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Environmental Research Laboratories

Studies of the Transfer of Radioiodine Gas to and From Natural Surfaces

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Air Resources
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April 1971

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STUDIES OF THE TRANSFER OF RADIOIODINE GAS TO AND FROM NATURAL SURFACES

A Summary of Controlled Environmental Release Test Analyses (1963-1969)

Earl H. Markee, Jr.

Research conducted with the support of the Division
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STUDIES OF THE TRANSFER OF RADIOIODINE GAS TO AND FROM NATURAL SURFACES

Earl H. Markee, Jr.[1]

Some significant results of studies of the transfer of radioiodine gas to and from natural grass surfaces at the National Reactor Testing Station in Idaho are presented. These results were obtained from experiments conducted in the field over pastures and in an environmental chamber. Some of the significant findings are: (1) the "resistance approach" yields good agreement with measured values during unstable conditions, (2) sorption of radioiodine gas was found to be proportional to a function of grass surface area and stomatal opening, and (3) the depletion from an effluent cloud of radioiodine gas appears to be independent of transfer velocity to the underlying surface and atmospheric stability. Suggestions for future research are presented.

1. INTRODUCTION

The Controlled Environmental Release Tests (CERT) program has been in progress since 1963 at the National Reactor Testing Station in Idaho. The general objectives of the CERT program are to study the transfer of radioiodine gas through the three links of the food chain (air-vegetation, vegetation-milk, and milk-human thyroid). To date there have been 24 field releases of I_2-131 gas and many studies and tests of the physical and chemical properties of this gas in an environmental chamber (CERTLE). Detailed descriptions of the many facets of the program are presented by Hawley et al. (1964), Hawley (1966), Bunch (1966; 1968) and Zimbrick and Voilleque (1969).

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The information presented in this Technical Memorandum portrays some transfer models, analysis of data, and significant findings related to the air-to-vegetation transfer link of the chain in which small scale atmospheric motions are important.

Eighteen of the 24 field releases of the gas have provided enough data to evaluate various transfer processes over open range grass and irrigated pasture grass during various meteorological conditions. The radioiodine measurements included initial retention on and removal from grass and carbon plates, concentration in air at a standard level of 1 m, low-level profiles of concentration in air, and retention profiles on grass. Other measurements included low-level wind velocity and temperature profiles and areal grass density. In addition to the field measurements, the effects of stomatal opening, humidity, and wetting of grass leaf surfaces on the retention of I_2-131 gas by grass were measured in the CERTLE chamber.

The combined results of these field and laboratory measurements have provided enough information to propose a semi-empirical transfer model for gases.

2. TRANSFER MODELS

According to perturbation theory, the average flux of a quantity is proportional to the covariance between fluctuations in the quantity and in the driving force for the sampling interval. Therefore,

$$\overline{F}_m = - \overline{u'w'} \qquad (1)$$

and

$$F_M = \overline{w'X'} \qquad (2)$$

if the positive direction of the flux is downward. $\overline{F}_m$ is the average flux of momentum, F_M is the flux of airborne matter, u is the horizontal component of velocity along the air flow, w is the vertical component of velocity, χ is the concentration in air of matter, and the primes indicate instantaneous deviations from the mean.

In practice it is difficult to evaluate some of these quantities at given instants in time. Therefore, the mixing length approach is often used in which the fluxes can be evaluated from averaged quantities and is expressed as

$$\overline{F} = K \frac{\partial \overline{\Gamma}}{\partial z} , \qquad (3)$$

where K is the diffusion coefficient of Γ, and $\overline{\Gamma}$ is a scaler quantity measured in the z (vertical) direction. If the mixing length is assumed to be proportional to height z and the stress is constant in the surface boundary layer of the atmosphere,

$$\frac{\partial \overline{u}}{\partial z} = \frac{u*}{Kz} \qquad (4)$$

and

$$K_m = ku*z, \qquad (5)$$

where u* is the friction velocity or square root of the average flux of momentum (-u'w'), k is von Karman's constant ($\approx$0.4), z is the height above the interface, and K_m is the diffusion coefficient for momentum. A logical assumption (Sheppard, 1958) is that an effluent which is a gas will diffuse at the same rate as momentum with molecular diffusion added (i.e., K_M = ku*z+D, where D is the molecular diffusion coefficient of the effluent gas). Then

$$\overline{F}_M = (ku*z+D) \frac{\partial \chi}{\partial z} . \qquad (6)$$

The solution of this differential equation, assuming that $ku^*xD^{-1} \gg 1$, is

$$\overline{F}_M = \frac{ku^*(\chi_z - \chi_o)}{\ln(ku^*zD^{-1})} \qquad (7)$$

for z>o. Since $\overline{F}_M \propto \chi_z$ we can define the constant of proportionality for a specific atmospheric condition as a vertical transport velocity $V_T(z)$ for mass where $\overline{F}_M = V_T(z)\chi_z$. With this substitution for $\overline{F}_M$, (7) becomes

$$V_T(z) = \frac{ku^*}{\ln(ku^*zD^{-1})} \left(1 - \frac{\chi_o}{\chi_z}\right) . \qquad (8)$$

If the interface is a perfect sink for the effluent gas ($\chi_o = 0$), then (8) can be evaluated from low level wind speed profile measurements.

In mass transfer problems a resistance approach is often used in which the flux of a scalar quantity can be described as the ratio of a driving force to a resistance. The driving force for average transfer or flux of gases between two levels is the difference in time averaged concentration in a medium between the levels. The formulation is

$$\overline{F}_L = \frac{\chi_n - \chi_{n-1}}{r_L} , \qquad (9)$$

where the subscript L indicates a value for the layer between n and n-1. The advantage of using the resistance approach is that the total resistance to transfer is equal to the sum of the individual transfer regime resistances. This can be demonstrated in the following manner. To preserve continuity of concentration differences between two layers,

$$\chi_2 - \chi_0 = (\chi_2 - \chi_1) + (\chi_1 - \chi_0) . \qquad (10)$$

Use of (9) and (10) yields the relationship

$$\overline{F}_T r_T = \overline{F}_A r_A + \overline{F}_B r_B \,, \tag{11}$$

where the subscript T refers to total and the subscripts A and B refer to layers. The continuity condition is

$$\overline{F}_T = \overline{F}_A = \overline{F}_B \tag{12}$$

which makes

$$r_T = r_A + r_B \,. \tag{13}$$

Each resistance in the series (r_A, r_B, etc.) represents a process affecting the transfer of an effluent gas from air to a surface (e.g., grass).

3. CERT DATA ANALYSES

The entire transfer process for gases to vegetation can be divided into three distinct regimes: (1) transfer through the lowest layer of the atmosphere above the vegetation canopy (surface boundary layer), (2) transfer within and slightly above the vegetation canopy (surface sublayer), and (3) sink characteristics of the vegetation and underlying soil. The removal from vegetation is the converse of the transfer process with the vegetation being a source rather than a sink for effluent gases. Understanding the processes involved and determining the magnitude of the effect in each regime on the transfer of gases were attempted from the field and laboratory experiments for the CERT project. Some of these processes have been investigated and understood more thoroughly than others due to experimental problems.

3.1 Surface Boundary Layer Transfer Process

Assuming that the diffusivity of a gas equals that of momentum, we can formulate the surface boundary layer transfer through use of momentum transfer derived from average wind velocity profiles. Use of the mixing length approach (1) results in the equation

$$\overline{F}_m = K_m \frac{\partial \overline{u}}{\partial z} , \qquad (14)$$

where K_m is the diffusion coefficient for momentum and $\partial \overline{u}/\partial z$ is the gradient of average wind velocity ($\overline{u}$) in the vertical (z) direction. Substitution of (4) and (5) into (14) yields

$$\overline{F}_m = u*^2 . \qquad (15)$$

$\overline{F}_m$ can be expressed as the product of mean wind velocity $\overline{u}(z)$ and a vertical transport velocity $V_T(z)$ for momentum. Thus

$$u*^2 = u(z)\ V_T(z) . \qquad (16)$$

If the flux of a gaseous effluent equals the flux of momentum, their transport velocities will be equal.

