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TALL STACKS AND THE ATMOSPHERIC ENVIRONMENT

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

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TALL STACKS AND THE ATMOSPHERIC ENVIRONMENT

by

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ENVIRONMENTAL PROTECTION AGENCY
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PREFACE

During the past decade tall stacks have been employed with increasing frequency, particularly on coal and oil-fired power plants. This trend has generated considerable debate concerning the impact of emissions from tall stacks on the air environment. Clearly, the present state of knowledge regarding the effectiveness of tall stacks as a means of achieving acceptable ambient air quality needs to be assessed.

Dr. Jeremy M. Hales, Battelle, Pacific Northwest Laboratories was asked to undertake the in-depth review of the effectiveness of tall stacks. Due to their research in plume chemistry and physics, Dr. Hales and his colleagues at Battelle are nationally recognized experts in dispersion from stacks. Another reason Dr. Hales was asked to undertake this review is that neither he nor Battelle is identified with pro or con positions on tall stacks. Moreover, to insure the independence of Dr. Hales' efforts, the EPA project officer and his associates conscientiously refrained from actions which might influence the review. Thus, this report is presented as an unbiased, technical assessment of the tall stack and its place in the effort to maintain and improve the quality of the air environment.

It should be noted that this assessment of tall stacks was undertaken prior to publication of the "Stack Height Increase Guideline"[1] by the Environmental Protection Agency. The guideline is based on three recent court rulings

[1] Environmental Protection Agency, "Stack Height Increase Guideline," Federal Register, pp. 7450-7452, February 18, 1976.

which interpret Section 110(a)(2)(B) of the Clean Air Act as requiring the use of constant emission limitations (as opposed to dispersion-dependent technology such as tall stacks) as the primary means for achieving ambient air quality standards. Dr. Hales' assessment of tall stacks also provides a valuable technical background for users of that quideline.

Joseph A. Tikvart
Project Officer
Environmental Protection Agency

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ACKNOWLEDGEMENTS

This report was written with the help and useful comments of several individuals and organizations in the Federal Government and private industry, and I would like to express my sincere appreciation to these groups and individuals for their assistance. Paricularly noteworthy in this regard are the personnel of the Federal Energy Administration and the EPA Source-Receptor Analysis Branch, who provided substantial support in data and information retrieval as well as in numerous additional areas. The NOAA Office of Aerial Charting and Cartography also contributed significantly to this project by granting access to their computer files on high obstacles within the United States. This capability was largely responsible for compilation of the table of stacks appearing in Appendix B.

Draft copies of this report were reviewed by a number of prominent meteorologists, whose highly constructive comments have been reflected to varying degrees in this final document. These reviewers are as follows:

F. A. Gifford	ATMOSPHERIC TURBULENCE AND DIFFUSION LABORATORY, NOAA
P. L. Finkelstein	U.S. ENVIRONMENTAL PROTECTION AGENCY (on assignment from NOAA)
D. R. Matt	ATMOSPHERIC TURBULENCE AND DIFFUSION LABORATORY, NOAA
L. E. Niemeyer	U.S. ENVIRONMENTAL PROTECTION AGENCY (on assignment from NOAA)
J. V. Ramsdell	BATTELLE, PACIFIC NORTHWEST LABORATORIES
M. E. Smith	SMITH-SINGER METEOROLOGISTS, INCORPORATED

I express my appreciation to each of these individuals for their assistance on this project. Although many of their ideas have been incorporated, it is emphasized that no implication exists for their full or partial agreement with the report's content, for which I as author am solely responsible.

