of the coast, rising to 250 feet above mean sea level 20 miles inland. There are a few cleared areas, used for weapon testing, and bombing ranges scattered over the reservation.

Wind flow is predominantly south to southwest during daytime hours in the summer with essentially calm or very light winds at night; the warm waters of the Gulf do not permit a sufficient temperature differential to develop a land breeze. Wind flow in the winter is pressure-gradient dominated, with primary directions of south to southwest and north to northwest. Summer temperatures near the coast are moderated by the sea breeze. Large daily changes in temperature may occur in the winter season with passages of cold fronts. The normal minimum in winter is near 40°F with a maximum near 55°F. According to Hosler (1961) inversion frequency varies from 25% to 35% of total hours.

Sycamore Canyon, California

The Sycamore Canyon missile test facility is operated by Convair Division of General Dynamics Corporation for the U.S. Air Force. The government-owned site is approximately 30 miles northeast of San Diego, California, from which personnel and supplies could readily be obtained to support an environmental hazards test program.

The Sycamore Canyon test facility occupies a 4 mile square area of hills and valleys with altitudes varying approximately 200 feet in 1/2 mile. The vegetation consists entirely of short (2 ft) bushes. The test pad is located in a canyon approximately in the center of the controlled land area. The site has been used for static firing of the Atlas as well as for conducting hot and cold LF_2/LO_2 diffusion tests. The Atlas gantry and associated facilities for missile testing are generally available although the facility has not been actively involved in sophisticated tests for some time. There is no permanently installed diffusion grid network, although three sampling arcs within 1 1/2 mile radial distance were established for past tests, with some samplers at a distance of about 5 miles. At the present time there are no meteorological measurements being taken except for an anemometer on the gantry tower. While the site is somewhat rugged, it is a mountainous location which could be properly instrumented and operated for limited-distance secondary-site diffusion tests. Hazardous tests would be restricted to the government-owned land area. It is probably feasible to sample beyond the boundaries of the facility on simulated sources although further investigation would be required.

The prevailing winds in the winter at the facility are easterly at night and in the morning and westerly in the afternoon, with speeds less than 9 mph 90% of the time. In the summer a daytime sea breeze from the west to west northwest dominates. The frequency of low-level inversions is low, with the maximum in the summer months. Unfortunately the climatological data for the specific site are quite limited.

Privately Owned Sites:

Boeing Boardman Test Facility, Oregon

Boeing's Boardman Test Range is located south of Boardman, Oregon, about 40 miles west of Pendleton, Oregon. It can be reached by automobile from Pendleton or Pasco, Washington Airports.

The site is a 12 mile square area leased by Boeing from the state of Oregon. There is a Navy bombing range adjacent to the property on the east with two air corridors retained by the Navy over the test facility, one is east-west across the center of the site and the second is southwest to northeast over the southeast corner of the site. A rocket test stand capable of supporting 100,000 lb downward firing and 300,000 lb horizontally-firing engines is located in the center of the site with associated test facilities. A second test stand capable of handling 20,000 lb engines is also present. A 32-meter meteorological tower provides temperature and wind observations at 2 meters and 32 meters by strip chart recording in the blockhouse. The area is extremely flat over the test site with a mean elevation of 6000 feet; hills rise to 2000 ft. immediately to the south.

Wind flow is primarily southwest to west in the summer and northeast to north in the winter. Normal annual precipitation is 8 inches with 2 to 3 inches of snow. Temperatures range from above 100°F in the summer to -10°F in the winter. Inversion frequency varies from 30 percent of total hours in summer to 45 percent of total hours in winter.

Aerojet-General, Florida

Aerojet-General Corporation's static firing test facility is located south and west of Homestead, Florida, in the Everglades. Homestead is 30 miles south of Miami and readily accessible by air and train from Miami.

The facility occupies 115 square miles consisting of two basic parcels connected by a two mile wide strip 6 miles long. The southern parcel occupies a rectangle 6 miles north to south by 7 miles east to west, south of Homestead. The other parcel, west of Homestead, is 9 miles north to south by 7 miles east to west. Land to the west and south is owned by the U. S. Government, Everglades National Park. Land to the east and north is privately owned and consists of the town of Homestead and farmland. Aerojet presently operates a static firing facility in the northwest corner of the southern parcel. The terrain is flat, covered with 30 inch grass and occasional small trees and has 3 to 6 inches of water over most of the area from April to October. The underlying surface is pulverized coral rock and not the usual mud associated with swampland. Adequate housing and office space are available in Homestead. Aerojet operates a small chemistry laboratory and instrument shop at their test facility.