Transport velocities for gaseous elemental iodine from the CERT field releases were calculated from point measurements of I_2-131 sorption per unit area on grass and carbon plates, and concentration in air at a height of 1 m. The number of transport velocities, based on measurements for a field release, varied from 10 to 60 and the median of these values, which usually varied by less than a factor of 2, was used to represent the release conditions. The relationship between momentum transport velocity, $u*^2/\overline{u}$, and the median transport velocities on carbon plates and on grass is shown, respectively, in figures 1 and 2 as a function of atmospheric stability. This stability was determined from temperature difference measurements usually between 1- and 4-m levels. The wide scatter of values shows a low correlation between momentum transport velocity and transport velocities for iodine gas to carbon plates and grass. This indicates that momentum is not the only factor affecting iodine gas transport (i.e., carbon plates and grass are not perfect sink surfaces for iodine gas). If other factors are influencing the ultimate sorption of iodine gas on these two surfaces, one of the two aforementioned approaches should provide better results.

The Sheppard flux-gradient approach is the simplest to apply to the data and therefore was tried first. Equation (8), without the portion in brackets, was evaluated for each field release assuming that the molecular diffusivity of gaseous elemental iodine is 0.08 cm^2/sec. Comparisons of these

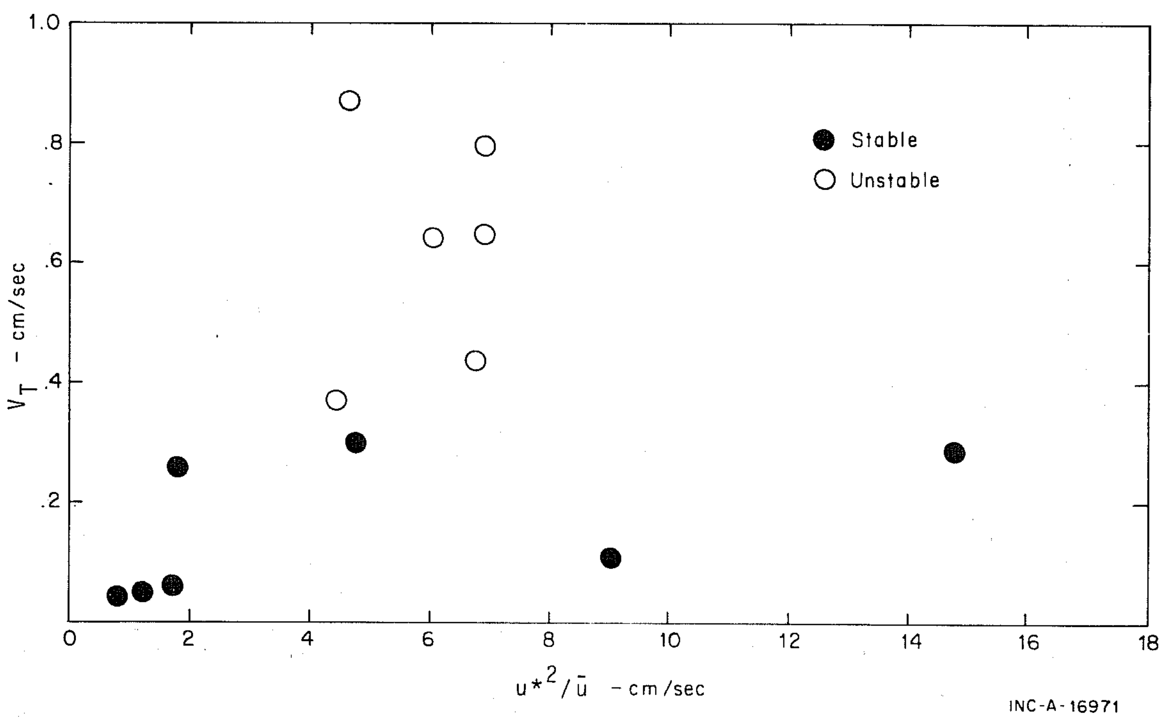

Figure 1. Relationship between median transport velocity to carbon plates and transport velocity for momentum.

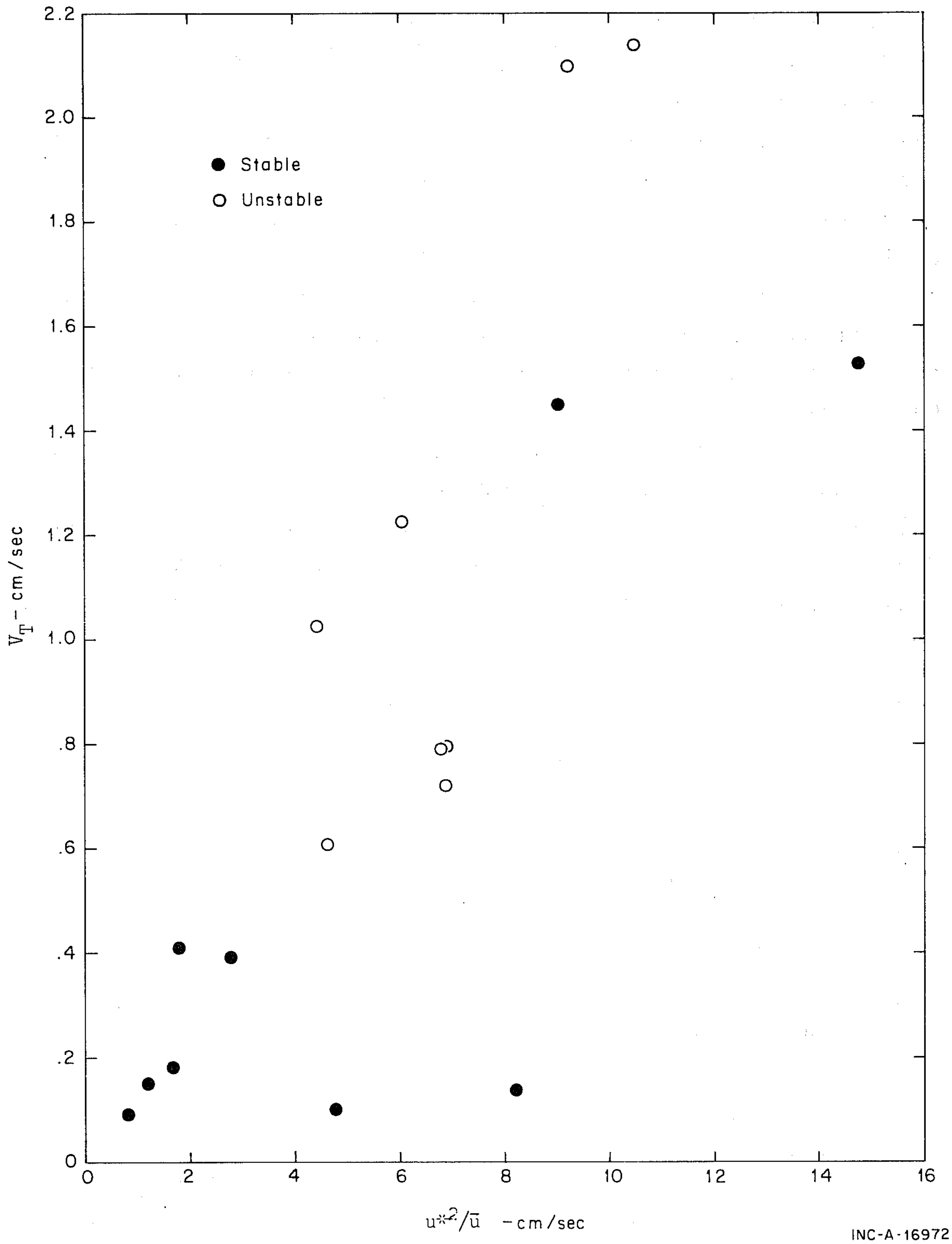

Figure 2. Relationship between median transport velocity to grass and transport velocity for momentum.

calculated values to measured values for carbon plates and grass are shown in figures 3 and 4, respectively. The line of best fit for carbon plate sorption (fig. 3) is V_T (carbon) = 0.270 V_T (Sheppard) and there is a high correlation, r, between the two. Theoretically, if the Sheppard approach is valid, a one-to-one correspondence between them should exist if the carbon plates are a perfect sink for gaseous elemental iodine. The regression result indicates that 27 percent of the iodine that reaches the carbon plate is sorbed. However, the results of an environmental chamber study, in which the sorption on carbon plates and silver coated screening (a near perfect sink substance for iodine) were compared, showed that the relative sink value for carbon plates was inversely related to the chamber's flow rate. This flow rate relationship shows that the relative sink of iodine on carbon plates is related to u*, which is also the dominant parameter in the Sheppard model. From this observation we concluded that the Sheppard model is not adequate for estimating fractional sorption effluent gases. The agreement between measurements of transport velocity to grass and calculations using the Sheppard model (fig. 4) was worse than the carbon plate-Sheppard model agreement. This result was anticipated because the transfer of a gas to a semirigid fibrous type of surface (e.g., grass) was expected to involve other parameters, such as the amount of grass per unit plane area and the biochemical receptiveness of the grass under different field conditions.

