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DEVELOPMENT OF VERTICAL DISPERSION COEFFICIENTS FOR DEEP-VALLEY TERRAIN

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1.0 EXECUTIVE SUMMARY

It is ERDA's objective to determine reliable dispersion coefficients for use with the Gaussian plume model, that will represent a broader range of topographic conditions than was intended for the standard Pasquill-Gifford σ_Z values. The U. S. Army has sponsored research with similar objectives, but most of the data generated has had little visibility beyond the Department of Defense. During the first phase of this ERDA project, release of these data was arranged, and in the second phase of work, data from Army tracer-diffusion tests were used to develop coefficients for dispersion in rural, rolling terrain. During Phase 3, dispersion coefficients for a shoreline environment and for deep-valley terrain have been developed. This report concerns the Phase 3 work directed toward development of dispersion coefficients for deep-valley terrain. The Phase 3 work regarding dispersion at coastal locations has been summarized in a separate report.

Total-vertical-dispersion coefficients (σ_{ZT}) for deep-valley terrain have been developed during this study from direct measurements of vertical dispersion made by the Norwegian Defense Research Establishment (NDRE) between 1965 and 1968, in three deep valleys, and one fjord located in northern Norway.

The σ_{ZT} values developed here represent mean values within ΔT stability classes and apply to continuously-emitting sources located at ground-level. The deep-valley σ_{ZT} values fall within a narrow band when compared with the Pasquill-Gifford σ_Z values; the Pasquill-Gifford dispersion rates for class A (extremely unstable) and class G (extremely stable) conditions are not observed in the mean in deep-valley terrain.

The deep-valley σ_{ZT} values reported here are similar in magnitude to σ_{ZT} values developed earlier in this ERDA project for rural, rolling terrain and for a shoreline environment. The implication is that the vertical dispersion rate in a deep valley is similar to the vertical dispersion rate found at non-valley locations having similar surface topography.

While this may be true for vertical dispersion, it would not be expected to hold in the case of horizontal dispersion within a deep valley. This is because the "walls" of a valley act, to some degree, as physical barriers to horizontal dispersion. It is recommended, therefore, that subsequent dispersion studies in deep-valley terrain be directed towards better quantification of the effects of the valley walls on the horizontal dispersion rate.

2.0 INTRODUCTION

The work reported here was carried out during the third phase of an atmospheric dispersion model validation project sponsored by the Energy Research and Development Administration (ERDA). It is ERDA's intent to determine dispersion coefficients (σ_y, σ_z) that will broaden the applicability of the Gaussian plume model. Dispersion coefficients have been developed in this study that will represent a broader range of atmospheric/topographic conditions that was intended by the standard Pasquill-Gifford[1,2] coefficients.

This ERDA project has employed test data previously generated by the NDRE with assistance from the U. S. Army Dugway Proving Ground, Utah. During Phase I[3] of the project, release of these data was arranged, and the data were catalogued for subsequent application toward ERDA objectives. During Phase 2[4], a selected portion of the Army tracer-test data was used to derive vertical dispersion coefficients characteristic of rural, rolling terrain.

The purpose of this third phase of the ERDA project has been to utilize other selected portions of the test data to develop two sets of vertical dispersion coefficients--one set representative of deep-valley terrain and the other representing the coastal environment. This report describes Phase 3 work directed toward the development of dispersion coefficients for deep-valley terrain. The Phase 3 work concerning development of dispersion coefficients for a coastal location has been reported separately.[5]

The test data utilized in the analysis reported here had been generated during an experimental test series conducted in deep-valley terrain in Norway by the Norwegian Defense Research Establishment (NDRE),[6] with assistance from the U. S. Army Dugway Proving Ground, Utah. The data resulting from the NDRE experiments are comprised of tracer-dispersion and meteorological measurements. This ERDA study has utilized data from 51 of the field tests conducted during the NDRE test series. All 51 tests employed continuous, point-source releases of atmospheric tracer material.

3.0 OBJECTIVES

The first objective of this study has been to utilize the NDRE field-test data to develop coefficients of total vertical dispersion representative of deep-valley terrain. Use of these coefficients with the Gaussian plume model would allow greater reliability to be placed in estimates made of ground-level concentrations resulting from continuous, point-source emissions from the valley floor.

A second objective was to assess the extent to which the model validation goals of ERDA for deep-valley terrain could be fulfilled by this study and, in turn, to identify needs for additional field estimates.

4.0 APPROACH

Total-vertical-dispersion coefficients (σ_{ZT}) for deep-valley terrain have been determined from direct measurements of plume-height (ΔZ) made during the NDRE test series. The plume-heights reported[6] by the NDRE researchers were based on the standard definition of plume-height, i.e., that the upper plume-boundary is taken to be the height above ground at which the concentration (or dosage) is one-tenth of the maximum concentration (or dosage).

In this study, σ_{ZT} has been derived from the measured plume-heights (ΔZ) by assuming a Gaussian distribution of material within the plume, and using the relationship

$$\Delta Z = 2\sigma_{ZT}. \tag{1}$$

By definition, the plume-height represented by $2\sigma_{ZT}$ encompasses greater than 95 percent of the dispersing material.

The total-vertical-dispersion coefficients (σ_{ZT}) derived in this study apply to continuously-emitting (one-hour) sources located at ground-level. These coefficients fully represent the combined effects of diffusive-scale and meander-scale turbulence upon the vertical dispersion rate. Data required to calculate separately the diffusive and meander components of total vertical dispersion were not, however, available from the NDRE test series.

5.0 DATA SOURCE - NORWAY DEEP-VALLEY TESTS

5.1 General

Between 1964 and 1968, an extensive series of tracer-dispersion tests[6] was carried out in deep-valley terrain in Northern Norway by the Norwegian Defense Research Establishment (NDRE). The field work and subsequent analyses were subsidized by the U. S. Army Dugway Proving Ground, Utah. The objectives of the program were to study the dispersive characteristics of deep valleys as compared with dispersion over flat land, and to develop a valley dispersion model.

5.2 Test-Area Topography

The experiments were performed in three deep, U-shaped valleys: Kirkesdalen, Målselvdalen, and Finnfjorddalen; and in a fjord, Malselvfjorden. For brevity's sake, these four test sites are referred to hereafter as the K-valley, the M-valley, and the F-valley; and simply, the fjord.

The approximate dimensions of the three valleys and of the fjord are:

- Width at floor: 2-5 kilometers
- Width at ridgeline: 6-8 kilometers
- Depth: 500-1,000 meters

The surface of the three valleys consisted of alternating farm land and forest-stands. The floor of the fjord, being a water surface, was aerodynamically smooth.

5.3 Test Summary

Fifty-three field experiments were performed during four different seasons in the three valleys and the fjord. The number and dates of the experiments performed at each of the four sites are summarized in Table 5-1.

During each experiment, a tracer dispersion test was carried out using fluorescent particle (FP) tracer material. Many experiments included a second (simultaneous) test in which visible oil-fog was used as the tracer. In all cases, tracer material was released at ground-level from a mid-valley location, or from a boat at mid-fjord, and the tracer material was dispersed continuously for periods of from one to several hours. Relevant meteorological observations were made during each tracer dispersion test, including stability (ΔT) and wind measurements.

During the tests, dispersion was measured to distances between three and 13 kilometers downwind from the release. For vertical sampling of the FP tracer, rotorods were placed below captive balloons to a maximum height of 150 meters. FP tracer dosages above this height were obtained using instrumented aircraft. To measure the vertical dispersion of the visible oil-fog tracer, time-lapse photography was utilized in conjunction with designated targets on the valley walls.

Wind data were measured on 25-meter masts at two or more locations at each of the four test sites. In addition, ΔT (24-2 meters) measurements were made during every test.

TABLE 5-1

NDRE DEEP-VALLEY DISPERSION EXPERIMENTS

Test Site	Year	Season	No. of Experiments
K-valley	1965-66	All four	28
M-valley	1967	Spring, Fall	14
F-valley	1968	Summer	4
Fjord	1968	Summer	7
All sites			53

5.4 Data Base

In Table 5-2, a summary of the data base for this ERDA study is provided. Plume-height (ΔZ) measurements were available from 25 valley tests where oil-fog tracer was employed, and 19 tests were fluorescent particle (FP) tracer was utilized. Many of the oil-fog tests and the FP tests were run concurrently. Plume-height measurements were also made during seven FP tests conducted in the fjord.

As shown in Table 5-2, the measured plume-heights to be used in this study span the entire range of stability conditions. The NDRE researchers defined stability classes by the ΔT ranges shown in Table 5-3. The equivalent NRC ΔT classes[7] are also shown in the table.