The climate is typical of a sub-tropical coastal location with small temperature ranges, humid, and with most rainfall occuring as afternoon showers from May through October. Average maximum and minimum temperatures are 78°F and 54°F in January and 91°F and 71°F in August. Wind flow is from the eastern quadrant 40% of the time. Summer winds are from the east to south-southeast 50% of the time while in the winter the frequency drops to 35% with a secondary maximum of 31% from the northern quadrant. Hosler (1961) indicates inversion frequencies of 10% to 20% of the total hours for this area based on Miami and Key West radiosonde data.

General Sites Subject to Multiple Lease Arrangements:

Texas Gulf Coast

The Gulf Coast Site is south of Corpus Christi where Padre Island is closest to the mainland. The nearest airport is at Corpus Christi and automobile travel is required from that point.

The area is near the scene of diffusion experiments conducted under the sponsorship of Dugway Proving Ground. The terrain is gently rolling and is primarily grass covered, used for grazing.

The climate is typical of coastal locations along the Gulf coast with fairly well established sea breezes in the summer and a moderate temperature range. Nocturnal temperature inversions may be expected about 20% of all hours.

Weather Bureau NSSL Network, Oklahoma

The National Severe Storm Laboratory is located at the University of Oklahoma, adjacent to Westheimer Field, 20 miles south of Oklahoma City and on the east side of the Canadian River. The area is easily accessible by air to Oklahoma City. Land for the laboratory is leased from the University of Oklahoma and an associated rain gauge network throughout Oklahoma exists through cooperative arrangements with private land owners.

All land in the area is privately owned and consists primarily of farm land. The terrain is very level and vegetative cover consists of various crops raised in the area. There are no existing facilities for diffusion programs.

The area is in "tornado alley" and exhibits large extremes in temperature range from fall through spring. Summer winds are predominantly southerly while numerous cold front passages provide a more evenly distributed wind rose in the other seasons. Hosler (1961) indicates that inversion frequency varies from 30 percent in spring to a maximum of 45 percent of total hours in the fall. This is also an area of pronounced low level jets associated with nocturnal inversions.

Dallas, Texas Site

Cedar Hill is located 15 miles southwest of the center of Dallas, Texas. It is the location of a 1420-ft. television transmitting tower and was the site of a diffusion program operated by Dugway Proving Ground in 1961.

Land in the area is privately owned with gently rolling grassland the typical terrain. Elevation changes of 100-200 ft. in 15 miles are typical of the area. The TV tower has been used for meteorological studies by Cambridge Research Laboratories and by Dugway Proving Ground.

Prevailing winds are from the south although all directions are encountered. Inversion frequency is 20 to 30 percent of all hours.

O'Neill, Nebraska Site

O'Neill was the site of the Great Plains Turbulence Experiment and is about 120 miles west of Sioux City, Iowa. It is accessible by automobile from Grand Island, or Sioux City, the closest major airports.

The terrain is very flat, all privately owned and primarily farming country. Wheat is the major crop. The facilities used previously are no longer in existence.

Wind flow is prevailingly south in the summer with a more circular wind rose apparent in other seasons. Inversion frequency can be expected to vary from 30 to 40 percent of total hours.

Air Force Site, Sublette, Kansas

An area of one square mile is leased by CRL 35 miles northeast of Liberal, Kansas, the closest airport, with the actual operating location consisting of about one acre of ground in the center. All land in the area is privately owned and farmed; wheat is the primary crop.

CRL operates a 32 meter meteorological tower to measure turbulence statistics during the summer months. The area is flat with a dry soil that makes the fields impassable for about two days after significant rains.

The climate exhibits large extremes of temperature, hot in summer with most rainfall as thundershowers, and numerous cold front passages in winter yielding warm then very cold conditions. The region is relatively dry compared to eastern U. S. and has inversion frequencies of 30 to 40 percent of total hours.

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