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U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Environmental Research Laboratories

Diffusion in a Canyon Within Rough Mountainous Terrain

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Air Resources
Laboratories
IDAHO FALLS,
IDAHO
August 1973

ENVIRONMENTAL RESEARCH LABORATORIES

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NOTICE

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ABSTRACT

An accelerated field measurements program was conducted to quantify atmospheric diffusion within a deep, steep-walled canyon in rough, mountainous terrain. Two principle objectives were pursued...impaction of plumes upon elevated terrain, and diffusion of gases within the canyon versus diffusion over flat, open terrain. Oil fog flow visualizations provided qualitative information; quantitative diffusion measurements were obtained using sulfur-hexafluoride gas with analysis by highly sensitive gas phase coulometric techniques. Eleven 45 to 60 minute gaseous tracer releases were conducted.

Stability category related differences in canyon diffusion versus flat terrain diffusion were found. Daytime lapse conditions showed little difference. Neutral stability tests showed five times greater dilution for canyon axial concentrations; strong inversion tests resulted in canyon plume centerline dilutions fifteen times greater than calculations using parameters derived for flat terrain. Plume effluents frequently impacted against elevated terrain. One hour total integrated concentrations measured on the canyon floor and walls compared to one minute axial concentrations collected away from the terrain showed peak-to-average concentration ratios of 1.5 to 3.

Enhanced mechanical turbulence associated with gradient windflows near the mountain tops, density flows originating in side canyons, and turbulent wakes from pronounced terrain irregularities within the canyon are believed to be some of the additional physical mechanisms affecting plume dilutions in Huntington Canyon.

The present results should be relevant, at least qualitatively, to similar deep, steep-walled canyons. They should not be applied indiscriminantly to sites with less extreme topography. Additional measurements are needed at sites in less rugged terrain.

Diffusion in a Canyon within Rough Mountainous Terrain[1]

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I. Introduction

During the past few decades considerable effort has been expended on theoretical and empirical field measurement programs to understand and quantitize the rate of dilution of airborne effluents. Most of this effort has been concentrated on atmospheric flows occuring over physically-flat or simple underlying ground surfaces and has been summarized by Slade (1968). This knowledge has been applied at distances of a few kilometers and time durations of a few hours with general success.

However, the need to assess the role of the atmosphere during dispersion of airborne effluents within a confined region such as a deep, steep-walled canyon has given rise to a number of fundamental concerns. There was and is a need to assess the environmental impact within this type of physical setting. Since the data and understandings are primarily limited to flat terrain, what are the rational alternatives for an evaluation in rough terrain? First, the simple, flatland models could be utilized as they exist. Second, for elevated effluent releases, the material could be assumed to flow horizontally until it impacts against the steeply-rising terrain, after which the effluent could be visualized as flowing along and bounded on the lower side by the underlying terrain. Third, under other

[1]Research carried out under the joint sponsorship of the Atomic Energy Commission (Division of Reactor Development and Technology) and the National Oceanic and Atmospheric Administration.

situations the elevated effluents might be envisioned as flowing up-and-over or out-and-around prominent physical features with minimal contact with the actual terrain surfaces. Many additional possibilities probably could be cited. From the existing state of knowledge it would be nearly impossible to rigorously determine defendable quantitative estimates of effluent concentrations. An alternative would be to develop estimates which would likely define upper bounds upon the highest concentrations expected through use of joint-frequency statistics, simple flat-terrain model(s), and a terrain impaction assumption. This alternative was chosen for an atmospheric diffusion model developed by the Air Resources Laboratory (ARL) in the meteorological report (Van der Hoven, et al, 1972) to the Department of the Interior as a part of their "Southwest Energy Study." A very similar model has been applied by the Environmental Protection Agency as a basis for estimating the extent of pollution abatement actions necessary in the matter of smelters and fossil-fueled plants in the southwestern United States. These models have been criticized as being unduly conservative. A critical assumption in the models was the impingement of the elevated plume centerline upon higher terrain under certain conditions. It was postulated that the impingement model represented the worst credible condition with regard to downwind surface pollutant concentrations and that modification towards enhanced dilution required new and substantive measured data. Also, current Atomic Energy Commission Regulatory practice assumes that an elevated plume centerline travels horizontally and impinges upon higher terrain. Concentrations are then calculated from "flat terrain" diffusion models. It was felt that changes in the dilution calculations for sources within a confined region as compared to calculations for flat terrain sources could be warranted. Calculations for facilities having stack releases in deep valleys in mountainous terrain would be particularly affected. Intuitively, most air pollution meteorologists would suspect that the rough terrain would produce greater mechanical overturning and mixing in the atmosphere with a resultant more rapid rate of effluent dilution (Hinds, 1967). Conversely, one could postulate separation of within-canyon-flow from above-canyon-flow (DeMarrais, 1968). This result could produce a volumetric dilution within the confines of the canyon or possibly a narrow plume filament or ribbon which could either flow around and/or over terrain, or impact (at essentially centerline value) into the elevated terrain. Almost any intermediate situation could be envisioned. No basis existed to resolve which of these physical effects should be incorporated to yield an appropriate dilution model nor to what quantitative extent they should be utilized.

These unique, rough-terrain and canyon effects had to be observed and quantitatively measured and compared with the much more numerous flat or open-terrain model experiments. Huntington Canyon, Utah, provided an excellent setting in which to perform an initial field measurement program. In addition, an existing 183 m chimney at the power plant construction site provided a valuable point of opportunity for the study of elevated, within-canyon effluent releases.

As a beginning point consider a single, continuous point source and its widely utilized Gaussian diffusion equation. At the plume axis or centerline for a given distance downwind from the source

$$\frac{\chi \bar{U}}{Q} = \frac{1}{\pi \sigma_y \sigma_z}$$

where

χ = effluent concentration gm^{-3}

Q = effluent source strength g sec^{-1}

$\bar{U}$ = mean windspeed m sec^{-1}

σ_y = standard deviation of effluent concentration in crosswind direction m

σ_z = standard deviation of effluent concentration in vertical direction m

Relationships between the standard deviation of effluent concentration (σ_y, σ_z) as a function of distance and measured meteorological parameters are given in several places (Pasquill, 1961; Slade, 1968; Yanskey, et al 1966; Turner, 1969 and many others). These relationships are based upon field observations collected at a number of flat terrain locations. The results, however, are generally quite similar. The most widely used diffusion categorization scheme is that developed by Pasquill (1961) and shown in table 1. The resulting σ_y and σ_z values as a function of distance, (Gifford, 1961) are shown in figures 1 and 2. With arguments of season of year and time of day (solar insolation factor), wind speed, and cloud cover, a determination of the stability results. The precision of this objective scheme (and several other potential schemes) is subject to considerable case-to-case variability. However, since this scheme is basically the practice incorporated in environmental impact evaluations, it provides a fair reference against which the actual observations may be compared.

The scope of the Huntington Canyon field measurement program had to be carefully restricted due to the pressure of time and resource limitations.

Table 1. Meteorological Categories

A. Extremely unstable conditions
B. Moderately unstable conditions
C. Slightly unstable conditions
D. Neutral conditions
E. Slightly stable conditions
F. Moderately stable conditions

Surface wind speed, m/sec	Daytime insolation			Nighttime conditions	
	Strong	Moderate	Slight	Thin overcast or ≥ 4/8 cloudiness	≤3/8 cloudiness
<2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
>6	C	D	D	D	D

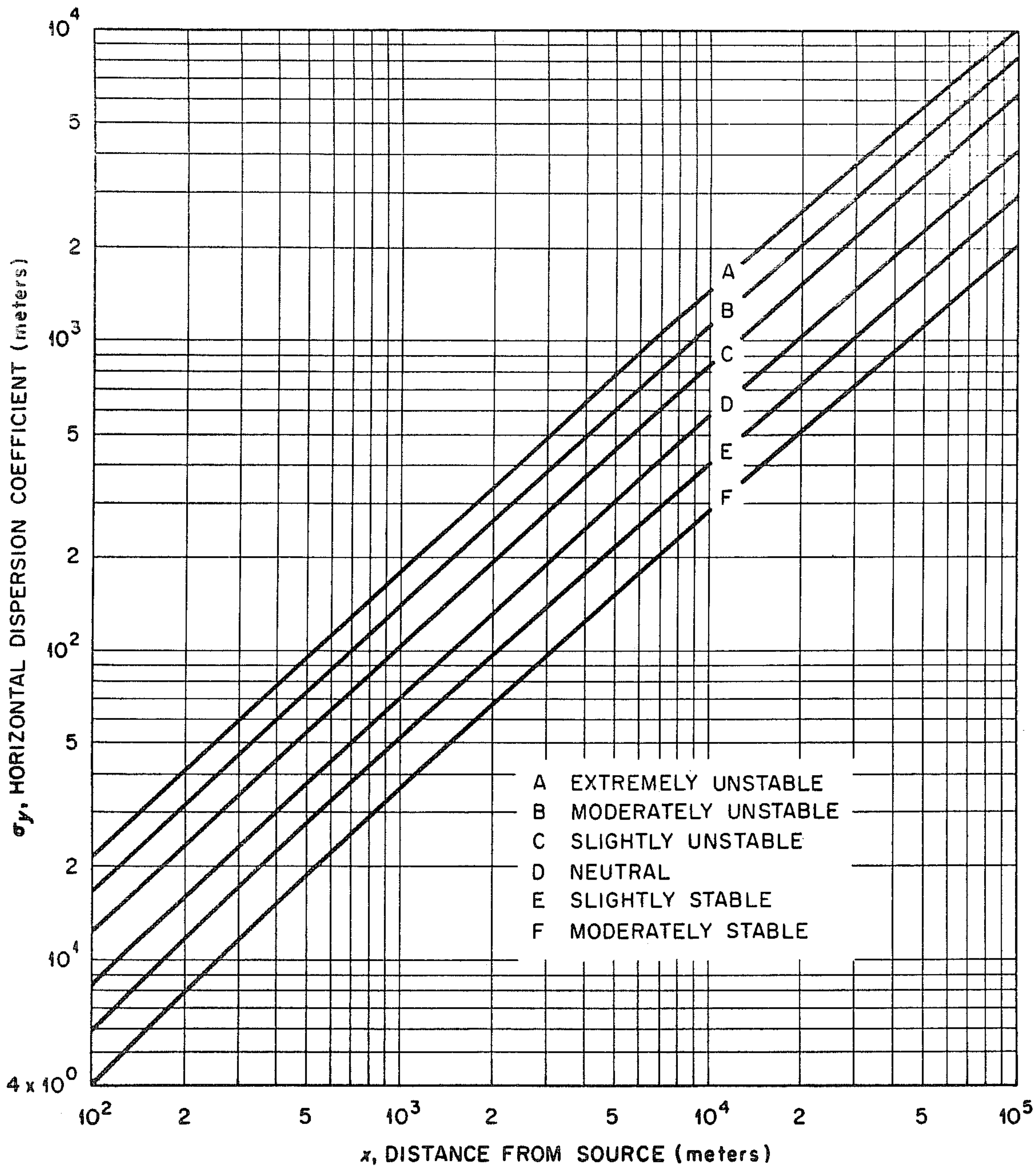

Figure 1. Horizontal dispersion, σ_y, meters, versus downwind distance, meters.

