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MEASUREMENT AND MODELING OF EXTERNAL RADIATION DURING 1985 FROM LAMPF EMISSIONS

by

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ABSTRACT

An array of three portable, pressurized ionization chambers (PICs) continued to measure external radiation levels during 1985 caused by radionuclides emitted from the Los Alamos Meson Physics Facility (LAMPF). The monitoring was at the closest offsite location, averaging 800 m north and northeast of the source, just across a 120-m-deep canyon. A Gaussian-type atmospheric dispersion model, using onsite meteorological and stack release data, was tested during this study. A more complex finite model, which takes into account the contribution of radiation at a receptor from different locations of the passing plume, was also tested.

Monitoring results indicate that, as in 1984, a persistent wind up the Rio Grande Valley during the evening and early morning hours is largely responsible for causing the highest external radiation levels to occur to the northeast and north-northeast of LAMPF. Daytime winds are more southerly, transporting more radionuclides toward the north and north-northeast. However, because of increased turbulent mixing during the day, external radiation levels are generally much less during the day than at night. External radiation levels during 1985 show approximately a 75% reduction over 1984 levels. This resulted from a similar percentage reduction in LAMPF emissions caused by newly implemented emission controls.

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 time periods. Comparison of predicted and measured hourly values indicates that the model generally tends to overpredict during the day and underpredict at night.

I. INTRODUCTION

The Los Alamos Meson Physics Facility (LAMPF) is an 800-million-electron-volt, 1-milliampere-intensity linear proton accelerator used for studying nuclear interactions with subatomic particles at relativistic velocities.

Routine operation of the accelerator results in formation of short-lived 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 external radiation at the Laboratory boundary.

During 1985, approximately 127,000 curies (Ci) of activation products were released from LAMPF. This produced a total measured radiation exposure of 11.4 mrem at the Laboratory boundary north-northeast of the LAMPF stack, which resulted in an estimated maximum individual dose of 7.3 mrem* (ESG 1986) or 29% of the Environmental Protection Agency (EPA) 25-mrem radiation protection standard (EPA 1985).

The 1985 emissions represent over an 80% reduction from those of 1984, when 734,000 Ci were released. The reduction in emissions was primarily accomplished by holding the radioisotopes before release through the stack, allowing the short half-life radionuclides to decay at the production point. The large emissions decrease was responsible for nearly a 75% reduction in radiation levels at the north-northeast boundary from those in 1984, when the total radiation exposure and estimated maximum individual dose were 44 and 31 mrem, respectively (ESG 1985).

Offsite radiation exposure levels from LAMPF operations have been routinely monitored since 1977. A network of thermoluminescent dosimeters (TLDs) was placed at the Laboratory boundary affected by LAMPF emissions. In 1982, a pressurized ionization chamber (PIC) was placed at the fence line location of the maximum external radiation level (Bowen 1982). This instrument has the capability of monitoring short-term radiation levels and short-term external radiation changes from the passing LAMPF plume. The PIC measurements are used as a baseline to compare with predictions given by a Gaussian-type atmospheric dispersion model that uses on-site meteorological and release data.

This study presents both monitoring and modeling results of external radiation levels at three locations during 1985 caused by LAMPF emissions. Measured radiation exposures are presented for all three locations during an 86-day period. Predicted daily levels using a simple Gaussian model are compared with daily measured values. Predicted values using a more complex finite model are also examined. Average, hourly predicted and measured external radiation levels are compared with each other and in relation to average winds. Accuracy of the model is tested for different times of the day, windspeeds,

horizontal wind, and vertical wind. Cumulative external radiation during the 86-day period, as measured by the PICs, is compared with both the sum of 24-hour estimates and the seasonal form of the model using average winds. 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 flanks 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 (~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. LAMPF is located on a mesa top just south of Los Alamos Canyon.

The LAMPF stack is located about 700 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 much less important because of either extremely short half-lives of a few seconds or the extremely small quantities. Because of positron annihilation from radionuclide decay, photon radiation is emitted from the plume of gases as it travels downwind from the stack. However, the total amount of plume radiation decreases with time (downwind distance) as the radionuclides decay. Some characteristics of these three radioactive gases are shown in Table 1. Note that the three gases account for 96% of the radioactivity of the effluent gas, with ^{11}C and ^{15}O being the largest sources of radiation. However, the percentage of ^{15}O remaining at 800 m (average distance of monitors from stack) varies dramatically with windspeed (travel time) because of its short half-life. The contribution of ^{15}O to the total plume radioactivity at the Laboratory boundary is directly proportional to windspeed. The contribution of radioactivity from ^{15}O at 800 m downwind is nearly equal to that from ^{13}N with a 6 m/s wind, while the radioactivity from ^{15}O is slightly greater than that from ^{13}N at greater windspeeds. The largest contribution of radioactivity comes from ^{11}C

*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.

Fig. 1. Regional location of Los Alamos.

at all windspeeds, because it is the predominant radionuclide at release and it has the longest half-life.

Table I shows that total radioactivity in the plume varies greatly with the windspeed. With stronger windspeeds, fewer radioactive atoms have decayed at a distance downwind; however, stronger winds enhance dilution of the gases, causing lower concentrations downwind. With increasing windspeed, the "dilution factor" mitigates some of the radionuclide "decay factor." For example, assuming the average release rate of 21 Ci/h (20 Ci/h resulting from the three gases) during 1985, 11.5 Ci/h or 57% of the original amount is estimated to remain

in the plume 800 m downwind with a 3 m/s windspeed. At twice the windspeed, 6 m/s, the amount remaining increases to 14 Ci/h, or 71% 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, the increased dilution at higher windspeeds more than offsets any increase in radiation from shorter travel times, resulting in a decrease in radiation levels. Also, windspeed can affect the stability, and in turn, indirectly affect plume concentrations and resulting gamma radiation.

Table I. Release Data of the Three Primary Radioactive Gases and Amounts of Radioactivity Remaining at 800 m Downwind During 1985

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)
¹¹ C	38	8.0	1230	64	86	93	96
¹⁵ O	36	7.5	123	1	22	47	64
¹³ N	22	4.5	598	40	74	86	91
Total	96	20.0	---	33	57	71	80

^aDenotes average release rate over 7-month operation period.

The mix of the three primary radionuclide gases during 1985 was quite different than in 1984 (Table II). Changes were made to the exhaust system in 1985 to reduce the emissions. The exhaust gas containing the radionuclides is held for a time before being released through the stack. The radionuclides are reduced by decay before entering the atmosphere. A comparison of Tables I and II shows that the relative fraction of the shorter half-life ^{15}O was 50% lower in 1985 than in 1984. Conversely, relative fractions of longer half-lived ^{11}C and ^{13}N are considerably higher during 1985 than during 1984. The larger percentage of "longer" half-lives in the effluent during 1985 is expected to allow a larger percentage of the radioactivity released to reach the Laboratory boundary. For example, with a very light wind of 1 m/s, 33% of the radioactivity should remain at 800 m downwind during 1985 compared with 13% during 1984. This percentage difference narrows with increasing windspeed. For a more typical windspeed of 3 m/s, 68% more of a unit curie would have remained at the boundary (800 m) during 1985 than in 1984. The larger percentage of longer half-lives is expected to slightly mitigate the reduction in total curies. Based on an 83% reduction in emission from 1984 to 1985, a 75% reduction in radioactivity from 1984 to 1985 is expected at a downwind distance of 800 m with a windspeed of 4 m/s. This reduction would increase with increasing windspeed.

