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MEASUREMENT AND MODELING OF EXTERNAL RADIATION DURING 1984 FROM LAMPF ATMOSPHERIC EMISSIONS

by

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ABSTRACT

An array of three portable, pressurized ionization chambers (PICs) measured short-term external radiation levels produced by air activation products from the Los Alamos Meson Physics Facility (LAMPF). The monitoring was at the closest offsite location, 700-900 m north and northeast of the source, and across a large, deep canyon. A Gaussian-type atmospheric dispersion model, using onsite meteorological and stack release data, was tested during this study.

Monitoring results indicate that a persistent, local up-valley wind during the evening and early morning hours is largely responsible for causing the highest radiation levels to the northeast and north-northeast of LAMPF. Comparison of predicted and measured daily external radiation levels indicates a high degree of correlation. The model also gives accurate estimates of measured concentrations over longer periods of time.

I. INTRODUCTION

The Los Alamos Meson Physics Facility (LAMPF) is an 800-million electron volt, 1 mA intensity linear proton accelerator used for studying subatomic particles at relativistic velocities. Routine operation of the accelerator results in the formation of short-lived air activation products, primarily in the beam stop section of LAMPF. These activation products, which are principally the radioisotopes ^{11}C , ^{13}N , and ^{15}O , are monitored and vented to the atmosphere, increasing the radiation field at the Laboratory boundary, although still less than 7% of the Department of Energy's Radiation Protection Standard (RPS) (DOE 1981).

During 1984, approximately 734 000 curies of activation products were released from LAMPF. This produced a total radiation exposure of 44 mrem at the Laboratory boundary north-northeast of the LAMPF stack, which resulted in an estimated maximum

individual dose of 31 mrem,* or 6% of the DOE's 500 mrem/year RPS for members of the public (ESG 1984).

Offsite radiation exposure levels from LAMPF operations have been routinely monitored in the location of maximum exposure since 1977 with a network of thermoluminescent dosimeters (TLDs). In 1982, a pressurized ionization chamber (PIC) was placed at the fenceline location of the maximum external radiation level (Bowen 1982). This instrument has the ability to monitor very low external radiation levels over short time periods, and is used with the TLD measurements to estimate external

*This dose is from exposures that exclude contributions from background radiation (cosmic, terrestrial, global fallout, and self-irradiation sources). The doses calculated are those believed to be possible to individuals under realistic exposure conditions.

radiation levels. Also, a Gaussian-type model, using onsite meteorological data and radionuclide release rates, is then used to predict daily radiation exposures and is compared with the PIC measurements.

This study presents both the monitoring and modeling results of external radiation levels at three locations during 1984 because of LAMPF emissions. Measured radiation exposures are presented for all three locations during a 49-day period. Hourly radiation levels are calculated for all sites and compared with the prevalent wind patterns during the study period. Predicted daily levels are compared with measured values at all of the sites. Accuracy of the model is compared for day and night conditions. The model accuracy is also tested for different wind speeds, horizontal wind variations, and vertical wind variations. Annual model predictions are also compared with TLD measurements.

II. BACKGROUND

The Los Alamos National Laboratory is located on the Pajarito Plateau on the eastern flank of the Jemez Mountains (Fig. 1). The Sangre de Cristo Mountains lie nearly 70 km to the east. The Rio Grande Valley runs north-northeast to south-southwest between the two mountain ranges. The plateau slopes downward to the east from the base of the Jemez Mountains (approximately 2500 m above sea

level or MSL) to the Rio Grande (approximately 1700 MSL) over a distance of 25 km. There also are numerous alternating "finger" mesas and canyons running along the slope line of the plateau. The canyons are 50-100 m deep and 100-200 m wide, while the mesas vary from 200-600 m in width. LAMPF is located on a mesa top just south of Los Alamos Canyon.

