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HUMBOLDT BAY NUCLEAR POWER PLANT SURVEY
MARCH THROUGH MAY 1971

Western Environmental Research Laboratory
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HUMBOLDT BAY NUCLEAR POWER PLANT SURVEY
MARCH THROUGH MAY 1971

by
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Environmental Surveillance

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ABSTRACT

A pilot study was conducted to evaluate the use of aerial surveillance techniques in tracking and sampling of gaseous effluent from nuclear power plants. Data derived from such measurements would be useful in measuring peak environmental exposures and in determining the effects of local terrain and meteorology on diffusion of the airborne effluent. The Humboldt Bay Power Plant, operated by Pacific Gas and Electric Company, near Eureka, California, was chosen for this study because of its relative nearness to the Western Environmental Research Laboratory. Exposure rates and concentrations measured during coordinated aerial and ground monitoring are compared to predicted exposure rates and concentrations based on measured release rates and observed meteorology. Plume centerline concentrations and exposure rates, measured from the aircraft, agreed within a factor of two with predicted values. Ground level concentrations, based on observed meteorology at the power plant, were about an order of magnitude below predictions, apparently due mostly to terrain effects.

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INTRODUCTION

A pilot study was conducted to evaluate the use of aerial surveillance techniques in tracking and sampling of gaseous effluent from nuclear power plants. This study was a cooperative effort by the Western Environmental Research Laboratory (WERL) of the Environmental Protection Agency, Pacific Gas and Electric Company (PG&E), U.S. Atomic Energy Commission (AEC), and California State Department of Public Health. This report covers all activities of the WERL at the Humboldt Bay Power Plant near Eureka, California, during fiscal year 1971. If successful, coordinated aerial and ground tracking and sampling of the airborne effluent would be used to measure effluent centerline concentrations and exposure rates at ground level and aloft. These concentrations and exposure rates would be used to determine the effects of local terrain and meteorology on the diffusion of airborne materials from individual plants.

Coordinated aerial and ground measuring and sampling provides several advantages over ground monitoring alone. Measurements aloft make it possible to locate the effluent rapidly. The ground monitor can then be directed to the centerline to conduct monitoring and sampling in the areas of peak exposure. With the freedom of movement available to an airplane, measurements of horizontal and vertical diffusion can be obtained that would not be made from the ground. Other measurements required to predict ground results or explain measured ground results, such as vertical temperature profile and plume rise, can only be made conveniently with an airplane.

The field activities for this study were designed to include:

1. collection of air samples to measure ambient centerline concentrations of individual radionuclides at ground level and aloft,
2. exposure rate measurements to determine net centerline exposure rates at ground level and aloft,
3. measurement of the vertical temperature profile,
4. observation of wind speed and direction,
5. measurement of stack discharge rates for individual radionuclides.

The observed exposure rates and concentrations would be compared to the predicted centerline exposure rates and concentrations at ground level and aloft using:

1. observed meteorological data, predicted plume rise, and Sutton's diffusion equations,
2. observed meteorological data, observed plume rise, and Sutton's diffusion equations,
3. observed meteorological data, observed plume rise, and Sutton's diffusion equations using observed crosswind standard deviation of concentration.

The success of this program will be the basis for conducting similar studies at nuclear power plants throughout the country.

EQUIPMENT

The aircraft used in this study was a C-45 modified for aerial surveillance. Special radiation measuring and sampling equipment was installed to detect

and measure the very low levels of activity anticipated. Figure 1 is a photograph of the installation. Figure 2 is a schematic of the radiation detection instrumentation. A 9- by 4-inch NaI(Tl) crystal is used as the detector in conjunction with a TMC-403 pulse height analyzer with simultaneous single-channel and multi-channel analyzer capability. The single-channel portion of the analyzer covers the range of 0.06 to 2.0 MeV. It is connected to a four-decade digital log ratemeter, the output of which drives the strip-chart recorder in the aircraft instrument panel. The multi-channel portion of the analyzer is calibrated to cover the energy range of 0 to 2 MeV in 200 channels. Gamma spectra are recorded on a paper tape printer and on punched paper tape. Plots of the gamma spectra are generated in the laboratory from the punched paper tape. Data from the paper tape printer provide a more accurate immediate analysis of the gamma spectrum than can be obtained from the oscilloscope on the TMC analyzer.

Aerial and ground exposure rate measurements were made using a Baird Atomic NE-148 scintillation survey meter with a range of 0 to 3 mR/h on three scales and an Eberline E-500B Geiger counter survey meter with a range of 0 to 2 R/h on five scales. The survey meters are calibrated with ^{137}Cs and are generally accurate to $\pm 20\%$ with regard to this calibration. For a given exposure rate the exposure rate indicated by the survey meters is a function of the gamma energies to which they are exposed.