3.2 Surface Sublayer Transfer Process

If the surface sublayer is defined as the layer of air within and slightly above the vegetation canopy, it becomes obvious that the transfer process is quite different from

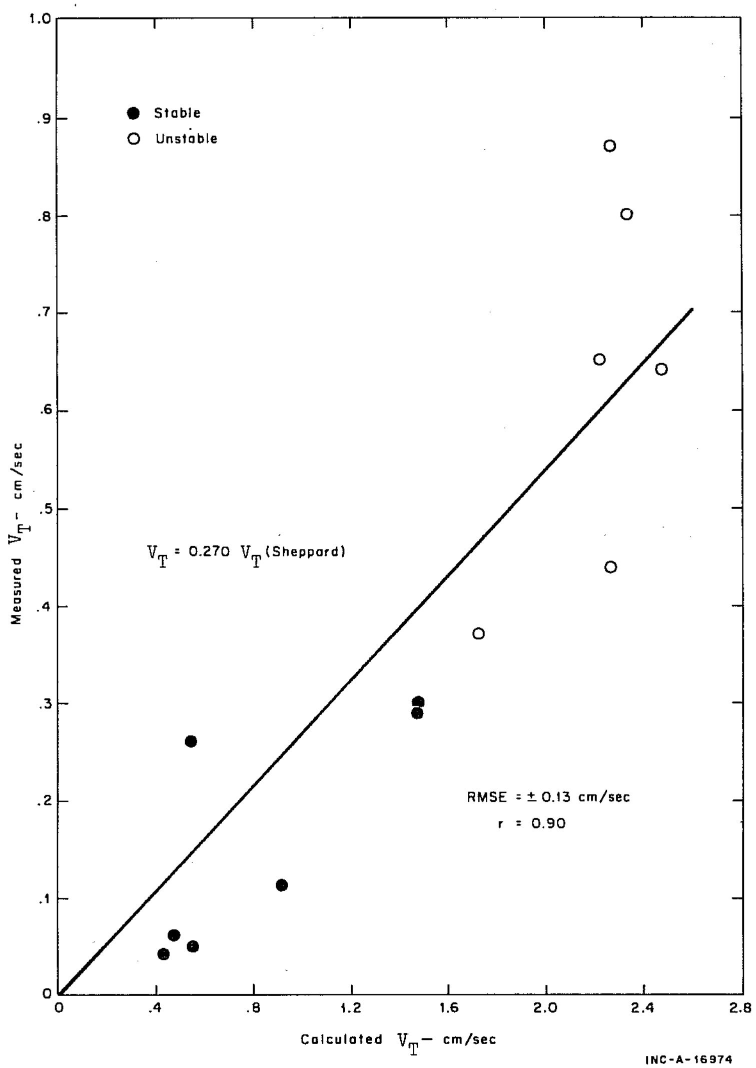

Figure 3. Comparison between median transport velocity to carbon plates and calculated transport velocity using the Sheppard flux-gradient model.

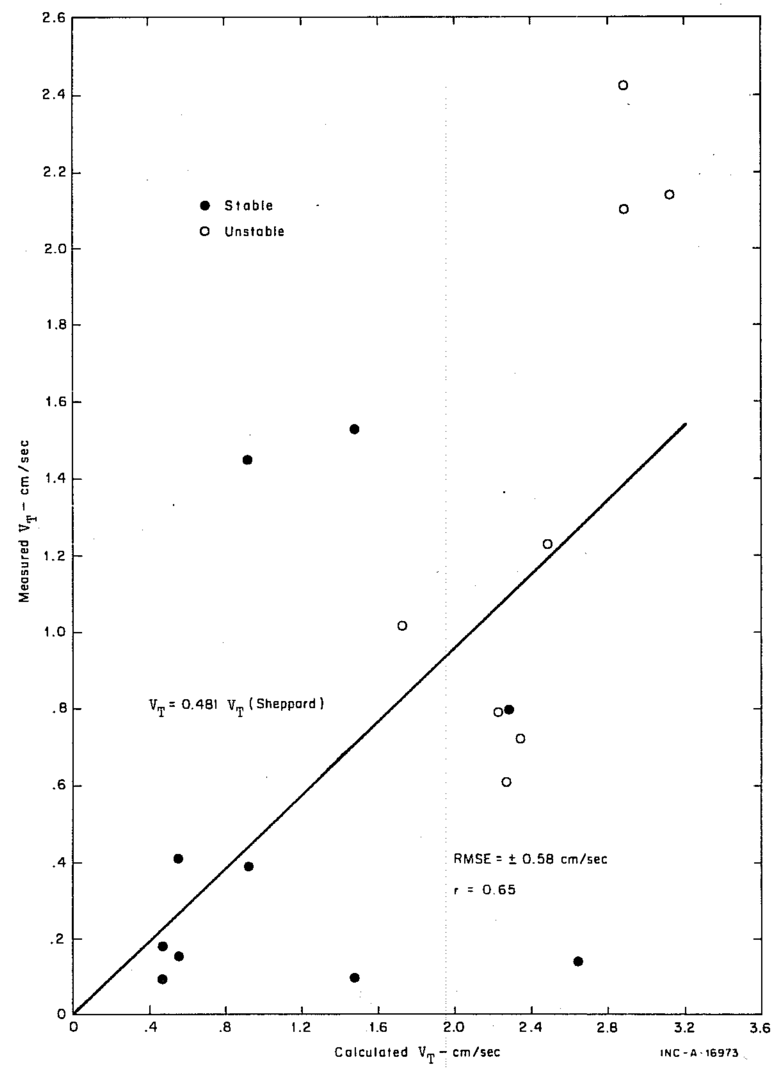

Figure 4. Comparison between median transport velocity to grass and calculated transport velocity using the Sheppard flux-gradient model.

that of the surface boundary layer. Cionco (1965) showed that the wind velocity within a crop canopy, in which the leaf surface area distribution with height is uniform, is an exponential function of height. Therefore sorption by grass is expected to be related to leaf surface area available. Since the leaf surface area for grass is not constant with height, the attenuation of momentum transfer and therefore the attenuation of mass transfer may not be an exponential function of height in the surface sublayer.

The effect of leaf surface area on total sorption of iodine gas was studied in the field and in the environmental chamber. A parameter, the relative leaf surface area A, was defined as the ratio of leaf surface area to plane surface area. Since direct measurements of relative leaf surface area for each individual grass plot in the field were not feasible, a relationship between the dry weight of grass (which was measured) and the leaf surface area was established from several representative samples. This relationship was found to be 38 g of grass/m^2 leaf surface area with a sample standard deviation of $\pm$ 2 g/m^2 about the mean.

The functional relationship between transfer velocity and relative leaf surface areas was established from one of the field releases for which a sufficient number of individual measurements of the two parameters were available (fig. 5).