The LAMPF stack is located about 800 m south of the closest Laboratory boundary location across the Los Alamos Canyon. Three short-lived, gaseous radioactive air activation products, ^{15}O , ^{11}C , and ^{13}N , account for virtually all downwind radiation levels. Several other radioactive gases are released; however, they are unimportant because of either extremely short half-lives of a few seconds or extremely small quantities. Because of the annihilation of positrons from the decay of these radionuclides, 0.511 MeV photon radiation is emitted from the plume of gases as it travels downwind from the stack. However, the total amount of radiation in the plume decreases with time (or downwind distance) as the gases decay. Some characteristics of these three radioactive gases are shown in Table I. Note that most of the radioactivity released is ^{15}O . However, the half-life ($T^{1/2}$) of ^{15}O is only 123 s. The contribution of ^{15}O to the total radioactivity in the plume at the Laboratory boundary increases with increasing windspeed. Note that although much less ^{11}C is emitted than ^{15}O ,

Fig. 1. Regional location of Los Alamos.

more ^{11}C remains at the Laboratory boundary distance than ^{15}O for windspeeds under 3 m/s. For greater windspeeds, ^{15}O becomes the dominant gas. The contribution of ^{13}N to the total radioactivity is small because it comprises only a small percentage of the releases and has a relatively short half-life.

Table I shows that the total radioactivity in the plume varies greatly with the windspeed. With stronger windspeeds, less of the radioactive gases decay; however, stronger windspeeds enhance dilution of the gases causing lower concentrations downwind. The "decay factor" of the radionuclide mixture mitigates much of the "dilution factor" with increasing windspeed. For example, assuming the average release rate of 156 Ci/h, 55 Ci or 34% of the original amount is estimated to still be available in the plume 800 m downwind with a 3 m/s windspeed. At a windspeed of 6 m/s, the amount of curies increases 56% to 85 Ci, or 55% of the original amount. However, the dilution is twice as great with a 6 m/s wind as it is for a 3 m/s wind. Therefore, over the typical windspeed range, photon radiation levels from the plume are expected to decrease slightly with increasing windspeed. Also, windspeed can affect the stability, and in turn, indirectly affect plume concentrations and resulting gamma radiation.

III. METHODOLOGY

A. Siting and Instrumentation

1. **LAMPF Releases.** The study area is shown in Fig. 2. The LAMPF stack is 30 m high and has a

Fig. 2. Map of study area.

diameter at the top of 0.9 m. A Kanne-type air-ionization instrument is used to monitor the radioactive gases before entering the stack. A voltage is recorded, which is correlated to the total radionuclide

Table I. Release Data of the Three Primary Radioactive Gases and Amounts of Radioactivity Remaining at 800 m Downwind

Radioactive Gases	%	Release ^a Rate (Ci/h)	T ^{1/2} (s)	% Remaining at 800 m for Different Windspeeds			
				1 (m/s)	3 (m/s)	6 (m/s)	10 (m/s)
^{15}O	72	122	123	1	22	47	64
^{11}C	16	27	1230	64	86	93	96
^{13}N	4	7	600	40	74	86	91
Total	92	156	---	13	34	55	69

^aDenotes average release rate over 5-month operation period.

air concentrations in curies per cubic meter (Ci/m³) in the stack gas. The percentage concentrations of ¹⁵O, ¹¹C, and ¹³N in the stack gas have been determined previously by analyzing bag samples of the stack gas. Stack velocity is measured continuously by an anemometer placed halfway up the stack and by periodic stack tests.

2. External Radiation Monitoring. Three PICs monitored real-time photon exposures to air during 1984 at the nearest offsite boundary across the Los Alamos Canyon. The instruments were located at azimuths of 0° (north), 22° (north-northeast) and 45° (northeast) of the LAMPF stack. The PICs located in the north and north-northeast are 725 m from the stack, while the northeast PIC is located 875 m from the stack. Each instrument uses a modified Reuter-Stokes high-pressure ionization chamber. The special electronics package was made to allow greater accuracy for the range of measurements in this study. A weatherproof metal box, containing a battery pack, a microprocessor, and data storage module, is located next to each PIC. A solar collector located at the top of each box maintains charge on the batteries. The microprocessors provide onsite summarization of radiation data. Because of the extreme temperatures that occur inside the boxes, a data storage module is used to store the data rather than a cassette recorder.

An array of 12 lithium fluoride TLD stations monitors long-term gamma doses on a routine basis. The network is located also along State Road 4 and extends from the north-northwest to the northeast of the LAMPF stack. The individual TLDs are approximately 70 m apart. Another TLD network unaffected by Laboratory operations provides the background absorbed dose levels for external radiation.

3. Meteorology. The meteorological tower that provided data for this study, the East Gate tower, is located between the north and north-northeast PICs at a distance of 725 m and a bearing of 12° from the LAMPF stack (Fig. 2). This tower has three-way propeller systems at heights of 1.3, 4.0, and 12.0 m, which measure horizontal and vertical winds. Thermistors equipped with blowers measure air temperature at 1.3 and 12.0 m. Solar radiation, relative humidity, and rainfall are also recorded at this site.