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 di-

ameter at the top of 0.9 m. A 5-liter, air-ionization instrument is used to monitor the radioactive gases entering the stack. A voltage is recorded, which is proportional to the total stack gas radionuclide air concentrations in Ci/m^3 . The release rate is then calculated by multiplying the air concentration by the stack flow. Stack velocity is measured continuously by an anemometer placed halfway up the stack and by periodic stack tests.

2. **External Radiation Monitoring.** Three PICs continued to monitor real-time external gamma radiation to air during 1985 at the nearest offsite boundary across the Los Alamos Canyon. The instruments are located at azimuths of 0° (north), 22° (north-northeast), and 45° (northeast) of the LAMPF stack.

The PICs are located 700, 750, and 915 m north, north-northeast, and northeast, respectively, from the stack. Each instrument uses a modified Reuter-Stokes high-pressure ionization chamber. A special electronics package was made to provide greater accuracy for the range of measurements (Van Etten 1987). A weather-proof metal box, containing a battery pack, a microprocessor-controlled datalogger, and solid-state data storage module is required for each PIC. A solar collector located on the top of each box maintains charge on the batteries. The dataloggers provide onsite summarization of radiation data. Because of the weather-induced temperature extremes that occur inside the boxes, a solid-state data storage module is used to store the data rather than a cassette recorder.

An array of 12 lithium fluoride TLD stations routinely monitors long-term gamma doses. The network is also located along State Road 4 and extends from the north-northwest to the northeast of the LAMPF stack.

Table II. Release Data of the Three Primary Radioactive Gases and Amounts of Radioactivity Remaining at 800 m Downwind During 1984

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)
^{11}C	16	27	1230	64	86	93	96
^{15}O	72	122	123	1	22	47	64
^{13}N	4	7	598	40	74	86	91
Total	92	156	---	13	34	55	69

^aDenotes average release rate over 7-month operation period.

Fig. 2. Map of study area.

TLD stations are approximately 70 m apart. Another TLD network unaffected by Laboratory operations provides the background absorbed external radiation dose levels.

3. Meteorology. The East Gate meteorological tower that provided data for this study 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). Horizontal winds are measured at levels of 1.3, 4.0, and 12.0 m and vertical winds at 4.0 and 12.0 m. Propeller vanes were installed at all levels in September of 1985 to measure wind direction and speed. Prior to this, wind di-

rection and speed were measured by two horizontal, orthogonal (U-V) propeller anemometers. Vertical velocity continues to be measured by a vertically oriented anemometer. Thermistors equipped with blower aspirators measure temperature at heights of 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 south side of Los Alamos Canyon. A three-way, orthogonal (U-V-W) propeller, anemometer system measures the horizontal and vertical wind at a height of 26 m.

B. Data

1. Data Gathering. All data (except TLDs) were collected by dataloggers. One datalogger collected the East Gate tower data on State Road 4. Another processed the source-term data and LAMPF tower-wind data. Dataloggers also collect the data at each PIC. The dataloggers provide 15-minute averages for all the data and standard deviations for the wind data.

2. Determination of Radiation Background. External radiation measured by the PICs included background levels as well as the levels caused by LAMPF emissions. It was, therefore, necessary to estimate and subtract background levels from the total 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 scanning daily plots of the three PICs. A minimum of 12 "plume-free" hours was desired to determine daily background. There frequently were periods of several days when it was impossible to estimate background. During these periods, the closest day (before or after) on which a background level could be calculated was used.

The long-term background was determined by using absorbed doses measured by a remote TLD network that is located in an area unaffected by Laboratory emissions. This background was then subtracted from the total levels measured by the State Road 4 TLD network.

3. Uncertainty. Typical data ranges and uncertainty are listed in Table III. Most of the uncertainties of external radiation, stack gas radioactivity, and radionuclide fractions are usually within $\pm 10\%$. However, stack velocity, which is directly related to stack release, has an uncertainty of $\pm 25\%$ based on stack tests. Stack tests using Pitot tube probes have shown a large variability in the past, probably because of the relatively low stack velocities. The anemometer placed in the stack shows a much smaller variability; however, it is difficult to know if it is representative of the entire stack cross section. Meteorological data uncertainties seem modest except for the wind direction. Instrument uncertainties at the two sites plus the uncertainty caused by using two different wind measurement systems can be important, considering the angle between two adjacent PICs is only 22.5° . A wind direction error of $5\text{--}10^\circ$ can shift a considerable amount of predicted external radiation levels from one PIC site to an

adjacent site. Also, the wind direction can actually differ at the two sites because of local terrain and the height differences above the ground of the sensors.

C. Resources

Meteorological data from the two towers were used in this study. The East Gate tower is used routinely to supply data on weather conditions in that area of Los Alamos. The LAMPF tower, which supplies only one level of wind data, is primarily maintained for this study. A datalogger also is in operation at LAMPF to collect meteorological tower and stack data. The ionization chamber that provides the stack release data is routinely maintained by the Accelerator Health Protection Group (HSE-11). Ionization chamber calibration and stack gas composition data are supplied by HSE-11.

IV. RESULTS AND DISCUSSION

A. Monitoring

1. Short-Term External Radiation. Short-term radiation levels, caused by LAMPF emissions, can vary dramatically over short time periods and distances. This is illustrated in Fig. 3 where plots of 15-minute radiation averages for the three PICs along with wind direction and speed and vertical velocity are shown for a day in 1985. Note the generally high external-radiation levels at the three sites during the first 8 hours of the day with light winds varying from southerly to southwesterly.* However, as the wind remains southerly from 0600-0800, a maximum gamma exposure is evident at the north PIC. Meanwhile, the NNE PIC, located just 300 m east, is only slightly affected by the plume, while the NE PIC shows no effect from the plume. The levels become rather low during the midday at all sites. Note how the plume appears to rotate clockwise along with the wind between 1600 and 1900. The gamma exposure first peaks at the N PIC, then at the NNE PIC, and finally at the NE PIC within a few hours, while the wind shifts from southerly to southwesterly. The reverse happens from 2100 to 2200.