SECTION I

CONCLUSIONS

This report has addressed the current state of knowledge regarding the performance of tall-stacks and their effect on the atmospheric environment. In performing this analysis it has been convenient to consider both the collective impact of multiple tall-stack usage on large geographic scales and the performance of individual units under hypothetical conditions where plumes are emitted into clean background environments and do not interact with effluents from other sources. While this "isolated-source" situation is never satisfied totally in practice, it is a useful concept both for interpreting the influence of individual sources on multiple, interacting plume systems and for analyzing tall-stack performance at distances relatively close to the point of emission. Key conclusions from this survey are itemized as follows:

1. From the survey in this report, it is readily apparent that in the proximity of an isolated source, the tall-stack provides an attractive means for minimizing the impact of emissions on ground-level air quality. This is not to say that ambient air quality standards are not violated by effluents from tall-stacks in specific situations, nor that simply providing a tall-stack will permit unlimited release of pollutants into the atmosphere. The available information does indicate strongly, however, that elevating the point of release without an increase in effluent will usually be accompanied by considerable benefit in the lowering of ground-level

concentrations of primary pollutants. However, it is obvious that much of a tall stack's benefit will be lost if it is placed in an area of complex terrain where the plume may intercept the surrounding ground surface.

2. The collective impact of primary pollutants has been analyzed by applying conservative assumptions in conjunction with a simple elevated area-source model. These results indicate that, although emissions from collective sources tend to usurp available clean air over large areas, ground-level concentrations of primary pollutants in source regions can be reduced by increasing emission height.

3. In contrast to the situation for SO_2 and other primary pollutants, ground-level concentrations of sulfates cannot be controlled adequately simply by increasing emission height. Diffusion model calculations indicate that, taken as an isolated source, any tall stack capable of satisfying existing annual SO_2 standards will be capable also of promoting acceptable annual ground-level sulfate concentrations under most atmospheric conditions. It must be noted here, however, that the long (approximately 1000 km) distances associated with sulfate transport renders this "isolated-source" analysis of limited usefulness.

   On a collective basis, widespread tall-stack utilization combined with projected increases in fuel consumption without control of sulfur compound emissions will aggravate existing ground-level sulfate concentration levels throughout the United States. Concentrations currently measured in some

United States metropolitan areas often exceed levels that are suspected to cause adverse health effects.

4. Although any effect of weather and climate modification is uncertain, it is reasonable to expect that a projected utilization of tall stacks without absolute source control for sulfur compounds will effect a measurable decrease in atmospheric visibility throughout much of the United States and the northern hemisphere.

   Such a utilization is also likely to produce a significant deterioration in precipitation quality. Resulting effects on soils, surface waters and surface ecosystems will depend to a large extent on the chemical composition of the local mantle. Data obtained to date suggest that the expected changes in precipitation chemistry will have a pronounced negative impact in a number of regions, especially on a long term basis.

5. Critical circumstances that determine the design basis for tall stacks differ according to power plant characteristics and geographical location. Conditions that are often the most important in promoting high ground-level concentrations in the vicinities of tall stacks are as follows:
   - Trapping beneath subsidence inversions, especially under low-wind conditions,
   - Fumigation under inversion-breakup conditions,
   - Fumigation from on-shore flows,

- Return-flow conditions, either in shoreline or inland environments, and
- Interaction with complex terrain.

6. The large-scale field data currently available are adequate to define the near-source transport and diffusion characteristics of primary pollutants from tall stacks under a majority of circumstances, and little additional field effort is needed in this area other than for routine siting and verification programs. The limited exceptions where further intensive near-source field study of transport and diffusion is recommended include complex terrain, stagnation conditions, and onshore flows.

SECTION II

INTRODUCTION AND OBJECTIVES

The trend toward taller industrial chimneys has progressed to a point where stacks approaching 400 meters in height are becoming increasingly prevalent throughout the United States and abroad. Because of their expanding deployment and also because of the rapid increases in fossil fuel consumption associated with their use, there has been substantial concern over the individual and collective impact of tall stacks on the atmospheric environment. This concern has resulted in considerable debate during the past decade. Many opposing viewpoints appear to exist, and presently it is apparent that a strong need exists to consolidate and summarize the current state of knowledge in this field.