Another tower is located about 100 m to the north-northwest of the stack on the LAMPF side of Los Alamos Canyon. A three-way propeller system measures the horizontal and vertical winds at a height of 23 m.

B. Data

1. Gathering. All data were collected by microprocessors, except for the TLD data. One microprocessor collected the source-term data and meteorological data from the tower near the stack. Another processed the data from the tower on State Road 4. All of the microprocessors provided 15-min averages and standard deviations for all of the data. A microprocessor was also used to collect the data at each PIC.

2. Determination of Radiation Background. Gamma levels measured by the PICs included background levels as well as the levels from LAMPF emissions. It was, therefore, necessary to estimate and subtract out background levels from the measured values. The daily background level at each PIC site was estimated by using total measured values during times when the LAMPF plume was not affecting the sites. These periods were determined by observing daily plots of the three PICs. A minimum of 12 "plume-free" hours was desired to determine the daily background. However, there were frequent periods of several days during which no background estimates could be made. When this occurred, a background estimate from the day closest to the period in question was used for the calculations.

The long-term background was determined by using absorbed doses measured by a remote TLD network. These background levels were then subtracted from the total levels measured by the TLD network on State Road 4.

IV. RESULTS AND DISCUSSION

A. Monitoring

The short-term radiation levels from LAMPF emissions can vary dramatically over short time periods and distances. This fact is illustrated in Fig. 3 where plots of 15-min radiation averages for the three PICs along with wind direction and speed and vertical velocity are shown for a day. Note the high photon exposure at the northeast PIC for the first 3 h of the day with the southwesterly* winds. Meanwhile, the north-northeast PIC, just 350 m to the west, is only slightly affected by the plume, and the north PIC

*Wind direction is defined as the direction from which the wind is blowing.

Fig. 3. External radiation and wind data during a day when the LAMPF plume is evident.

is affected even less. As the wind becomes more west-southwesterly after 0300, the exposure levels at all three sites drop to near background levels of 12-15 $\mu\text{R}/\text{h}$.*

The plume appears to rotate counterclockwise along with the wind between 0600 and 0800. Note how the gamma exposure peaks first at the northeast PIC and then to the north-northeast and north over an hour's time while the wind shifts from southwesterly to southerly. During the midday hours, winds continue southerly, with the north PIC showing the most exposure and less exposure indicated by the other PICs. The wind changes direction after 1700, with the direction becoming more southwesterly. Again, rather high peaks of exposure are indicated by the northeast PIC. Total gamma exposures for the day at all three PICs are well above the typical background of 290-350 μR .

Two characteristics of the data on this particular day are also common on many other days. One is that the highest concentrations occur during the nighttime hours. This is probably because of the decreased turbulence of the atmosphere at night. Observe that the standard deviations of wind direction and vertical velocity are greatly reduced during early morning and evening, when gamma exposures are greatest. Even though the winds are southerly during midday, the north PIC shows relatively low gamma levels probably because of the increased daytime ranges of wind direction and vertical velocity (increased turbulence). This day also has persistent southwesterly winds during the early morning and evening hours, and as a result, relatively high gamma levels at the northeast PIC. This pattern has been seen repeatedly on other days.

The predominance of south-southwesterly and southwesterly winds is shown by the wind roses in Fig. 4. These wind roses represent wind data for 49 days during 1984 on which data were available for all PICs. This limited period is representative of average summer season winds. The high frequency of southwesterly winds can be seen clearly in the night wind rose. About 28% of the nighttime winds are southwesterly, while the directions south-southwest, southwest, and west-southwest account for a total of

nearly 54% of nighttime winds. For all hours, south-southwest and southwesterly winds account for over 34% of all winds during the study period. Much of the high frequency of southwesterly winds is probably because of the channeling of the winds by the Rio Grande Valley. Because the predominant winds are southerly and westerly, the local winds follow the orientation of the valley and become southwest and south-southwesterly. This process occurs more frequently at night when the vertical mixing is at a minimum.

The daytime wind pattern is more complex and varied. Besides the channeling effect, some southwesterly winds result from a mountain-valley wind up the Rio Grande Valley caused by strong solar heating (Bowen 1981). These winds are especially frequent during the summer season because of a lack of strong and persistent large-scale winds.