Gamma exposures remain relatively high at the NE and NNE PICs after 2100 because of southwest and south-southwesterly winds. Total gamma exposures for

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

Table III. Ranges and Uncertainty of Data Used in Study

Data	Instrument	Typical Range	Uncertainty	Comment
External Radiation	PIC	10-50 $\mu\text{R/hr}$	$\pm 2-6 \mu\text{R/hr}$	Also some uncertainty in distinguishing LAMPF contribution from background
External Radiation	TLD	20-40 mR (total for 3 months and averaged for 12 locations)	$\pm 1-2 \text{ mR}$	
Stack Gas Radioactivity	Ionization chamber	0-200 $\mu\text{Ci/m}^3$	$\pm 10\%$	
Stack Velocity (Flow) at halfway up stack	Pitot probes	2.7-4.5 m/s (10,500-17,500 CFM)	$\pm 25\%$	Range taken from stack tests performed over last 4 years
Stack Velocity (Flow) at halfway up stack	Anemometer	3.0-3.6 m/s (11,700-14,000 CFM)	$\pm 10\%$	Additional uncertainty because placement of anemometer may not represent flow across the radius of the stack
Radionuclide Fractions	Grab samples and gamma spectrometry	1985: ^{11}C -38% ^{15}O -36% ^{13}N -22%	$\pm 10\%$ for each radionuclide	The resulting uncertainty of radioactivity remaining at 800 m downwind ranges from 1-2% for strong winds (10 m/s) to $\pm 10-15\%$ for light winds (1-2 ms)
Wind Direction (and standard deviation)	Propeller anemometer, U-V wind system	0-360° (2-45°)	$\pm 4^\circ$ ($\pm 2^\circ$)	There is also uncertainty involved in using 2 different wind measurement systems
Windspeed	Propeller anemometer, U-V wind system	1-10 m/s	$\pm 0.3 \text{ m/s}$	
Vertical Windspeed	Vertically oriented propeller	(-0.2)-(+1.5) m/s	$\pm 0.2 \text{ m/s}$	
Temp. Difference (12 m-1.3 m)	aspirated thermistors	(-3.0)-(+3.0)°C	$\pm 0.4^\circ\text{C}$	

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

the day at all three PICs are well above the typical background of approximately 300 microroentgens (μR). This day indicates that the contribution from LAMPF is actually less than the background contribution. Only several days during 1985 indicated contributions by LAMPF of over 300 μR (total exposure >600 μR). This contrasts with exposures during 1984, when LAMPF contributions frequently exceeded 300 μR , with some daily contributions as high as 1500 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 because of the decreased atmospheric turbulence at night. Observe that on this day, the standard deviations of wind-speed and vertical velocity are greatly reduced during early morning and much of the evening, when the gamma exposures were greatest. On many days the standard deviation of wind direction is also considerably less during the night than the day. Even though winds are southerly and south-southwesterly and directed toward the N and NNE PICs, these PICs indicate relatively low gamma levels because of increased vertical velocity ranges, and to a lesser extent (on this day), wind direction ranges. This day also has south-southwesterly and southwesterly winds during early morning and evening hours, and as a result, relatively high radiation levels at the NE and NNE PIC. The pattern is seen repeatedly on other days.

2. Wind. The predominance of southerly through southwesterly winds is shown by East Gate wind roses in Fig. 4. These wind roses represent wind data for 86 days during 1985 on which data were available from all PICs and both towers. This limited period is representative of annual winds. A maximum frequency of winds is spread rather evenly over the southeast through south-southwest. About 45% of the daytime winds come from these directions. Much of the high frequency of the southeasterly and southerly winds results from a thermally driven upslope wind that occurs on days with sunshine and light, large-scale winds. Winds are most often south-southwesterly through southwesterly during the evening hours, with fewer southerly winds. Much of the high frequency of southwesterly and south-southwesterly winds is from the Rio Grande Valley channeling winds. Because predominant, large-scale winds are southerly, local winds flow along the orientation of the Valley and become southwesterly and south-southwesterly. The channeling occurs more frequently at night when the vertical mixing is at a minimum. The south-southwesterly and southwesterly

winds account for 30% of all winds at night. The stable, low-level atmosphere prevents exchange of higher-level winds, thereby preserving the channeled flow.

Also, a secondary northeast wind maximum frequently occurs, especially during the morning hours. Some of these winds are possibly caused by channeling of winds down the Rio Grande Valley.

The frequency of winds from the south through southwest during 1985 appeared to have changed from that of 1984 (Fig. 5), although the general pattern of winds remained similar. Note that the southerly wind frequency increased during the daytime in 1985, while fewer southwesterly and south-southwesterly winds occurred. The change in frequencies is even more dramatic at night, with the southwesterly wind frequency decreasing from 28% to 15%. The south-southwesterly wind frequency increased somewhat, and, as during the daytime, southerly winds were more frequent. Annual wind roses were nearly identical for the years 1982-1984 before new wind sensors were installed.

Detection of subtle wind changes appears, however, to have been caused by replacement of orthogonal wind propellers (U-V) with a wind vane system. Correction factors must be applied to the propeller speeds of the U-V system to account for the cosine response associated with the angle of attack between the orientation of the propellers and the wind. The correction factors were determined and applied to the U and V propeller 15-minute averages instead of being applied to U and V instantaneously. This correction caused some slight errors in wind direction and a slight underestimation of wind speed.

This effect was also observed at the Occupational Health Laboratory (OHL), when the U-V wind system was replaced by the propeller system during early 1984. As in the East Gate case, the general wind pattern appears similar using the two different wind sensor systems. But specific wind frequencies changed rather dramatically and average wind speed increased slightly after the replacement with the propeller anemometer. At OHL the annual wind roses were virtually the same for the years 1980-1983 until the wind system was replaced. There is reason to believe, therefore, that changes of wind direction frequencies at East Gate from 1984-1985 were primarily because of the sensor changes, not the winds themselves.

LAMPF wind roses during the study period in 1985 are shown in Fig. 6. The winds are similar to those at East Gate (Fig. 4), although there are some noticeable

Fig. 4. Day, night, and total wind roses from East Gate at 12 m during an 86-day study period in 1985.

Fig. 5. Day, night, and total wind roses from East Gate at 12 m during a 49-day study period in 1984.

Fig. 6. Day, night, and total wind roses from LAMPF at 26 m during an 86-day study period in 1985.

differences. First, more south-southeast and southeasterly winds are apparent at East Gate than at LAMPF. The ground slopes downward more on the mesa just to the east of the East Gate tower than it does to the east of LAMPF. This may force more up-slope winds at East Gate.

Another daytime wind difference is the larger spike of east-northeast winds at East Gate than at LAMPF. One possible reason is that winds from this direction are very light, and the wind sensors at LAMPF register a less than 0.5 m/s wind (calm) sometimes when East Gate sensors register winds greater than 0.5 m/s wind from the east-northeast. Therefore, many of the light east-northeast winds at LAMPF are classified as calm winds. In fact, the total percentage of calm winds is much greater at LAMPF than at East Gate for both day and night. Winds appear to be quite similar at the sites at night, except that at LAMPF, there is a slight spike of winds from the west-northwest, while there is not at East Gate. These winds are probably downslope winds formed by radiational ground cooling at night. The mesa slopes more to the west of LAMPF than the mesa slopes to the west of East Gate. Also, there appear to be more northerly winds at East Gate than at LAMPF. However, this also may be because these winds are light, and there is a larger percentage of calm winds at LAMPF.