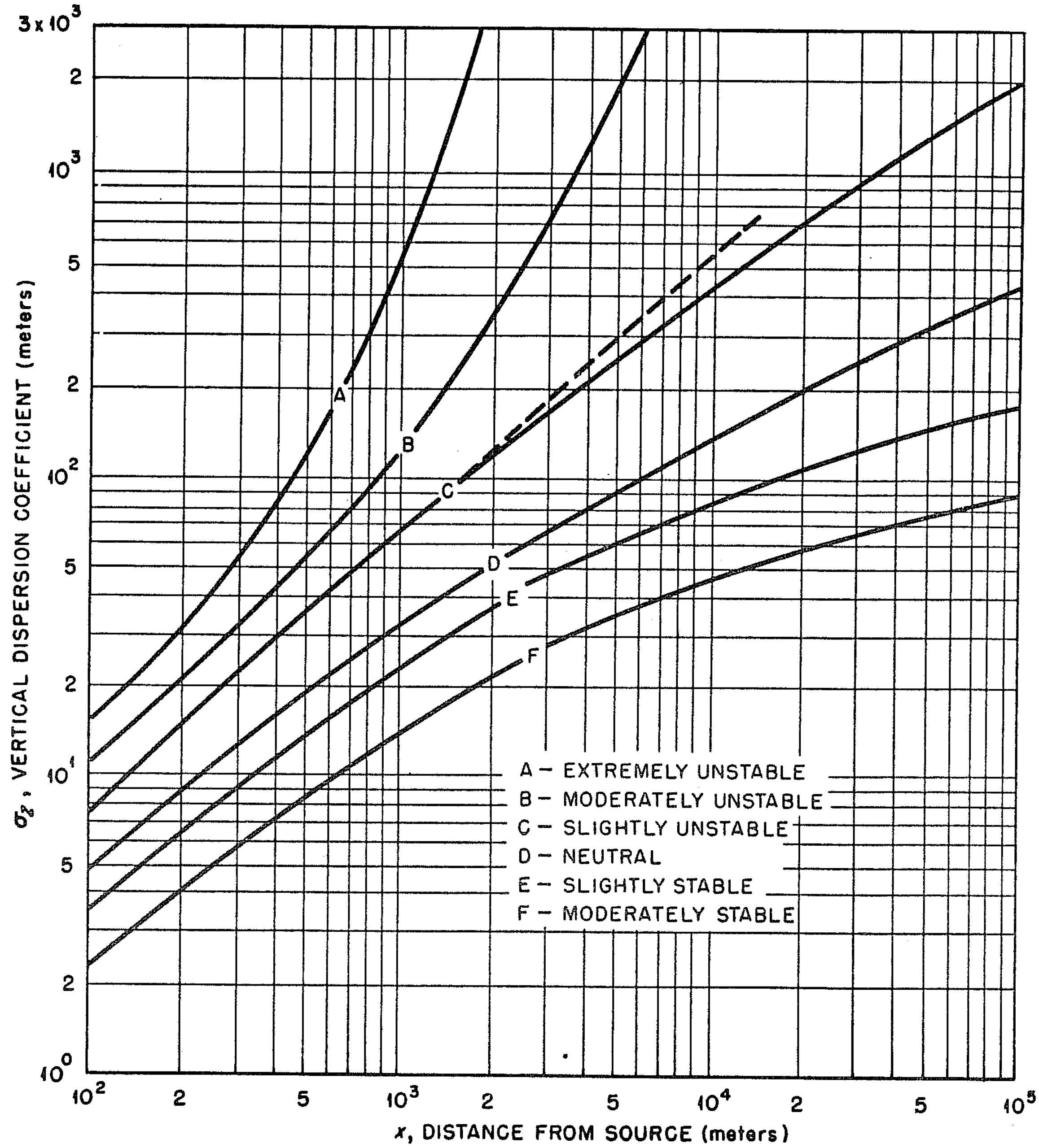

Figure 2. Vertical dispersion, σ_z, meters, vs downwind distance, x, meters.

Two principle objectives were selected to receive the primary emphasis. First, and fundamental to the application of the ARL Southwest Energy Study concentration model, was the investigation of the validity of plume impaction upon elevated terrain. Second, and of equal importance, was the measurement of gaseous tracer concentrations within the canyon. These tracer concentration measurements were needed both within the canyon, but far from the canyon walls, and at numerous points along the walls and floor. As a result of these measurements, two important facets of dilution within the canyon could be examined. The mid-canyon measurements were expected to show the rate of tracer dilution versus downwind distance within the canyon (and allow comparisons with the expected rates of dilution over flat or open terrain) and to show any difference between canyon surface and plume center-line or mid canyon concentrations (quantify impaction behavior).

It was not intended to treat the area of mountain meteorology in any depth. Defant (1951), Thyer (1962), DeMarrais (1968), etc, have reported on specific studies of meteorology in mountainous terrain and the reader is referred to their work. Extensive supporting meteorological data were desirable, but priorities prohibited an extensive program. Wind and temperature data sufficient to describe diffusion classes were collected to document conditions during the actual tracer measurement cases.

II. Methods and Instrumentation

Wind and temperature instrumentation for the Huntington Canyon study consisted of an array of sensitive anemometer-wind vane stations located throughout the canyon, and aspirated resistance thermometers placed at various levels on the 183-m stack.

The six wind stations up canyon from the stack (Little Bear, bottom; Little Bear, top; Trail, bottom; Trail, top: Bear Creek, and Wild Horse; see figure 4), consisted of 3-m towers upon which were placed battery-powered Climet low threshold cups and vanes. Our calibration showed reliable response beginning at 0.2 m sec^{-1}. Springwound strip-chart recorders were used to record the data. The stations on the canyon floor were located in open meadows near the canyon centerline. Locations for those on the rim were chosen in areas free from timber-induced eddies, toward the tip of protrusions from the canyon wall.

Bendix model 126 aerovane transmitters were used to instrument the top of the 183-m stack, the 9.1-m tower down the canyon from the stack at Orchard, and on the 3-m tower on the rising bench at Deer Creek. These data were recorded on the Bendix-Friez strip chart recorders, from which the data were read, coded, and processed.

Three aspirated type A bulb resistance thermometers were placed on the power plant stack at the 183-, 92- and 3-m levels. Aircraft temperature soundings were also taken on a routine basis every morning and afternoon during the test period. A Cessna 206 using a fast response resistance thermometer and a strip-chart recorder took soundings from near stack-top height up through 3400 m MSL.

A visual track of the approximate tracer plume position was provided by a smoke generator which emitted an intensely dense cloud of white smoke for as long as desired. The unit consisted of a portable gas turbine in which high grade fog oil was burned. The unit could be easily transported to various release points in the canyon.

Photographic coverage of the experiments provided valuable plume positioning, and a means of evaluating the significance of the helicopter samples. During the actual testing, four 35 mm cameras were positioned at various sampling locations in the canyon, and Ektachrome slide photographs taken of the sampling helicopter and plume. Time synchronization among the cameras, helicopter and release was achieved by means of portable radio sets which used a repeater positioned atop the 183-m stack. Airborne pictures were also taken from the helicopter. An Airflex 16 mm movie camera using ECO (Ektachrome commercial) film, a Nikon-F using high speed Ektachrome, and a 4x5 Linhof, were used at various times in the helicopter.

Volumetric sampling of the tracer plume was carried out using helicopter-borne and surface-based samplers which pumped a known volume of plume gas into inert saran bags. Careful attention was given to recording the beginning and ending sampling times so that tracer concentrations could later be normalized.

The Bell H-1 helicopter carried a battery powered air sampling pump built by Unico Environmental Instruments, Incorporated. The pump drew short-term samples through a 28-m length of hose which hung in the air beneath the helicopter. The hose assured that the sampled air was not unnaturally diluted by the helicopter rotor turbulence; previously conducted research has shown that beyond 21 m below the rotors the free air is undisturbed by the downwash.

Portable radio units were used by personnel at samplers on the canyon wall to assist in vectoring the helicopter to center-plume positions.

The ground-based volumetric samplers were similar to metal suitcases which contained a battery pack powering a calibrated air pump. The pump drew ambient air from outside the box into a saran sample bag for the duration of each test run. Immediately after each test run the saran bags were collected and analyzed in a mobile gas analysis laboratory at the test site. Several samples were drawn from each bag and inserted into an electron capture gas chromatography system which had been custom-built to our specifications. SF_6 separation was accomplished using 5A molecular sieve, 80-100 mesh, columns. The electron capture detectors used 15 mCi Ni-63 sources.

To facilitate quick sample analysis the chromatograph system was assembled with two columns and detectors in parallel; two samples could be run simultaneously. Data were graphically displayed using dual pen Hewlett-Packard strip-chart recorders. The saran bag volumes were determined using a wet test meter so that the pumping rates of the calibrated ground samplers could be checked and also so that the dilution of the samples could be taken into account in the concentration calculations. After analysis and volumetric determination the saran bags were purged with ultra-high purity nitrogen in preparation for reuse.

III. Results

A. Canyon Dispersion

The gaseous tracer measurement program was separated into two main parts....elevated releases from the top of the 183-m stack during lapse to neutral stability conditions, and releases from the canyon wall or floor during strong inversion stabilities. Eleven releases of SF_6 were made. Helicopter collected plume center samples were unavailable for tests 4 and 9. During test 4 the oil fog system failed and plume centerline positions could not be visually located. During test 9 the helicopter was inoperative. Tests 1 to 6 were elevated releases from the top of the 183-m stack. Tests 7 to 11 were conducted from a release point nearly 10 km up-canyon from the plant construction site. The dates, times, durations of release, sky conditions, mean wind speeds, atmospheric stability categories, and amounts of SF_6 released are listed in table 2. Table 3 lists the wind directions and speeds as recorded by three main wind stations and the wind speed at 10 m above the ground (for use in determining appropriate stability categories) during the eleven SF_6 tracer tests. Figure 3 illustrates the location of Huntington Canyon and gives some perspective on its size and relation to other major topographical features in the area. (Height contours are labeled as feet above mean sea level.)

Figure 4 illustrates the general shape and topography of Huntington Canyon. The locations of the 183-m stack and the two up-canyon release points (near Little Bear Canyon, about 10 km up-canyon from the plant) are shown by small triangles. The nine wind station locations were also indicated. The basic region of interest extended from the orchard site (about 1½ km down-canyon from the plant) to Little Bear nearly ten km up-canyon. Sizable "feeder" or side-canyons are evident. The locations used for canyon wall and floor gas samples are in figure 5, along with the names of the principle feeder canyons and ridges. Release points are depicted as small triangles and sampling points as small boxes; dots within boxes indicate individual samplers. The names of the sampler strings are listed along side of the box symbols. To emphasize the terrain features of Huntington Canyon, several cross-sections have been prepared. Figure 6 provides the horizontal locations of these cross-sections. During tracer releases from the 183-m stack, samplers were operated along the cross canyon arcs shown in figure 7. Figure 8 depicts the same type of cross-sections for releases from the Little Bear up-canyon sites (tests 7 to 11).

The results of the SF_6 sampling program are shown in figures 9, 10, 11 and 14. Aerial samples of about 1-min duration, taken by helicopter in the plume center as visualized by simultaneous smoke emission, are depicted as circles with an inscribed cross. No aerial samples were taken during tests 4 and 9. Surface-level samples on canyon walls and floor were collected over about one hour periods and are shown by the letter 'x'. Figure 9-a through f are for the six releases from the 183-m stack during lapse and neutral conditions. In each plot of figure 9 the ordinate values were wind speed normalized relative axial concentrations, with units of m^{-2}. The wind speeds used in computing normalized relative concentrations were determined from oil fog arrival times reported by several field observers at varied distances downwind of the source point. These speeds represent the effective displacing wind (through a considerable vertical depth) and were the best available estimates. The solid line represents the expected open-terrain or flat-land values for the Pasquill stability categories as determined by the criteria in table 1. Figure 10 shows helicopter and ground data and only helicopter data, respectively, from class D tests (2, 3, 5, and 6). The dashed line in figure 10-b is the least-squares first order curve fitting of these data points. This same line is entered on figure 9-d, since no plume center samples were available. In every stack release case the canyon floor and wall samples were of lower concentrations than the corresponding helicopter obtained (plume center) sample concentrations. The centerline concentrations were more dilute than concentrations expected over flat terrain.