The NE-148 scintillator was used to obtain exposure rates below the range of the E-500B Geiger counter survey meter. Because the scintillator is energy-dependent, it responds differently from the Geiger

Figure 1. Interior of Aircraft

Figure 2. Aircraft Instrumentation Schematic

counter when exposed to gamma energies other than those for which it is calibrated. An experimental correlation of the NE-148 and E-500B readings obtained during aircraft sampling was used to normalize the scintillator readings to E-500B exposure rates.

One-cubic-meter grab samples of air are collected in a plastic bag as the aircraft passes through the effluent plume. The sample is then compressed into oxygen cylinders for transport to the laboratory. Air samples were collected on the ground by compressing air directly into the oxygen cylinders.

Stack samples were collected from fittings installed in the discharge stack by PG&E for that purpose. On one set of samples, air was drawn through a glass fiber filter for particulate collection and a cannister of 13X molecular sieve for collection of water vapor and CO₂. The air was then compressed into oxygen bottles using a portable battery-operated compressor. On the other set of samples the molecular sieve was omitted so that the water vapor and CO₂ were pumped into the oxygen bottle.

PROCEDURES

Upon entering the vicinity of the nuclear power plant, the plane flew a circle on a one-mile radius around the discharge stack to locate the direction of movement of the effluent. When this had been accomplished, the approximate elevation of maximum activity was located. A pattern was then flown at that altitude to determine if a well-defined plume existed for a distance of six to ten miles. A background gamma spectrum was collected at the same altitude,

away from the effluent trajectory, with the 9- by 4-inch detector and multi-channel analyzer. These spectra were stored on punched paper tape. A spiral descent was then flown near the reactor site, starting well above the top of the effluent, to measure the vertical temperature profile. Temperature and wind velocity measurements were obtained on the ground simultaneously with the aerial temperature profile to provide a complete vertical temperature profile.

Two sampling distances were selected with one at the farthest distance at which reliable measurements and samples could be obtained and one at approximately half that distance. Locations were selected where the ground monitor could be positioned at the centerline and the aircraft could make passes completely across the effluent path at altitudes as low as 500 feet above the centerline ground level elevation. The ground monitor was then directed to the closest selected location.

While the ground monitor was collecting a compressed air sample at the centerline, the aircraft made passes over his location on headings normal to the effluent trajectory. Passes were straight and level while crossing the trajectory and were made every 250 feet in altitude between 500 feet above ground level and the plume top. At approximately the middle of the ground sample collection period, a one-cubic-meter grab sample was collected on a pass across the plume. When the vertical activity profile had been completed and the grab sample collected, the aircraft was circled over the ground monitor while obtaining a gamma spectrum. The same sampling procedure was repeated at the second location.

SAMPLE ANALYSIS

Water vapor and CO_2 , removed from the molecular sieve, were separated by cryogenic techniques and counted in a liquid scintillator for ^3H and ^{14}C , respectively. Combustible gases collected in the stack sample bottles were oxidized and the resulting water of combustion was counted for ^3H . Any ^3H detected in the water of combustion was assumed to be due to the presence of tritiated hydrogen gas (HT) and methane (CH_3T). The CO_2 resulting from combustion was analyzed for ^{14}C .

The noble gases, Xe and Kr , were fractionated by gas chromatographic and cryogenic techniques and counted in a liquid scintillation counter with dual window capability. Radionuclide activity for each noble gas was determined by simultaneous equations based on differences in half lives and beta energies. The higher level activity noble gases from the stack samples were also counted on a solid state detector (lithium-drifted germanium) for isotopic identification and quantitation.

CALCULATIONS

Radioactivity concentrations in all samples were extrapolated to the time of collection using the individual radionuclide half lives in the equation:

$$A_o = A_t e^{\lambda t}$$

where; A_o = Activity at time of collection.

A_t = Activity at time of count.

λ = Radioactive decay constant.

t = Elapsed time from collection to count.

Plume centerline concentrations of aerial samples were derived by multiplying the sample concentration by the ratio of centerline gross gamma count rate to average gross gamma count rate during sample collection. Sutton's diffusion equations had been used in the Final Hazards Summary Report¹ for predicting off-site airborne concentrations; therefore, these equations were used for comparing measured and predicted concentrations for this study. Using Sutton's equations the predicted concentrations were calculated for the plume centerline and for ground level. These concentrations were then compared to the measured centerline and ground level concentrations. Observed dilution factors were calculated from the measured concentration of each radionuclide quantitated.

Predicted exposure rates were derived from the predicted concentrations of the individual radionuclides quantitated in the stack discharge measurements. Exposure rates were calculated using the equation:²

$$D_r = \frac{51C\bar{E}}{\rho_a} \quad \text{rads/day}$$

where; D_r = Absorbed dose rate (rads/day).

C = Concentration in surrounding medium ($\mu\text{Ci/cc}$).

$\bar{E}$ = Average energy emitted per disintegration (MeV).

ρ_a = Density of surrounding medium (air) (g/cc).