3. Average Measured External Radiation. The complex wind pattern causes large external radiation variations at the PIC sites from LAMPF emissions. Average hourly radiation levels resulting from LAMPF emissions for the 86-day study period are shown in Fig. 7. Both the highest and lowest hourly average occur at the NE PIC. The highest averages of nearly 7 $\mu\text{R/h}$ occur during the early morning hours because of the high southwesterly wind frequency. Midday values are very low at the NE PIC because of the up-valley wind (Rio Grande) scarcity. The NNE PIC shows a similar, but more moderate daily radiation variation. The N PIC shows a relatively uniform average radiation level throughout the day. It must be stressed that increased daytime atmospheric mixing plays an important role in reducing radiation levels at all three sites. Also, we must remember that the NE PIC is located 20% further from the emission stack than are the other PICs. The levels would be nearly 10% higher at the NE PIC if its downwind distance equaled those of the other PICs.

4. Turbulence Parameters. Figure 8 shows the increased daytime mixing, which contains standard deviation histograms of horizontal wind (σ_θ) and vertical wind (σ_ϕ) by hour. The values of σ_θ are twice as large during the midday hours as they are during the late-night and early morning hours. The values of σ_ϕ are also larger during the day than at night. The diurnal variation of σ_θ is somewhat greater than that of σ_ϕ .

5. Release Data. The daily variation in the LAMPF release rate also contributes somewhat to radiation variations. Average hourly release rates are shown in Fig. 9. The average release rate is at a slight minimum during the day, when routine LAMPF beam maintenance is the greatest. The release rates used to calculate external radiation levels in the study are based on a stack velocity (midway) of 3.5 m/s or a stack flow of 13,500 CFM. This corresponds to the average velocity indicated by the anemometer and is close to the stack test averages over the past 4 years.

6. Hourly Wind. A more detailed look at diurnal wind patterns is shown in a hourly frequency diagram in Fig. 10. Note that the up-valley wind starts to develop during the afternoon and becomes more frequent later in the evening and early morning hours. Southwesterly winds account for over 25% of all winds over a 5-hour period. These persistent winds are responsible for the maximum radiation levels at the NE PIC during the evening and early morning hours. By 0400, the frequency of up-valley winds decreases while down-valley winds become more important. By late morning, down-valley, northeasterly winds account for over 20% of all winds. Also, upslope southeasterly winds over the Pajarito Plateau are somewhat frequent during the late morning and early afternoon hours.

B. Modeling

1. Discussion and Equations. Two primary considerations in the modeling of radiation resulting from a plume are the receptor distance from the plume and the radiation intensity given off by the plume. These are in addition to the problem of estimating the downwind plume configuration and the radionuclide concentrations. A photon-emitting cloud with small dimensions compared with the distance the radiation travels is termed a finite

Fig. 7. Average hourly external radiation at three sites from LAMPF emissions during an 86-day study period.

Fig. 8. Average hourly standard deviation of horizontal wind direction (σ_θ) and vertical wind (σ_ϕ) at East Gate during an 86-day study period.

cloud for modeling purposes. The following equation for finite clouds is suggested in *Meteorology and Atomic Energy* (Healy 1968):

$$\gamma D(x, y, 0) = \frac{0.1456 \mu \mu_a \bar{E}_\gamma Q_x (I_1 + k I_2)}{\bar{r}^2} \quad (1)$$

where

- γD = dose (rads) or exposure (roentgens);
- μ = total photon absorption to air coefficient (1/m);
- μ_a = energy absorption coefficient for photons in air (1/m);
- E_γ = average photon energy emitted at each disintegration (1.022 MeV/Dis);

- Q_x = amount of source material remaining in a plume after a travel distance, x (Ci);
- $I_1 + k I_2$ (or I_1) = integrals accounting for the geometry of the plume and radiation from the plumes; and
- $\bar{U}$ = average wind speed (m/s).

E_γ is twice the LAMPF energy level of 0.511 MeV because two photons are discharged for each disintegration. Also, the effect of lower air density because of the elevation at Los Alamos (2140 m MSL) 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 photon radiation travel away from the plume. Healy suggests using this finite cloud model when the plume spread

Fig. 9. Average emissions release rate from LAMPF during an 86-day study period.

Fig. 10. Hourly wind direction frequency diagram for East Gate during an 86-day study period.

standard deviation (σ) is less than $1/\mu$ ($1/\mu$ is approximately 120 m considering the photon energy of LAMPF emissions and the density of air at Los Alamos). The calculated σ (geometric mean of σ_y and σ_z) at 800 m downwind equals 60 m.

A much simpler infinite cloud model can be used for photon 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 (Ci/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. This equation is directly proportional to χ . Because χ is relatively easy to determine by using the Gaussian dispersion model, the infinite model is much easier to calculate than is the finite model.

Healy suggests that Eq. 2 be reduced by a factor of 0.5 for the ground-level case. This is because a ground-level receptor only receives radiation from half of the idealized cloud or plume. The equation becomes:

$$\gamma D = 0.23 \bar{E}_\gamma \chi \quad (3)$$

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

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

where

- χ = air concentration in Ci/m³,
- Q_x^1 = effective release rate (Ci/s),
- σ_y, σ_z = dispersion coefficients in the crosswind and vertical directions (m),
- Y = distance from plume centerline (m),
- H = effective stack release height (m), and
- $\bar{U}$ = average wind speed (m/s).

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

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

where

- $D_T(x, \theta)$ = sector averaged integrated concentration (Ci - s/m³);
- Q_x = total release remaining at downwind distance, X (Ci);
- $f(\theta)$ = frequency of wind direction toward the sector, θ ;
- σ_z = average vertical dispersion coefficient (m);
- $\bar{U}$ = average wind speed (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:

$$\sigma_y = \sigma_0 X f_1(T/T_1) \quad (6)$$

$$\sigma_z = \sigma_w \frac{X}{\bar{U}} f_2(T/T_1) \quad (7)$$

where

- σ_0 = 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 wind speed (m/s),
- f_1, f_2 = functions of downwind distance and thermal stability,
- T = downwind distance in time (s), and
- T_1 = constant dependent on stability and whether vertical or horizontal.

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

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

where

ΔH = stack rise (m),
 V_s = stack exit velocity (m/s),
 $\bar{U}$ = average wind speed (m/s), and
 D = stack diameter (m).

A value of 9.7 m/s, based on stack anemometer measurements, was used for V_s during 1985, the same value used during 1984. This velocity gives ΔH a range from 17 m for 1 m/s winds to as little as 1-2 m for strong winds.

The plume was assumed to remain at effective release height after crossing the canyon. Although the plume is assumed to have the same height above the ground after crossing the canyon, it probably does sink somewhat as it crosses the canyon. Air containing the emissions is expected to speed up as it travels northward over the "smooth" canyon. Conversely, the air slows down as it approaches and crosses the mesa on the other side. Also, the air probably rises as it approaches the mesa. Indeed, when southerly and southwesterly winds occur, the wind data show enhanced positive (upward) vertical velocity at East Gate. Because of the aerodynamic effects, the plume is expected to dip slightly as it moves across the canyon and to rise as it encounters the mesa.