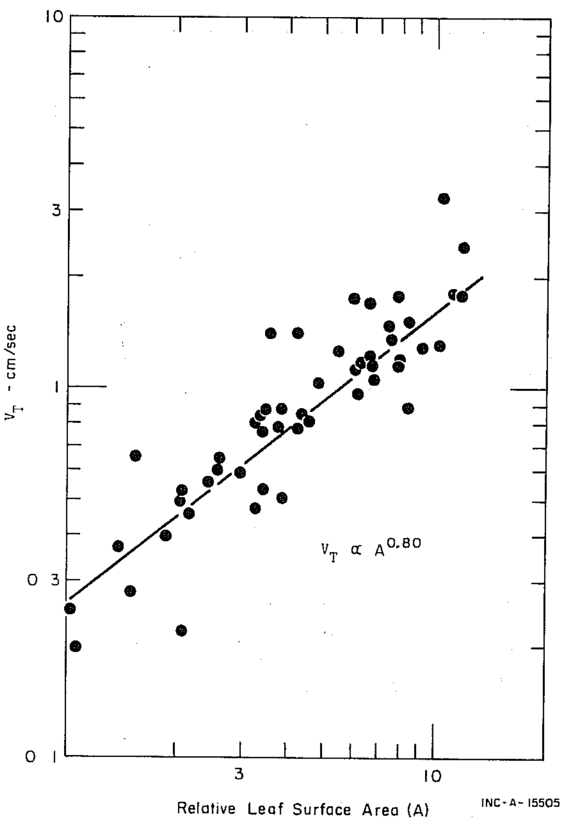

Figure 5. Relationship between transfer velocity to grass and relative leaf surface area for one field release. Test No. 2.

The least squares statistical method of curve fitting produced a power law relationship $V_T \propto A^{0.80}$. The scatter of individual measurements about the relationship can be attributed to measurement uncertainties and spatial heterogeneity of the terrain. Similar analysis of several other field tests revealed that the exponent of A is between 0.70 and 0.80.

As an independent check of this relationship of relative leaf surface area to transfer velocity, data from measurements of vertical profiles of sorption and leaf surface area were used. These vertical profiles were constructed from measurements at 7.6 cm (3 inch) increments for three locations in each of four field releases over relatively tall grass (figs. 6, 7, 8, and 9). Figures 6, 7, and 8 show the profiles for a

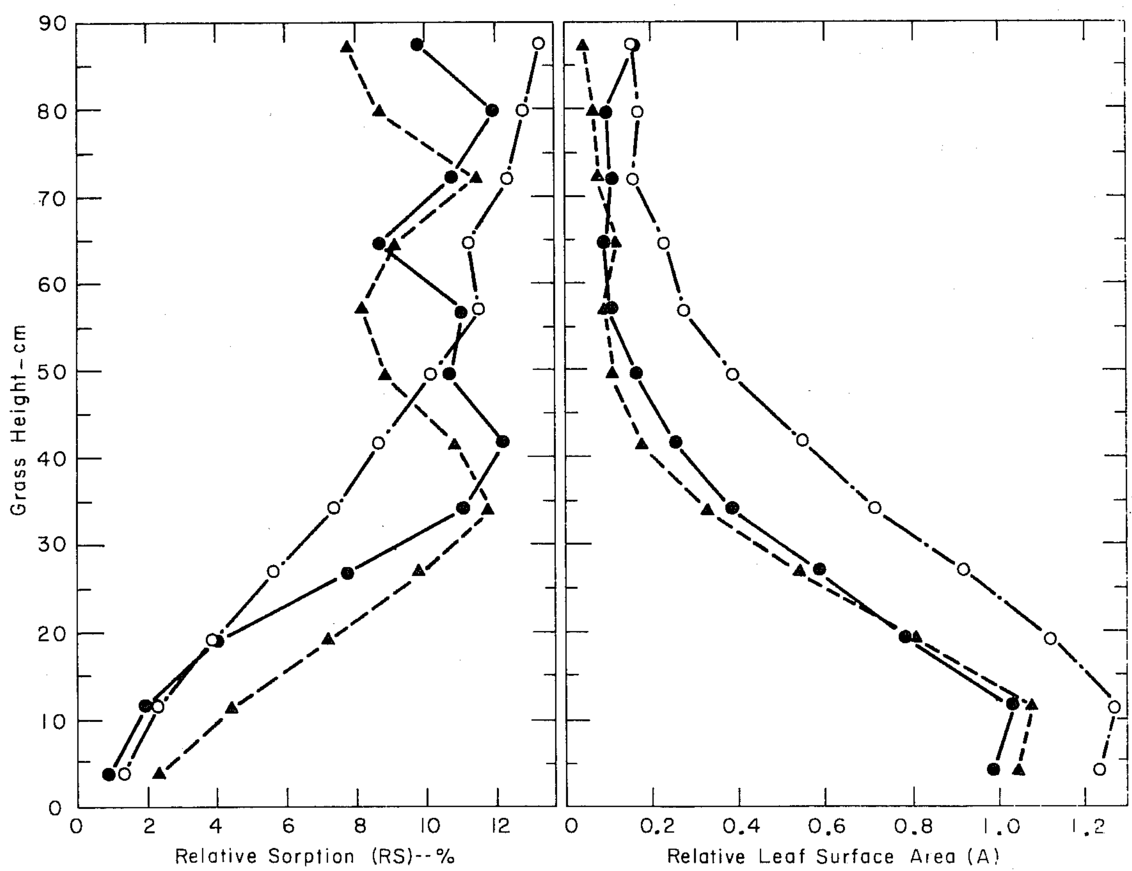

Figure 6. Comparison between relative sorption and relative leaf surface area at three locations for test conducted on July 6, 1967, at 1300 MST.

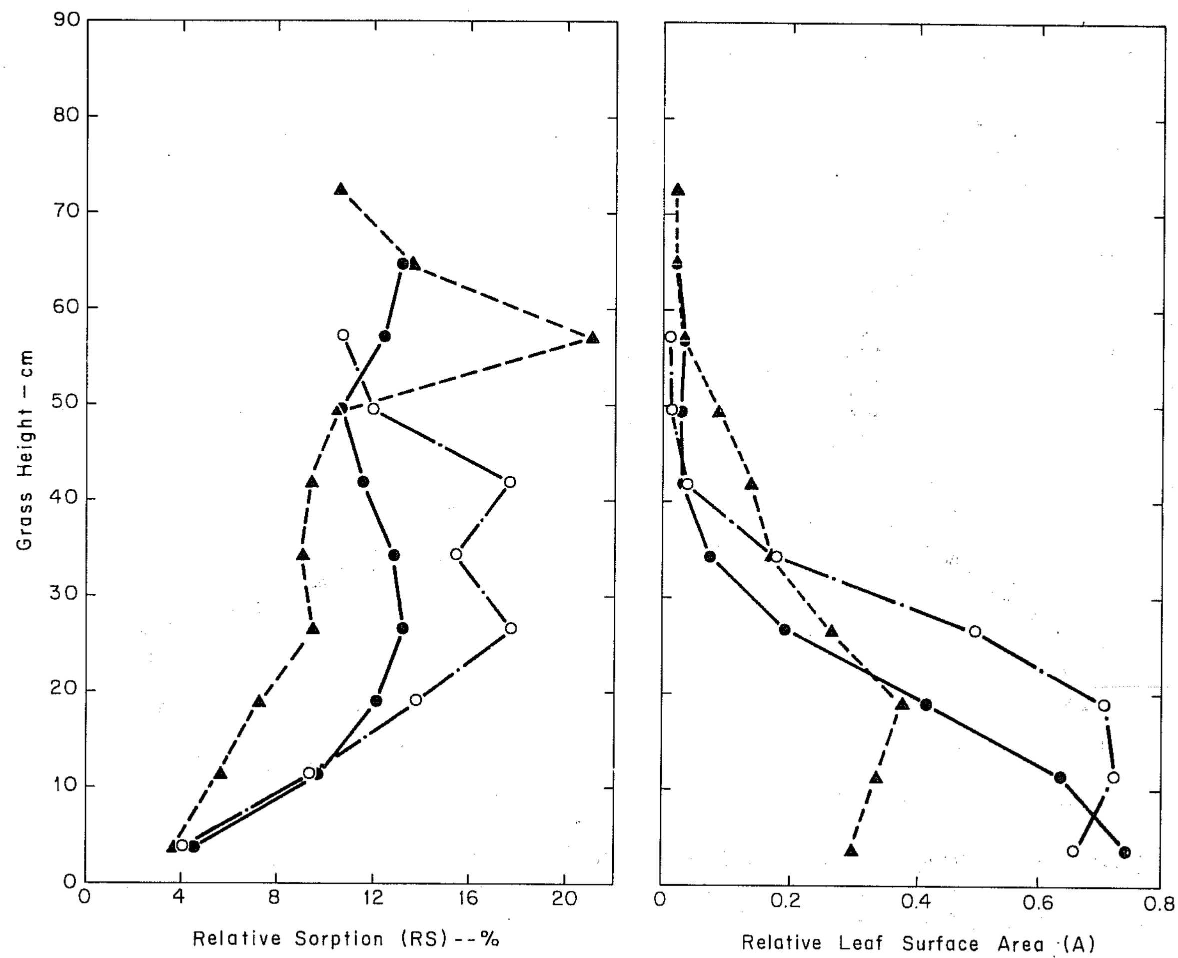

Figure 7. Comparison between relative sorption and relative leaf surface area at three locations for test conducted on September 22, 1967, at 1415 MST.