This dose rate in air was then corrected to an exposure rate using the ratio of 1.15 roentgens per rad. Individual predicted radionuclide concentrations were calculated as described above, taking into consideration radioactive decay and ingrowth between release point and sampling point. Table 9 lists the exposure rate per pCi/m^3 for each of the radionuclides considered.

¹Pacific Gas and Electric Company Final Hazards Summary Report, Humboldt Bay Power Plant, Unit No. 3, dated September 1, 1961.

²Blatz, Hanson, (Ed) "Radiation Hygiene Handbook" McGraw-Hill, 1959.

STACK SAMPLING, MARCH 10, 1971

A. Sample Collection

On March 10, 1971, six stack samples were collected at the nuclear power plant. Sample air for all samples was drawn through glass fiber filters for particulate collection. In order to characterize and quantitate the ^3H in the effluent, samples numbered 1-3 were drawn through molecular sieve for removal of water vapor and CO_2 before being compressed into bottles, while samples numbered 4-6 were collected without molecular sieve. Sample volumes were approximately one cubic meter. Samples #1 and #4 were forwarded to the AEC for analysis at the Nuclear Reactor Testing Station (NRTS). Pacific Gas and Electric Company also took a sample (a 14-ml vial of air ejector gas before dilution) on the same day.

B. Results

A comparison of independently obtained noble gas analytical results is shown in Table 1. Tritium and ^{14}C results are given in Table 2. The samples provided to the AEC were not analyzed until March 19, 1971; therefore, only ^{133}Xe is reported. Good agreement for ^{133}Xe is seen between the AEC and WERL data on the samples collected both with and without molecular sieve; however, the samples collected without molecular sieve showed about twice the concentration measured in the samples collected with molecular sieve. A similar effect was noted for ^{85}Kr on the samples analyzed by WERL. It is believed that the concentrations determined from the samples collected without molecular sieve were correct, and that the samples collected with molecular sieve indicate some collection of xenon and krypton. Therefore,

the concentrations shown for Sample 2 in Table 1 should be doubled for comparison to the results obtained by PG&E. Western Environmental Research Laboratory and PG&E results for the longer-lived isotopes, expected to be identified in plume samples by WERL, generally agreed within about 20%. On this basis it was felt that the field study could be conducted using PG&E release rate measurements and WERL plume measurements.

AERIAL SAMPLING, APRIL 7, 1971

A. Sample Collection

On April 7, 1971, an aerial plume tracking and sampling mission was performed around the power plant site, as shown in Figure 3. The purpose of the mission was to evaluate the performance of the aircraft systems and laboratory analysis on the low concentrations expected in the effluent. The plume was initially tracked to the west of the power plant site, where a spiral descent was limited by a cloud cover at 1500 feet above mean sea level (MSL).

However, this probably represented the maximum altitude of activity. This spiral descent was followed by a 4-minute gamma spectrum collected in the plume, three miles downwind at 1000 feet MSL. During the spectrum measurement, or shortly before, a wind shift occurred which carried the activity to the southeast. This was determined by flying a complete circle around the power plant site after losing contact over the ocean.

A second gamma spectrum was obtained approximately 2-1/2 miles southeast of the site. A grab sample was then collected 2-3/4 miles southeast at 1000 feet MSL. Another gamma spectrum was collected in the same general location as the second spectrum. Both of these spectra showed the presence of ^{138}Cs , and possibly ^{87}Kr , ^{88}Kr , ^{135}Xe , and ^{138}Xe .

SPIRAL DESCENT
OVER OCEAN

NET EXPOSURE RATE, μ R/h

SPIRAL ASCENT
OVER HUMBOLDT HILL

NET EXPOSURE RATE, μ R/h

Figure 3. Aerial Tracking Results - April 7, 1971

A spiral ascent was performed 2-1/2 miles southeast of the power plant from 1100 feet MSL through the top of the radioactivity. The plot of net exposure rate versus altitude, shown in Figure 3, indicates a stable layer at 3000 feet MSL with some activity extending up to 4700 feet. Scattered clouds were observed with bases at about 2000 feet MSL. Wind speeds at this time were approximately 6 to 8 miles per hour. Finally, a second grab sample was obtained about 2-1/2 miles southeast of the power plant at 2500 feet MSL. The wind direction was beginning to shift again and the sample was collected in two portions because the aircraft overran the plume before the sample could be collected on the first attempt.

B. Results

The plume was tracked by means of the 9- by 4-inch NaI(Tl) crystal detector to a distance of about five miles from the power plant to the southeast. By the time the leading edge had reached five miles, the new wind shift began carrying the effluent to the northeast and no further tracking was performed.

Results of laboratory analysis of the samples are listed in Table 3. Radionuclide concentrations are shown, along with the observed dilution factors based on PG&E and WERL stack sample results of March 10. Measurements by WERL of ^{85}mKr and ^{135}Xe shown in Table 1 were corrected for the collection of these gases on molecular sieve, as demonstrated by the ^{85}Kr and ^{133}Xe results.