Another secondary maximum of winds from the south-southeast and southeast can be seen during the daytime. These winds are caused by a solar driven upslope wind over the Pajarito Plateau.

Also, a northeast wind has frequently been observed during the morning hours. Some of these winds are possibly caused by channeling of winds down the Rio Grande Valley.

The complex pattern of winds causes large variations of gamma levels with time of day. Average hourly gamma levels caused by LAMPF emissions for the 49-day study period are shown in Fig. 5. Both the highest and lowest hourly averages occur at the northeast PIC. The highest averages of 40 $\mu\text{R}/\text{h}$ occur around midnight because of the high frequency of southwesterly winds. Midday values are very low at the northeast site from a scarcity of up-valley winds at this time. The north-northeast site shows a similar, but more moderate daily gamma radiation variation. The north PIC shows a rather uniform average radiation level throughout the day. Increased daytime mixing of the atmosphere plays an important role in reducing gamma radiation levels at all three sites.

The increased daytime mixing is shown vividly in Fig. 6, which contains histograms of standard deviation of horizontal wind (σ_h) and vertical wind (σ_v) by hour. Values of both σ_h and σ_v are more than twice as large during the early afternoon hours as they are during the late-night and early-morning hours. The diurnal variation of the two are quite similar.

The variation during the day in the LAMPF release rate also contributes somewhat to radiation variations. Average hourly release rates are shown in Fig. 7. Observe that the average release rate is at a

*Exposure to air is expressed in units of roentgens. All gamma exposures, both measured and modeled, will be expressed in roentgens throughout this report. However, the units of roentgens and rems, the units of dose, are virtually interchangeable (1R = 0.96 rem).

Fig. 4. Day, night, and total wind roses from East Gate at 12 m during a 49-day study period.

Fig. 5. Average hourly external radiation at three sites from LAMPF emissions during a 49-day study period.

minimum during the day, when routine maintenance of the LAMPF beam is the greatest.

A more detailed look at diurnal wind patterns is shown in an hourly frequency diagram in Fig. 8. Note how the up-valley wind develops in the afternoon hours and becomes more frequent later in the evening and early morning hours. Southwesterly winds account for over 30% of all winds for over 5 hours. These persistent winds are responsible for the maximum gamma levels at the northeast PIC during this time. By 0400, the frequency of up-valley winds decreases while down-valley winds become more important. By late morning, down-valley winds account for over 20% of all winds. Also, note that upslope winds over the Pajarito Plateau are somewhat frequent during the late morning and early afternoon hours. This figure illustrates the slight clockwise turning of the local winds as they reach

Fig. 6. Average hourly standard deviation of horizontal wind direction (σ_θ) and vertical wind (σ_ϕ) at East Gate during a 49-day study period.

maximum frequencies. This is probably from the delayed effect of the Coriolis force.

B. Modeling

1. Discussion. Two major considerations in the modeling of radiation caused by a plume are the distance of the receptor from the plume and the intensity of the radiation emanating from it. These considerations are in addition to the problem of estimating the downwind configuration of the plume and the concentration of radionuclides within it. A gamma-emitting cloud with small dimensions compared with the distance the radiation travels is termed a finite cloud for modeling purposes. The following equation for finite clouds is suggested in *Meteorology and Atomic Energy* (Healy 1968):

Fig. 7. Average release rate from LAMPF emissions during a 49-day study period.

Fig. 8. Hourly frequency diagram of wind direction for East Gate during a 49-day study period.

$$\gamma D(x,y,0) = \frac{0.1456 \mu \mu_a \bar{E}_\gamma Q_x (I_1 + kI_2)}{\bar{U}} \quad (1)$$

where

γD = dose (rads) or exposure (roentgens),

μ = total gamma-ray absorption to air coefficient (1/m),

μ_a = energy-absorption coefficient for gamma rays (1/m),

$\bar{E}_\gamma$ = average gamma energy emitted at each disintegration (MeV/dis), = 0.511

Q_x = amount of source material remaining in a plume after a travel distance X (curies),

$I_1 + kI_2$ (or I_1) = integrals accounting for the geometry of the plume and radiation from the plume, and

$\bar{U}$ = average windspeed (m/s).