mixture of Brome, Orchard, and Fescue grasses while figure 9 is for Sundangrass. In the figures, the sorption values per unit grass surface area for each height increment are plotted as a percentage of the total sorption per unit grass surface area RS. Relative leaf surface areas were calculated for each height increment from the dry weight of grass using the method and constant mentioned previously. As a general rule, for relative leaf surface areas less than about 0.4 near the grass tops, the relative sorption does not vary systematically with height, but for greater relative leaf surface areas the relative sorption decreases with decreasing height. Two possible explanations for this behavior are

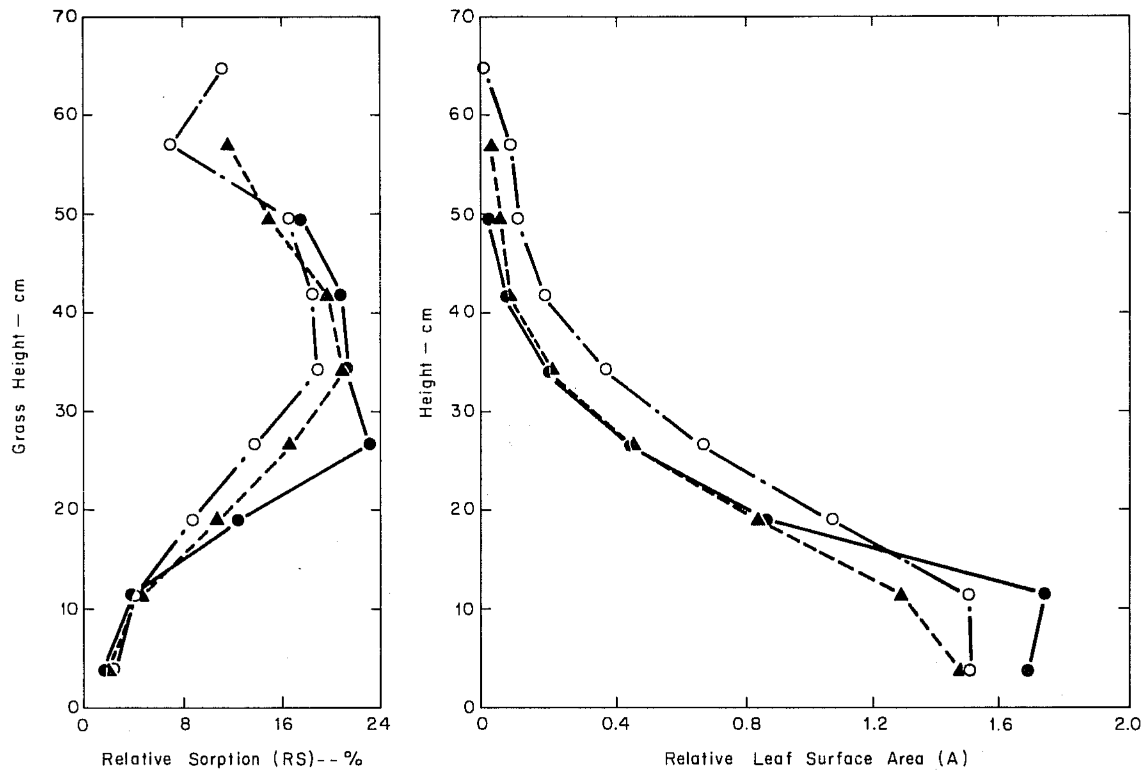

Figure 8. Comparison between relative sorption and relative leaf surface area at three locations for test conducted on June 17, 1968, at 1410 MST.

(1) the resistance to sorption becomes greater as the gas approaches the ground because the number of stomata per unit leaf surface area increases with height (Meidner and Mansfield, 1968); and/or (2) radioiodine gas transfer is reduced because momentum transfer is reduced.

From these grass profile measurements, the effective grass surface area (EGSA) for sorption can be estimated through use of the variations in relative sorption with height. EGSA is defined as the relative leaf surface area A times the complement of the fractional variability in sorption per unit grass surface area. The equation used for computing EGSA is

$$EGSA = \frac{A\{100 - \sum_i |RS_i - \overline{RS}|\}}{100} , \qquad (17)$$

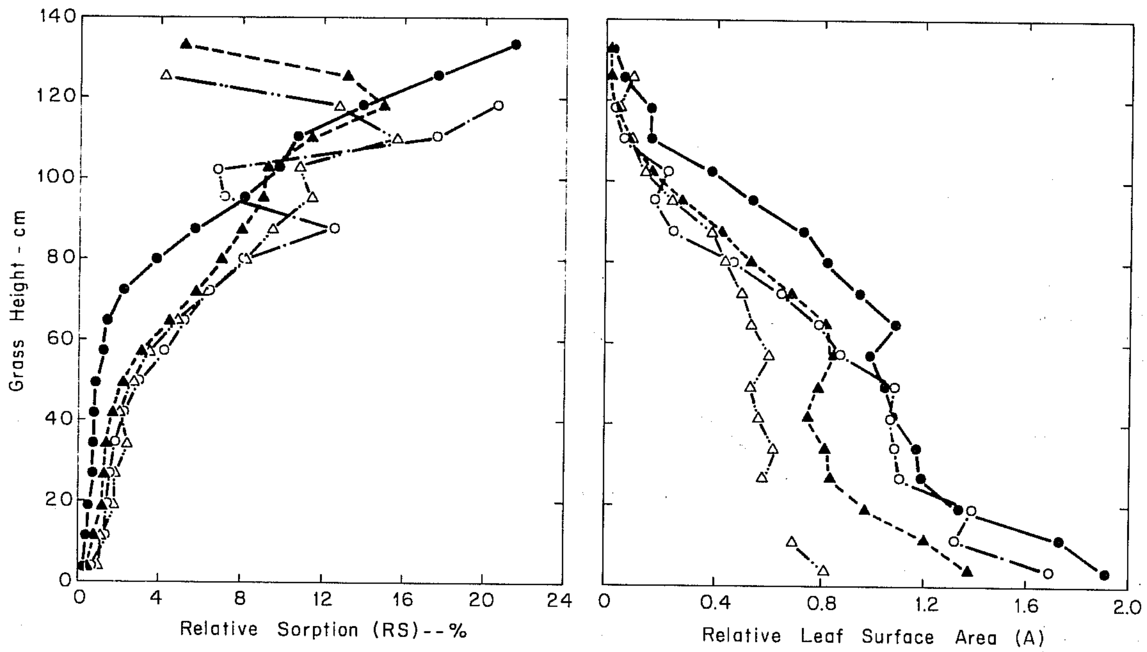

Figure 9. Comparison between relative sorption and relative leaf surface area at three locations for test conducted on August 15, 1968, at 1100 MST.

if there is no variation in sorption on the grass with height, EGSA = A. EGSA values were computed from the data in figures 6, 7, 8, and 9 and plotted as a function of A for three locations in each of four field releases (fig. 10). With A < 10, EGSA $\propto A^{0.75}$; however, for A > 10, EGSA decreases as A increases as indicated by the open triangles in figure 10. For high values of A, which means that either the grass is very tall or the spacing between individual grass leaves is small, most of the gas was sorbed near the grass tops and a very small amount penetrated to lower levels. Sudangrass, with an average height of 1 m, was the surface for sorption when A > 10, so that the difference in leaf size and orientation from that of Bromegrass may have influenced these results.