COORDINATED AERIAL AND GROUND SAMPLING, MAY 14, 1971

A. Sample Collection

On May 14, 1971, an aerial tracking and simultaneous aerial and ground sampling mission was performed. The locations are shown in Figure 4. The effluent

Figure 4. Aerial Tracking Results - May 14, 1971

was initially located by flying a one-mile radius circle around the site. A trajectory was defined to the southeast over Humboldt Hill. Humboldt Hill is a ridge approximately 600 feet high extending to the southeast from Fields Landing. A spiral descent was performed one mile northeast of the stack to determine the vertical temperature profile. The wind was from the north at seven to eight miles per hour. Skies were clear south of the power plant; however, a low-flying cloud layer over the coast was slowly moving inland.

Further tracking showed the plume turning south after crossing Humboldt Hill. Radioactivity levels returned to background at eight miles south of the power station.

The ground monitor was directed to a location under the centerline $3\frac{1}{4}$ miles south of the site and the aircraft proceeded to make a number of passes over his location at different altitudes to determine the vertical profile of activity along the centerline. A grab sample was collected at 1500 feet MSL simultaneously with a compressed air sample being taken on the ground. A 4-minute gamma spectrum was collected at the same location.

Several passes at varying altitudes $6\frac{1}{2}$ miles south of the power station showed a plume with poorly defined edges. A range of hills along the east side of the plume prevented the aircraft from making passes normal to the trajectory at the desired low elevations except at $5\frac{3}{4}$ miles south. A valley extending into the hills at that location allowed the passes to be made in safety. A second grab sample was taken at 1000 feet MSL with a simultaneous ground sample at the same distance.

After finishing sampling at 5-3/4 miles south another gamma spectrum was taken at the first sampling location.

B. Results

Aerial sample results are summarized in Table 4. Centerline concentrations are given for ^{133}Xe and ^{135}Xe at 3-1/4 and 5-3/4 miles south. Krypton-85 was at background and the shorter-lived radio-kryptons were in concentrations too low for accurate analysis. Ground sampling results are presented in Table 5. As in the aerial samples, only ^{133}Xe and ^{135}Xe were quantitated at levels above background. Measured and predicted exposure rates are tabulated in Table 6 for plume centerline aloft and at ground level.

DISCUSSION

A. Stack Sampling, March 10, 1971

Comparison of the March 10 stack sample results showed a satisfactory agreement between PG&E and WERL measurements on the radionuclides of interest. Therefore, it was decided that in the plume diffusion studies to be conducted at the Humboldt Bay power station, PG&E stack sample data would be used with WERL aerial and ground sample data.

B. Aerial Sampling, April 7, 1971

Although the samples and measurements of April 7 were not made for the purpose of studying diffusion rates, and no stack sampling was performed, the data were applied to determine the approximate agreement between theory and observed results for the conditions encountered. The April 7 mission was

conducted to evaluate the aircraft systems and to collect samples of different concentrations for evaluation of the laboratory analytical capability.

The vertical profile of exposure rate, plotted in Figure 3, indicates a stable layer at about 3000 feet MSL. A neutral condition was assumed to exist below the stable layer; therefore, predicted concentrations and exposure rates were based on Sutton's diffusion equation for fumigation, using an average wind speed of seven miles per hour.

Using observed meteorological parameters, Sutton's virtual diffusion coefficient, C_y , would predict standard deviations of distribution across the plume of 470 and 500 meters at 2-1/2 miles and 2-3/4 miles, respectively, as shown in Table 7. The predicted dilution factor at 2-1/2 miles was 3.7×10^5 . The average observed dilution factor at 2-1/2 miles, shown in Table 8, was 5.0×10^5 based on the March 10 PG&E stack discharge measurement and 3.7×10^5 based on the WERL stack discharge measurement. At 2-3/4 miles the predicted dilution factor was 3.8×10^5 . The observed average dilution factors were 4.7×10^6 and 3.3×10^6 for PG&E and WERL stack release measurements, respectively.

As shown in Table 7, the observed standard deviation of distribution across the plume was in excess of 1000 meters at both distances. Using the observed σ_y in Sutton's diffusion equation, predicted diffusion factors at 7.6×10^5 and 7.9×10^5 were calculated for 2-1/2 and 2-3/4 miles, respectively.

The measured maximum exposure rates of 32 $\mu R/h$ at both distances agree very well with the predicted exposure rates of 27 and 26 $\mu R/h$ at 2-1/2 and 2-3/4 miles.

Tritium analyses of the molecular sieve samples showed the tritium concentration in atmospheric moisture to be in the range of normal background, which is approximately one to two pCi per ml of water. The predicted and observed dilution factors, along with the observed absolute humidity, showed that the increase of tritium above background would be only a small fraction of the normal background and could not be expected to be identified. Therefore, no further aerial tritium sampling was planned for this power plant.