The primary objective of this report is to fulfill this need by providing a comprehensive, critical review of published material regarding tall stacks and atmospheric quality. It is intended that this review will be useful in resolving some of the controversy that has been associated with tall-stacks during recent years. In addition, this report is intended to identify some of the important unresolved questions regarding tall-stack performance, and thus help identify future research needs.

The two sections immediately following describe pertinent general aspects regarding tall-stack trends and performance, and interactions of plumes in the upper regions of the planetary boundary layer.

These initial sections are followed by a critical review of articles pertinent to the question of transport and dispersion of pollutants from tall stacks. For convenience, the critical review is divided into three units. The first of these deals directly with the ability of tall stacks to promote acceptable ground-level pollutant concentrations under hypothetical "isolated-source" conditions, wherein their plumes are emitted into clean background environments and are assumed not to interact with emissions from other sources during their course of travel. The second unit addresses this same question for tall-stack effluents that interact with emissions from other sources. The final review section deals with aspects of tall-stack effluents that are not directly associated with standards, such as dry deposition, precipitation scavenging, visibility, and climate and weather modification. Conclusions of this report are summarized in Section I, and an annotated bibliography of tall-stack literature is presented in Appendix C.

SECTION III

BASIC ASPECTS OF TALL STACKS

THE SIGNIFICANCE OF TALL STACKS

The subject of tall-stacks is an increasingly important one at the present time for several reasons, which are keyed strongly to the rapidly increasing energy demands in the United States and abroad. Presently these demands are resulting in large increases in fossil-fuel consumption, pressing the need for substantial improvements in atmospheric pollution-control procedures. In addition, this situation has forced the shift toward less desirable fuels -- from the sulfur pollution standpoint, at least; and as a consequence there is a distinct tendency for sulfur emissions to experience an increase even greater than that of energy production itself. Moreover, the costs and technological problems associated with sulfur emission-control processes[1] have provided a clear incentive for large sulfur emitters to rely on tall stacks as a basic means for maintaining ambient air quality standards. This last aspect - reflecting the intrinsic relationship between tall-stack utilization and absolute emission control (such as flue-gas desulfurization) - is a subject of strong and continuing conjecture.

Several of the above points are illustrated graphically in Figures 1-4. Figure 1 reflects the rapidly increasing utilization of fossil fuels in this country. Total generation of electricity by fossil fuels has increased to