TABLE 5-2

DATA BASE

Plume-Height (ΔZ) Measurements During
The NDRE Deep-Valley Tests

NDRE Stability Class	Number of Tests with ΔZ Measurements from:		
	Oil-Fog Tracer	FP Tracer	
	K-Valley	K, M, and F Valleys	Fjord
Unstable	7	0	0
Neutral	10	14	7
Stable	5	5	0
Very Stable	3		
Totals	25	19	7

TABLE 5-3

ATMOSPHERIC STABILITY

NDRE Deep-Valley Tests

NDRE Deep-Valley Tests		Equivalent NRC ΔT-Stability Class
ΔT(24-2m)°C	Stability Class	
ΔT< -0.2	Unstable	A, B, C, D
-0.2≤ΔT≤ 0.0	Neutral	D, E
0.0<ΔT≤ 2.0	Stable	E, F, G
ΔT> 2.0	Very Stable	G

6.0 ANALYSIS

6.1 General

Total-vertical-dispersion coefficients (σ_{ZT}) for deep-valley terrain have been determined by the method described in Section 4.0 from direct measurements of plume-height (ΔZ) made during the NDRE test series. With this method, values of σ_{ZT} are derived from the measured plume heights by assuming a Gaussian distribution of material within the plume, and using the relationship given by Equation (1).

6.2 Total Vertical Dispersion - σ_{ZT}

6.2.1 Valley σ_{ZT} - Oil Fog Tracer

In their summary report,[6] the NDRE researchers presented plume-height (ΔZ) measurements that they made in the K-Valley during 25 oil-fog tracer dispersion tests. These tests were conducted over a full range of stability conditions.

In Figure 6-1, individual plume-height observations reported by the NDRE researchers for unstable conditions are reproduced. A curve representing mean-observed plume-height versus distance has been fitted to the NDRE data, and appears as the bold line in Figure 6-1.

Observed plume-height data for oil-fog tracer releases made under neutral, stable, and very stable conditions are presented in Figures 6-2, 6-3, and 6-4, respectively. With unstable and neutral conditions, the range of observed ΔZ about the mean values appears to be considerable, at least a factor of two greater than the mean.

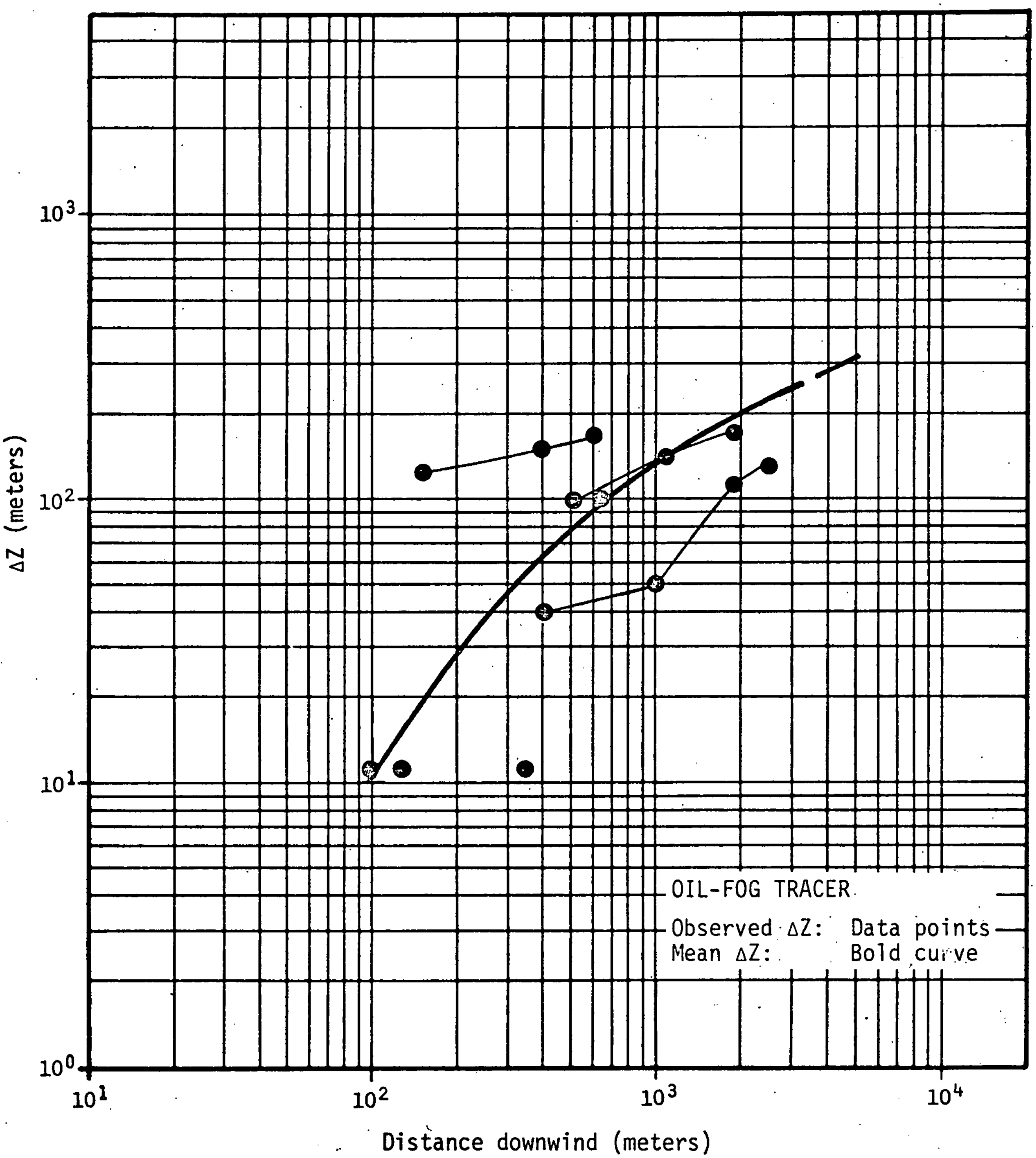

Figure 6-1: Observed and Mean-Observed Plume Height vs. Distance

Stability: Unstable
Test Site: K-Valley
Source: Continuous, ground-level release of oil-fog tracer

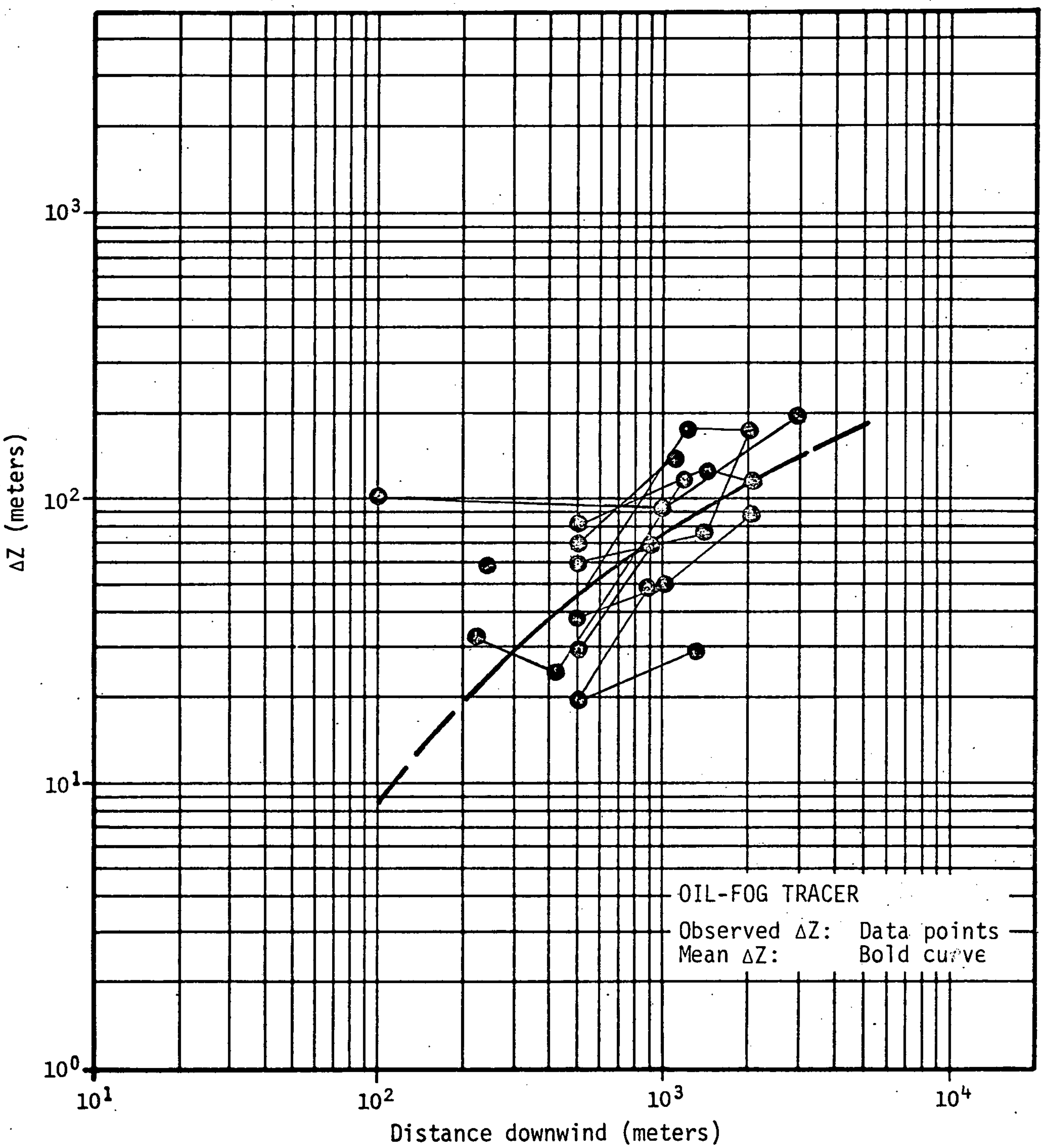

Figure 6-2: Observed and Mean-Observed Plume Height vs. Distance

Stability: Neutral
Test Site: K-Valley
Source: Continuous, ground-level release of oil-fog tracer