During the course of the SF_6 measurement program it became apparent that at this time of year it was highly unlikely that concentration measurements up-canyon (to the northwest) could be obtained during inversion conditions when tracer releases were made from the top of the 183-m stack. Flows at night were down-canyon and carried the plume southeastward where it entered the broad main valley to the east, away from the mountains and the elevated terrain. Up-canyon flows were occurring during daytime lapse conditions.

Because dilution during inversion conditions and terrain impaction of plume centerline concentrations were the critical points to be examined, the test procedures were altered following test 6. A prominent, elevated point, jutting out into the canyon was found about 10 km up-canyon from the plant site (Little Bear, top) for use as a new release location; its position is shown in figure 4. The height above the canyon floor was about 168 m, nearly the same as the physical stack height at the plant site. This release location was adopted in the expectation that a narrow, filament or ribbon-like plume could develop during down-canyon, inversion flows. During the first 3 km down canyon from this release point the canyon was fairly straight and the walls were moderately smooth without major side or feeder canyons. Beyond 3 km the canyon underwent a number of minor bends and several sizable feeder canyons entered from each side. It was in this region that observations of plume impaction were anticipated.

Figure 11-a through e contains the data points collected from up-canyon releases during strong inversion conditions. The solid line in each plot represents the expected Pasquill class F, open-terrain relative centerline concentrations versus downwind distance. Measurements have been plotted with the same symbolism used for the stack releases (tests 1-6) shown by figures 9 and 10.

Test 7 results, shown in figure 11-a, were for a morning release from Little Bear, top. The test 7 plumes flowed away from the elevated release point (on the canyon wall) with seeming little influence from the ground surface. However, a narrow plume filament failed to materialize. Instead, the plume was transported upward along the shaded canyon wall toward the mountain tops while moving down-canyon within the basic wind flow. Figure 12 shows this plume from an aerial vantage about 4 km down-canyon.

If enhanced mechanical turbulence in the higher regions of the canyon were responsible for the transport upward along the shaded canyon wall, the next alternative was to release from the very bottom. There, if anywhere, the plume was expected to be isolated from turbulent effects near the mountain tops. Tests 8 to 11 (figure 11-b through e) were conducted with the same canyon floor release point.

Two changes were evident for tests 7-11. First the differences between expected Pasquill, flat-terrain and observed centerline concentrations were greater for these cases than for the observed stack

Table 2. General Conditions and times during SF_6 sampling

Test #	Release Pt.	Date	SF_6 (kg)	Time	Weather & Sky	$\bar{U}$ Smoke ($m\ sec^{-1}$)	Stab.
1	Stack	3/16/73	5.99	1050-1142	Clear. Visibility 30+ miles. Few contrails.	4.3	B
2	Stack	3/19/73	5.19	1540-1624	Estimated 6/10's sky cover at 11,000 ft.	4.5	D
3	Stack	3/20/73	5.78	0914-1003	Overcast. Sun not visible. Estimate ceiling at 18,000 ft.	2.3	D
4*	Stack	3/20/73	3.54	1511-1541	Estimated 6/10's sky cover at 12,000 ft. Occasional snow flurries	est. 10.	D
5	Stack	3/21/73	5.19	1025-1109	Overcast. Ceiling at 10,000 ft. Few breaks in overcast. Snow showers up canyon.	5.3	D
6	Stack	3/22/73	6.60	0945-1041	Broken clouds at 9,000 ft. Snowing on mountains.	3.8	D
7	Upper Pt. Little Bear	4/4/73	7.48	0725-0810	Clear. Few small cumulus clouds over mountains in the distance.	2.9	F
8	Sfc. Little Bear	4/4/73	6.92	1745-1833	Clear	1.8	F
9	Sfc. Little Bear	4/5/73	7.48	0658-0758	Clear. Visibility 30+ miles.	7.9	F
10	Sfc. Little Bear	4/5/73	4.65	1750-1823	Broken clouds above 20,000 ft. About 1/10 of sky cover opaque	3.2	F
11	Sfc. Little Bear	4/6/73	6.35	0628-0703	Clear. Visibility 30+ miles	3.0	F

*No smoke this test.

Stability classification criteria: Gifford, F. A., (1961) and Turner, D. B., (1961)

Table 3. Wind data during SF_6 releases in Huntington Canyon, Utah

Test #	Date	Time (MST) Begin	Time (MST) End	Stack Average DD	Stack Average VV	Orchard Average DD	Orchard Average VV	Deer Creek Average DD	Deer Creek Average VV	Oil Fog[α] VV	Source Point VV at about 10 m
1	3/16/73	1051	1142	Msg	Msg	140	1.8	120	2.7	4.3	1.8
2	3/19/73	1541	1624	120	4.0	130	1.3	120	3.1	4.5	1.3
3	3/20/73	0914	1003	120	3.6	140	.9	120	2.2	2.3	.9
4	3/20/73	1511	1540	140	2.7	170	.9	110	1.3	10 est.	.9
5	3/21/73	1026	1110	150	6.3	Msg	Msg	140	4.0	5.3	2.6
6	3/22/73	0944	1040	110	1.8	100	Msg	100	1.8	3.8	1.5
7	4/4/73	0725	0810	*	4.5	360	3.6	320	1.8	2.9	1.0
8	4/4/73	1745	1833	150	.9	250	1.3	230	.9	1.8	3.1
9	4/5/73	0658	0758	350	Msg	320	2.7	310	2.2	7.9	8.1
10	4/5/73	1750	1823	300	.4	240	.9	230	1.8	3.2	4.2
11	4/6/73	0628	0703	Msg	Msg	310	1.3	300	1.3	3.0	2.1
Anemometer Height				183 m		9.5 m		3.5 m			

DD - Direction in degrees from which the wind blows

VV - Speed in m sec^{-1}

Msg - Missing data

*Averaged 300^{o} for six hours before the test. DD lost at 0545; back in service 0940

[α]Based upon field observations of speeds of oil fog plume movements.

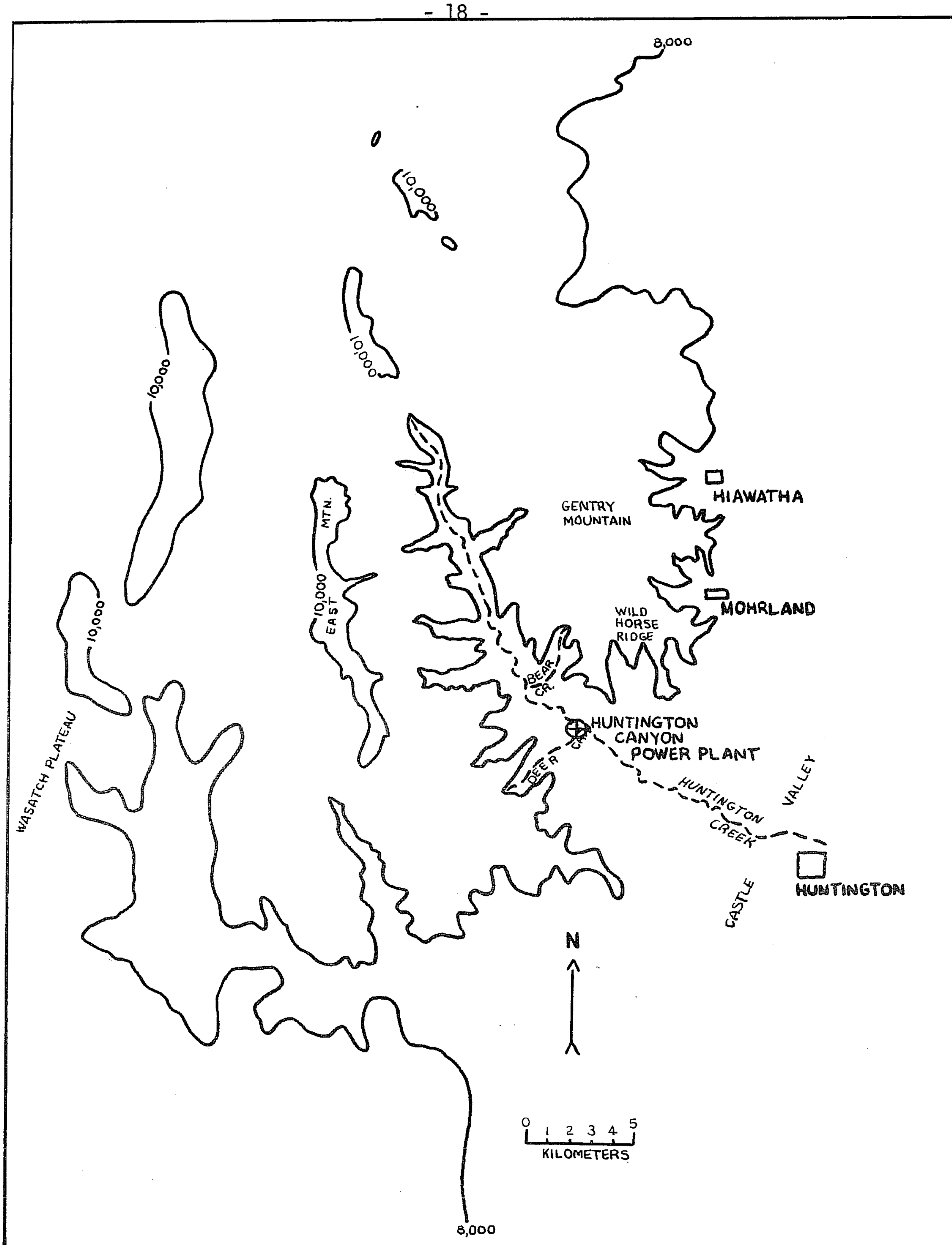

Figure 3. Huntington Canyon and surrounding area.

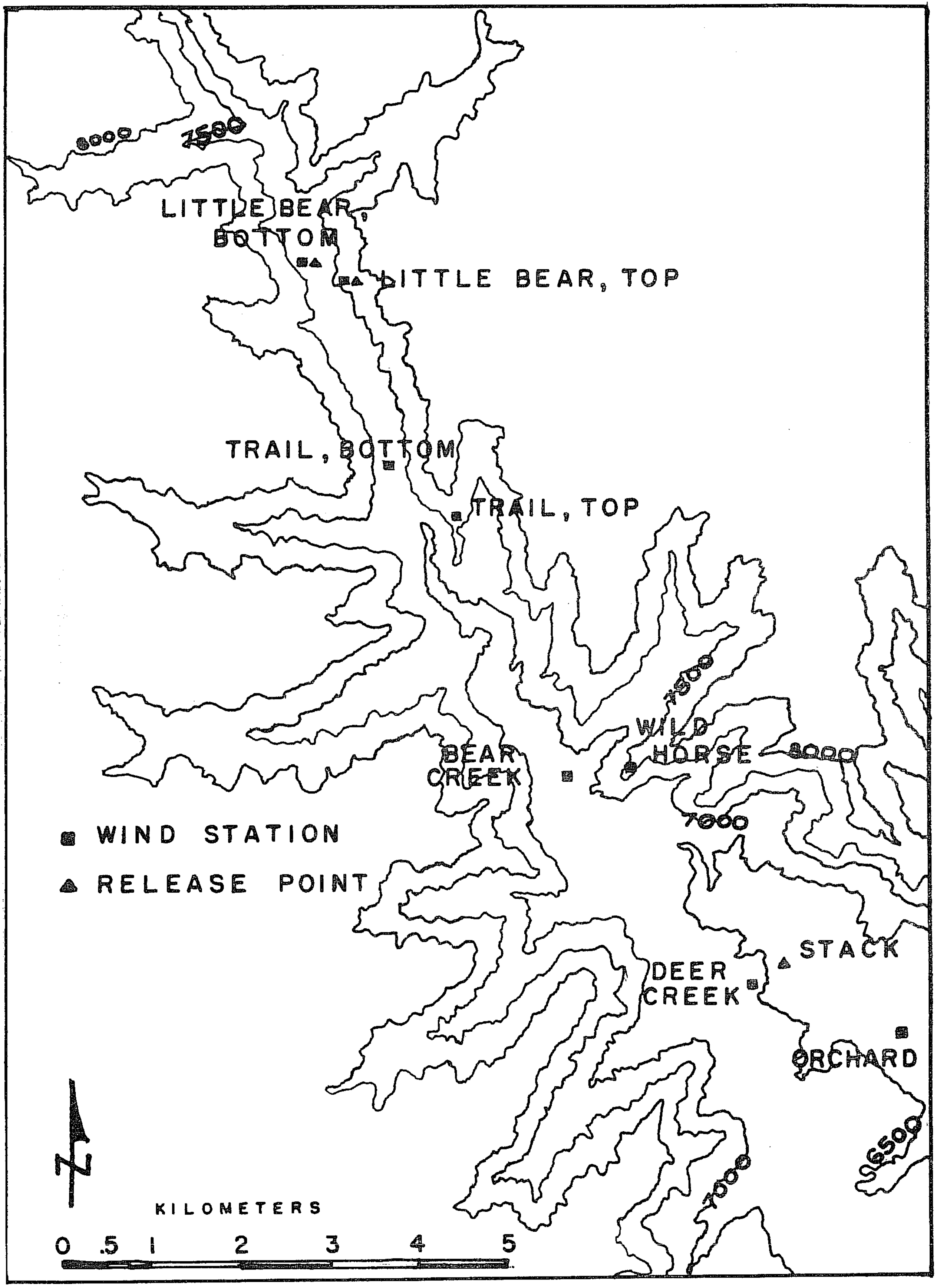

Figure 4. Wind station locations and SF_6 release points in Huntington Canyon.