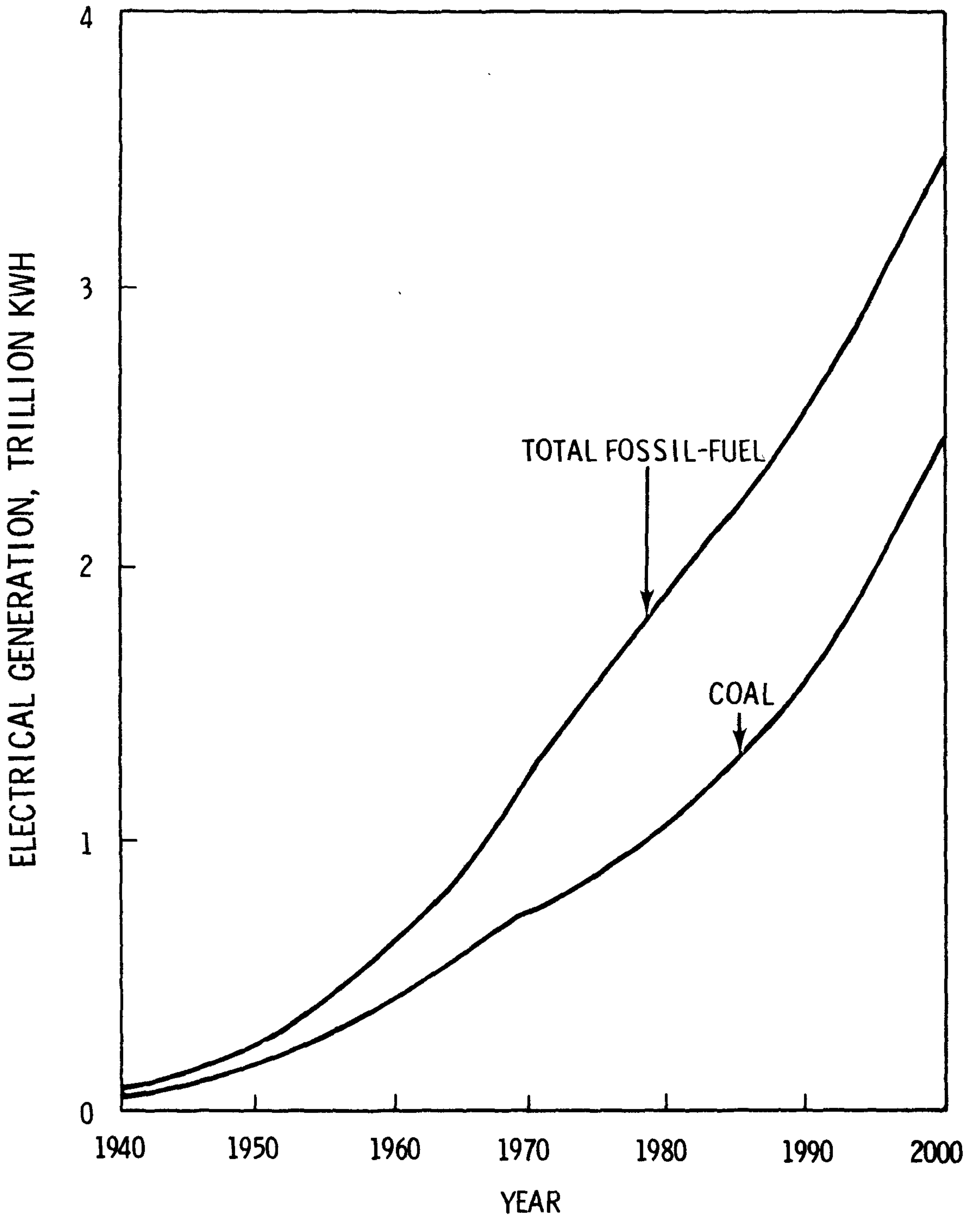

FIGURE 1. Past and Predicted Electrical Generating Trends. Sources: Dupree and West,[2] Nassikas.[3] See also FEA,[4] Chapman, et al.,[5] Schurr and Netschert,[6] Evans, et al.,[7] U.S. Bureau of Census,[8] Macrakis,[9] and Intertech.[10]