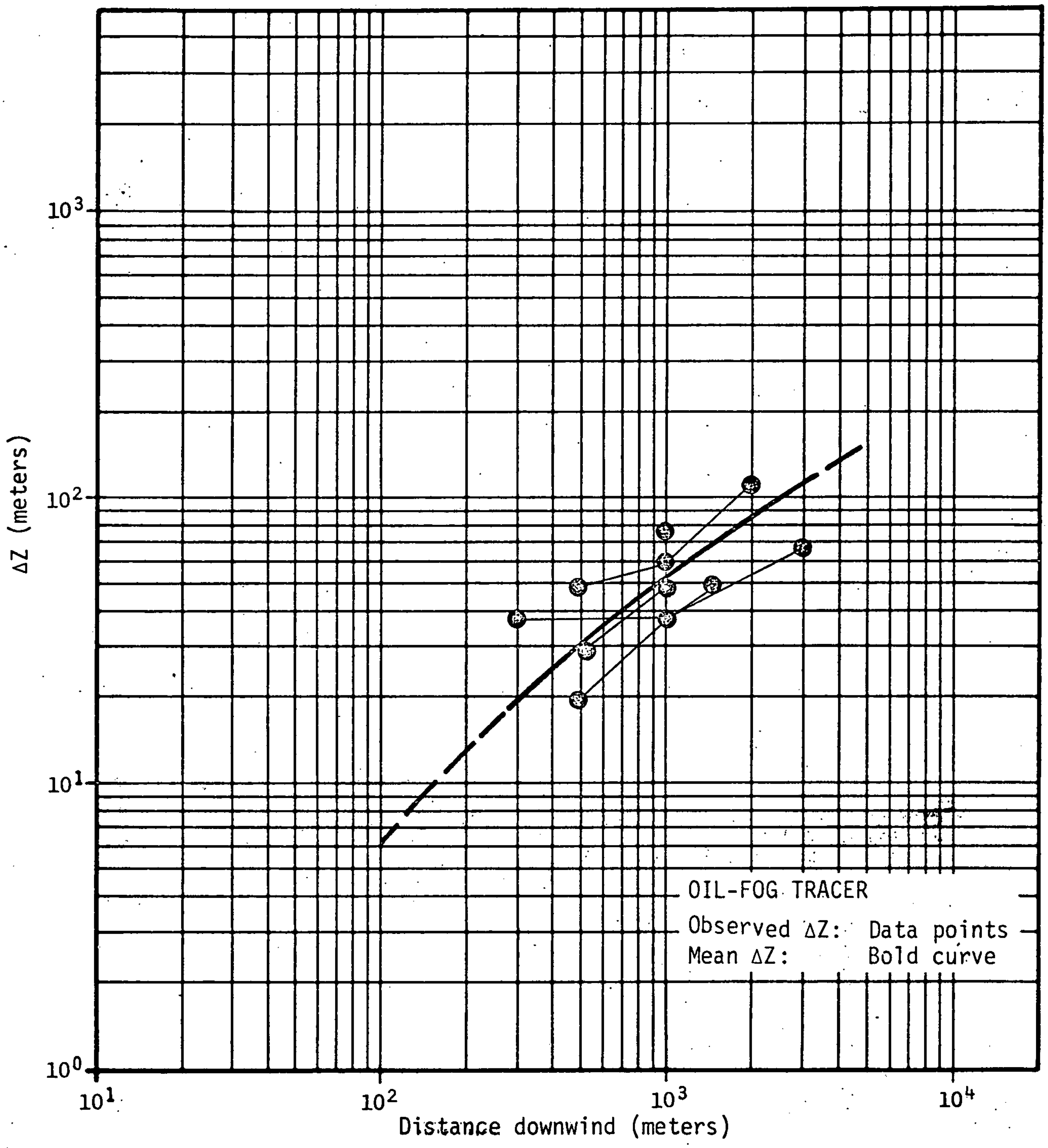

Figure 6-3: Observed and Mean-Observed Plume Height vs. Distance

Stability: Stable
Test Site: K-Valley
Source: Continuous, ground-level release of oil-fog tracer

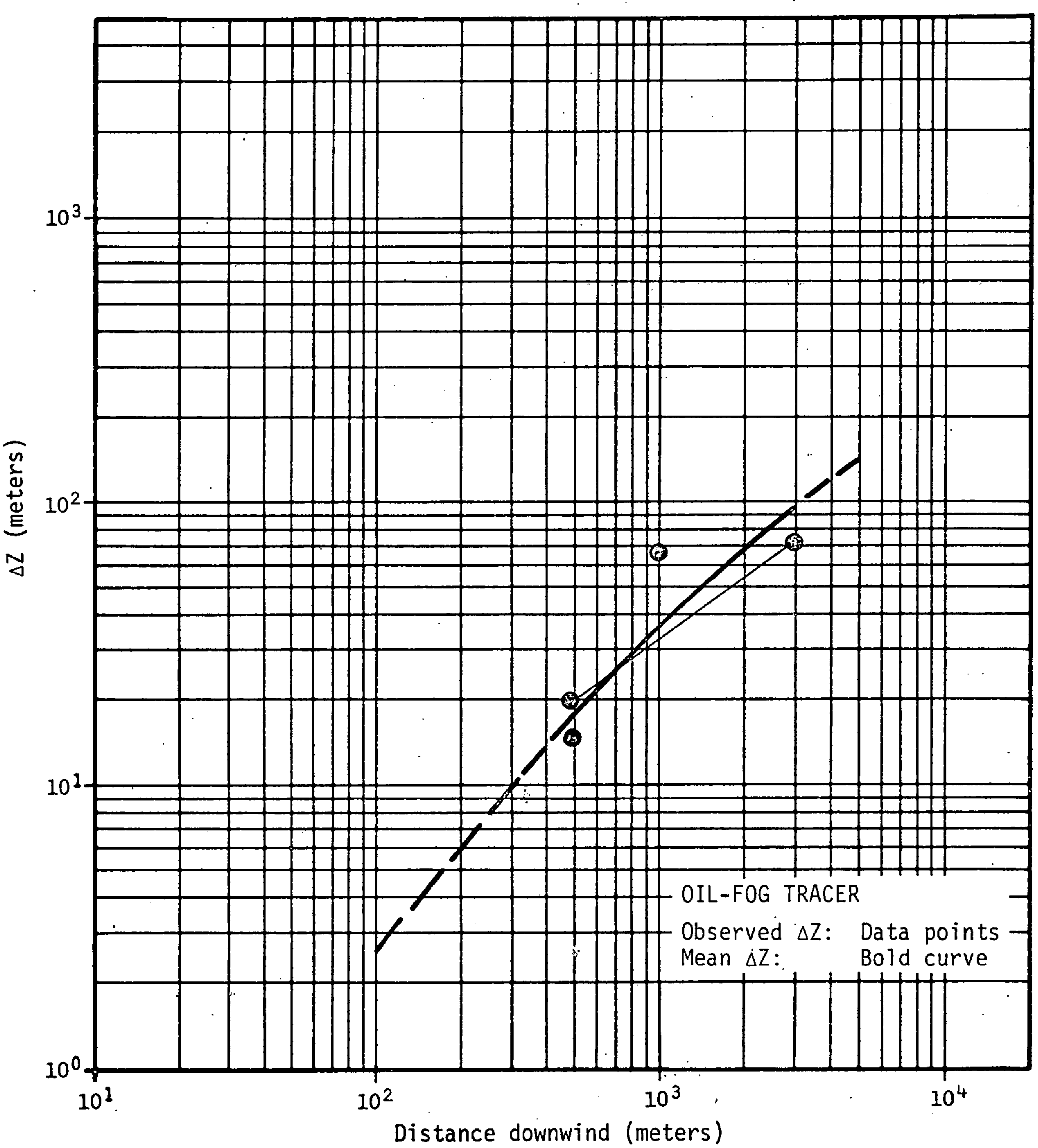

Figure 6-4: Observed and Mean-Observed Plume Height vs. Distance

Stability: <u>Very stable</u>
Test site: K-Valley
Source: Continuous, ground-level release of oil-fog tracer

In Figure 6-5, the mean-observed plume-heights from Figures 6-1 through 6-4 are compared. These mean curves comprise a narrow band and order in a consistent manner by ΔT stability class.