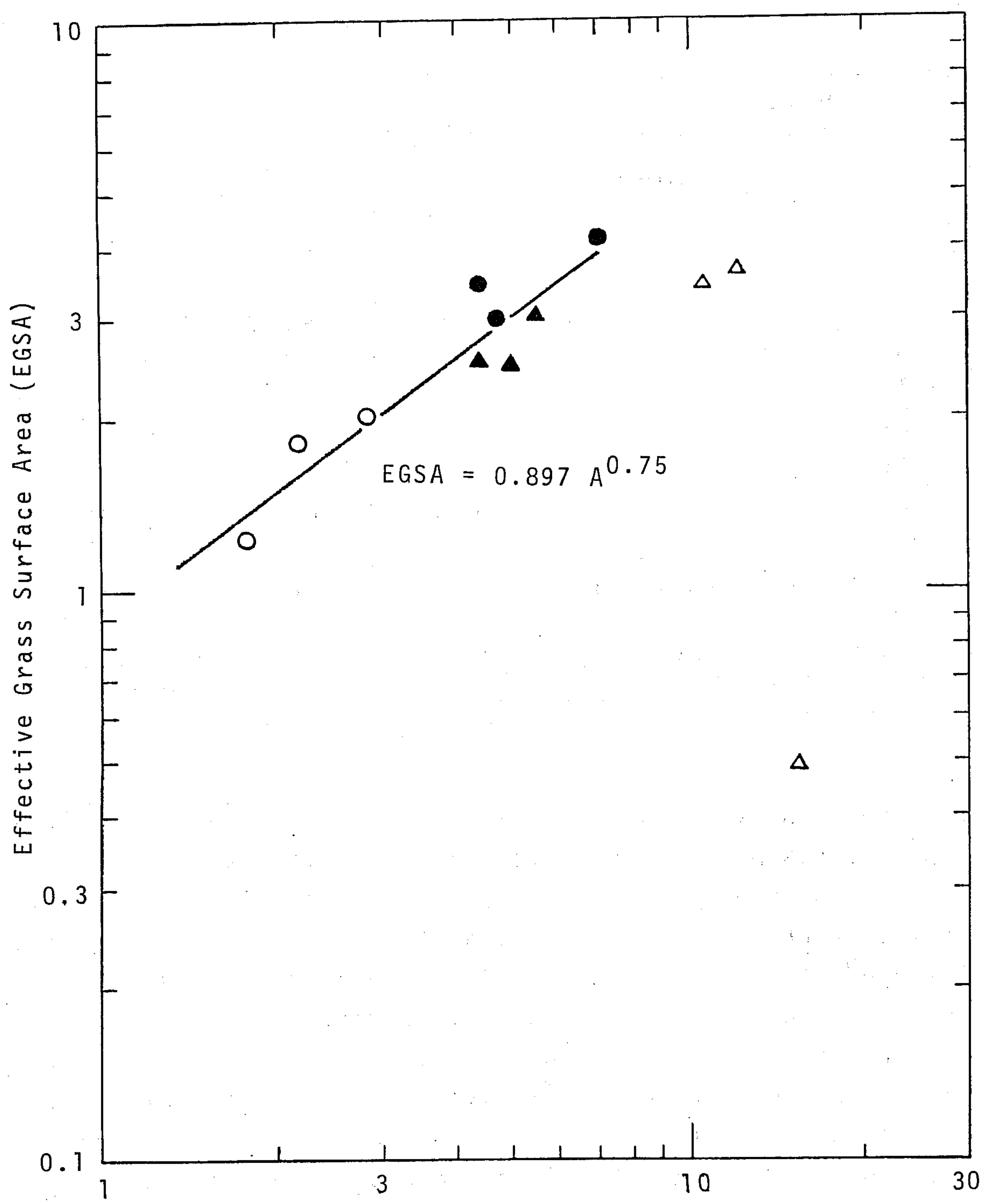

Figure 10. Relationship between effective grass surface area and relative leaf surface area.

Since two independent methods of calculation produced similar functional relationships between transfer of radioiodine gas from air to grass, the reliability of the general relationship EGSA $\propto A^p$ has been established even though the physical processes are not well understood. The parameter p was found to be near a value of 0.75 for all the measurements but varies with grass species and possibly with turbulence conditions.

3.3 Grass Surface Sorption

An evaluation of the grass surface sorption depends on whether the grass leaf cuticle and/or the stomata are the sites for adsorption of the gaseous material. Studies in the environmental chamber have provided some insight into these relative effects for elemental radioiodine gas. Fourteen releases of known amounts of radioiodine gas were made in the chamber over trays containing Bromegrass. The size of stomatal openings and the number of stomata per unit leaf surface area were measured for each release. The methods used in this study are presented by Adams (1969). From these stomatal data the percentage of the total leaf surface area with stomatal openings was calculated. For fully open stomata the value is 0.71 percent. Five of the tests were conducted with fully closed stomata.

The results of this study are shown in figure 11 as a graph of mean radioiodine adsorption per unit mass of grass (dry weight) divided by the total amount of radioiodine gas released versus relative leaf surface area composed of open stomata. A transfer resistance could not be calculated because a measured concentration of radioiodine in the chamber's airstream would have little significance, because it could not be related to turbulent boundary layer theory in a natural atmosphere. Some difficulty was encountered in maintaining open stomata during iodine contamination, and during

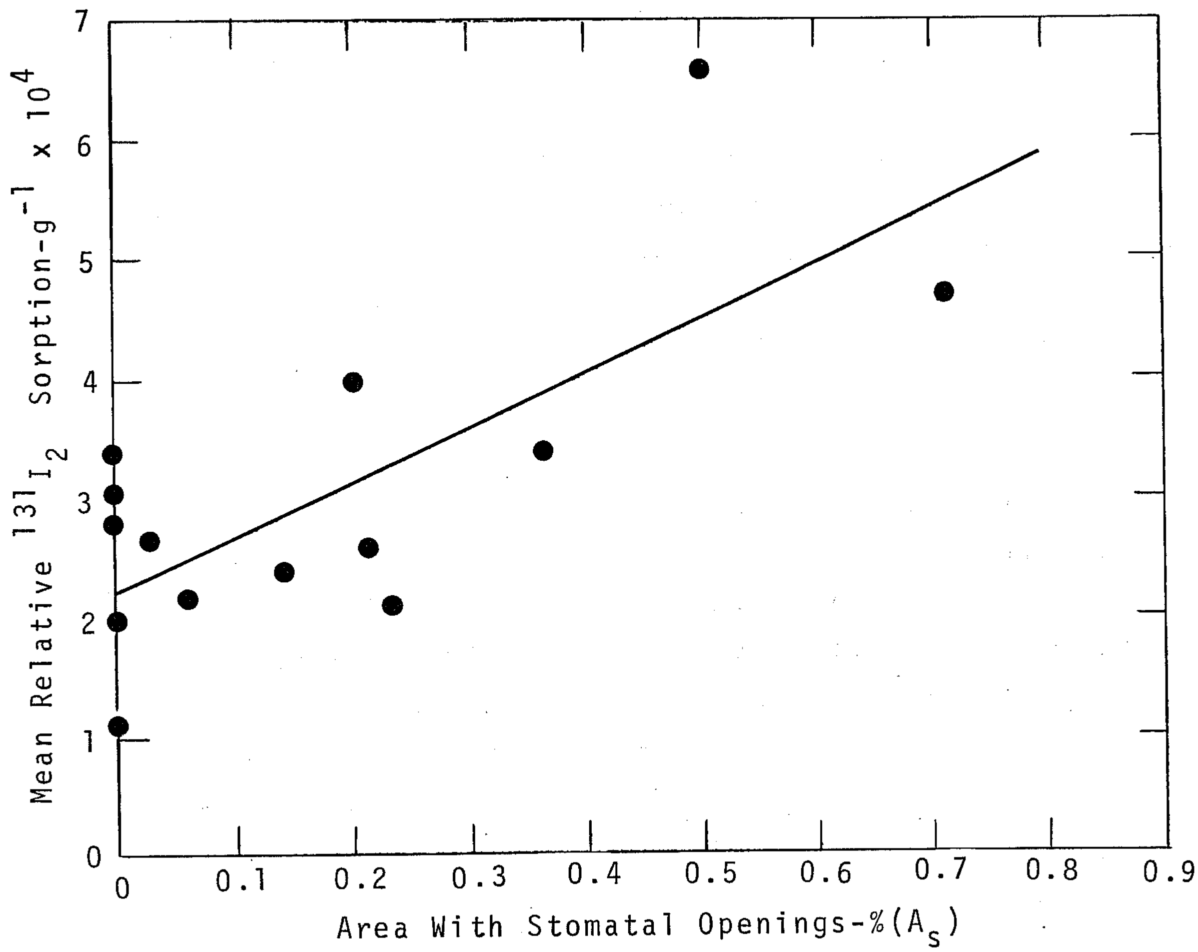

Figure 11. Effect of stomatal opening on iodine sorption.