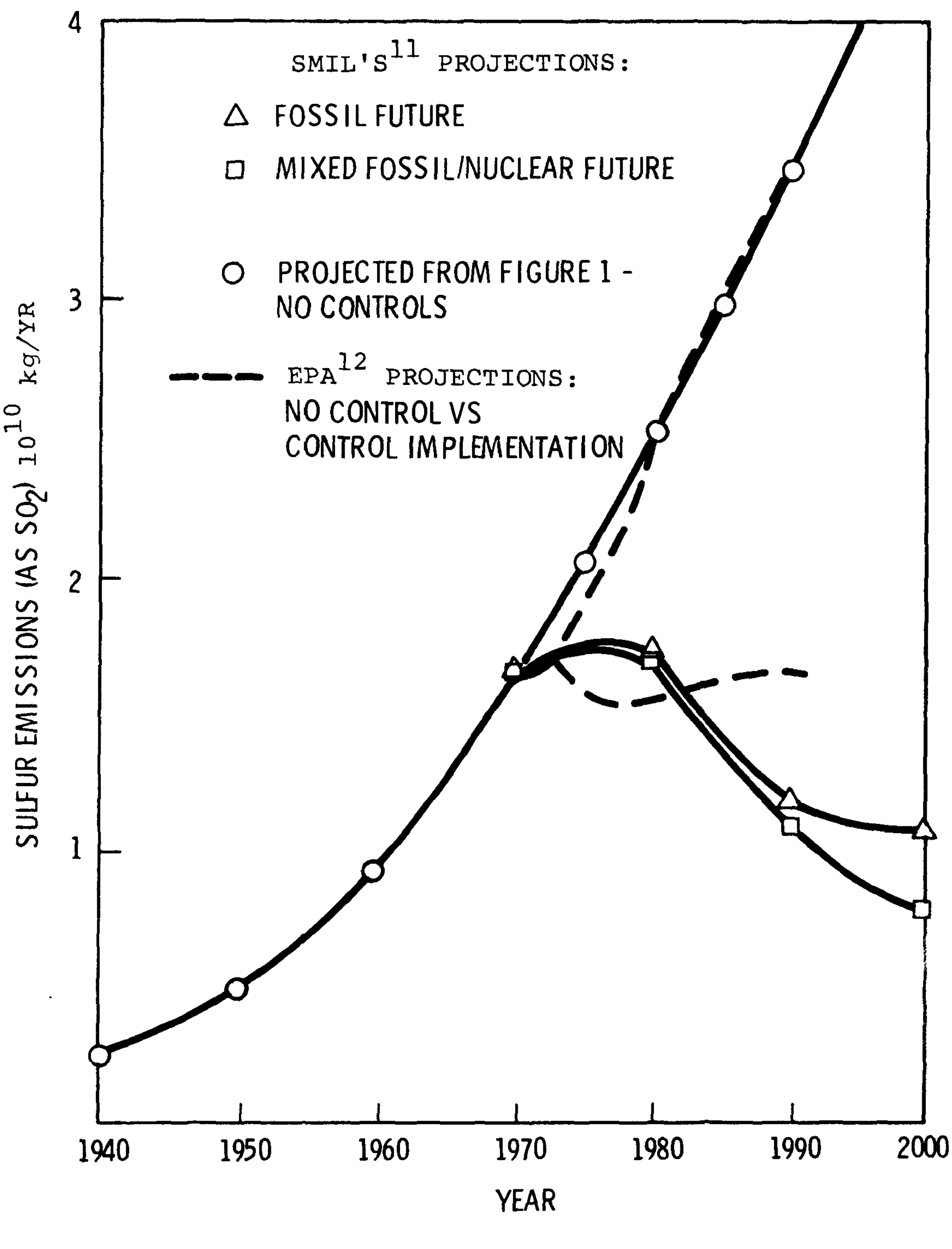

FIGURE 2. Projected U.S. SO_2 Emissions.