Also, the effect of lower air density resulting from the higher elevation at Los Alamos is accounted for by multiplying γD by 1.3. Note that the integrals I_1 and I_2 used in this model must be determined by chart or by a computer routine. These integrals are used to account for the travel of gamma radiation from the plume. Healy suggests using this finite cloud model when the standard deviation of the spread of the plume (σ) is less than $1/\mu$ ($1/\mu$ is approximately 120 m considering the gamma energy of LAMPF emissions and the density of air at Los Alamos).

A much simpler infinite cloud model can be used for gamma-ray plumes at relatively large downwind distances. The following model for infinite clouds is taken from *Meteorology and Atomic Energy* (Healy 1968):

$$\gamma D = 0.457 \bar{E}_\gamma \chi \quad (2)$$

where χ is the radionuclide concentration (curies/m³). This equation can be used during equilibrium or near-equilibrium conditions when just as much energy absorption per unit volume occurs as energy release per unit volume. The value of γD is directly proportional to χ . Since χ is relatively easy to determine by using the Gaussian dispersion model, the infinite model is much easier to calculate than the finite model.

The finite model was used to predict 24-h exposures at the three sites by adding up 15-min esti-

mates. The results indicated that the model underestimated the actual exposures by more than 50%.

The infinite model was then used to estimate 24-h gamma exposures at the three sites. Healy suggests that Eq. (2) be reduced by a factor of 0.5 for the ground level case. This is because a receptor at the ground would only receive radiation from half the idealized cloud or plume. However, a reduction factor of 0.25 was empirically used instead in this study to give:

$$\gamma D = 0.24 \bar{E}_\gamma \chi \quad (3)$$

This equation is a compromise between the idealized infinite cloud and the ground level cases. One reason for its use is because the PICs are located close to the edge of the canyon. As the plume crosses the canyon and approaches the PICs, it possibly spreads below the top of the canyon (e.g., below the PIC heights.) Therefore, some radiation from the plume below the canyon top can possibly contribute to the total external radiation received by the PICs. Also, the highest exposures are expected to occur at the release level, slightly above the ground at all three sites. Unlike the strict idealized case, a net amount of radiation would be expected to travel toward the ground because of higher photon concentrations above ground.

The ground-level form of the Gaussian dispersion was used:

$$\chi = \frac{Q}{\pi \sigma_y \sigma_z \bar{U}} \exp \left[-\frac{1}{2} \left(\frac{Y}{\sigma_y} \right)^2 \right] \exp \left[-\frac{1}{2} \left(\frac{H}{\sigma_z} \right)^2 \right] \quad (4)$$

where

χ = air concentration in Ci/m³,

Q_x = effective release rate (Ci/s),

σ_y, σ_z = dispersion coefficients in the crosswind and vertical directions (m),

$\bar{U}$ = average windspeed (m/s),

Y = distance from plume centerline (m), and

H = stack release height (m).

For long-term integrated concentrations, the following form of the Gaussian dispersion equation was used:

$$D_T(x,\theta) = \frac{2.03 Q_x f(\theta)}{\sigma_z U X} \exp \left[-\frac{1}{2} \left(\frac{H}{\sigma_z} \right)^2 \right] \quad (5)$$

where

- $D_T(X, \theta)$ = sector averaged integrated concentration (curies-sec/m³),
 Q_x = total release remaining at downwind distance X (curies),
 $f(\theta)$ = frequency of occurrence of wind direction toward the direction, θ ,
 σ_z = average vertical dispersion coefficient (m),
 $\bar{U}$ = average windspeed (m/s), and
 X = downwind distance (m).

The coefficients σ_y and σ_z were determined directly from the onsite meteorological data using a method suggested by Draxler (1976). The equations used are:

$$\sigma_y = \sigma_\theta X f_1(T/T_i) \quad (6)$$

$$\sigma_z = \sigma_w \frac{X}{\bar{U}} f_2(T/T_i) \quad (7)$$

where

- σ_θ = standard deviation of the horizontal wind direction (radians),
 σ_w = standard deviation of the vertical wind speed (m/s),
 X = downwind distance (m),
 $\bar{U}$ = average horizontal windspeed (m/s), and
 f_1, f_2 = functions of downwind distance and thermal stability.

The stack release gas at LAMPF is very close to the ambient temperature. The stack rise is, therefore, expected to be from momentum only. The following stack rise equation presented by Briggs (1969) was used:

$$\Delta H = 1.5 \left(\frac{V_s}{\bar{U}} \right) D \quad (8)$$

where

- ΔH = stack rise in m,
 V_s = stack exit velocity in m/s,
 $\bar{U}$ = average windspeed in m/s, and
 D = stack diameter in m.