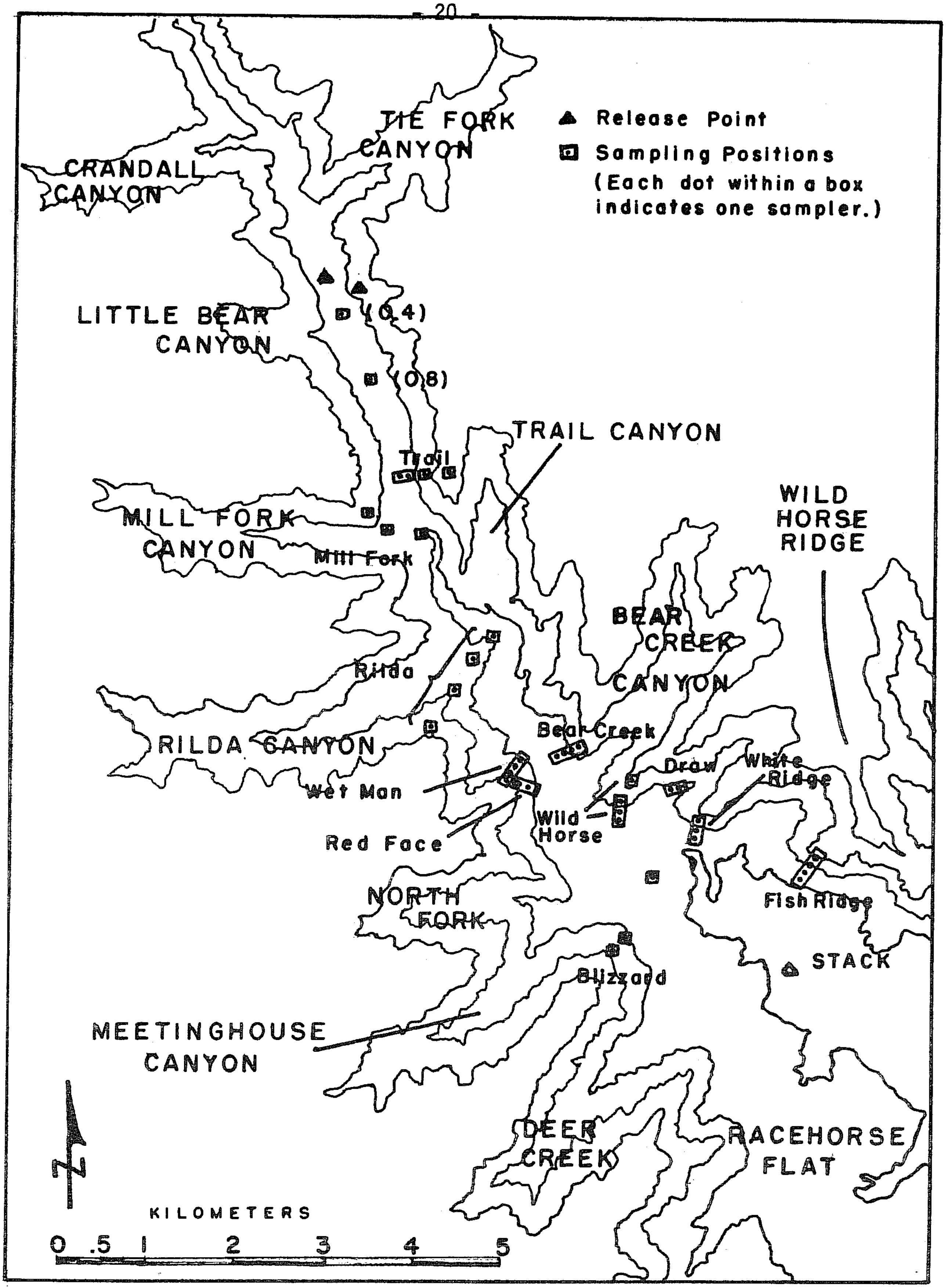

Figure 5. SF_6 sampler positions and location names.

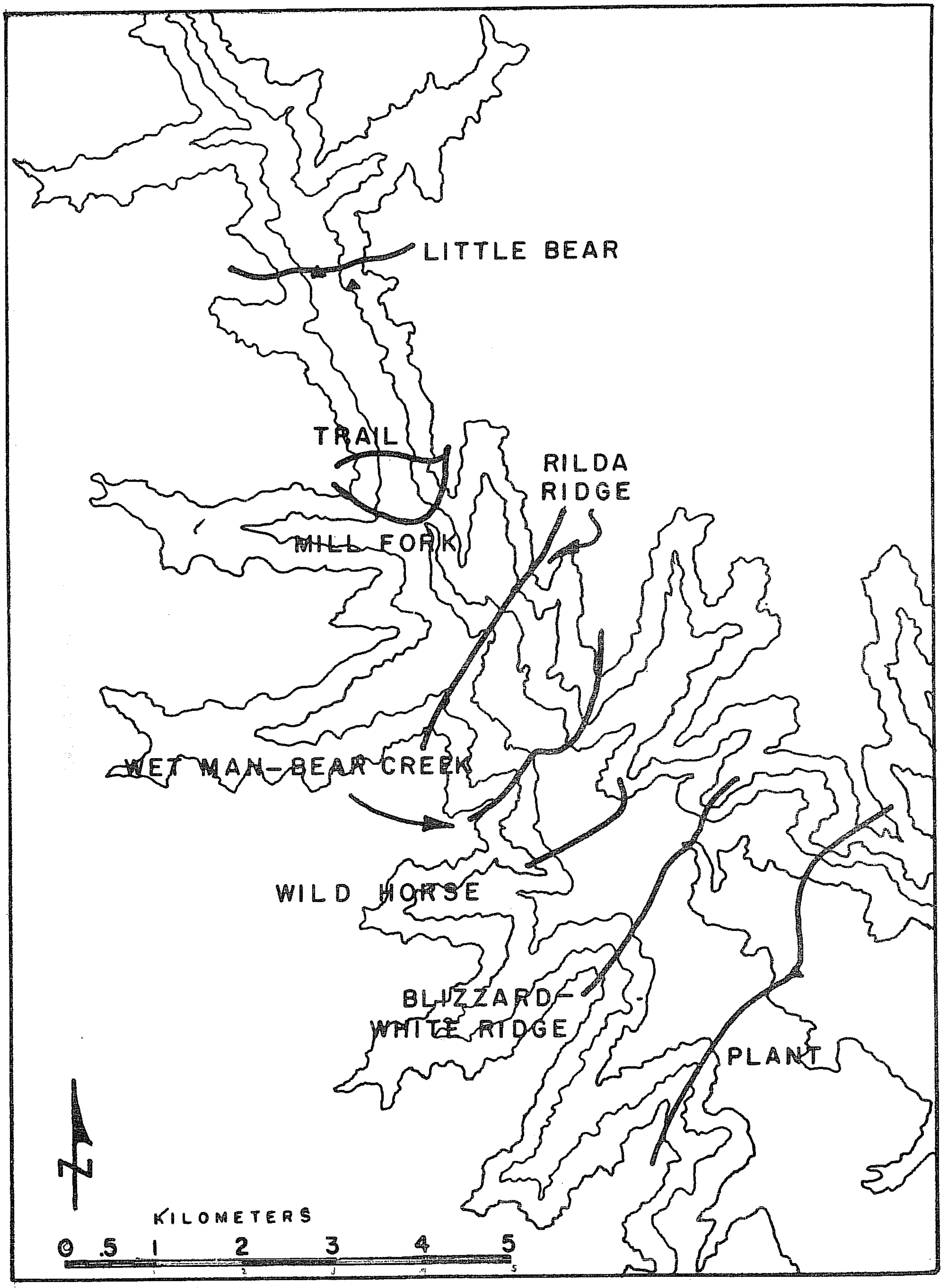

Figure 6. Locations of cross-canyon terrain profiles.

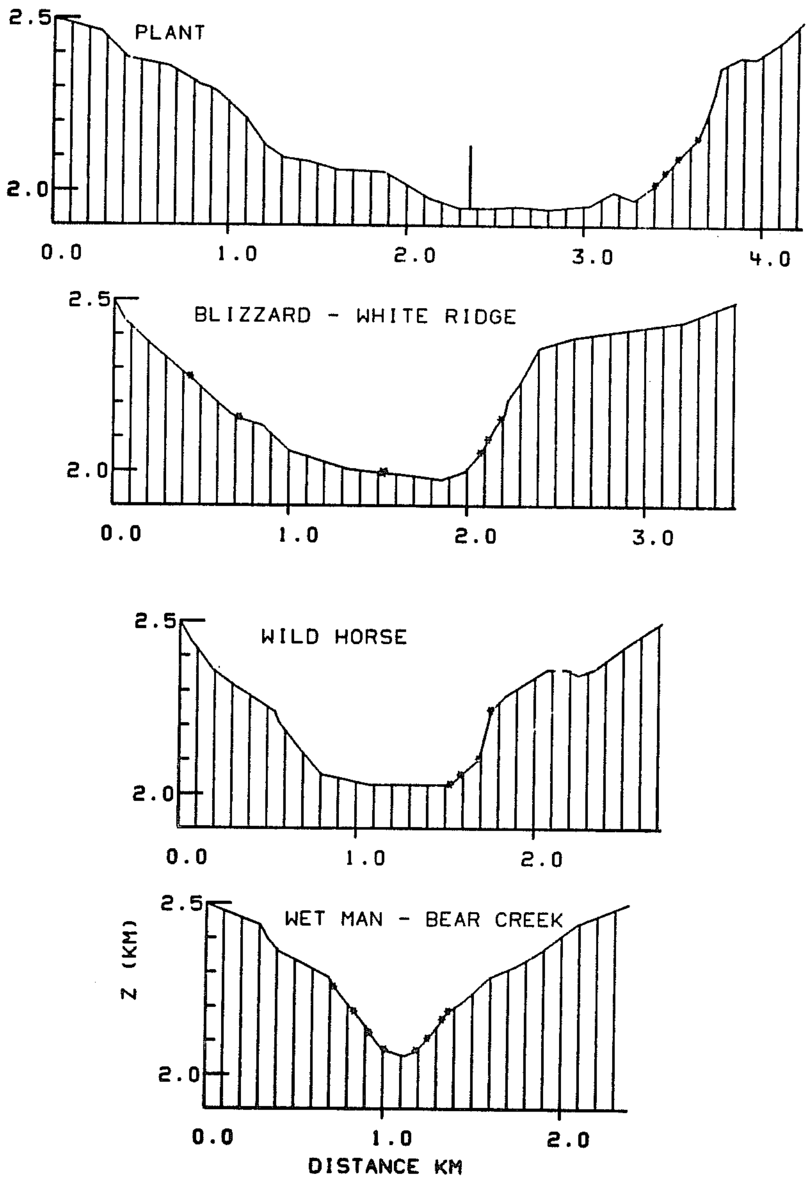

Figure 7. Cross-canyon arcs for stack tracer gas releases. These cross-sections have been ordered top-to-bottom with the release point at the top to provide successive downwind views from the release point. The vertical scale is twice the horizontal. Asterisks denote the height locations of the fixed sampler boxes.