For simplicity, it is also assumed that all available plume gases cross the canyon. Realistically, some of the gases are mixed into the canyon by turbulence. In fact, single channel analyzers have detected annihilation x-rays with energy levels equal to those given off by LAMPF in canyons at the Pajarito (TA-18) and Omega (TA-2) sites, located in Pajarito and Los Alamos Canyons, respectively. This process occurs more during the daytime when turbulent mixing is at a maximum. 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 LAMPF building is not expected to have a large effect on the transport and dispersion of the emissions. 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 ex-

tends 0.4 km to the west. It is unknown how this building affects the low-level winds.

The LAMPF meteorological tower's top is 26 m above ground (stack base). The tower sits on a hill that is 12 m high. It is unclear how much effect, if any, the hill has on the windflow at wind sensor level. Also, the building with the stack, located just southeast of the tower, probably causes the winds to be lighter at wind sensor level for southeasterly winds. However, southeasterly winds do not transport LAMPF releases toward any of the PICs.

2. Wind Differences Between the Two Sites.

a. Directional Shear. Variation of wind direction and speed with height is important in determining diffusion of pollutants released from a stack. The wind is slowed down by the frictional effects of the ground. The wind becomes stronger and turns clockwise with increasing height, until, at a certain height (top of the boundary layer), the wind blows parallel to the isobars and at a speed produced by the pressure gradient force. The top of the boundary layer is usually between 500 to 1000 m. The greatest change of wind direction usually takes place over the first 100 m above the ground (surface layer), where much of the speed shear also takes place. Both directional and speed shear of wind can be very dramatic over the lowest 100 m during the evening. During conditions of light gradient winds and clear skies, radiational cooling of the ground produces a ground-based inversion that promotes vertical stability. Winds near the ground often become "decoupled" from winds above, giving large wind shears. The ASME (1979) suggests a wind shear of 15-30° between the surface and gradient level winds over level terrain. Directional wind shear can be even larger over sloping terrain because of locally produced winds. Radiational cooling over sloping surfaces can cause nighttime drainage winds to flow downslope over the lowest 50 m or so. Gradient or local winds continue above 50 m. Winds can turn with height over sloping terrain because of local winds.

The importance of directional wind shear on the LAMPF plume direction was noticed on several nights in 1985 with limited turbulent mixing. Elevated photon exposures are sometimes seen at the NE PIC, while the 12 m anemometer at East Gate indicates south-southwesterly (202°) winds. However, the anemometer at the 26-m level at LAMPF indicates the winds are 15-20°

clockwise of the East Gate winds, or directed more toward the NE PIC. The elevated levels at the NE PIC site during these times suggest that emissions at the 35 m level are being carried by southwesterly winds. Winds indicated by the higher LAMPF anemometer correlate better with the direction of the highest photon levels than do the winds given by the East Gate anemometer during these times.

We believe that the difference in winds between the two sites during some nights results more from height difference than from site difference. Many other nights show that the wind directions are much more similar between the two sites. This underlines the variable characteristics of wind shear from night to night, if not from hour to hour. Also, based on the PIC measurements, the wind shear takes place near the effective stack release level (35 m) but not at the 12 or 26 m level on some nights.

Because there is uncertainty in estimating vertical wind shear by comparing two sites, wind direction shear was looked at by comparing winds at different levels at the 92-m, TA-50 tower located 4 km west-southwest of the LAMPF stack. A consistent wind shear is observed on many nights; a low-level westerly wind occurs at the 11- and 22-m levels, while a southwesterly wind is observed at the 46- and 92-m levels. Wind shear is a result of a low-level drainage wind along the sloping plateau and a higher-level wind resulting from channeled flow by the Rio Grande Valley. Because East Gate is at a lower elevation (closer to the Rio Grande Valley) and it has a more gentle slope immediately to the west, drainage winds do not occur as often as at TA-50. However, nighttime winds probably also tend to be more southwesterly at East Gate and LAMPF with increasing height.

It was not possible to incorporate directional wind shear into the modeling in this study. Changing wind direction up to stack level is sometimes important at night. However, modeling errors are expected to be modest when averaged over large time periods.

Other effects from wind shear were not taken into account for simplicity. First, the directional shear was not considered to estimate the plume radionuclide concentrations. In fact, vertical directional wind shear has the effect of spreading out the release in the horizontal (higher σ_y) and thereby causing lower concentrations in the plume. The variations of wind direction (σ_θ) and vertical velocity (σ_w) also change with height, thereby changing the horizontal (σ_y) and vertical (σ_z) spread of the plume. The horizontal wind turbulence generally decreases with

height; this would tend to make the centerline concentration higher downwind, and less of the radionuclides would spread laterally. Vertical turbulence tends to increase with increasing height near the ground; therefore, vertical winds taken at a higher level would tend to spread more of the radionuclides down to the ground than winds at a lower level. However, winds during the 86-day study period indicate that average values of σ_θ and σ_ϕ were quite similar between the two tower sites. So the expected dominant effect is an increase in σ_y because of wind direction changes with height.

We believe that the model accuracy results suffer when the 12-m height rather than the effective stack height is used. The accuracy of the transport direction is best when estimated stack level wind direction is used.

b. Speed Differences. The sometimes large wind speed differences between the two sites were not taken into account in this study for simplicity. Much of the wind speed variation is attributed to the effect of the Los Alamos Canyon. Air speeds up while passing over the Canyon because the Canyon is aerodynamically smooth compared to the adjacent mesas. East Gate average wind speeds and ratios of East Gate/LAMPF winds are plotted in Fig. 11 for different wind directions. Note that the strongest winds are centered over the southwesterly direction, indicating the persistent channeled winds flowing up the Rio Grande. Winds are considerably higher at East Gate than at LAMPF for the directions east-southeast through southwest. These are all winds that bring air across the Los Alamos Canyon to East Gate.

3. Model Sensitivity. The effects of changes in different variables on predicted concentrations are shown in Table IV. The infinite model is most sensitive to changes in distance from plume centerline (Y) or wind direction. The effect of increasing the distance from the plume centerline is the greatest during stable periods (σ_y is smaller). A change in Y from 0 to 100 m can cause a decrease in χ of 69%. At a downwind distance of 800 m, a difference of 100 m in Y is equal to a change of wind direction of only 6°. Therefore, the model is extremely sensitive to wind direction. Windspeed can also affect concentrations. A threefold increase in windspeed gives close to a 50% reduction in χ . Therefore, based on measurement uncertainty (Table III) of wind direction and speed, χ can be largely affected by wind direction measurement uncertainties, but less by windspeed. The effects of changes of other variables can be seen to be smaller.

Fig. 11. East Gate/LAMPF windspeed ratio and East Gate windspeeds by direction during an 86-day study period.