Mean values of the total-vertical-dispersion coefficient (σ_{ZT}) have been derived from the mean-observed ΔZ values presented in Figure 6-5 by using Equation (1). In Figure 6-6, curves representing mean σ_{ZT} versus downwind distance for the oil-fog tracer releases are presented. Like the mean ΔZ curves, the σ_{ZT} curves presented here fall within a narrow band, and stability-order in a logical manner.

6.2.2 Valley σ_{ZT} - FP Tracer

In their summary report,[6] the NDRE researchers also presented mean values of the plume-heights (ΔZ) they observed during 19 releases of FP tracer material in the K, M, and F-Valleys. The mean ΔZ values are shown as data points in Figure 6-7, to which curves representing mean-observed plume-height (ΔZ) versus distance have been fit. The curves presented here are essentially reproduced from the NDRE summary report, but with some minor adjustments in the curve-fitting. The mean-ΔZ curves for neutral and stable conditions have similar slopes, and stratify in expected order by ΔT stability class.

By using Equation (1), mean values of the total-vertical-dispersion coefficient (σ_{ZT}) have been derived from the mean-observed ΔZ values presented in Figure 6-7. Curves representing mean σ_{ZT} versus distance for the FP tracer releases are presented in Figure 6-8. The mean σ_{ZT} curves have an approximate one-to-two slope beyond one kilometer downwind, in agreement with dispersion theory; and the curves order logically by ΔT stability class.