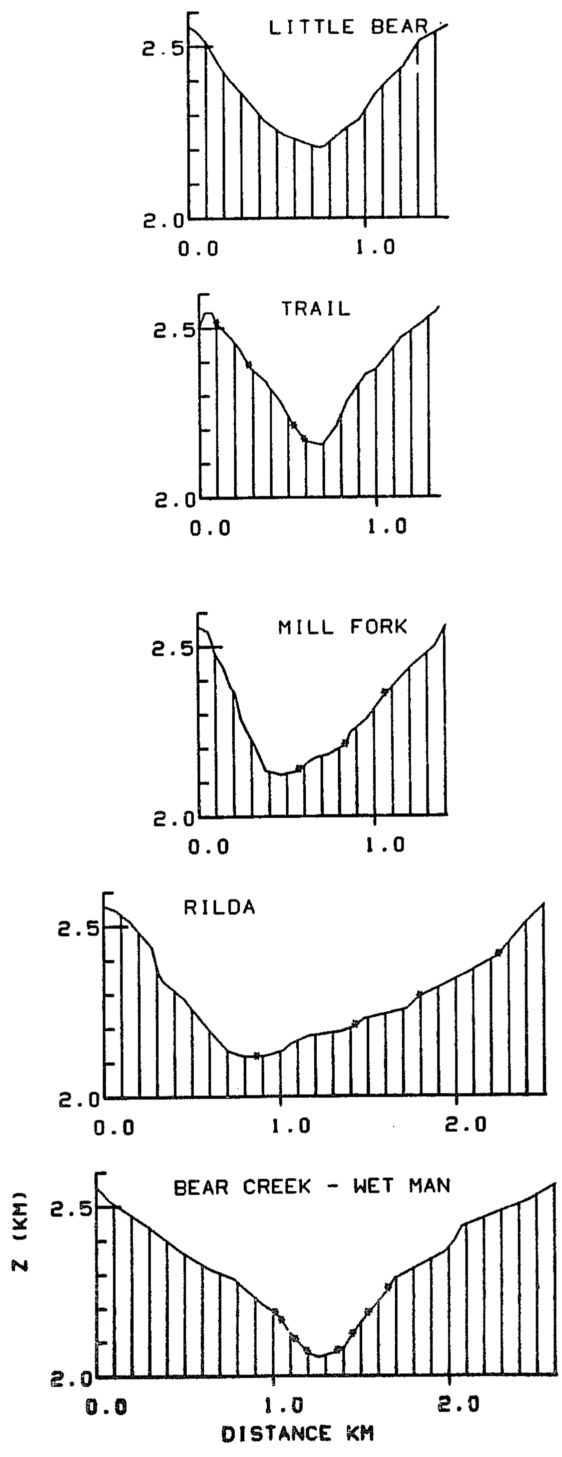

Figure 8. Cross-canyon arcs for Little Bear tracer gas releases. These cross-sections have been ordered top-to-bottom with the release point at the top to provide successive downwind views from the release point. The vertical scale is twice the horizontal.

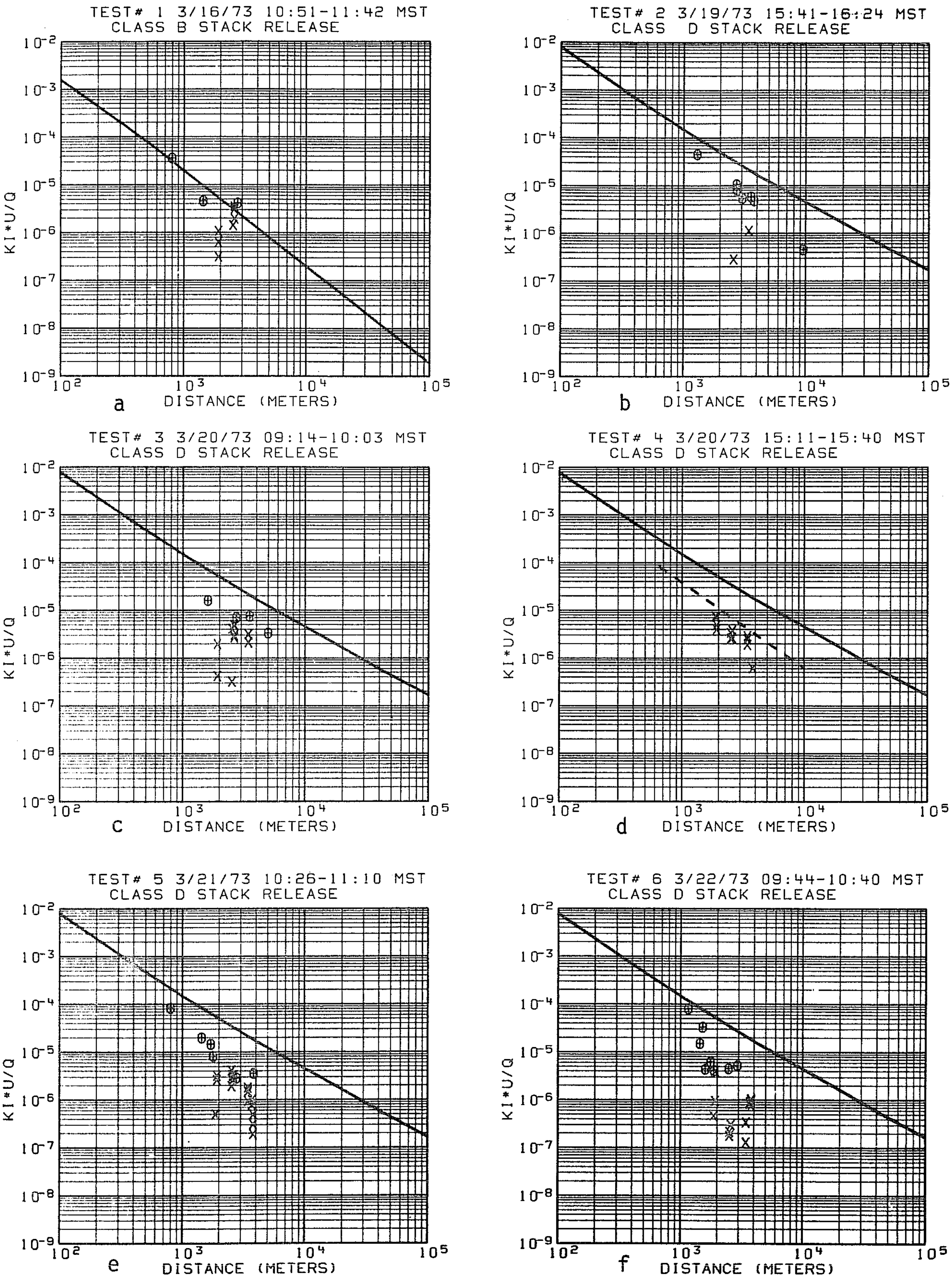

Figure 9. Results of SF_6 tracer gas sampling program for lapse and neutral stability categories (B and D). ⊕ - Aerial samples, x - Canyon wall and floor samples.

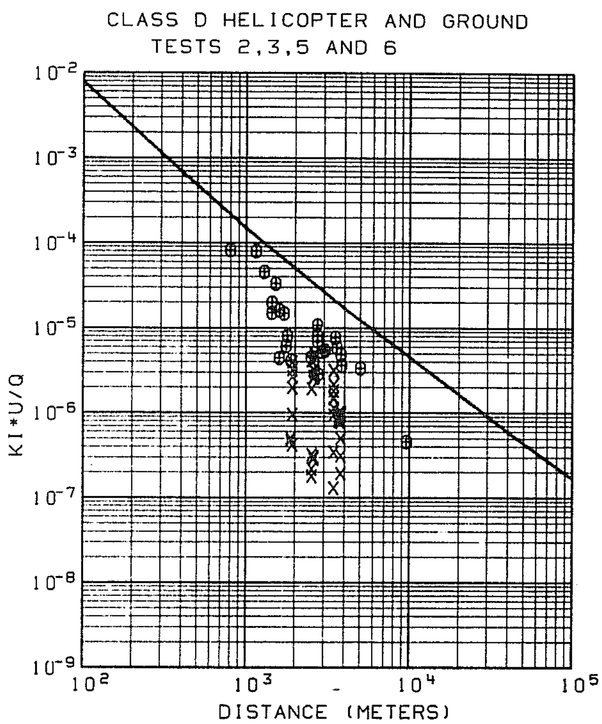

Figure 10a. Helicopter and ground samples. D stability; Tests 2, 3, 5, 6.

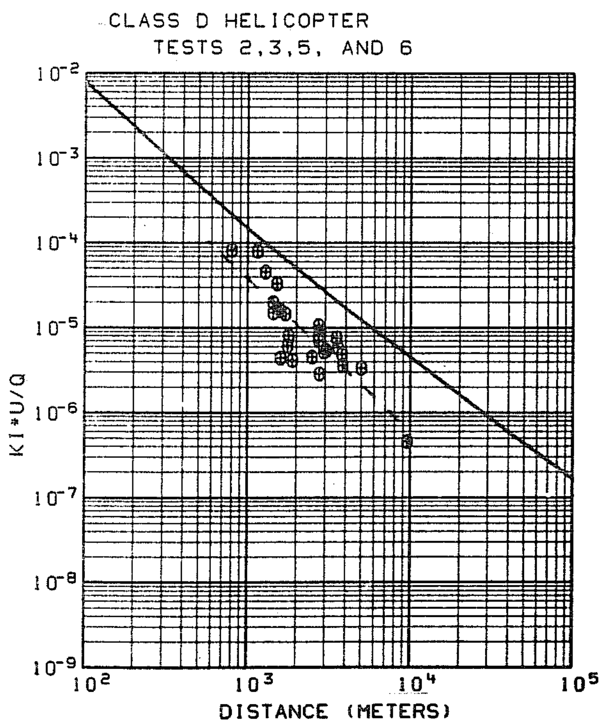

Figure 10b. Helicopter samples only. D stability; Tests 2, 3, 5, 6.