C. Modeling Results - Short Term

Daily model predictions, based on integration of 15-minute predictions, were made and compared with measured values during 1985. Comparison of predicted and measured values for the three sites is shown in Fig. 12, and the related statistics are shown in Table V. There is good correlation between predicted and measured data. Correlation is strongest at the north-northeast site and not as strong at the other two sites. However, the correlation is still high at these sites, with $R = 0.78$ and 0.72 and corresponding R^2 values of 0.62 and 0.52 . This implies over half of the measured values variation is explained by the model at these sites, with an even higher R^2 of 0.81 at the north-northeast site. The regression line slopes are close to 1 at the north and north-northeast sites, indicating a close correspondence of predicted and measured values.

The finite model was also used to predict daily LAMPF plume photon radiation. This model's predictions are less than predictions given by the infinite case and most measured values (Table VI). The ratio of finite/

infinite daily predictions ranged from 0.72 for the north site to 0.79 for the north-northeast and 0.84 for the north-east site. For all sites, the correlation coefficients using the finite model were nearly identical to those using the infinite model. The ratios of finite/infinite are closer to 1 at the north-northeast and northeast sites.

The infinite model clearly is a more conservative radiation level indicator. The infinite model is preferred because its predictions are closer to measured values than those of the finite model. It is also important that the infinite model is much simpler and less expensive to run than the more complicated finite model. For the remainder of this report, "model" is understood to mean "infinite model" unless otherwise stated. Furthermore, short term and seasonal models are both based upon the infinite model.

Daily model predictions were also made using the LAMPF wind data (Fig. 13 and Table VII). Correlation is good between measured and predicted values at the north and north-northeast sites, with correlations of 0.81 and 0.76 , respectively. However, the model overpredicts the

Table IV. Sensitivity of Air Concentration ($\bar{X}$) from Variable Changes

$$(Q_x', Y, H, \bar{U}, \sigma_y, \sigma_z) \text{ in model: } \bar{X} = \frac{Q_x'}{\pi \sigma_y \sigma_z \bar{U}} \exp \left[-\frac{1}{2} \left(\frac{Y}{\sigma_y} \right)^2 \right] \exp \left[-\frac{1}{2} \left(\frac{H}{\sigma_z} \right)^2 \right]$$

	Q_x' (Ci/s)	$Y(m)^*$	$H(m)$	$\bar{U}$ (m/s)	σ_y (m)**	σ_z (m)***
Variable Changes	$\pm 10\%$	to 50 from 0 (to 100 from 0)	+5 (+10)	to 3 from 1 (to 10 from 3)	+10% at $Y = 50$ m (+10% at $Y = 100$ m)	+10% at $H = 30$ m (+10% at $H = 45$ m)

Stability

Unstable ($\sigma_y = 110$ m; $\sigma_z = 70$ m)	$\pm 10\%$	-10% (-34%)	-3.5% (-8.0%)	-42% --	-6.5% (-2.0%)	-7.6% (-5.8%)
Neutral ($\sigma_y = 85$ m; $\sigma_z = 50$ m)	$\pm 10\%$	-16% (-50%)	-6.5% (-14%)	-- (-58%)	-6.0% (-1.5%)	-6.2% (-2.5%)
Stable ($\sigma_y = 65$ m; $\sigma_z = 35$ m)	$\pm 10\%$	-26% (-69%)	-15% (-28%)	-42% --	-2.5% (+11%)	-3.1% (+4.9%)

.....
 *50 m = 3° wind direction at 800 m downwind.

**Plus 10% change in σ_y at $y = 0$ yields -10% in $\bar{X}$.

***Plus 10% change in σ_z at $z = H$ yields -10% in $\bar{X}$.

Fig. 12. Predicted versus measured daily external radiation from LAMPF emissions at sites north, north-northeast, and northeast of LAMPF on State Road 4 using East Gate winds.

Table V. Regression Analysis Statistics for Predicted Versus Measured Daily External Radiation at Three Sites from LAMPF Emissions During 1985
(predictions are based on East Gate winds, Fig. 12)

PIC	Slope	Y- Intercept	R*	R ²	P**	Measured (X)	Predicted (Y)	Number of Days
N	0.85	15	0.78	0.62	99.9%	74	78	123
NNE	1.14	8	0.90	0.81	99.9%	100	122	110
NE	0.72	13	0.72	0.52	99.9%	77	70	101

*Correlation coefficient.

**Probability correlation did not happen by chance.

Table VI. Comparison of Infinite and Finite Model Results with Measured Daily External Radiation at Three Sites from LAMPF Emissions During 1985
(predictions are based on East Gate winds)

PIC	Number of Days	Measured (μ R)	Predicted		Finite/ Infinite
			Finite	Infinite	
N	123	74	56	78	0.72
NNE	110	100	96	122	0.79
NE	101	77	59	70	0.84

north sector by 78%. The model underpredicts the north-east sector, besides having a lower correlation coefficient of 0.65. Apparently the plume travels more frequently toward the northeast than the LAMPF wind data indicates.

The pattern of correlation using the LAMPF winds during 1985 is very similar to the one during 1984: the model considerably overpredicts in the north sector and underpredicts in the northeast sector. The measured versus predicted correlation coefficient drops off for the northeast site. The correlation using East Gate winds is better than the correlation using LAMPF winds during both years, especially in the northeast sector. It appears that the winds measured at LAMPF cannot represent the plume spread over the three directions as well as the East Gate winds can.

It is likely that the data measured by the LAMPF U-V wind system, with angle of attack corrections applied to the 15-minute averages, are not as representative as the

East Gate propeller anemometer system installed during 1985. It has been observed at both OHL and East Gate that the winds tended to be concentrated or "spiked" in one direction as measured by the U-V system, while the propeller vane system showed the winds to be more evenly distributed around that specific direction.

D. Accuracy of Model vs Meteorological Variables

Further analyses were made to check the model's accuracy versus wind speed, standard deviation of wind direction (σ_θ), and standard deviation of vertical wind direction (σ_ϕ) at each of the three sites. These analyses were made for both daytime and nighttime and were limited to an 86-day period, which contains data for all three sites. Predicted and measured values were calculated and added up under each category of wind speed, σ_θ and σ_ϕ .

Ratios of predicted versus measured radiation exposures for different windspeeds are shown in Table VIII.

Fig. 13. Predicted versus measured daily external radiation from LAMPF emissions at sites north, north-northeast, and northeast of LAMPF on State Road 4 using LAMPF winds.

Table VII. Regression Analysis Statistics for Predicted Versus Measured Daily External Radiation at Three Sites from LAMPF Emissions During 1985
(predictions are based on LAMPF winds, Fig. 13)

PIC	Slope	Y- Intercept	R*	R ²	P**	Measured (X)	Predicted (Y)	Number of Days
N	1.35	32	0.81	0.66	99.9%	74	132	123
NNE	1.02	25	0.76	0.58	99.9%	100	127	109
NE	0.41	6	0.65	0.43	99.9%	77	37	102

*Correlation coefficient.