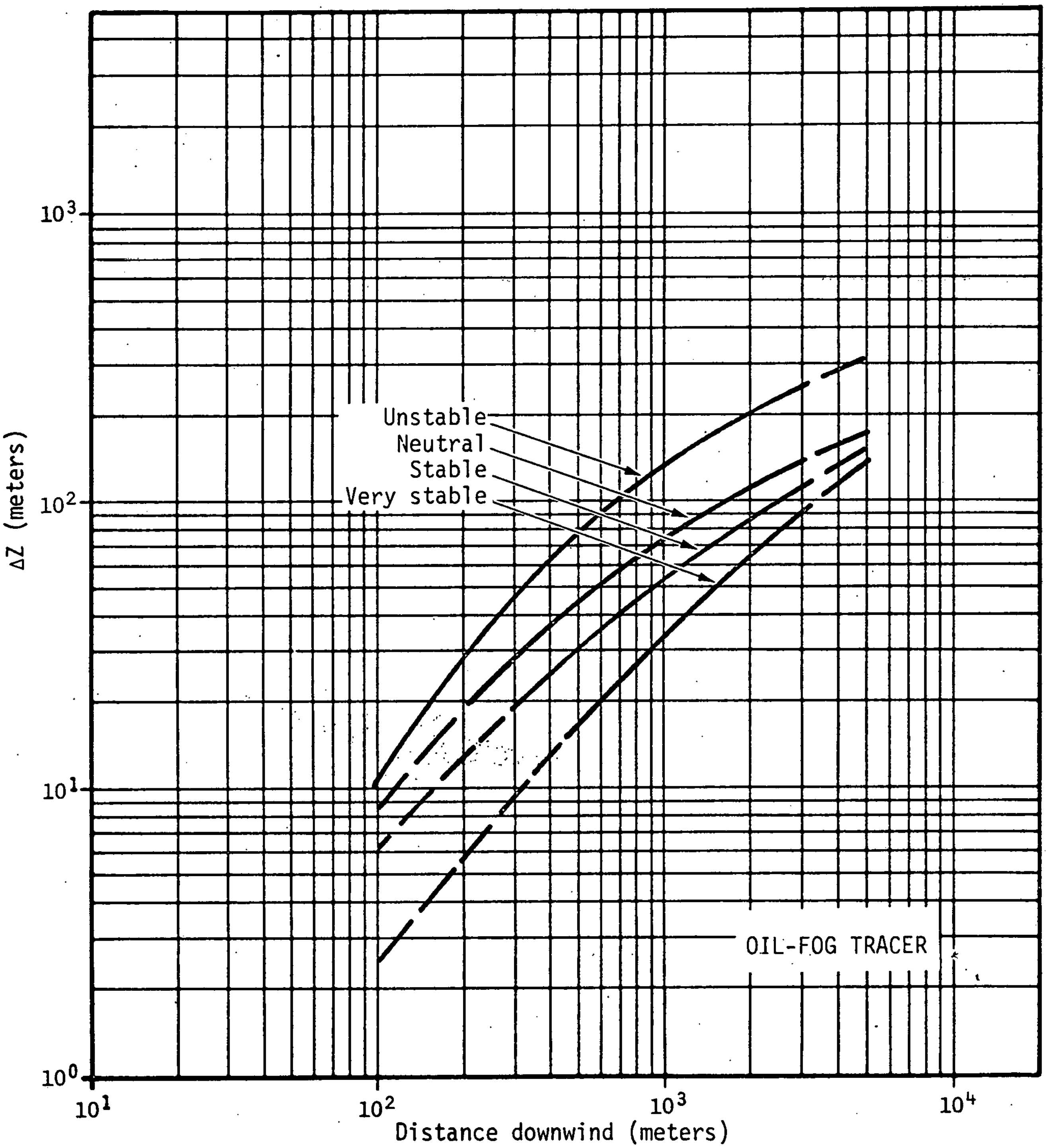

Figure 6-5: Mean-Observed Plume-Height (ΔZ) vs. Distance

Test site: K-valley
Source: Continuous, ground-level release of oil-fog tracer

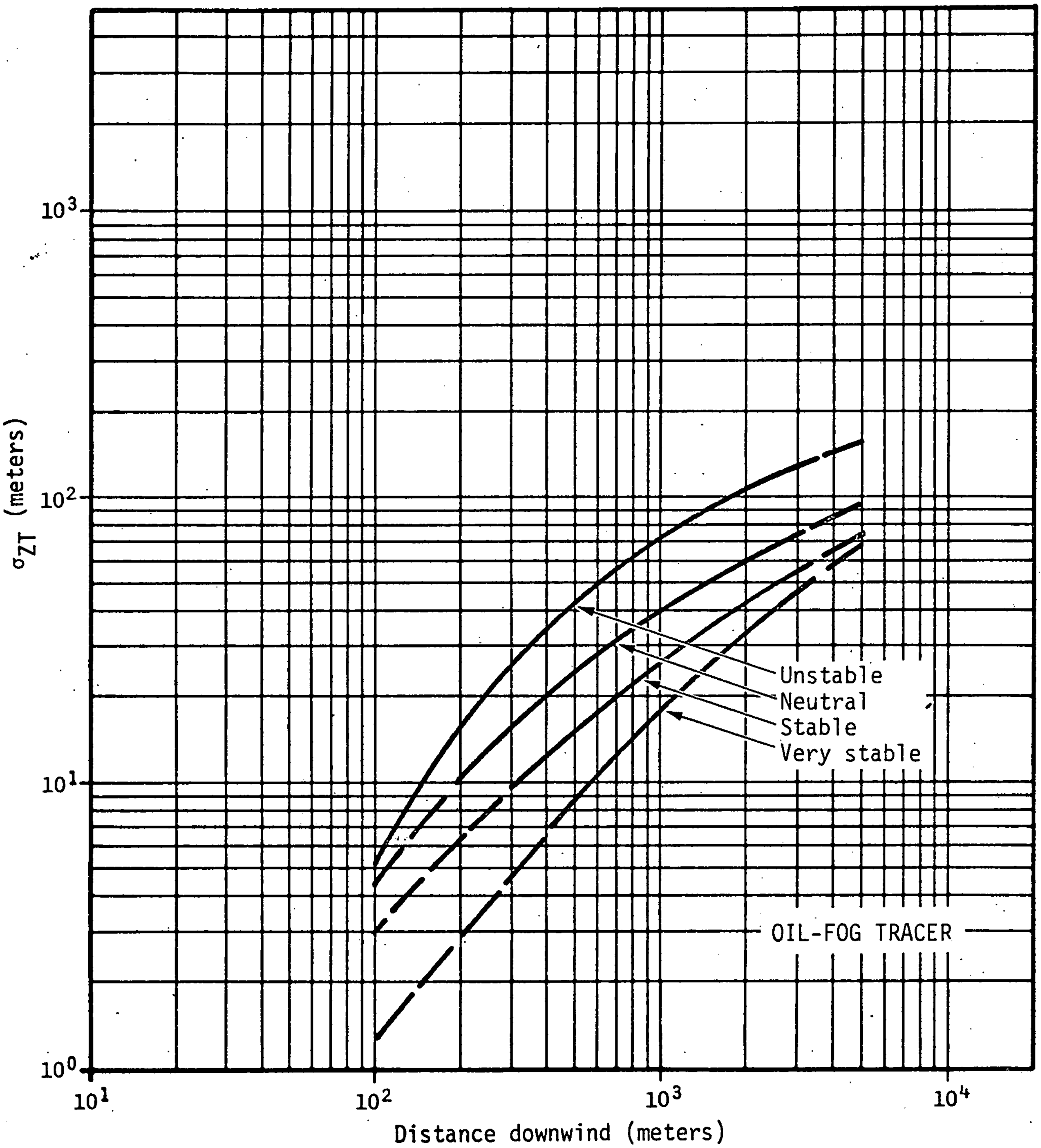

Figure 6-6: Mean Vertical-Dispersion Coefficient (σ_{ZT}) vs. Distance

Test Site: K-Valley
Source: Continuous, ground-level release of oil-fog tracer

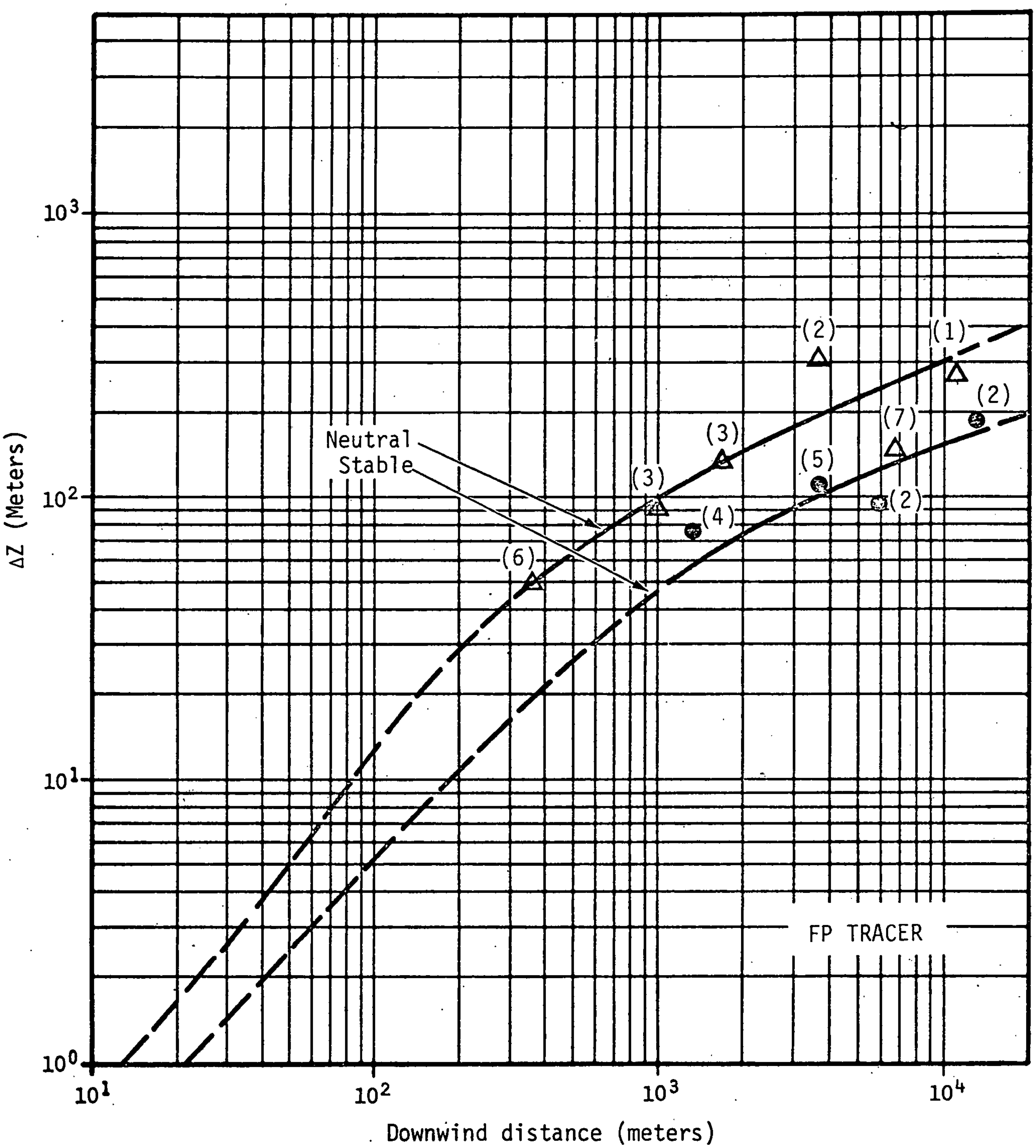

Figure 6-7: Mean-Observed Plume Height (ΔZ) vs. Distance

Stability: △ - Neutral, ● - Stable
Test Site: K, M, and F-Valleys (combined data)
Source: Continuous, ground-level release of fluorescent particle (FP) tracer
Data Base: Data points are mean plume heights derived from the number of observed heights shown in parentheses

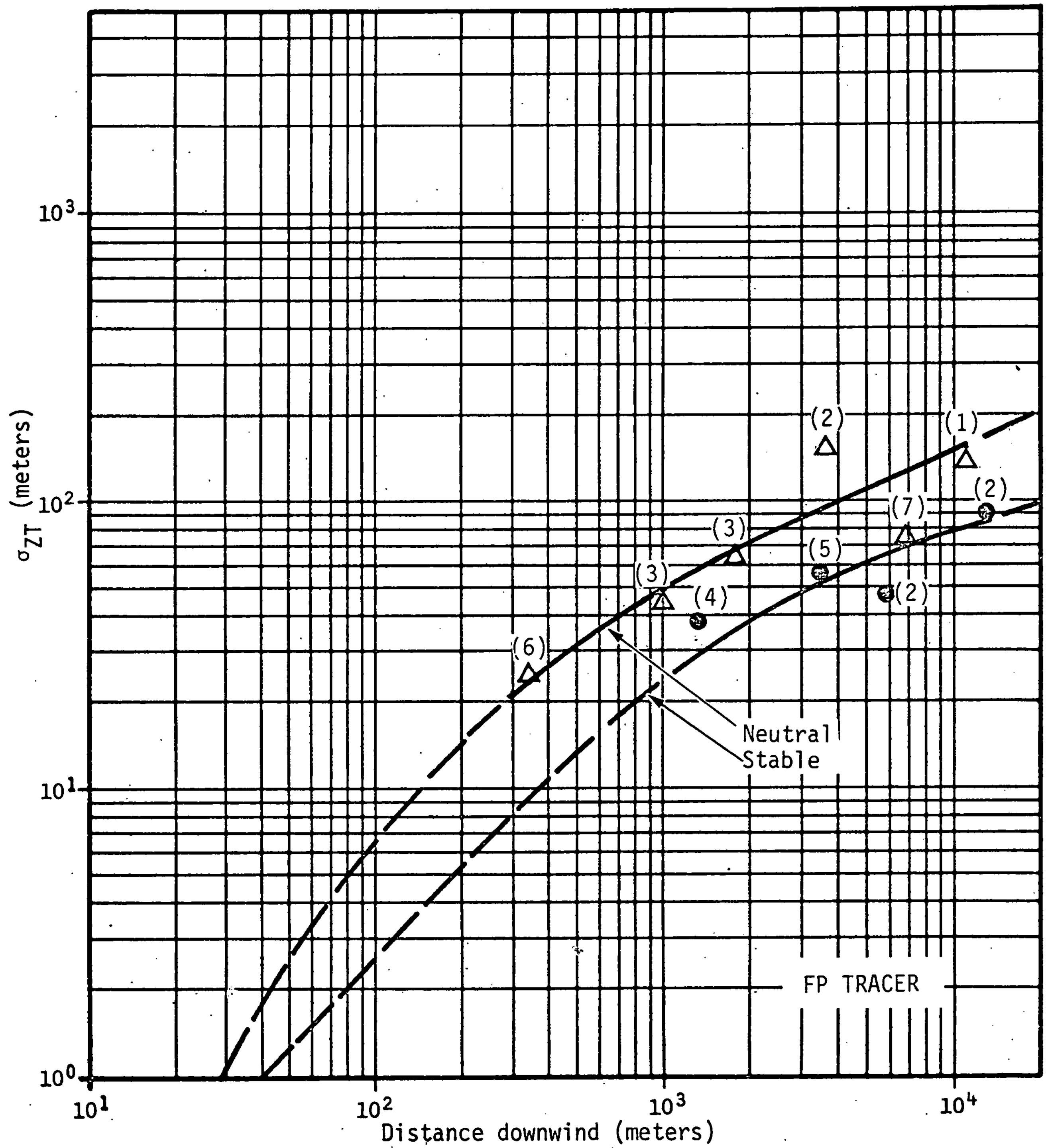

Figure 6-8: Mean Vertical-Dispersion Coefficient (σ_{ZT}) vs. Distance

Stability: △ - Neutral, ● - Stable
Test Site: K, M, and F Valleys (combined data)
Source: Continuous, ground-level release of fluorescent particle (FP) tracer
Data Base: Data points are mean σ_{ZT} values derived from the number of plume-height observations shown in parentheses

6.2.3 Fjord σ_{ZT} - FP Tracer

In the NDRE summary report,[6] mean values were presented of plume-heights observed during seven releases of FP tracer material in the Målselvfjorden Fjord. Stability conditions for the entire series of seven tests were near-neutral, owing to the moderating effect of the fjord's water body on air temperature. The mean ΔZ values for the fjord are shown as data points in Figure 6-9. The curve in Figure 6-9 represents mean-ΔZ versus distance, and was reproduced from the NDRE summary report.