most of the tests the stomata were less than one-half open. The line of best fit by the least squares method showed a significant relationship between stomatal opening and radioiodine adsorption. With fully open stomata, the adsorption was near 2.5 times that when the stomata were closed. The regression line (fig. 11) shows that at full stomatal opening, adsorption by the cuticle accounts for about 40 percent of the total. Therefore, the results demonstrate that grass leaves with open stomata definitely lower the transfer resistance, but the cuticle of the leaf also makes a significant contribution to adsorption.

A preliminary study of the effect of humidity on the adsorption of gaseous radioiodine by grass was also made in the environmental chamber. Radioiodine gas was released in the chamber over trays of grass during dark (simulated nighttime) and light (simulated daytime) conditions with 35 and 90 percent relative humidity conditions. The relative humidity in the chamber was controlled by changing the air temperature; 35 percent relative humidity was achieved at 86°F and 90 percent relative humidity at 72°F. During the dark, the ratio of high to low humidity adsorption was 1.3, and during the light the ratio was 2.3. The larger ratio observed during the light condition indicates that stomatal activity and other physiological processes in the living plants may have masked the chemical adsorption effects in the presence of increased atmospheric water vapor. Stomatal openings were not measured during this series of tests; therefore, stomatal activity cannot be evaluated.

Another environmental chamber study yielded preliminary results on the effect of wetted leaf surfaces on adsorption of radioiodine. Two tests consisting of eight trays of grass, four wet and four dry placed in the chamber in a checkerboard pattern, were made using known releases of radioiodine gas during daylight conditions. The average ratio of wet-to-dry leaf surface adsorption was approximately 1.4, a significant difference in adsorption. Stomatal opening measurements were not made during these tests; so this result may either be an indirect result of stomatal activity or be a direct result of chemical reaction between elemental radioiodine and the grass leaf cuticle with the presence of water.

3.4 Combined Effect of Transfer Regimes

The resistance approach was used to evaluate the combined effect of the three transfer regimes on total sorption. The total resistance can be expressed in accordance with (13) in terms of the surface boundary layer resistance r_{SS},

$$r_T = r_{BL} + r_{SS}; \tag{18}$$

r_T can only be measured directly if the sorption surface is a perfect sink for the gaseous effluent. Perfect sink surfaces for gases are rarely encountered in nature. Therefore, (18) must be altered to account for nonperfect sink conditions. In accordance with (9)

$$r_T = \frac{X_2}{\overline{F}_T} - \frac{X_o}{\overline{F}_T} \quad , \tag{19}$$

where $X_2/\overline{F}_T$ can be calculated from measurements of the gas concentration level X_2 (i.e., 1 m) and the deposition rate $\overline{F}_T$ at the interface (e.g., on grass). For a perfect sink interface $X_o = 0$ and the second term in (19) would equal zero. The general expression for r_T is then

$$r_T = r_M - r_S, \tag{20}$$

where r_M is the partial resistance that is measured and r_S is the resistance at the interface. Substituting (20) into (18) gives

$$r_M = r_{BL} + r_{SS} + r_S \quad , \tag{21}$$

which is the basic equation for use in evaluation of the combined effect of transfer regimes.

If the surface boundary layer resistance r_{BL} is assumed to be adequately represented by $\bar{u}/u*^2$, this resistance can be subtracted from the total measured resistance r_M and the quantity can be multiplied by u* to obtain a dimensionless relative flux $u*(r_M - r_{BL})$ with the effects of surface boundary layer resistance removed. This relative flux was then related to the reciprocal of EGSA ($A^{-0.75}$) from the data obtained during the 18 field releases of radioiodine gas in the form

$$u*(r_M - r_{BL}) = \frac{a}{A^{0.75}} + b, \qquad (22)$$

where $a/A^{0.75} = u*r_{SS}$ and $b = u*r_S$ in which the presumed constants a and b will be evaluated by the statistical method of least squares. One value of r_M, the median, was used in the computation for each field release. The results are depicted in figure 12. The statistically fitted line for data collected during unstable atmospheric conditions yielded the regression equation

$$u*(r_M - r_{BL}) = \frac{70.5}{A^{0.75}} + 5.5 \; . \qquad (23)$$

The data collected during stable atmospheric conditions were scattered widely about this line, which probably indicates that momentum flux relationships, established for near neutral atmospheric conditions, are not applicable during stable conditions.

If the resistance approach is valid, the surface resistance can be expressed as

$$r_S = \frac{5.5}{u*} \; . \qquad (24)$$

The magnitude of r_S found for these experiments is probably indicative of the value for partly open stomata. The surface

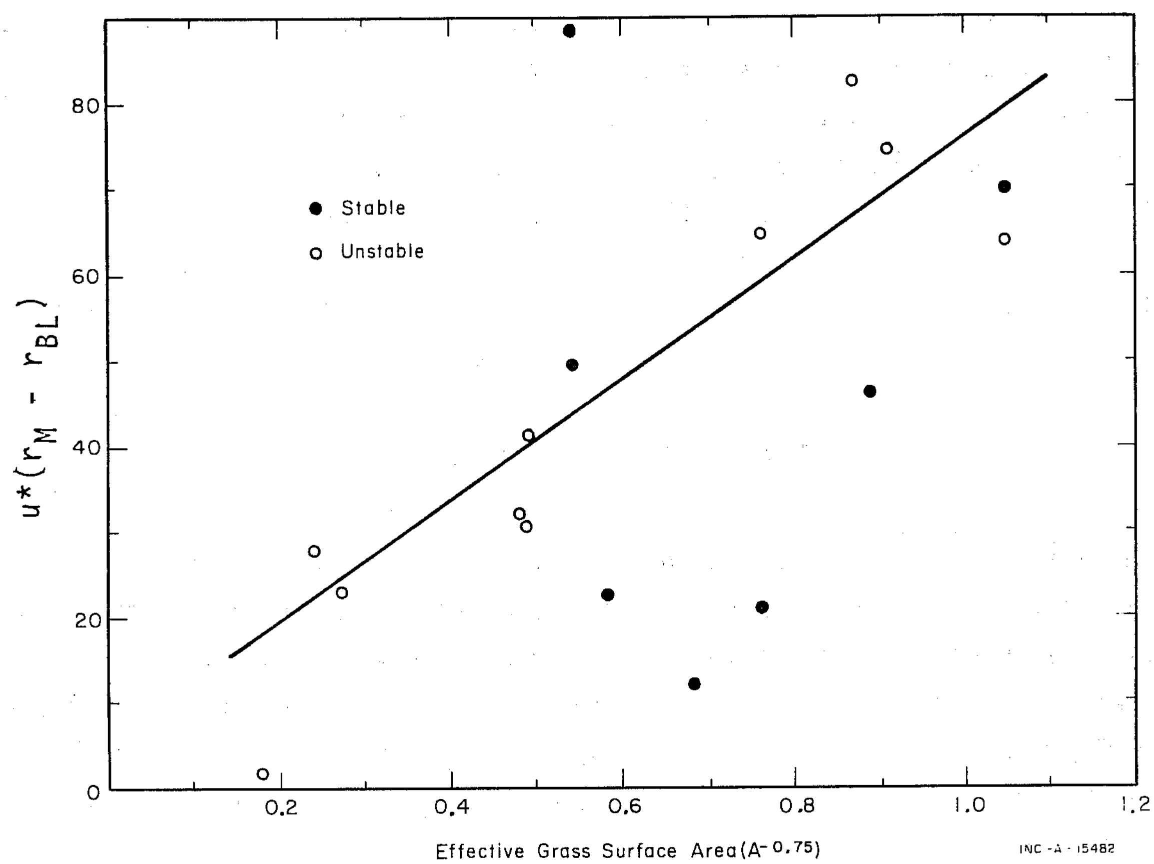

Figure 12. Comparison between calculated, $u^*(r_M - r_{BL})$, and measured, $A^{-0.75}$, normalized surface sublayer resistances.