C. Coordinated Sampling, May 14, 1971

Inspection of the vertical temperature profile at 0955 hours showed that a slightly stable condition existed. Aerial monitoring data at 5-3/4 miles indicated that a stable layer developed at about 2000 feet MSL by the time the data were collected there at approximately 1130 hours. On the basis of the observed plume development at the two sampling distances, concentrations and exposure rates were predicted using Sutton's diffusion equation at 3-1/4 miles and Sutton's diffusion equation for fumigation at 5-3/4 miles.

1. 3-1/4 Mile-Location

An effective stack height of 110 meters was calculated from stack discharge and meteorological parameters. Using this effective stack height and Sutton's diffusion equation, a dilution factor of 9.3×10^4 was predicted for the plume centerline aloft at 3-1/4 miles. The predicted centerline dilution factor on the ground was 8.3×10^4 at that distance. The observed average dilution factors were 3.8×10^5 and 7.8×10^5 for aerial and ground centerline locations, or 4.1 and 9.4 times the predicted dilution factors, respectively.

The observed exposure rate at ground level, as shown in Table 6, was 8 μ R/h, or 28% of the predicted 29 μ R/h.

The predicted dilution factors and exposure rates were then calculated using the observed meteorological parameters and the observed effective stack height of 370 meters. The altitude of maximum activity was considered to be the effective stack height. This changed the predicted aerial centerline dilution factor to 1.2×10^5 and the ground level centerline dilution factor to 1.8×10^6 . The observed dilution factors of 3.8×10^5 aloft and 7.8×10^5 on the ground were then 3.2 and 0.4 times the predicted dilution factors. The predicted exposure rate at ground level by this means was 1.3 $\mu\text{R/h}$ compared to the observed exposure rate of 8.0 $\mu\text{R/h}$. The aircraft measure of 13 $\mu\text{R/h}$ in the centerline was 34% of the predicted 38 $\mu\text{R/h}$.

An empirical determination of the standard deviation of radioactivity distribution across the plume yielded a value of 560 meters, as compared to the predicted value of 230 meters. New predictions of dilution factors were made using this value in Sutton's diffusion equation with the observed effective stack height of 370 meters. The observed dilution factor aloft in the plume centerline was 1.3 times the predicted dilution factor of 2.9×10^5 . The observed dilution factor at ground level was 18% of the predicted dilution factor of 4.3×10^6 .

2. 5-3/4 Mile-Location

At the distance of 5-3/4 miles from the power plant the plume width was about three miles wide. The radioactivity concentration was relatively uniformly distributed both horizontally and vertically. Using the observed meteorological parameters and Sutton's diffusion equation for fumigation, a dilution factor of 5.9×10^6 was predicted for both aerial and ground level locations. The average observed dilution factors were 9.6×10^5 for the aircraft sample and 6.7×10^6 for the ground sample, or 1.6 and 11 times the predicted value.

The observed net exposure rates of 4.1 $\mu\text{R/h}$ with the aircraft and 4.0 $\mu\text{R/h}$ on the ground were 57% and 110% of the predicted net exposure rates of 7.2 and 3.6 $\mu\text{R/h}$, respectively. The predicted exposure rate aloft is twice that predicted at ground level due to the 4π geometry aloft compared to 2π geometry on the ground.

Because of the wide plume and relatively uniform concentration-gradient across the plume, the observed σ_y at 5-3/4 miles was 1200 meters compared to the predicted σ_y of 360 meters. This large σ_y increased the predicted dilution factor by about three times to 1.9×10^6 , when introduced into Sutton's diffusion equation for fumigation. The observed dilution factors then were 0.5 and 3.5 times the predicted dilution factors aloft and on the ground.

SUMMARY

The most obvious result of the two aerial missions is that generally good agreement is seen between predicted and observed dilution factors at different distances and under different conditions. An advantage of using aircraft is seen in the ability to collect, and factor into the predictions, the empirical measures of effective stack height and σ_y .

The ratios of observed dilution factors to predicted dilution factors obtained by using (1) predicted σ_y and predicted stack height, (2) predicted σ_y and observed stack height, and (3) observed σ_y and observed stack height, all with Sutton's diffusion equations, are given in Table 10. With the exception of the aerial sample at 2-3/4 miles the observed dilution factors agree reasonably well with the predicted values aloft and at ground level when

using the observed σ_y and observed stack height. Although the agreement is generally somewhat better when using the predicted σ_y rather than the observed σ_y , it is believed that the latter is preferable. Assuming an accurate prediction model, any samples collected would be expected to be equal to or less than the predicted centerline concentrations. Allowing for errors in the prediction model and input data for these two missions, this is the case found in the final column of Table 10. The demonstrated agreement between theory and observation in the aerial samples--with the exception of the 2-3/4-mile sample--is considered very good and indicates an accurate prediction model as long as accurate input data are provided.