For the LAMPF stack, V_s averages 10 m/s and $D = 0.9$ m. The calculated ΔH ranges from 13 m for 1 m/s winds to as little as 1-2 m for strong winds.

The different heights of the three receptors relative to the source were accounted for in the modeling. Air containing the emissions is expected to slow up as it travels northward over the "smooth" canyon. Conversely, the air speeds up as it approaches the mesa on the other side. This is caused by a Venturi-type effect: a volume of air will speed up if, in this case, the vertical distance through which it is traveling is reduced. Likewise, the air will slow down slightly approaching the canyon. Indeed, when southerly and southwesterly winds occur, the wind data show positive (upward) vertical velocity at the PIC sites. Because of these aerodynamic effects, the plume would be expected to slightly dip as it moves across the canyon and rise as it encounters the mesa.

Because the PICs are at the edge of the canyon where the air is still rising, the plume is probably below the original effective release height of 35 m above the ground. Therefore, as a compromise, the plume was assumed for modeling purposes to travel halfway between constant terrain (mesa top) height and height above sea level. For example, the north PIC is at a height 17 m above the base of the LAMPF stack. For modeling purposes, this reduces to 8.5 m. Even at the north PIC, the highest monitor, this one-half height adjustment in the model only increases estimates approximately 10% over the case without height adjustment. The effect is even less at the north-northeast PIC, which is only 10 m higher than the ground level at LAMPF.

For simplicity, it is also assumed that all available gases in the plume cross the canyon. Realistically, some of the gases are lost by turbulence into the canyon. However, the transport of the radionuclides into the canyon by turbulent exchange is expected to be small compared with the amount transported across the canyon.

The possible effects resulting from the LAMPF building on the transport and dispersion of the emissions were not taken into account in this study. The effective stack height of 35 m is slightly greater than twice the building height. Therefore, any building wake affecting the plume is expected to be slight. Also, the building with the stack is connected to a long, narrow building housing the proton accelerator beam. This extends 0.25 mile to the west, but how its length affects the low-level winds is unknown.

2. Daily Model Results. Daily model predictions, based on integration of 15-min predictions, were made and compared with measured values. Comparison of the predicted and measured values for the three sites are shown in Fig. 9, and the related

Fig. 9. Predicted versus measured daily external radiation from LAMPF emissions at sites N, NNE, and NE of LAMPF on State Road 4.

statistics are shown in Table II. There is good correlation between the predicted and measured data. Correlation is strongest at the north-northeast site and weakest at the northeast site. However, even at the northeast site, the correlation coefficient is high at 0.83 with a corresponding r^2 value of 0.69. This implies that 69% of the variation of measured values is explained by the model at the northeast PIC, with higher r^2 values at the other two sites.

Note that the model closely predicted measured exposures at the north-northeast and northeast PICs with slopes of nearly one. However, the slope of 0.61 at the north PIC indicates that the model underpredicts at this site. This rather large difference in slope of the north PIC data may be related to the large difference of wind frequency in south and south-southwest winds. Radiation from the plume traveling toward the north-northeast PIC possibly affects the north site.

Daily model predictions were likewise made using winds measured with the LAMPF tower and compared with measured values. This comparison indicates close agreement at the north and north-northeast PICs, while the model underpredicts by 70% at the northeast site. This is because of a greater frequency of southerly winds and much less frequency of southwesterly winds at LAMPF than at the East Gate tower. Possibly, the buildings and/or the hill on which the tower is standing may disturb the wind-flow. Conceivably, the winds are often southerly at LAMPF and become more southwesterly over the canyon downwind. This will be investigated in more detail. Clearly, the correlation of predicted versus measured radiation levels is significantly less than using the East Gate wind data. For example, the correlation coefficient between measured and predicted values is only 0.54 in the northeast sector when LAMPF wind data are used. For this reason, the meteorological data taken from the East Gate tower were used for the modeling in this study.

Further analyses were made to check the model's accuracy versus windspeed, standard deviation of wind direction (σ_θ), and standard deviation of vertical wind (σ_z) at each of the three sites. These analyses were made for both daytime and nighttime and were limited to the 49-day period, which contains data for all three sites.