Mean values of the total-vertical-dispersion coefficient (σ_{ZT}) have been derived from the mean-observed ΔZ values shown in Figure 6-9 by using Equation (1). A curve representing mean σ_{ZT} versus distance for neutral conditions in the fjord is presented in Figure 6-10. For purposes of comparison, mean σ_{ZT} values for neutral conditions in the valleys (from Figure 6-8) are also shown.

From Figure 6-10, it is apparent that under neutral stability conditions, vertical dispersion in the fjord is substantially less than in the valley. In fact, over the range of distances for which concurrent observed data exist, the mean values of σ_{ZT} for the valleys are about four times greater than the mean σ_{ZT} values for the fjord. This observation can, of course, be attributed to the aerodynamically smooth water surface in the fjord as compared with the "rougher" surfaces of the land valleys.

6.2.4 Comparison of Deep-Valley σ_{ZT} with Pasquill-Gifford σ_Z

The two sets of valley-σ_{ZT} curves presented earlier in Figures 6-6 and 6-8--one set for oil-fog tracer, the other for FP-tracer--are reproduced in Figure 6-11 for mutual comparison and for comparison with

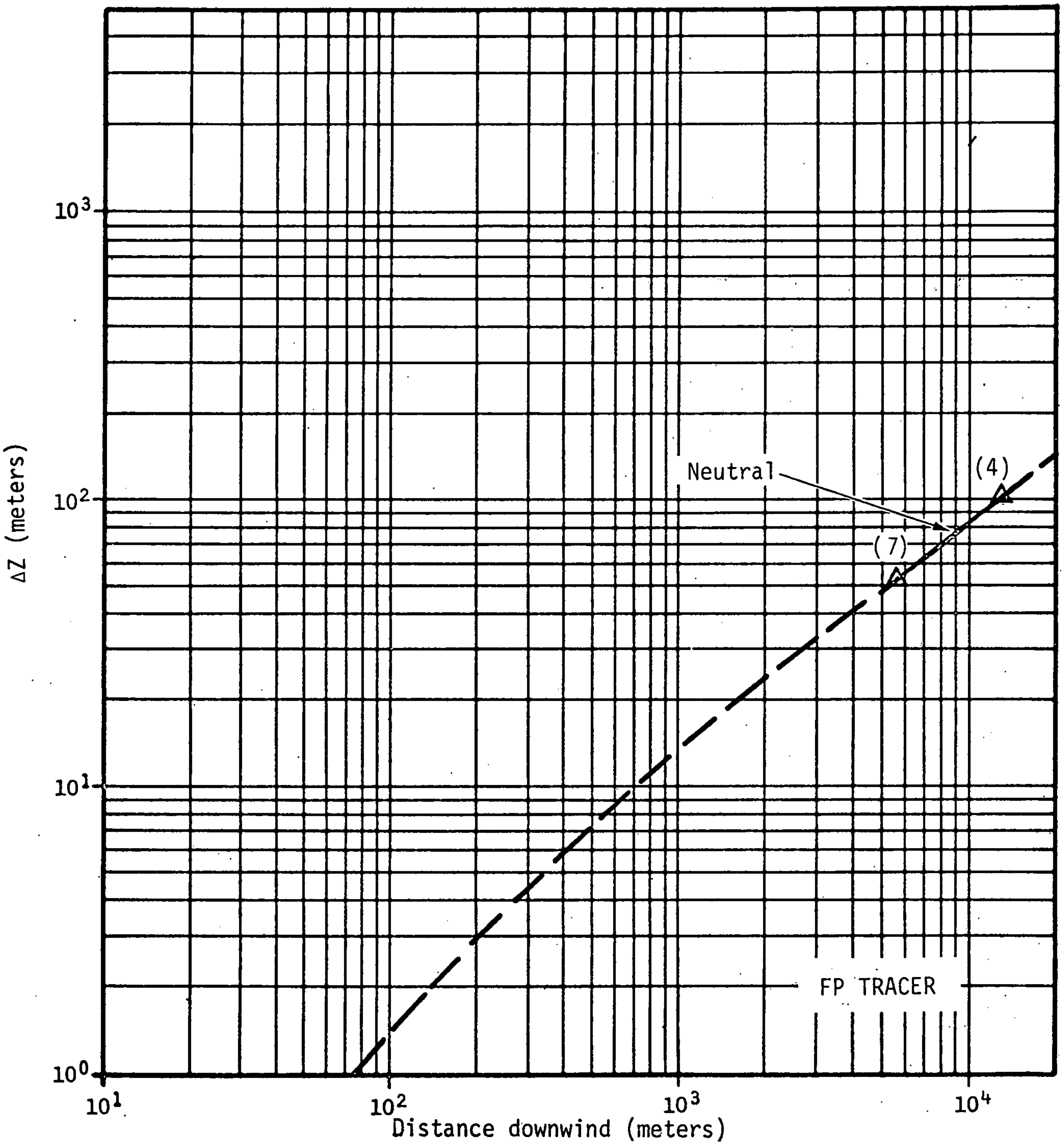

Figure 6-9: Mean-Observed Plume Height (ΔZ) vs. Distance

Stability: Δ - Neutral
Test Site: Fjord
Source: Continuous release at the water surface of fluorescent particle (FP) tracer
Data Base: Data points are mean plume heights derived from the number of observed heights shown in parentheses