The real interest, of course, is the ability to predict ground level exposures under a variety of meteorological and topographical conditions. As shown in Table 10, using standard prediction techniques normally available at the power plant, the diffusion model used overestimates the concentrations from a southerly trajectory by an order of magnitude, apparently because of the increased effective stack height caused by the northwest tip of Humboldt Hill. By incorporating the observed effective stack height, better agreement is seen at 3-1/4 miles where Sutton's diffusion equation is used. When both the observed effective stack height and observed σ_y are used the model underestimates the radionuclide concentrations at 3-1/4 miles by a factor of 4.5 and overestimates the concentrations at 5-3/4 miles by a factor of 3.5.

Assuming that the equations used were the appropriate ones, several factors can explain this behavior. As seen in Figure 4, the exposure rate measurements show that the vertical distribution of radioactivity was not Gaussian as

assumed in the model. This is probably due to increased turbulence near the ground as the plume crossed the end of Humboldt Hill. The concentrations at 5-3/4 miles were based on a fumigation condition existing all the way from the stack to the sampling point allowing σ_z to become equal to half the height of the inversion. In actuality, it appears that the fumigation condition existed only beyond the 3-1/4-mile-location. Therefore, it would be expected that the radioactivity would not have diffused to the ground in the amounts expected.

Although net exposure rate measurements at the low exposure rates encountered are subject to large errors due to the statistical variations encountered in the radiation measurement and the uncertainty of the background exposure rate at the location being surveyed, quite good agreement was seen between the predicted exposure rates and observed exposure rates.

CONCLUSIONS AND RECOMMENDATIONS

From the results obtained it is concluded that Sutton's diffusion equations accurately predict plume diffusion along the centerline as long as accurate input data are provided. Topography was shown to play an important role in affecting ground level concentrations. In addition to the reduction in concentrations observed for a southerly trajectory from the Humboldt Bay power plant, it would be expected that other effects, such as increased concentrations on Humboldt Hill, would be demonstrated by further such surveillance.

The experience of the May 14 operation demonstrates the value of a coordinated ground and aerial surveillance mission. It is recommended that additional such surveys be made under different wind conditions, particularly with winds to the southeast over Humboldt Hill and with fumigation conditions over

Eureka. Included in these surveys should be more detailed meteorology data obtained from mobile weather towers and airborne temperature and turbulence meters. These will make the predictions much more precise.

TABLE 1
Stack Sample Noble Gas Results
March 10, 1971

Radionuclide	Concentrations, pCi/m ³				
	With Molecular Sieve		PG&E	Without Molecular Sieve	
	Sample #1a	Sample #2b		Sample #4a	Sample #6b
^{85m} Kr		1.2x10 ⁸	3.03x10 ⁸		
⁸⁵ Kr		9.1x10 ⁴			1.8x10 ⁵
⁸⁷ Kr		1.6x10 ⁸	9.72x10 ⁸		
⁸⁸ Kr		4.3x10 ⁸	1.04x10 ⁹		
^{131m} Xe		6.7x10 ⁵			
^{133m} Xec		8.5x10 ⁶	1.06x10 ⁷		
¹³³ Xe	(1.4±0.2)x10 ⁸	1.2x10 ⁸	2.32x10 ⁸	(3.0±0.3)x10 ⁸	2.9x10 ⁸
^{135m} Xec			5.56x10 ⁸		
¹³⁵ Xe		3.3x10 ⁸	1.40x10 ⁹		

^aAnalyzed by the AEC.

^bAnalyzed by the WERL.

^cPredicted from distribution of measurable nuclides.

TABLE 2
³H and ¹⁴C Stack Concentrations
March 10, 1971

Radionuclide	Form	Concentrations, pCi/m ³		
		Sample #2	Sample #3	Sample #5
³ H	H ₂ O	8700	8200	8800
³ H	Non-H ₂ O	NA*	1100	1100
¹⁴ C	CO ₂	95	890	NA
¹⁴ C	Non-CO ₂	NA	0.86	0.3

*NA = No analysis.