⊕ - Aerial samples

x - Canyon wall and floor samples

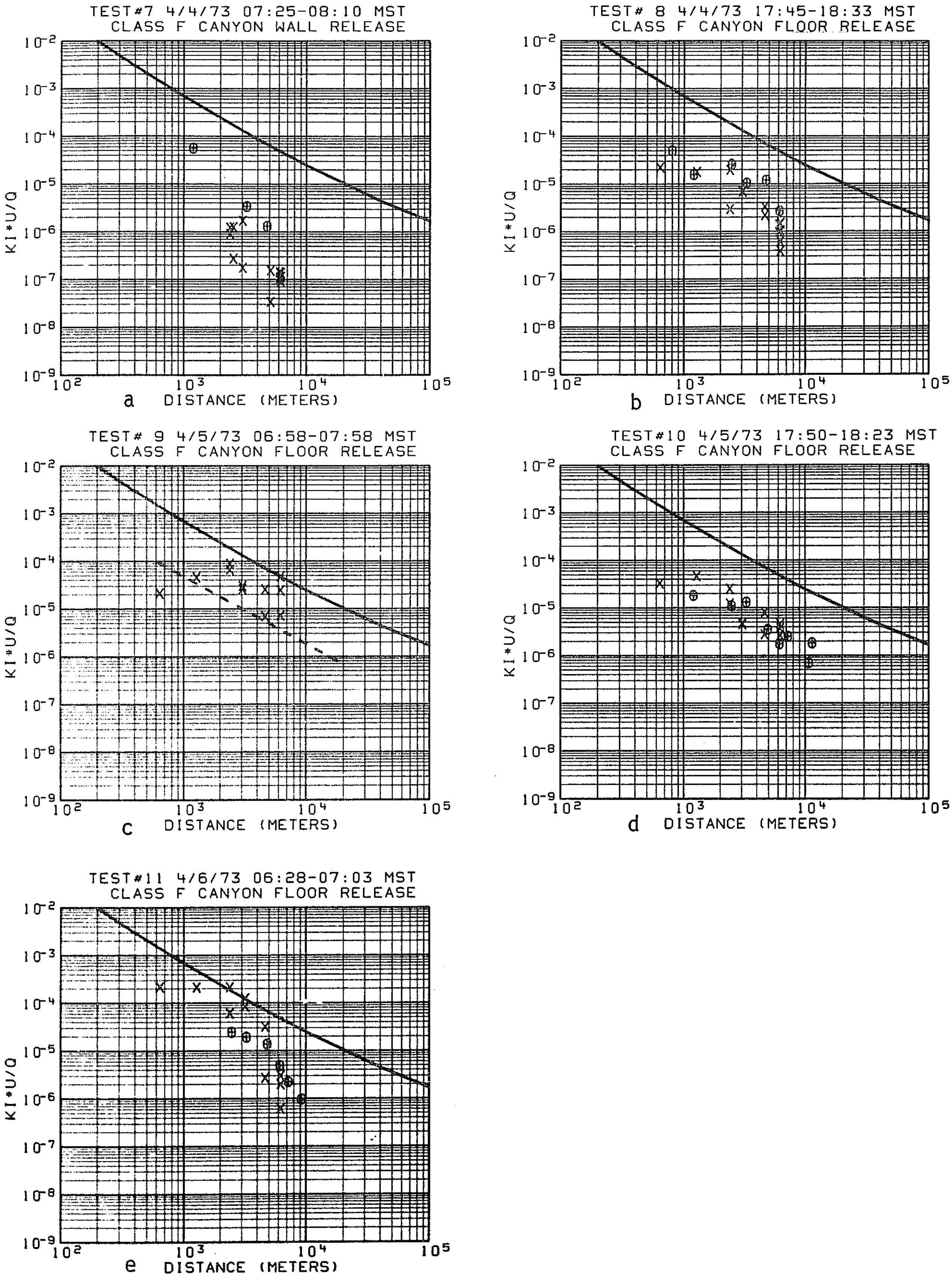

Figure 11. Results of SF_6 tracer gas sampling program for inversion conditions, (Stability category F). ⊕ - Aerial samples, x - Canyon wall and floor samples.

Figure 12. Oil fog plume being carried upward along the down-canyon shaded wall. (Test 7, 4/4/73, 0740 MST - 8400 ft looking North).

releases during lapse and neutral conditions. Second, the helicopter 1-min centerline concentrations and the 1-hr canyon wall and floor concentrations were more nearly equal, as opposed to results from tests 1 through 6.

Some test 11 canyon wall and floor data (figure 11-e) at first seemed to be contradictory because values exceeded the class F flat terrain curve. Upon closer examination there was no discrepancy. According to other estimation schemes (Yanskey, op.cit.) much if not all of each stable test case fell into a "G" category. Tests 7-11 were denoted class F in table 2 since the Pasquill classifications in table 1 ended with the class F category and a generally accepted curve for class G was not available. The test 11 concentration data at short travel distances approached values expected for a projected G stability curve (see Yanskey, op.cit., fig. 3-4).

The test 11 samples obtained at short distances using the helicopter were believed to be collected away from the plume axis; consequently they were expected to be less than the actual axial concentrations.* The first downwind sampling points along the canyon floor (640 and 1250 m) seemed consistently to provide concentrations more dilute than expected from an extrapolation back towards the source of a stright-line (subjective) fitting of data points at the longer distances. A minor S-like off-set of the canyon axis between the source and the first sampling point may

*There was a very practical reason. The helicopter could not be safely flown within the dense smoke close to the source. At those distances samples were of necessity collected near the upper plume boundary; a significant gradient of concentration must have still existed in the vertical during this particular case.

have produced a subtle but systematic effect on concentrations measured there. A similar off-set existed near 1250 m down-canyon.

Since the canyon wall and the plume "center" expected concentrations were nearly the same, it was concluded that a volumetric dilution process (i.e., turbulent mixing producing a nearly uniform concentration) occurred along the bottom of the canyon. Were no other information available, this conclusion would be only hypothesis. Oil fog visualizations and photography during these same SF_6 tests clearly showed this process. Figure 13 was reproduced from one of the aerial photographs of oil fog dispersion to illustrate this volumetric spread of effluent within the lower canyon. Other diluting mechanisms were operative as well. These mechanisms will be disucssed in a later portion of the text.

A plot of the relative concentrations from test 9 (fixed samplers in the canyon only) is given in figure 11-c. Test 9 was an early morning release, similar to test 11; the canyon bottom concentrations tended to be slightly greater for the early morning releases than for evening releases. The two test 9 samples collected nearest the source again showed enhanced dilution compared to more distant values. Figure 14 shows a composite of the tracer samples for tests 8, 10, and 11, all of which were released from the canyon floor under inversion conditions. Figure 14-a shows the combined helicopter and ground samples while figure 14-b shows the helicopter samples alone.

The results of measured plume center concentrations versus expected centerline concentrations over flat terrain during similar meteorological conditions are summarized in table 4. The test-by-test comparisons have

Figure 13. Oil fog visualization of volumetric dilution of airborne effluent within the lower part of Huntington Canyon during evening inversion conditions. (Test 10, 4/5/73, 1836 MST - 7400 ft.)

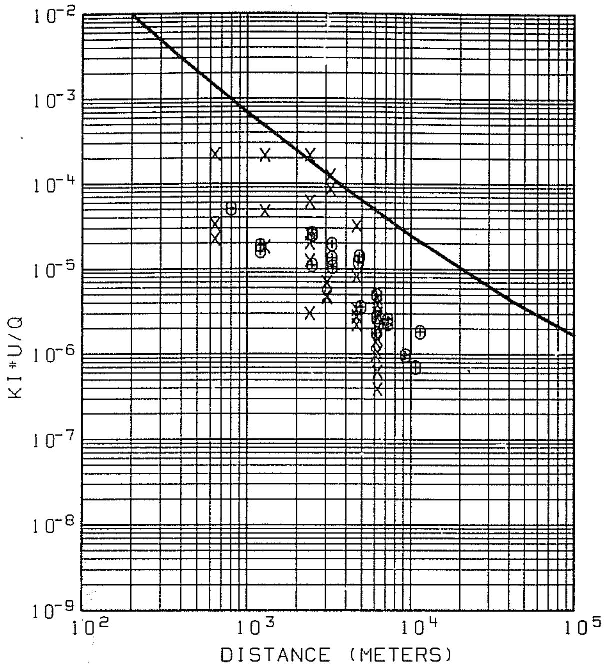

Figure 14a. Helicopter and ground samples. F stability; Tests 8, 10, 11.

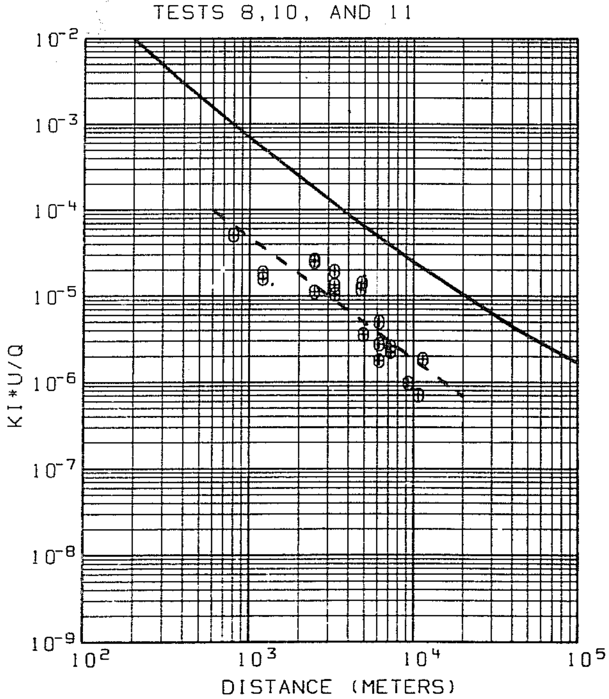

Figure 14b. Helicopter samples only. F stability; Tests 8, 10, 11.

⊕ - Aerial samples

x - Canyon wall and floor samples

been listed in the upper part of the table. Perhaps of most significance is the summary by stability categories at the bottom. Only little difference was apparent for the lapse conditions. During neutral stabilities the average expected to observed canyon plume center concentration ratio was 5. For class F conditions the ratio was about 15. Test 7 resulted in even greater dilution than canyon floor releases when compared to expected flatland plume center concentrations. However, since test 7 was a single test performed under unique conditions, it is probably advisable to place little emphasis on its results; SF_6 helicopter samples from this test may not have been suitably within the plume. Therefore a value of 15 for canyon bottom releases is probably most appropriate until more data are collected.

B. Plume Impaction on Elevated Terrain

The second major item investigated was the question of plume impaction on elevated terrain. Unquestionably, the plume impacted against the terrain, but the concept of impaction must be applied with certain qualifications.

1. A coherent, narrow or filament-like plume axis is improbable within the transporting winds of a steep-walled, deep canyon such as Huntington Canyon.

2. Plume segments from elevated sources dispersed laterally (somewhat like a horizontal analogy to looping) and when they approached elevated terrain could be expected to produce transient effluent concentration levels for a few minutes which approached centerline concentration levels. For longer time averagings (approximately an hour) the canyon wall and floor samples averaged at least 1½ to 3 times more dilute than 1-min centerline concentrations. This range of values agreed well with peak-to-average air concentration findings of many researchers (Slade, 1968).

3. During the uniform mixing within the lower confines of the canyon under inversion conditions, there was little difference between

peak-to-average (1-min centerline to 1-hr samples) concentrations. However, the ratio of expected flat-terrain to observed concentrations were larger in these stable cases than in the unstable and neutral stack releases.

Figure 13 illustrates volumetric dilution and its type of terrain impaction. An example of transient impaction of plume segments from the 183-m stack has been shown in figure 15. Many occurrences of this behavior were observed and photographed.

C. Mechanisms for Enhanced Canyon Dilution

The application of simple mountain meteorological concepts to the estimation of diffusion in mountainous terrain should be done only with great care. It appeared in this study (Huntington Canyon) that canyon winds seldom behave like air flows described by simple models of density air flow. Instead, the air was in a highly disrupted turbulent state--a state in which air flows may have really averaged to be as described in simple mountain-valley circulations, but with an enhanced turbulent state.

Mechanical turbulence generated by the rough terrain of the mountain-canyon environment, and not evident over flat terrain in similar stability conditions, is believed to be the mechanism producing enhanced dilution of airborne effluents within Huntington Canyon. Three physical mechanisms are offered as the instigators of enhanced mechanical turbulence. First, the mountain tops are visualized as a very rough surface around which considerable turbulence is generated, some of which penetrates downward into the canyons. A schematic illustration of this effect is given in figure 16 where the downward transport of momentum is related to the cross-canyon flow component. Figure 12 shows a plume released from an elevated point along the canyon wall and illustrates how it would be expected to develop while slowly moving down-canyon within the total air flow.