Ratios of predicted versus measured gamma exposures for different windspeeds are shown in Table III. The ratios are consistently close to 1 during the daytime for the north-northeast and northeast PICs at all windspeeds, while the ratios decrease at the

north PIC with increasing windspeed. The increasing underestimation with increasing windspeed for the north PIC is even more evident during the night. However, the great majority of winds greater than 5 m/s are from the south-southwest and southwest. Conversely, the model tends to overpredict at the northeast PIC at night for higher windspeeds. As stated earlier, an appreciable amount of gamma radiation may be given off by the plume, and received by the north PIC, while the plume travels to the north-northeast and northeast.

A similar analysis, but for different σ_θ 's is shown in Table IV. For the most part, the model closely predicts the exposures at the north-northeast and northeast PICs for both daytime and nighttime cases. The model clearly underpredicts at the north PIC during periods of low horizontal dispersion. Once again, these conditions occur during strong south-southwest and southwest winds from the up-valley wind.

Finally, another analysis based on σ_z 's is shown in Table V. This model consistently predicts the exposures well at both the north-northeast and northeast PICs during the daytime and nighttime. The model accuracy is not affected much by a change in σ_z during the daytime. However, as in the case of σ_θ , the model underpredicts during conditions of low vertical dispersion at nighttime. Again, these conditions most often occur during times of strong south-southwest and southwest winds.

3. Long-Term Model Results. The long-term Gaussian model was used to estimate exposures at the three sites for the 49-day study period. These estimates are compared with the estimates derived from adding up the separate 24-h estimates and with the measured data (see Table VI). Results show that the long-term model is very useful in predicting exposures, but not as accurate as the short-term model. The long-term model yields estimates rather close to those of the short-term model, with both substantially underpredicting in the north sector. However, the long-term model does overpredict in the northeast sector. The long-term modeling would possibly provide even more accurate estimates if different classes of wind speed and stability (σ_z) were incorporated in the model rather than average values. Still, the long-term model, which yields estimates with more error than the short-term model, gives a very accurate estimate for the entire north-northeast sector.

**Table II. Regression Analysis Statistics for
Predicted Versus Measured Daily External Radiation
at Three Sites on State Road 4
(see Fig. 9)**

PIC No.	Slope	Y-Intercept	R^a	R²	P^b	Number of Days
N	0.61	15	0.84	0.71	>99%	84
NNE	1.18	-11	0.89	0.79	>99%	68
NE	0.88	54	0.83	0.69	>99%	103

^aDenotes correlation coefficient.

^bDenotes probability correlation did not happen by chance.

**Table III. Ratios of Predicted Versus Measured External Radiation
Exposures at Three Sites for Different Windspeeds
(over entire 49-day study)**

Windspeed (m/s)	Day			Night			Total		
	N PIC	NNE PIC	NE PIC	N PIC	NNE PIC	NE PIC	N PIC	NNE PIC	NE PIC
0-3	0.84	1.17	1.22	0.64	0.97	0.74	0.70	1.00	0.77
3-5	0.88	1.21	1.21	0.57	1.24	1.01	0.69	1.24	1.02
5-7	0.67	1.20	0.96	0.37	1.12	1.37	0.55	1.15	1.27
>7	0.43	1.12	1.12	0.22	1.20	1.52	0.35	1.17	1.42
Total	0.77	1.19	1.09	0.56	1.13	1.02	0.65	1.15	1.03

**Table IV. Ratios of Predicted Versus Measured External Radiation at
Three Sites for Different Standard Deviations of Horizontal Wind (σ_θ)
(over entire 49-day study)**

σ_θ (degrees)	Day			Night			Total		
	N PIC	NNE PIC	NE PIC	N PIC	NNE PIC	NE PIC	N PIC	NNE PIC	NE PIC
<7.5	---	---	---	0.31	1.21	1.06	0.31	1.21	1.06
7.5-12.5	0.36	1.14	1.00	0.34	1.11	1.08	0.34	1.11	1.08
12.5-17.5	0.66	1.17	0.95	0.70	1.20	0.91	0.69	1.19	0.92
>17.5	0.88	1.21	1.29	0.87	1.00	0.75	0.88	1.13	0.94
Total	0.77	1.19	1.09	0.56	1.13	1.02	0.65	1.15	1.03