TABLE 3

Comparison of Measured and Predicted Aerial Concentrations
April 7, 1971

Radionuclide	Concentration (pCi/m ³)					Dilution Factor		
	Stack ^a		Plume			Measured		Predicted ^d
	PG&E	WERL	Measured WERL	Predicted		PG&E ^b	WERL ^c	
				PG&E ^b	WERL ^c			
#1 2-3/4 miles downwind								
^{85m} Kr	3.0x10 ⁸	2.4x10 ⁸	9.4x10 ¹	7.9x10 ²	6.4x10 ²	3.2x10 ⁶	2.6x10 ⁶	3.8x10 ⁵
¹³³ Xe	2.3x10 ⁸	2.9x10 ⁸	1.3x10 ²	6.1x10 ²	7.6x10 ²	1.8x10 ⁶	2.3x10 ⁶	3.8x10 ⁵
¹³⁵ Xe	1.4x10 ⁹	8.0x10 ⁸	1.6x10 ²	3.7x10 ³	2.1x10 ³	9.1x10 ⁶	5.0x10 ⁶	3.8x10 ⁵
#2 2-1/2 miles downwind								
^{85m} Kr	3.0x10 ⁸	2.4x10 ⁸	5.4x10 ²	8.1x10 ²	6.4x10 ²	5.6x10 ⁵	4.5x10 ⁵	3.7x10 ⁵
¹³³ Xe	2.3x10 ⁸	2.9x10 ⁸	1.2x10 ³	6.2x10 ²	7.8x10 ²	1.9x10 ⁵	2.4x10 ⁵	3.7x10 ⁵
¹³⁵ Xe	1.4x10 ⁹	8.0x10 ⁸	1.9x10 ³	3.8x10 ³	2.2x10 ³	7.4x10 ⁵	4.2x10 ⁵	3.7x10 ⁵

^aFrom March 10 stack samples (WERL concentrations shown in Table 1 have been doubled as discussed in the text).

^bBased on March 10 PG&E stack sample results.

^cBased on March 10 WERL stack sample results.

^dBased on Sutton's diffusion equation - $x_{\text{fumigation conc.}} = \frac{Q}{(\pi)^{1/2} C_y \bar{u} H x^{(2-n)/2}}$

where; x = Concentration (Ci/m³)

Q = Emission rate (Ci/s)

x = Distance downwind (m)

C_y = Diffusion coefficient in the Y plane [(m)^{n/2}]

n = Nondimensional parameter associated with stability

$\bar{u}$ = Mean wind speed (m/s)

H = Height of inversion (m)

TABLE 4
Comparison of Measured and Predicted Aerial Concentrations
May 14, 1971

Radionuclide	Concentration (pCi/m ³)			Dilution Factor	
	Stack (PG&E)	Measured (WERL)	Predicted	Measured	Predicted
#1 3-1/4 miles south					
¹³³ Xe	1.44x10 ⁸	4.6x10 ²	1.2x10 ³ *	3.1x10 ⁵	1.2x10 ⁵ *
¹³⁵ Xe	8.62x10 ⁸	1.9x10 ³	7.2x10 ³ *	4.5x10 ⁵	1.2x10 ⁵ *
#2 5-3/4 miles south					
¹³³ Xe	1.44x10 ⁸	2.0x10 ²	2.4x10 ² **	7.2x10 ⁵	5.9x10 ⁵ **
¹³⁵ Xe	8.62x10 ⁸	7.2x10 ²	1.5x10 ³ **	1.2x10 ⁶	5.9x10 ⁵ **

*Based on Sutton's Diffusion Equation:

$$x = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} \{ \exp[-1/2(\frac{z-h}{\sigma_z})^2] + \exp[-1/2(\frac{z+h}{\sigma_z})^2] \}$$

$$\text{where: } \sigma_y = \frac{1}{\sqrt{2}} C_y x^{(2-n)/2}; \sigma_z = \frac{1}{\sqrt{2}} C_z x^{(2-n)/2}$$

**Based on Sutton's Diffusion Equation:

$$x_{\text{fumigation conc.}} = \frac{Q}{(\pi)^{1/2} C_y \bar{u}_H x^{(2-n)/2}}$$

x = Concentration (Ci/m³)

x = Distance downwind (m)

z = Vertical distance (m)

H = Height of inversion (m)

u = Mean wind speed (m/s)

h = Effective stack height (m)

σ_y, σ_z = Standard deviation of the distribution of material in a plume
in the y- and z- directions

C_y, C_z = Diffusion coefficient in the y- and z- planes [(m)^{n/2}]

TABLE 5
Comparison of Measured and Predicted Ground Level Concentrations
May 14, 1971

Radionuclide	Concentration (pCi/m ³)			Dilution Factor	
	Stack (PG&E)	Plume (WERL)	Plume Predicted	Measured	Predicted
Sample #1 3-1/4 miles south 110-meter predicted effective stack height					
¹³³ Xe	1.44x10 ⁸	2.5x10 ²	1.7x10 ³ *	5.8x10 ⁵	8.3x10 ⁴ *
¹³⁵ Xe	8.62x10 ⁸	8.8x10 ²	1.0x10 ⁴ *	9.8x10 ⁵	8.3x10 ⁴ *
Sample #1 3-1/4 miles south 370-meter actual effective stack height					
¹³³ Xe	1.44x10 ⁸	2.5x10 ²	8.0x10 ¹ *	5.8x10 ⁵	1.8x10 ⁶ *
¹³⁵ Xe	8.62x10 ⁸	8.8x10 ²	4.8x10 ² *	9.8x10 ⁵	1.8x10 ⁶ *
Sample #2 5-3/4 miles south					
¹³³ Xe	1.44x10 ⁸	30	2.4x10 ² **	4.8x10 ⁶	5.9x10 ⁵ **
¹³⁵ Xe	8.62x10 ⁸	100	1.5x10 ³ **	8.6x10 ⁶	5.9x10 ⁵ **