The second postulated process is illustrated in figure 17. Downslope density flows can be visualized to proceed from the bottom of a side or feeder canyon out into the main canyon. Where the main canyon is moderately narrow, the flow from the feeder canyon could rise up the opposite slope due to a momentum type of overshoot. This flow, when coupled with downslope density flows along the walls of the main canyon, could be envisioned as generating pulses of helical-like circulations. The frequency and time persistence of such circulations were not measured. However, this effect was expected to be more clearly observed during strong temperature inversions and with minimal downward momentum transport from the mountain tops, i.e., when other effects were less likely to mask it. Oil fog visualizations showed effects of this type; field observers noted them in their observation logs. Figure 18 shows this type circulation. The camera point was 2.4 km downcanyon from the surface release point. The elevated filaments of oil fog can be seen extending part way across the canyon while the bulk of the plume is near the canyon wall on the right-hand side of figure 18. At times, small portions of the plume were dashed against the canyon where they were shattered into smaller fragments. Figures 19-a and 19-b show a two-part sequence in which a wave-like mass of oil-fog filled air is forced against the canyon wall and disperses in a manner akin to an ocean wave breaking against a shoreline cliff. This particular sequence covered a minute time span. Other slides later showed a continued dispersion of the wave remnants.

Table 4. Calculated vs observed plume center concentrations.

Test #	Date	Time Begin	Time End	Stability	$(m\ sec^{-1})$**	Mean Ratio*
1	3/16/73	1051	1142	B	4.3	1.4
2	3/19/73	1541	1624	D	4.5	4.4
3	3/20/73	0914	1003	D	2.4	3.7
5	3/21/73	1026	1110	D	5.3	5.6
6	3/22/73	0944	1040	D	3.8	7.5
7	4/4/73	0725	0810	F	2.9	29.3
8	4/4/73	1745	1833	F	1.8	14.8
10	4/5/73	1750	1823	F	3.2	18.9
11	4/6/73	0628	0703	F	3.0	11.8

Summary of Stability Categories

Class	Ratio	
B	1.4	
D	5.3	
F	18.7	All cases
	29.3	Elevated case (Test #7)
	15.2	Canyon bottom cases

* The Mean Ratio is $\chi_T/\chi_{observed}$ where χ_T is the expected value of χ calculated according to Turner (1969).

** Speeds calculated from observations of movements of oil fog plumes at several downwind locations.

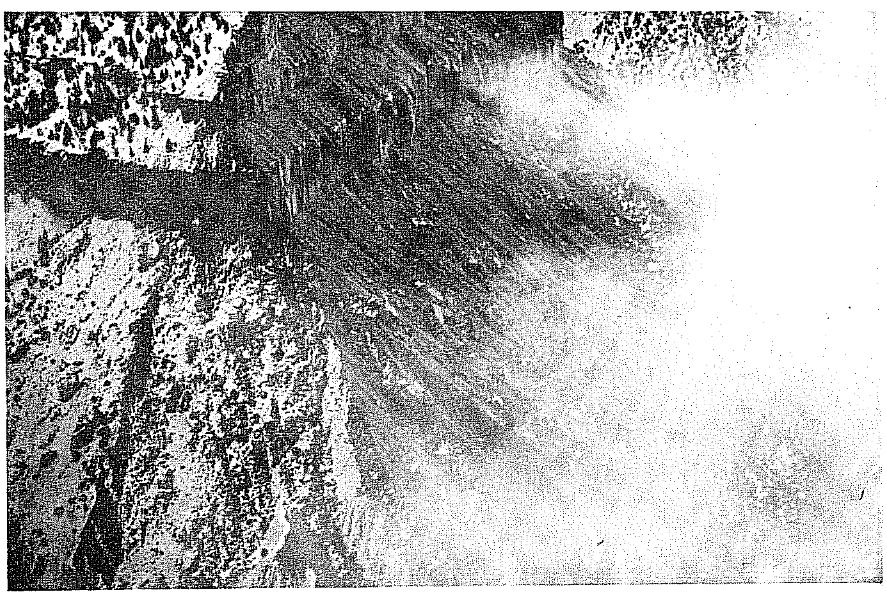

Figure 15. Plume segment impaction upon elevated terrain during lapse conditions. Source - top of 183-m smokestack. (3/1/73 - 0950 MST - 8700 ft.)

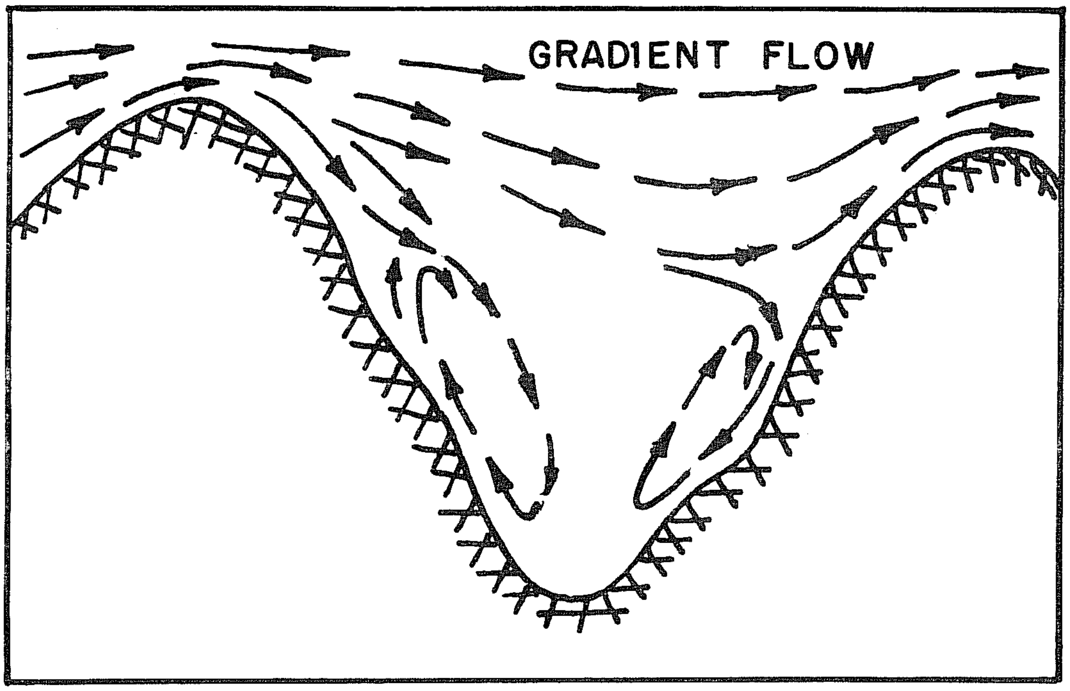

Figure 16. Schematic illustration of mountain top influences upon the gradient level flow component and the downward transporting of gradient flow momentum.

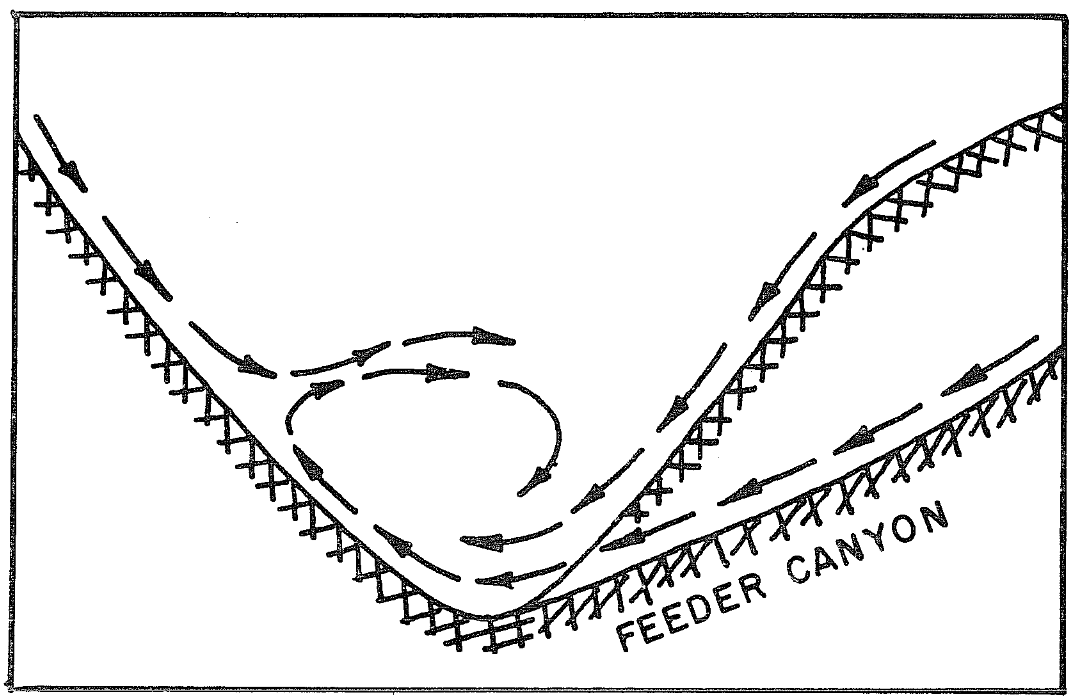

Figure 17. Schematic illustration of circulations triggered by slope density flows and air drainage from a side feeder canyon.

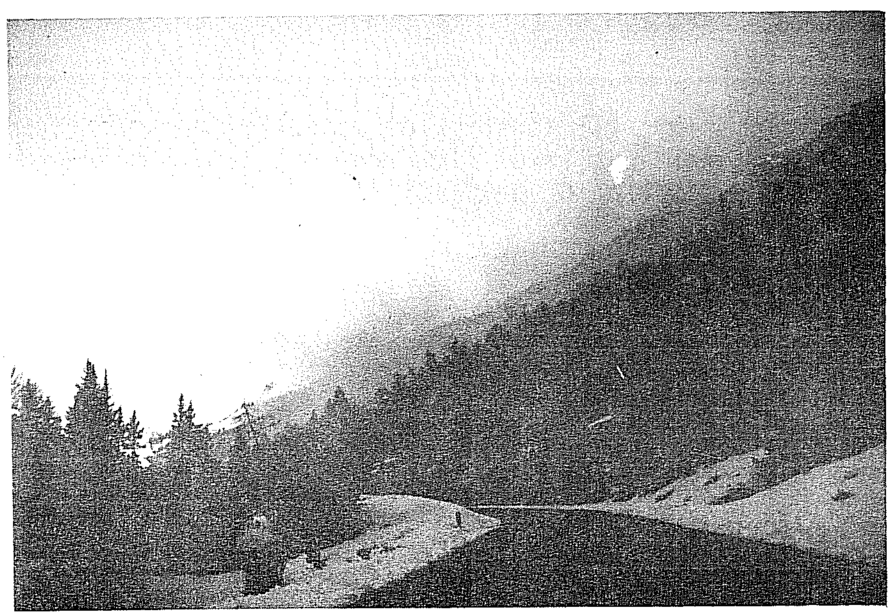

Figure 18. Oil-fog visualization of lower canyon helical-like circulations. (4/5/73, 0712 MST - from canyon floor 2.4 km down-canyon from the release.)

Figure 19a. Wave-like mass of oil-fog filled air forming on plume from a canyon bottom release. (Test 11, 4/6/73, 0637 MST - 7700 ft.)

Figure 19b. Shattered remnants of earlier wave after being dashed against canyon wall. (Test 11, 4/6/73, 0638 MST - 7700 ft.)

The third process contributing to enhanced dilutions is a type of wake turbulence. The wake turbulence is the smallest scale process of the three postulated mechanisms. As air flows within the canyon it must of necessity flow over and around protruding cliffs and abutments, and partially across indentations and shallow, steep-floored draws up the side walls of the main canyon. The concept of flow around a canyon-wall obstacle and the turbulent wake effects are schematically shown in figure 20. The wake region extends downwind from the obstacle and contains a region of reduced wind speed and enhanced turbulence often termed a cavity. If down-slope density flows were dominant (i.e., slope cooling effect), little oil fog might be expected within these draws; they perhaps would be zones of clean air which were draining down from heights above the oil fog plume. Quite the opposite was observed. Figure 21 is a typical photograph showing filaments or fingers of oil fog extending up the canyon walls, particularly within the shallow, steep draws where they were least expected. Some of the classical concepts of valley or canyon slope density flows need additional investigations; observations in Huntington Canyon have suggested that there may be some important exceptions to the simple models.