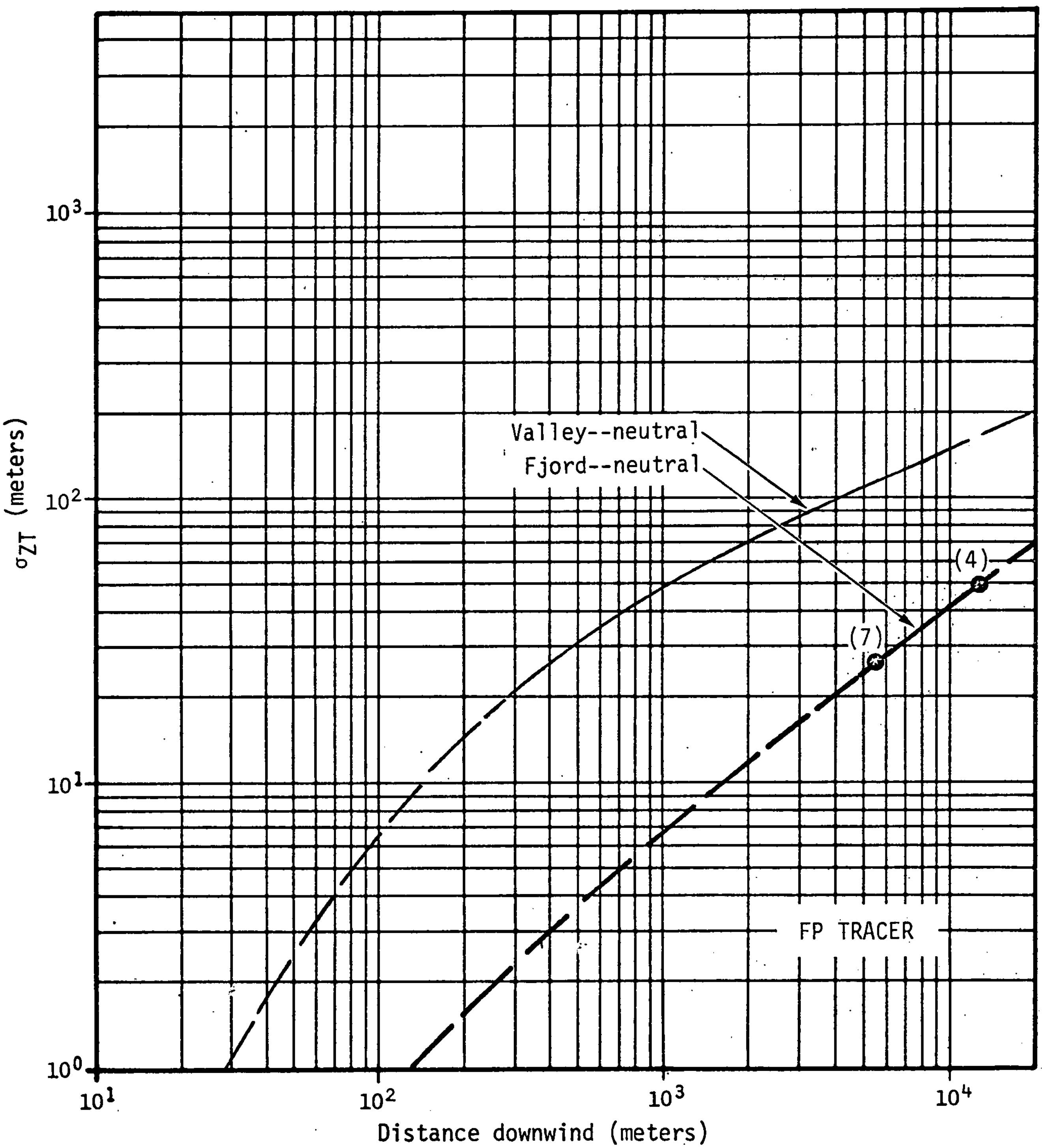

Figure 6-10: Mean Valley σ_{ZT} and the Mean Fjord σ_{ZT} vs. Distance

Stability: Neutral
Test Site: 3 valleys, 1 fjord
Source: Continuous, suface-level release of fluorescent particle (FP) tracer
Data Base: Data points are mean σ_{ZT} values derived from the number of plume-height observations shown in parentheses

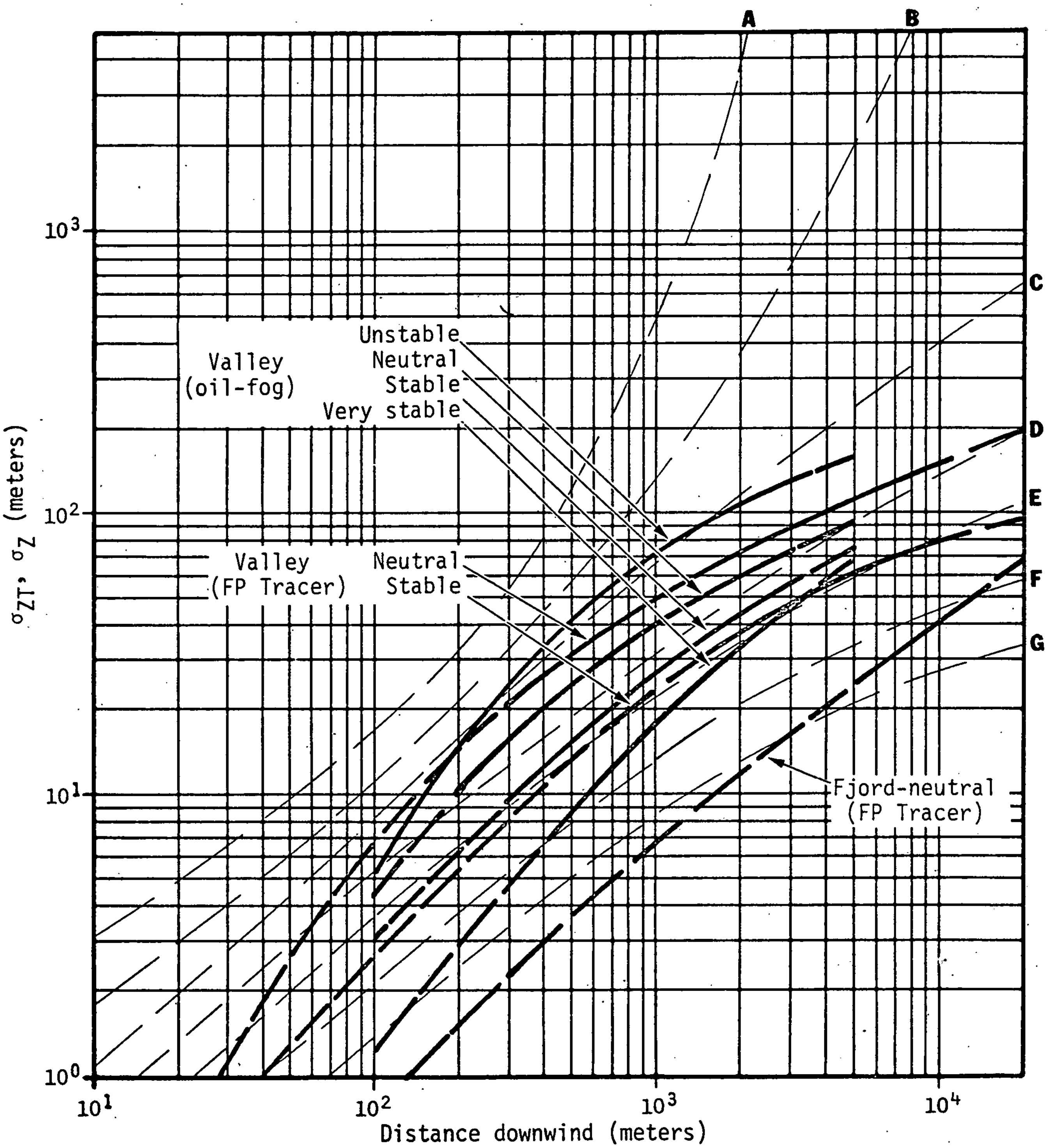

Figure 6-11: Mean Valley-σ_{ZT}, Fjord-σ_{ZT}, and Pasquill-Gifford σ_Z vs. Distance

Test Site: K, M, F Valleys, fjord
Source: Continuous surface-level releases of oil-fog and fluorescent particle (FP) tracer

the Pasquill-Gifford σ_Z values (light, dashed lines). It is apparent from Figure 6-11 that the two sets of valley-σ_{ZT} curves have very similar magnitudes and slopes. This demonstrates that the two different experimental techniques employed by the NDRE researchers, i.e., oil-fog tracer with time-lapse photography, versus FP tracer with rotorod dosage sampling, can yield consistent measurements of total vertical dispersion.

It was pointed out earlier that the valley-σ_{ZT} curves are confined to a narrow band. This is especially apparent in Figure 6-11 if one compares the two sets of mean valley-σ_{ZT} curves with the Pasquill-Gifford σ_Z curves. The valley-σ_{ZT} curves, although spanning the entire range of ΔT stability classes, are confined between the Pasquill-Gifford dispersion rates for class B and class F stability conditions, over the range of downwind distances from between 0.4 to 10 kilometers. (Most of the valley-σ_{ZT} values for distances less than 0.4 kilometers downwind are extrapolated values.) The conclusion is that the extreme Pasquill-Gifford vertical-dispersion rates, i.e., the class A and class G rates, are not observed <u>in the mean</u> in deep valleys.

The mean fjord-σ_{ZT} (neutral stability) curve taken from Figure 6-10 is reproduced in Figure 6-11 for comparison with the Pasquill-Gifford σ_Z curves. The segment of the fjord-σ_{ZT} curve that lies between five and 15 kilometers downwind is based on observed (not extrapolated) data, and is seen to fall between the Pasquill-Gifford classes F and G dispersion rates. Unlike in the deep land-valleys, a Pasquill-Gifford class G dispersion rate does indeed describe mean vertical dispersion in a fjord. This observation is explained, again, by the fact that the water surface of the fjord is aerodynamically smoother than the surface of the land-valleys.

6.2.5 Comparison of Deep-Valley σ_{ZT} with Rolling-Terrain σ_{ZT} and Shoreline σ_{ZT}

During Phase 2[4] of this project, the meandering plume hypothesis was applied to existing Army field data in order to calculate mean values of σ_{ZT} that represent total vertical dispersion in rural, rolling terrain. During the first part[5] of Phase 3, the meandering plume hypothesis was similarly applied to generate calculated values of mean σ_{ZT} for a shoreline environment. In the Phase 3 work described in this report, mean values of σ_{ZT} for deep-valley terrains have been developed from direct observations of total vertical dispersion.

The mean-σ_{ZT} values calculated for rolling terrain, those calculated for the shoreline environment, and the observed mean-σ_{ZT} values reported here for deep-valley terrain all superimpose upon the Pasquill-Gifford σ_Z curves, but in bands that are narrower than the range of Pasquill-Gifford σ_Z values. The magnitudes of the rolling-terrain, shoreline, and deep-valley σ_{ZT} values are basically similar with all three sets of curves being constrained within the Pasquill-Gifford σ_Z curves for class B and class F stability conditions. The similarity of the mean σ_{ZT} values calculated for rolling terrain and shoreline environments, and the observed mean σ_{ZT} values for deep-valley terrain supports previous assertions[4,5] that the meandering plume hypothesis can be applied to calculate realistic values of σ_{ZT} from field measurements of simple diffusion and of vertical turbulence.