*Based on Sutton's Diffusion Equation:

$$X = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} \exp\left[-1/2\left(\frac{h}{\sigma_z}\right)^2\right]$$

$$\text{where: } \sigma_y = \frac{1}{\sqrt{2}} C_y x^{(2-n)/2}; \sigma_z = \frac{1}{\sqrt{2}} C_z x^{(2-n)/2}$$

**Based on Sutton's Diffusion Equation for fumigation:

$$X_{\text{fumigation conc.}} = \frac{Q}{(\pi)^{1/2} C_y \bar{u} x^{(2-n)/2}}$$

TABLE 6
Comparison of Measured and Predicted Exposure Rates

Date	Distance (Miles)	Net Exposure Rate (μ R/h)		Percent of Predicted
		Measured	Predicted	
April 7	2-1/2 (aerial)	32	27	120
April 7	2-3/4 (aerial)	32	26	120
May 14	3-1/4 (aerial)	13	38	34
May 14	3-1/4 (ground)	8.0	1.3*	620
			29**	28
May 14	5-3/4 (aerial)	4.1	7.2	57
May 14	5-3/4 (ground)	4.0	3.6	110

* Based on measured effective stack height of 370 meters.

**Based on predicted effective stack height of 110 meters.

TABLE 7
Standard Deviation of Radioactivity Distribution
Normal to Plume Axis, σ_y

Date	Distance (Miles)	Standard Deviation, σ_y (meters)	
		Predicted	Observed
April 7	2-3/4	500	>1000
April 7	2-1/2	470	>1000
May 14	3-1/4	230	560
May 14	5-3/4	360	1200

TABLE 8
Plume Centerline Dilution Factors

Date	Distance (Miles)	Dilution Factors		
		Predicted ^a	Observed	Predicted ^b
Aerial		(Average)		
April 7	2-3/4	3.8x10 ⁵	4.7x10 ⁶ (3.3x10 ⁶) ^c	7.9x10 ⁵
April 7	2-1/2	3.7x10 ⁵	5.0x10 ⁵ (3.7x10 ⁵) ^c	7.6x10 ⁵
May 14	3-1/4	1.2x10 ⁵	3.8x10 ⁵	2.9x10 ⁵
May 14	5-3/4	5.9x10 ⁵	9.6x10 ⁵	1.9x10 ⁶
Ground				
May 14	3-1/4	8.3x10 ^{4d}	7.8x10 ⁵	2.0x10 ^{5d}
May 14	3-1/4	1.8x10 ^{6e}	7.8x10 ⁵	4.3x10 ^{6e}
May 14	5-3/4	5.9x10 ⁵	6.7x10 ⁶	1.9x10 ⁶

^aCalculated using predicted σ_y .

^bCalculated using observed σ_y .

^cBased on WERL stack discharge measurement.

^dCalculated using predicted effective stack height of 110 meters.

^eCalculated using observed effective stack height of 370 meters at 3-1/4 miles.

TABLE 9
Isotopic Exposure Rates
Infinite Cloud Model

Radionuclide	Average γ Energy $\bar{E}$ (MeV)	Exposure Rate* $\mu\text{R/h/pCi/cm}^3$
$^{83\text{m}}\text{Kr}$	0.0008	--
$^{85\text{m}}\text{Kr}$	0.15	2.8×10^2
^{87}Kr	1.38	2.6×10^3
^{88}Kr	0.57	1.1×10^3
^{88}Rb	1.77	3.3×10^3
$^{133\text{m}}\text{Xe}$	0.03	5.7×10^1
^{133}Xe	0.03	5.7×10^1
$^{135\text{m}}\text{Xe}$	0.42	7.9×10^2
^{135}Xe	0.25	4.7×10^2
^{138}Xe	2.86	5.4×10^3
^{138}Cs	2.08	3.9×10^3

* $D_r = 1.89 \bar{E} \times 10^3 \mu\text{R/h/pCi/cm}^3$

TABLE 10
Ratio of Observed Dilution Factors to Predicted
Dilution Factors

Distance from Stack (Miles)	Dilution Factor Obtained From:		
	Predicted σ_y , Predicted Stack Height	Predicted σ_y , Observed Stack Height	Observed σ_y , Observed Stack Height
Aerial			
2-1/2		1.35	0.66
2-3/4		0.12	0.06
3-1/4	4.09	3.16	1.31
5-3/4	1.63	1.63	0.51
Ground			
3-1/4	11.6	0.53	0.22
5-3/4	11.3	11.3	3.5