**Probability correlation did not happen by chance.

Table VIII. Predicted Versus Measured External Radiation Ratios at Three Sites for Different Windspeeds
(over entire 86-day study - East Gate Winds)

Windspeed (m/s)	Day			Night			Total		
	N PIC	NNE PIC	NE PIC	N PIC	NNE PIC	NE PIC	N PIC	NNE PIC	NE PIC
0-2.5	2.06	1.83	1.37	0.45	0.38	0.42	1.04	0.75	0.60
2.5-5.0	1.77	1.86	1.33	1.27	1.56	0.97	1.54	1.68	1.05
5.0-7.5	1.20	1.24	1.12	1.66	2.12	1.22	1.30	1.59	1.19
>7.5	<u>0.82</u>	<u>0.91</u>	<u>1.27</u>	<u>0.93</u>	<u>2.00</u>	<u>1.25</u>	<u>0.85</u>	<u>1.43</u>	<u>1.25</u>
Total	1.64	1.60	1.27	0.95	1.30	0.90	1.32	1.42	0.99

The model is seen to overpredict at all sites with light, daytime winds. These are times when the atmosphere is the most unstable (most diffusive). It is possible some of the radionuclides are being mixed down into the canyon during these periods - the model does not account for this. Or, the dispersion parameters, σ_y and σ_z may be underestimating the true atmospheric diffusive power at these times. The predicted values are closer to or even less than measured values for stronger daytime winds or more neutral conditions. Predicted and measured values show good agreement for the night as a whole. However, predicted values are less than measured values at all sites at night for light winds, while predicted values generally exceed measured values at night for stronger winds. In general, the model tends to overpredict during unstable cases and underpredict during stable cases.

A similar analysis, but for different σ_θ 's, is shown in Table IX. The model again appears to overpredict during unstable daytime conditions (larger values of σ_θ). The model also underpredicts during stable, nighttime hours (smaller values of σ_θ), especially in the north. The values of σ_θ are probably not representing the true lateral diffusive capabilities of the atmosphere during the most unstable cases.

Another analysis based on σ_ϕ 's is shown in Table X. Results are similar to those analyses for different windspeeds and σ_θ 's, namely, that the model generally overpredicts for very unstable cases (large σ_ϕ) during the daytime and underpredicts for very stable conditions (small σ_ϕ) during the night. However, the model clearly underpredicts for small σ_ϕ 's and tends to overpredict for large σ_ϕ 's at night. It appears that the accuracy of the model is

**Table IX. Predicted Versus Measured External Radiation Ratios at Three Sites
for Different Horizontal Wind Direction Standard Deviations (σ_θ)
(over entire 86-day study - East Gate Winds)**

(degrees)	Day			Night			Total		
	N PIC	NNE PIC	NE PIC	N PIC	NNE PIC	NE PIC	N PIC	NNE PIC	NE PIC
<7.5	---	---	---	0.14	1.05	1.01	0.24	0.98	1.01
7.5-12.5	0.99	1.49	0.89	0.86	1.52	0.89	0.90	1.51	0.89
12.5-17.5	1.42	1.41	0.82	1.22	1.31	0.93	1.33	1.36	0.89
17.5	<u>1.96</u>	<u>1.92</u>	<u>2.62</u>	<u>0.89</u>	<u>0.80</u>	<u>0.81</u>	<u>1.63</u>	<u>1.48</u>	<u>1.49</u>
Total	1.64	1.60	1.27	0.95	1.30	0.90	1.32	1.42	0.99

**Table X. Predicted Versus Measured External Radiation Ratios at Three Sites
for Different Vertical Wind Direction Standard Deviations (σ_ϕ)
(over entire 86-day period - East Gate Winds)**

(degrees)	Day			Night			Total		
	N PIC	NNE PIC	NE PIC	N PIC	NNE PIC	NE PIC	N PIC	NNE PIC	NE PIC
<5	1.10	1.45	1.02	0.31	0.92	0.82	0.46	1.00	0.85
5-7.8	1.50	1.44	1.06	1.28	1.55	0.94	1.39	1.50	0.98
7.8-10	1.50	1.51	1.45	1.31	1.36	1.31	1.45	1.45	1.38
>10	<u>2.35</u>	<u>2.50</u>	<u>3.21</u>	<u>1.10</u>	<u>1.79</u>	<u>1.15</u>	<u>2.09</u>	<u>2.30</u>	<u>2.17</u>
Total	1.64	1.60	1.27	0.95	1.30	0.90	1.32	1.42	0.99

more dependent on values of σ_ϕ than of σ_θ . One possible reason is that with large vertical turbulence or σ_ϕ , more of the gases are mixed down into the canyon, thereby causing an overprediction. Also, larger vertical turbulence (σ_ϕ) does not necessarily reflect a similar increase of horizontal turbulence (σ_θ). Another possible cause is that the method used to calculate σ_ϕ is not representing the actual vertical dispersion accurately. Also note that the model overpredicts for large σ_ϕ 's. However, only a small amount of hours during the night have $\sigma_\phi > 7.8^\circ$.

Average predicted and measured values were also compared hourly for the 86-day period (Fig. 14). The data clearly indicate that the model systematically overpredicts at all sites during the daytime. One possible reason is that some of the radionuclides may be mixing down into the canyon, while the model assumes no mixing. Another possibility is that the afternoon turbulence is understated by the method used to calculate σ_y and σ_z .

The nighttime exposure, especially after midnight, is underpredicted at the north site, while the model closely predicts the nighttime measured values in the north-northeast and northeast.

E. Modeling Results - Seasonal

The seasonal model was used to estimate exposures at the three sites for the 86-day period with complete data. These estimates are compared with the estimates derived from adding up the separate 24-h estimates and with the measured data (see Table XI). The sums of the 24 h predictions closely match the measured values, except at the north-northeast PIC, where the model overpredicts by 25%. The seasonal model, which uses an average wind-speed and σ_z for the entire period, gives somewhat higher estimates, and overpredicts at all sites.

Fig. 14. Average hourly predicted and measured external radiation at three sites from LAMPF emissions during an 86-day study period.

**Table XI. Comparison of PIC-Measured External Radiation Levels
With Predicted Levels (mR) from LAMPF Emissions
Using East Gate Winds for 86 Days During 1985**

<u>PIC Site</u>	<u>Measured</u>	<u>Short-Term Model</u>	<u>Seasonal Model</u>
N	5.6	5.9	8.1
NNE	8.0	10.0	11.3
NE	<u>7.0</u>	<u>6.9</u>	<u>9.6</u>
N through NE	6.9	7.6	9.7

The seasonal model was also broken down into periods of day and night. The results (Table XII) show that when the model is calculated using separate σ_z and wind-speeds for day and night, predictions are less conservative and closer to measured values. The estimates are also closer to values derived from the sum of 24 h estimates. The separate evaluation of day and night levels is a slight improvement over using a single calculation when using the seasonal model. One reason may be that daytime calculations fully reflect the rather large σ_z values, while the combined day and night values do not.