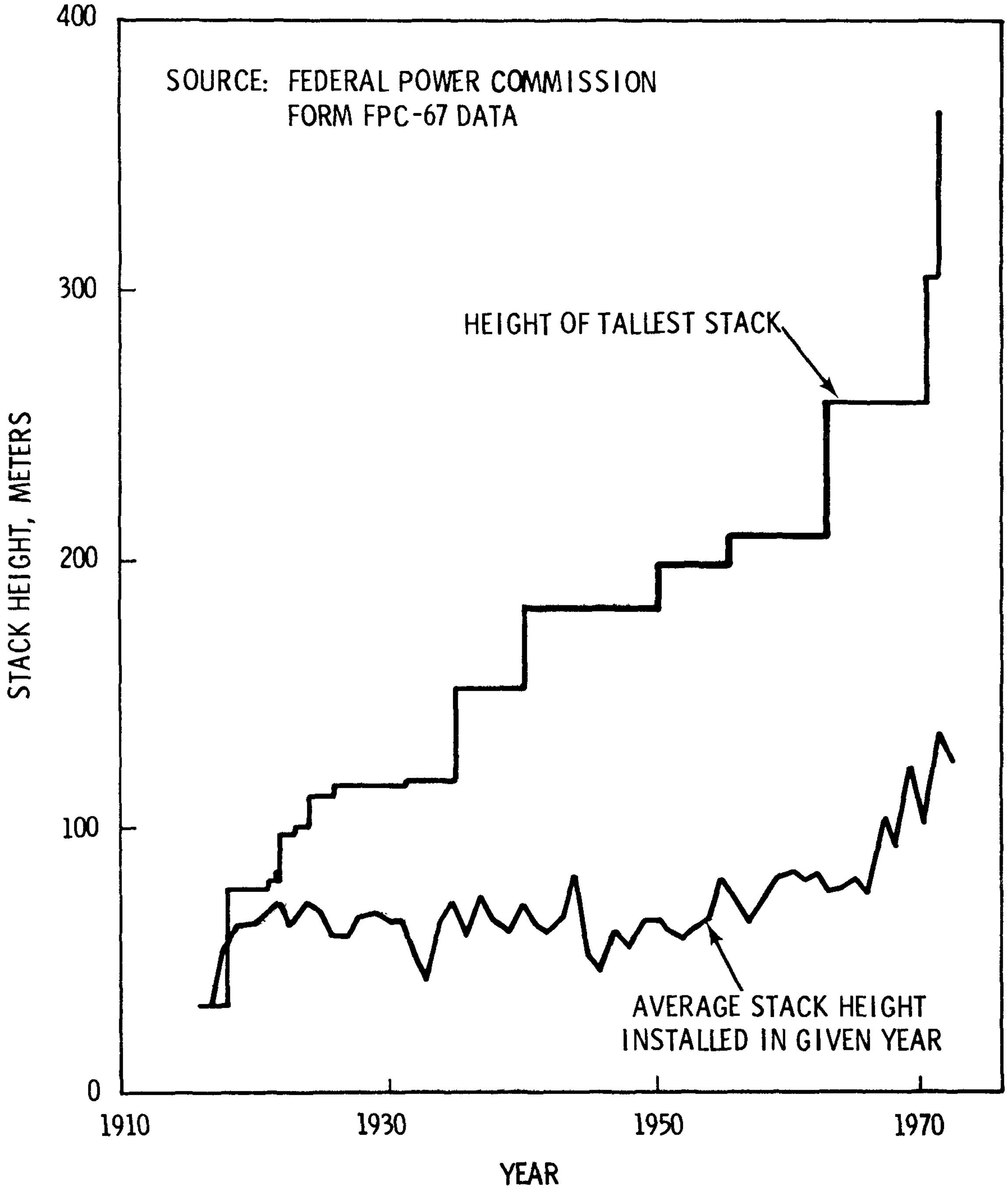

FIGURE 3. Stack Height Trends in U.S. Power Industry.