Investigations by Davidson (1963) and wind tunnel modeling by Halitsky, Magoney, and Halpern (1965) described wake turbulence effects and wind variabilities in the lee of mountain ridges. While the terrain for their investigations was less rugged than the Wasatch Plateau/Huntington Canyon setting, they found similar enhanced turbulence and wind variabilities corresponding to the mountain top turbulence and wake effects presented in this paper.

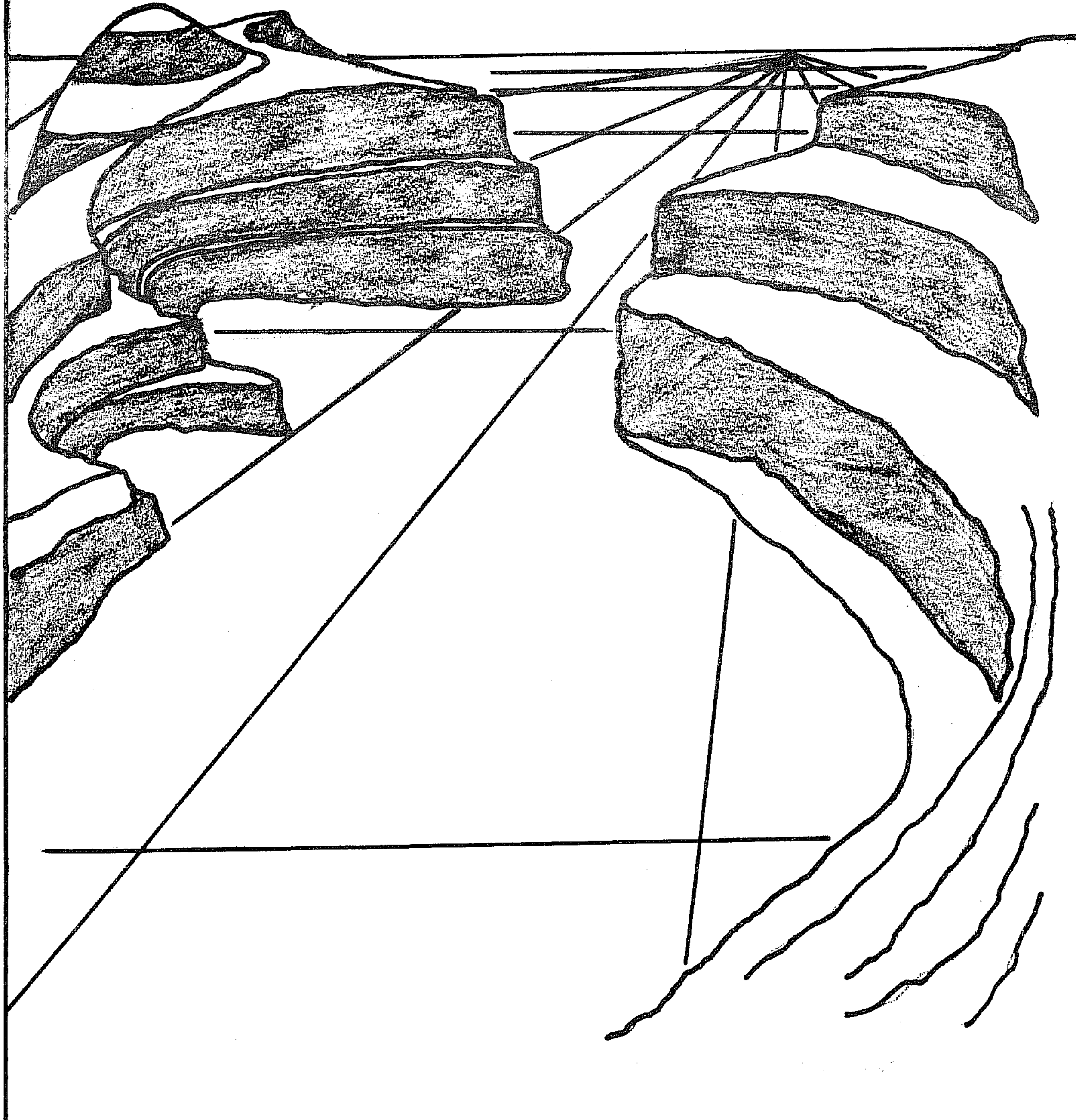

Figure 20a. Schematic view of the type of terrain capable of affecting the wake turbulence illustrated in figure 20b. This same terrain is depicted in figure 20b with arrows added to show the type of secondary air flow caused by such protrusions into the primary flow of the canyon.

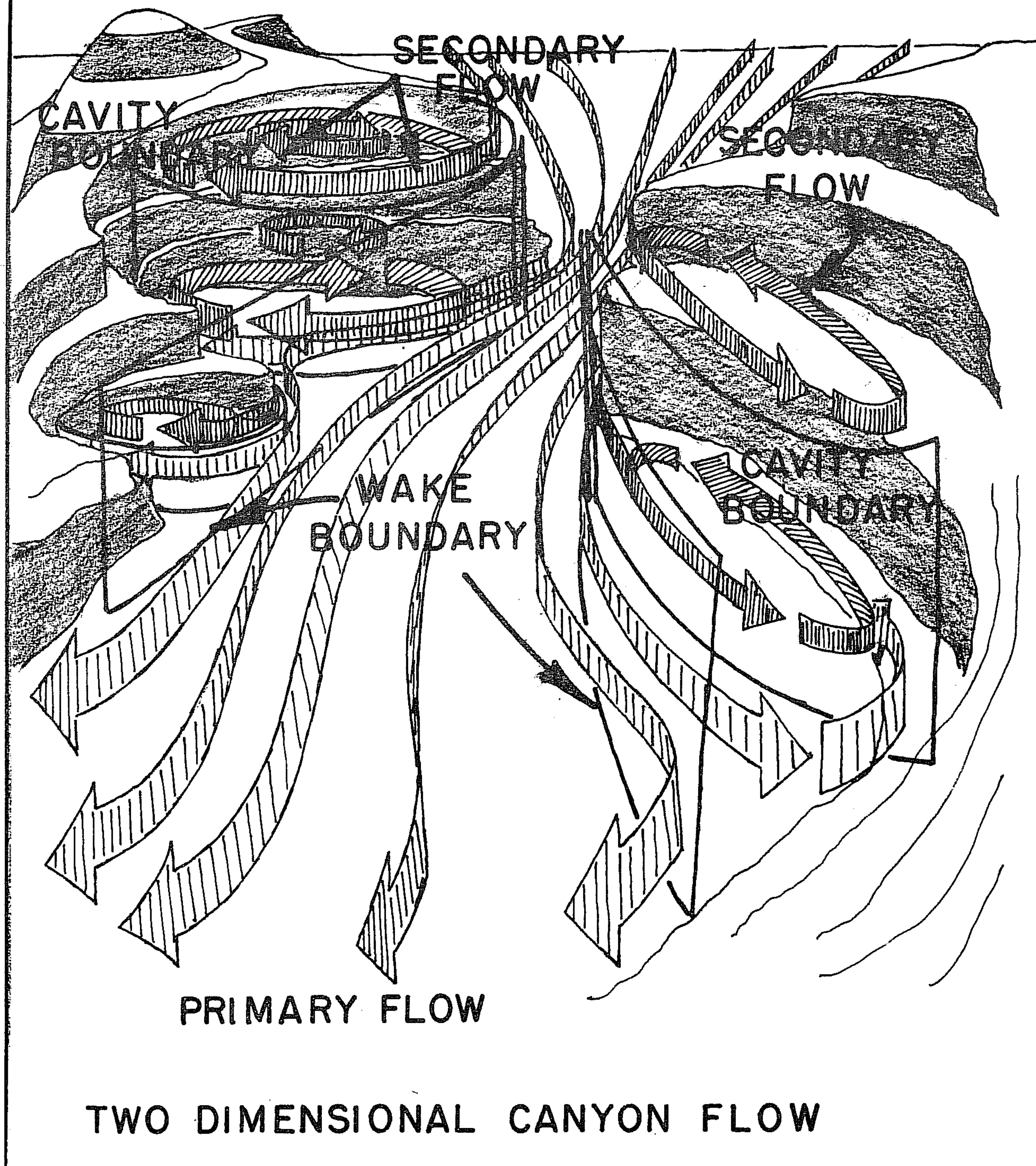

Figure 20b. Schematic illustration of turbulent wake effects caused by obstacles protruding into the primary flow pattern.

Figure 21. Plume filaments drawn up on the canyon side walls within shallow, steep-floored draws. (4/11/73, 0654 MST - 7540 ft.)

IV. Summary and Conclusions

The results of this study apply, strictly speaking, to Huntington Canyon. They should be applicable to similar deep, steep-walled canyons. Intuitively, diffusion within regions of less rugged terrain should occur at rates bounded by rates for flat, open terrain and the findings for Huntington Canyon.

The rates of dilution of airborne gases are different within a deep, steep-walled canyon from rates of diffusion over flat, open terrain under similar stability conditions. The differences vary with changes in the well-known Pasquill stability categories. During moderate to strong temperature lapse the difference is minimal. During neutral stabilities canyon dilutions are about 5 times greater than for "standard" flat-terrain curves; during strong inversions stabilities gases average 15 times more dilute than calculated from the standard curves.

These more dilute concentrations impact frequently against elevated terrain. During lapse conditions transient impactions (a few minutes) may occur at any given point. The longer term (approximately one hour) total integrated concentrations collected at fixed locations on the canyon walls and floor averaged 1½ to 3 times more dilute than concentrations expected from one minute aerial plume centerline samples. These lower concentration ratios are consistent with time variations of peak-to-average concentrations reported by other researchers.

Enhanced mechanical turbulence is believed to be the phenomenon producing greater effluent dilution within Huntington Canyon. Three factors are suggested as the plausible sources of this enhanced mechanical turbulence. They are turbulence generated near the mountain tops and the upper confines of the canyon, airflows originating within side canyons, and wake effects of airflows over and around canyon topographic variations.

No sampling was done under extreme stagnation conditions--none was intended during such periods. Instead, testing was done during typical canyon conditions and these findings were compared to what would customarily be calculated. Such a result would point up what systematic differences may occur between the two.

Stagnation on the synoptic scale is not expected to be the worst condition for canyon diffusion since strong diurnal wind cycles would develop. The worst situation at Huntington Canyon may be synoptic blocking of one half of the diurnal cycle; but even then, gradient winds would probably affect the type of momentum transfer illustrated in figure 16, inducing mechanical turbulence and dilution of the effluent within the canyon.

Before proper modeling adaptations may be applied over a broad range of topographic and meteorological situations additional investigations should be conducted using intermediate topographic settings. A more comprehensive meteorological measurement program is recommended along with a continuation of single or multiple gaseous tracer measurements, oil fog visualizations, and balloon trajectory studies. While generalizing changes in rates of diffusion with changes in topography, the relative contributions of synoptic or gradient flows near the mountain tops, the feeder canyons, and within-canyon wake-producing topographic variations should be resolved.

Enhanced mechanical turbulence associated with gradient windflows near the mountain tops, density flows originating in side canyons, and turbulent wakes from pronounced terrain irregularities within the canyon are believed to be some of the additional physical mechanisms affecting plume dilutions in Huntington Canyon.

The present results should be relevant, at least qualitatively, to similar deep, steep-walled canyons. They should not be applied indiscriminantly to sites with less extreme topography. Additional measurements are needed at sites in less rugged terrain.

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