6.2.6 Range of Observed σ_{ZT} Values

Thus far, this report has been concerned with mean values of σ_{ZT} (by ΔT stability class) for deep-valley terrain. A brief consideration is now given to the range of σ_{ZT} about the mean observed values. In Figure 6-2, observed and mean-observed plume heights (ΔZ) for neutral conditions in the K-valley were presented. From the range of observed ΔZ values in Figure 6-2, a corresponding range of σ_{ZT} values can be obtained using the relationship given in Equation (1). A range of "observed" σ_{ZT} values has been determined in this manner and is represented by the shaded area shown in Figure 6-12. Also shown in Figure 6-12 are the mean σ_{ZT} curve (neutral conditions) reproduced from Figure 6-6, and the Pasquill-Gifford σ_Z curves.

From Figure 6-12, it would appear that the range of observed σ_{ZT} under neutral conditions is a factor of two or more greater than the mean σ_{ZT} values. The range here does, however, remain within the bounds of the Pasquill-Gifford σ_Z curves. From the available observations of ΔZ presented in Figures 6-1 through 6-4, it would appear that the range of σ_{ZT} is at least a factor of two greater than the mean values for unstable, as well as neutral conditions, but that for stable conditions, the range of σ_{ZT} could be less than a factor of two.

It is seen that the mean σ_{ZT} values (stratified by ΔT stability class) presented in this report yield realistic mean σ_{ZT} curves for deep-valley terrain; however, the range (within class) of observed σ_{ZT} values is quite large, at least with unstable and neutral conditions. It is our speculation that the range about the mean in each stability class might be

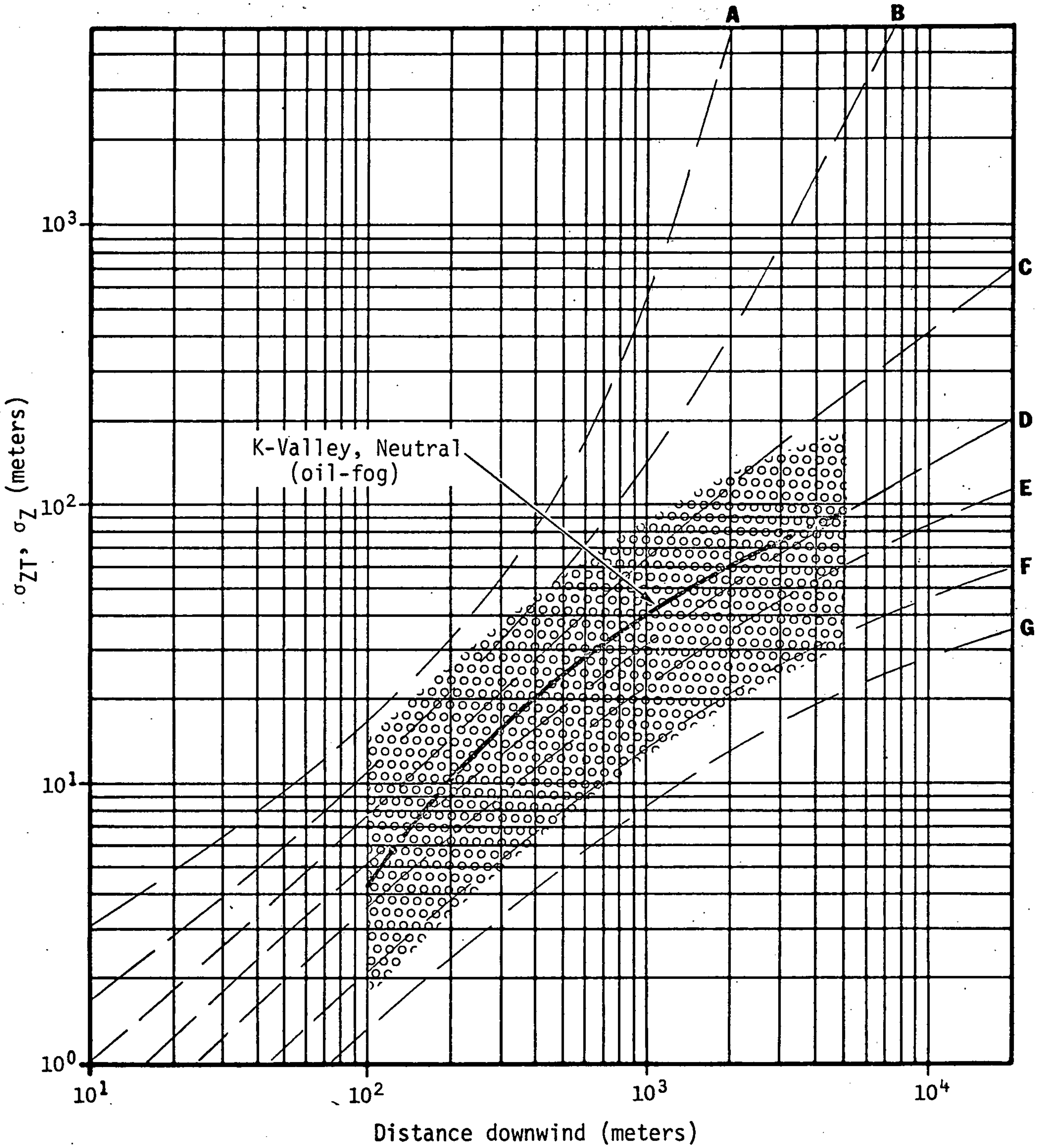

Figure 6-12: Mean σ_{ZT}, Range of σ_{ZT}, and Pasquill-Gifford σ_Z vs. Distance

NOTE: Mean σ_{ZT} curve (neutral stability) is from Figure 6-6. Shaded area is range of σ_{ZT} for neutral stability, determined from range of observed plume-heights shown in Figure 6-2.

narrowed by stratifying mean σ_{ZT} values in classes based not on ΔT alone, but on ΔT plus a vertical-turbulence indicator, for example, $\sigma_\phi(Z)$.

7.0 CONCLUSIONS

1. The mean-σ_{ZT} curves developed in this study for deep-valley terrain are based on direct measurements of vertical dispersion. The deep-valley σ_{ZT} curves span the entire range of ΔT stability classes and fall within a narrow band when compared with the range of Pasquill-Gifford σ_Z curves.

2. The Pasquill-Gifford dispersion rates for class A (extremely unstable) and class G (extremely stable) conditions are not observed in the mean in deep-valley terrain.

3. The set of deep-valley σ_{ZT} values reported in this study and the sets of σ_{ZT} values developed earlier in the project for rural, rolling terrain and for a shoreline environment fall within narrow bands and are of similar magnitude. This would imply that the vertical dispersion rate in a deep valley is similar to the vertical dispersion rate found at non-valley locations having similar surface topography.

4. The fact that the "measured" deep-valley σ_{ZT} values are similar to the calculated rolling-terrain and shoreline σ_{ZT} values supports our previous assertions[4,5] that the meandering plume hypothesis can be applied to calculate realistic values of σ_{ZT} from field-measurements of simple diffusion and of vertical turbulence.

5. The σ_{ZT} values stratified by ΔT and presented in this report provide realistic mean σ_{ZT} curves for deep-valley terrain. The range (within stability class) of observed σ_{ZT} is, however, shown to be greater than the mean values by a factor of two or more, especially under unstable and neutral conditions. It is suggested that the range within each stability class might be narrowed significantly by stratifying mean σ_{ZT} values in classes based not on ΔT alone, but on ΔT plus a vertical turbulence indicator, for example, $\sigma_\phi(Z)$.

6. The mean deep-valley σ_{ZT} curves presented in Figures 6-6 and 6-8 are based on reliable, direct field-measurements of total vertical dispersion. Accordingly, these σ_{ZT} curves are suitable for inclusion in references, such as Meteorology and Atomic Energy[8], Section 4-4, where a need exists for hard data relevant to vertical dispersion from continuously-emitting sources.

7. It has been demonstrated that two different experimental techniques, i.e., use of oil-fog tracer with time-lapse photography, versus fluorescent particle (FP) tracer with rotorod dosage sampling, can yield consistent measurements of total vertical dispersion. This conclusion should be of great interest to those faced with the task of designing comprehensive yet cost-effective tracer-dispersion experiments.

8.0 RECOMMENDATIONS

1. The results of this study indicate that vertical dispersion in a deep valley may differ little from vertical dispersion in less severe terrain. This observation, however, would not be expected to hold true for horizontal dispersion because the valley "walls" act, to some degree, as physical barriers to horizontal dispersion. We, therefore, recommend that subsequent dispersion studies carried out in deep-valley terrain be directed towards better quantification of the effects of the valley "walls" on the horizontal dispersion rate.

2. A major effort should be directed towards defining vertical-stability classes from other parameters besides ΔT. As a start, we recommend that a study be carried out to evaluate use of $\sigma_\phi(Z)$ together with ΔT, or $\sigma_\phi(Z)$ alone to stratify σ_{ZT} values into stability classes.

9.0 REFERENCES

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