The seasonal model, using combined day and night conditions, and the short-term model were also used to calculate radiation levels using winds measured at LAMPF. These estimates are compared with measured values in Table XIII. The seasonal model overpredicts in all sectors, especially in the north-northeast. The seasonal model also gives higher estimates than those given by the short-term model, except in the north sector. The LAMPF winds give generally less accurate estimates for specific sectors than the East Gate winds using both the short-term and seasonal models. There are more extremes (over and underprediction) using the LAMPF winds.

The results also show that there is poor correlation between the short-term and seasonal models using LAMPF winds. It is likely that the measured LAMPF winds are not as uniformly distributed across the sectors as the East Gate winds are.

The seasonal model was also used to predict annual external radiation on State Road 4 during 1985 from LAMPF emissions. Predicted values using East Gate winds ranged from a maximum of 21 mR to the north-northeast, 18 mR to the northeast, 16 mR to the north, and to 11 and 6 mR to the north-northwest and northwest of LAMPF, respectively. The combined predicted value of nearly 14 mR is slightly higher than the 11.4 mrem measured by the TLD network.

V. SUMMARY AND CONCLUSIONS

A network of monitors on State Road 4 continued to measure external radiation levels from LAMPF emissions. The exposure levels along with onsite meteorological data were analyzed to determine spatial and temporal patterns. The meteorological data along with LAMPF release data were also used to predict photon exposures and were compared with measured values.

**Table XII. Comparison of Seasonal Model Predicted External Radiation (mR)
Using Combined Day and Night and Separate Day and Night
Periods for 86 Days During 1985**

<u>PIC Site</u>	<u>Combined</u>	<u>Separate (Day + Night)</u>	<u>Day</u>	<u>Night</u>
N	8.1	7.6	3.2	4.4
NNE	11.3	10.6	3.4	7.2
NE	<u>9.6</u>	<u>8.9</u>	<u>2.8</u>	<u>7.0</u>
N through NE	9.7	9.0	2.8	6.2

**Table XIII. Comparison of PIC-Measured External Radiation Levels
With Predicted Levels (mR) from LAMPF Emissions Using
LAMPF Winds for 86 Days During 1985**

<u>PIC Site</u>	<u>Measured</u>	<u>Short-Term Model</u>	<u>Seasonal Model</u>
N	5.6	9.9	8.3
NNE	8.0	10.1	14.7
NE	<u>7.0</u>	<u>3.4</u>	<u>8.9</u>
N through NE	6.9	7.8	10.6

In summary, the infinite cloud approximation was found to be an excellent indication of daily exposures at 700-900 m downwind of the LAMPF stack, using East Gate winds. The more complex finite cloud model consistently yielded lower daily estimates. Based on its simplicity, the infinite cloud method is recommended over the finite method at 700 m downwind or greater. Although the infinite model gives good overall results, it does systematically overpredict during the day or in unstable conditions. The seasonal form of the infinite model generally overpredicts exposures over longer time periods (months). The seasonal model gives better results when average day and night statistics are calculated separately. Although the seasonal model is quite accurate and convenient to use, the addition of 24 h estimates based on the short-term infinite model gives considerably more accurate estimates of long-term, measured external radiation.

The primary conclusions of this study are the following:

- 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, while a southerly upslope wind also helps to give higher exposures to the north.
- 2) The channeling of large-scale winds, especially at night, is most likely responsible for the high frequency of up-valley winds, while the upslope flow is forced by daytime solar heating.
- 3) An 80% reduction in the 1985 LAMPF emissions from 1984 resulted in a reduction of exposures by nearly as much.
- 4) External radiation is much greater to the northeast of LAMPF, somewhat greater to the north-northeast, and slightly less to the north during the night than during the day, largely because of persistent south-southwesterly and southwesterly winds.
- 5) Generally, external radiation is considerably higher during the night due to decreased atmospheric dispersion.
- 6) Predicted daily exposures using the simple infinite cloud approximation correlate very well with measured exposures. The more complex finite cloud model estimates are over 20% less than those of the infinite model.
- 7) Differences in wind, especially direction, causes uncertainty in model predictions for specific directions. There are additional uncertainties in using winds lower than the stack height because shear can be significant over the lowest 50 m above the ground.
- 8) External radiation estimates using LAMPF winds continue to be less accurate than those using East Gate winds.
- 9) Windspeeds at East Gate are higher than those at LAMPF for southeast through southwest winds.
- 10) Predicted exposure values consistently exceed measured values during the daytime. This may be from radionuclide mixing into the Canyon not accounted for by the model, the underestimation of diffusion

caused by calculated values of σ_y and σ_z , or because the concentration distributions are not Gaussian.

- 11) The seasonal model yields rather accurate exposure estimates, which are generally higher than measured values and estimates derived from adding up 24-h predictions. The seasonal model is seen as a useful tool in determining accurate long-term exposure estimates.
- 12) The seasonal model gives somewhat lower external radiation estimates that are closer to measured values when average day and night conditions are calculated separately.
- 13) Based on these modeling results and those in 1984, a Gaussian model is expected to accurately (within a factor of 2) predict daily radioactive or nonradioactive levels up to 1 km or so downwind (on mesa top) if onsite meteorological and source data are available. The accuracy of the model for specific locations is less for smaller averaging periods (15 minutes to several hours) and greater for larger averaging periods (several days to months). The difficult part of the modeling is generally not estimating the concentrations, but the precise direction of travel. Further model validation using additional PIC sites or using some form of tracer would increase confidence in the models.

VI. NEW DEVELOPMENTS AND FURTHER STUDY

The three PICs will continue to monitor radiation levels in the future. A propeller anemometer system was recently installed at the LAMPF meteorological tower. This wind system is identical to the one now in use at East Gate. Further insight should be gained into why the winds have differed between the two sites. The differences in winds as measured by the new propeller system and the orthogonal U-V system previously used will also be investigated.

The overprediction of daytime radiation levels will be investigated further. It is crucial to determine the amount of radionuclides that are mixed down into the Los Alamos Canyon in transport. Therefore, a PIC may also be placed at the bottom of the Los Alamos Canyon to see if photon radiation is present because of the LAMPF plume. An additional PIC may be placed to the east of

LAMPF at a distance of 500-1000 m. Wind roses show that westerly winds occur frequently enough in the afternoon to give usable data. The canyon effect on diffusing radionuclides can be examined by comparing radioactive levels resulting from transport over the mesa with transport over the canyon. In addition, different methods for calculating the dispersion parameters σ_y and σ_z will be considered for the very stable cases of light nighttime winds along with the very unstable cases of light daytime winds. We hope that other methods will improve the representativeness of these variables during times of extreme stabilities. Other possible PIC locations for brief periods would be the Bayo Sewage Treatment Plant to the northeast of LAMPF and other locations along State Road 4. Differences in the winds between the two sites could be taken into account to give more accurate model results. A simple trajectory model, using winds from both sites, should be used to better estimate winds across the canyon. Finally, other ways will be looked at to estimate and incorporate wind shear. A taller East Gate tower is recommended to give the best estimates of stack-level winds.

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