sublayer resistance is indicated to be

$$r_{SS} = \frac{70.5}{u^* A^{0.75}} \ . \tag{25}$$

Since the values of A were usually between one and 10, the largest resistance of the three is r_{SS}. This means that most of the radioiodine gas entering the air in the grass canopy is carried around individual grass leaves in the aerodynamic flow without contacting the grass surface. The constant 70.5 expresses the average effect of turbulence and molecular diffusion on surface sublayer transport.

Owen and Thomson (1963) show that surface sublayer transport of heat to rough surfaces with bluff-type roughness elements can be expressed as

$$r_{SS} = \frac{a}{u^*} \, Re^{0.45} \, Pr^{0.8} = \frac{a}{u^*} \left(\frac{u^* z_0}{\nu}\right)^{0.45} \left(\frac{\nu}{\kappa}\right)^{0.8} , \qquad (26)$$

where Re is the Reynolds number, Pr is the Prandtl number, α is a function of the type of roughness elements, z_0 is the roughness length derived from the logarithmic wind velocity profile, ν is the kinematic viscosity of air, and κ is the thermal conductivity of air. For gas transfer to fibrous types of roughness elements (e.g., grass), a plausible expression analogous to (26) is

$$r_{SS} = \frac{a}{u^*} \left(\frac{u^* L}{\nu}\right)^{0.45} \left(\frac{\nu}{D}\right)^{0.8} , \qquad (27)$$

where L is a characteristic length probably related to grass density and height, and D is the molecular diffusivity of the gas ($D = 0.08$ cm^2/sec for I_2). The average value of $Re^{0.45}$ $Pr^{0.8}$ is about 70.5 for the field data collected during unstable conditions if L is taken as the grass height. Therefore, the Owen-Thomson type expression for surface sublayer transfer of heat to bluff surfaces appears to be a plausible expression for the transfer of iodine to fibrous surfaces if $\alpha \propto A^{-0.75}$.

3.5 Effluent Cloud Depletion

The radioiodine deposited on the entire pasture was calculated for six of the releases for which there were sufficient field data. The resulting calculations are shown in table 1 as a percentage of the amount of radioiodine released. The distances downwind between which these total deposition values were measured are also shown. These data show that the total depletion for these distances is nearly constant regardless of stability. There was also no apparent correlation with grass density. Thus air concentrations and deposition velocities tend to counterbalance one another. During stable conditions the air concentration is relatively high and the deposition velocity is usually low and during unstable conditions the converse is true.

3.6 Retention Studies

Measurements of apparent I_2-131 retention per unit mass (dry weight) of grass were made after nine of the field releases. There are at least three factors influencing these measurements of apparent retention of sorbed material by vegetation: (1) radioactive decay, (2) plant growth, and (3) resuspension of the material. The effect of radioactive decay can be removed from apparent retention data, if the data are converted to half-life per unit mass of grass,

Table 1. Percent of Total Amount of Radioiodine on Pasture

Test No.	Percent of Total	Range (m)	V_T (cm/s)	u* (m/s)	Stability
1	1.06	100-300	0.72	0.60	Unstable
2	1.07	100-380	0.61	0.58	Unstable
4	0.70	50-100	0.15	0.12	Stable
5	1.33	50-300	0.10	0.36	Stable
7	2.97	100-380	1.02	0.43	Unstable
19	1.04	100-380	1.23	0.64	Unstable

through use of the half-life relationship,

$$T_R = \frac{T_D \; T_M}{T_D - T_M} \quad , \qquad (28)$$

where T_R, T_D, and T_M are the removal, radioactive, and measured apparent half-lives, respectively. The results of the calculations for the field releases are shown in table 2. Mixed pasture grasses denote a mixture of Manchor Smooth Bromegrass, Fescue, and Orchardgrass. Generally, the results show $\bar{T}_M$ is 3.6 days, $\bar{T}_R$ is 6.8 days, and $\bar{T}_R$ is 30.9 days. These results indicate that the half-life caused by resuspension of I_2-131 is very long when compared with the half-lives caused by radioactive decay and plant growth. No correlation was found between resuspension rates and meteorological factors such as wind, temperature, and precipitation.

Table 2. Removal Rates from Grass

Release Date	Half-Life in Days: Measured T_M	Half-Life in Days: Apparent Removal T_R	Grass Type and Conditions
May 1963	3.0	4.8	Crested Wheatgrass, growing rapidly.
Sept. 1964	5.5	17.6	Mixed pasture grasses, dormant.
Nov. 1965	6.5	34.7	Mixed pasture grasses, dead leaves.
Sept. 1966	4.1	8.4	Mixed pasture grasses, growing.
Nov. 1966	5.8	21.1	Mixed pasture grasses, dead leaves.
July 1967	3.3	5.6	Mixed pasture grasses, growing.
Sept. 1967	6.9	50.2	Mixed pasture grasses, dormant.
June 1968	4.1	8.4	Mixed pasture grasses growing.
Aug. 1968	3.7	6.9	Sudangrass, growing.

4. SUMMARY

Evaluation of transfer properties of a gas from air to a surface using the resistance approach appears to give reasonable results if formulations for each resistance regime can be obtained. During unstable conditions the use of simple formulations for surface boundary layer and surface sublayer resistances showed good agreement with measured resistance. During stable conditions these same formulations produced relatively poor agreement.

During unstable conditions sorption was found to be proportional to the effective grass surface area or $A^{0.75}$. Also I_2-131 gas was found to be readily adsorbed by the leaf cuticle as well as being taken up through stomatal openings.

The depletion from an effluent cloud of I_2-131 gas appears to be independent of V_T and atmospheric stability at short distances downwind. This independence can be attributed to high air concentrations usually being associated with low transfer velocities and vice versa.

The retention studies have shown that resuspension is a slow process when compared with radioactive decay and plant growth. Both dormant and dead leaf grass conditions yielded comparable retention values.

5. SUGGESTIONS FOR FUTURE RESEARCH

A study of the structure and scales of turbulence within the grass canopy will lead to a better understanding of the turbulent transfer process involved in the empirical relationship between leaf surface and sorption. This study should be coupled with a similar study in the surface boundary layer within a few meters of the grass tops. A better understanding of turbulent transfer processes during stable atmospheric conditions may be an important result of these studies.

A definitive study of the relative sink of I_2-131 gas on grass compared to a perfect sink material (e.g., copper or silver) should be made in the environmental chamber to see if there is a linear relationship to u* as assumed in section 3.4 of this report. The perfect sink material should have the same physical configuration as grass.

Although no persistent relationship of V_T with distance downwind was observed for the field releases out to 380 m, V_T did show a persistent increase over mid-plume values at the outer limits of the plume in the lateral direction. These values along the plume edges were observed to be as high as a factor of 3 higher than plume center values. There are many factors that could lead to this result. First, the radiological analysis methods may be inadequate when low values are measured. Second, the relative sink of grass for I_2-131 gas may be a function of the amount already on the grass. Third, the flux-gradient hypothesis from which the transport velocity was derived may not be applicable at the plume edge where there is a larger variation in instantaneous concentrations in air. Each of these is a plausible explanation for this behavior of V_T, but experiments will have to be designed to determine whether any or all of these factors are causes.

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