**Table V. Ratios of Predicted Versus Measured External Radiation at
Three Sites for Different Standard Deviations of Vertical Wind (σ_p)
(over entire 49-day study)**

σ_p (degrees)	Day			Night			Total		
	N PIC	NNE PIC	NE PIC	N PIC	NNE PIC	NE PIC	N PIC	NNE PIC	NE PIC
<5	---	---	---	0.13	0.82	1.09	0.13	0.82	1.10
5-7.8	0.60	1.22	1.04	0.44	1.26	1.04	0.48	1.25	1.04
7.8-10	0.82	1.28	0.98	0.63	1.15	0.97	0.71	1.19	0.97
>10	0.79	1.11	1.17	0.74	1.60	0.75	0.77	1.05	0.88
Total	0.77	1.19	1.09	0.56	1.13	1.02	0.65	1.15	1.03

**Table VI. Long-Term External Radiation Estimates Based on a
Long-Term Model, Short-Term Model, and Measurement (mR)
(over 49-day study)**

PIC Site	Long-Term Model	Short-Term Model	Measured
N	10.9	12.6	20.7
NNE	27.9	27.6	25.5
NE	33.0	22.0	23.0
N thru NE	23.9	20.7	23.1

Long-term exposures were also calculated for 1984 at locations along State Road 4. The estimated exposures (mR) are: 75 in the northeast, 50 in the north-northeast, 39 in the north, and 28 in the north-northwest. This gives an average of 59 mR for the sector from north-northwest through northeast. This compares with the 44 mR as reported by the TLD network.

V. SUMMARY AND CONCLUSIONS

A network of monitors on State Road 4 measured short-term gamma exposure levels resulting from LAMPF emissions. Onsite meteorological data were analyzed to determine possible spatial and temporal patterns. The meteorological data along with LAMPF source term data were used to predict gamma exposures for 24-h and longer periods.

The primary conclusions of the study are:

- (1) A persistent, locally produced up-valley wind is responsible for causing the maximum exposures to occur to the northeast and north-northeast of LAMPF.
- (2) The channeling of large-scale winds, especially at night, is most likely responsible for the high frequency of up-valley winds.
- (3) External radiation is generally considerably higher during the nighttime hours because of decreased atmospheric dispersion and, to a lesser degree, increased emission rates.
- (4) Predicted daily exposures using the simple infinite cloud approximation correlate very well with measured exposures. The more complex finite cloud model gives estimates more than 50% less than measured values.

- (5) The short-term model does underpredict exposures to the north of LAMPF, especially during the nighttime and/or times with weak atmospheric mixing. However, these periods coincide with the persistent southwesterly and south-southwesterly up-valley winds. Photon radiation from the adjacent plume may affect the north PIC and is not accounted for in the model. Another possibility is that because of building effects at LAMPF, the winds there are more southerly and are directing the plume more often toward the north PIC.
- (6) The long-term model yields rather accurate exposures, but not as accurate as the short-term model. Based on these results, a long-term model is seen as a useful tool in determining estimates of long-term exposures.
- (7) Based on these modeling results, a Gaussian model is expected to accurately predict radioactive or nonradioactive levels up to several miles downwind if onsite meteorological and source data are available. However, further calibration of the models using some form of tracer would increase confidence in the use of the models.

VI. NEW DEVELOPMENTS AND FURTHER STUDY

New emission controls have been implemented at LAMPF during 1985. The radioactive gases are now held for a period of time before being released into the stack. Because of the short half-lives of these gases, the amount of radioactivity released is decreased. Readings from the Kanne chamber indicate at least a 70% reduction in release rate from that of 1984. External radiation at all three PICs likewise indicates a significant reduction in levels from 1984.

The three PICs will continue to monitor radiation during 1985. Possible future study includes placement of additional PICs at other locations in order to estimate the effect of LAMPF emissions. Possible locations include the canyon bottom between LAMPF and the PIC sites and the Bayo Sewage Treatment Plant, located 2.2 km northeast of LAMPF. A function accounting for the radiation shine from the plume will possibly be developed and incorporated in the model. Frequency of different wind speed and stability classes can be used by the long-term model to possibly improve its accuracy. A further examination should be made into why the LAMPF wind data, which provide less accurate model results, are so different from the East Gate wind data. A simple trajectory model, incorporating

East Gate and LAMPF wind data simultaneously, may be tested to address the problem of why the north PIC is underestimated using the East Gate wind data alone.

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