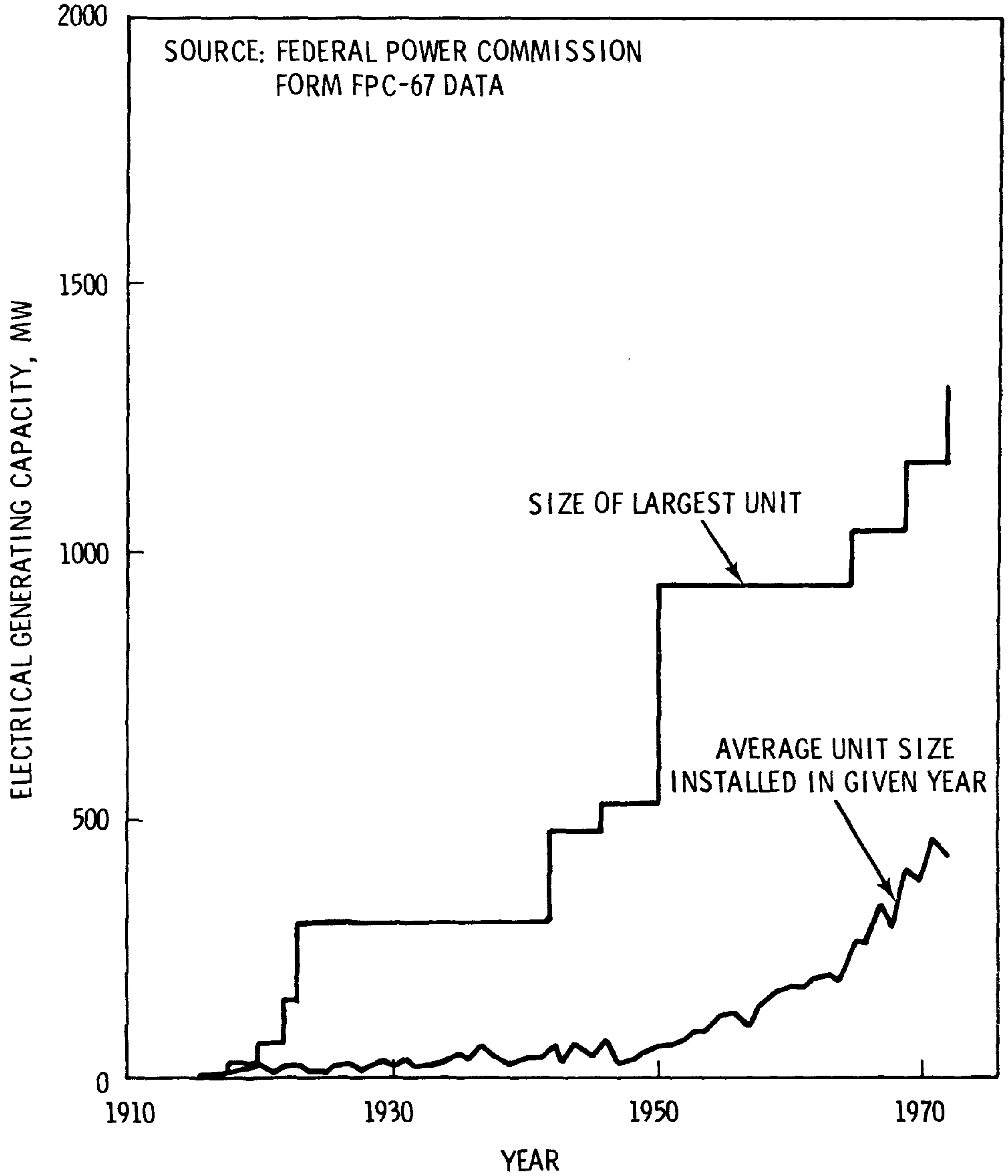

FIGURE 4. Generating Unit Size Trends in the U.S.

over twice the 1960 level by 1975, and is projected to more than double again by the year 2000.* Owing primarily to sulfur pollution considerations, coal utilization has increased proportionately slowly during recent years, but is expected to increase rapidly in the future as a consequence of the current national energy situation. Previous estimates[2] suggest that the percentage of coal used in generation of electricity (both directly and in converted form) will increase from a current 55 percent to about 70 percent by the year 2000.

Figure 2 shows trends and projections of SO_2 emissions from United States power generation facilities. The upper projection is based simply on extrapolation with the projected fuel utilization rate, assuming SO_2 source control will not be implemented. The two lower curves are taken from the projections of Smil,[11] who estimates future emissions based upon various assumptions regarding future energy sources and emission controls for SO_2. Previous EPA estimates[12] (dashed lines) are shown for comparison.

The large discrepancies between the projections in Figure 2 reflect the uncertainty that presently exists with regard to several aspects of future energy supply. Smil's curves are lower partly because they are based upon electricity demand estimates[5] that are reduced from those traditionally applied, and also because of their obvious reflection of anticipated control technology. Other estimates[14,15] generally range between the extremes shown in the figure, and it is apparent that while the upper curve obviously

* One should note that at the present time forecasts of generating demand are clouded by a host of uncertainties, and a number of varying predictions of future energy trends exist. Several of these are cited in Figure 1.

represents a high asymptote, it is still not totally unreasonable to speculate that future SO_2 emissions may be appreciably higher than those suggested by the lower curves.

Figure 3 indicates the trend in electric-utility stack heights in the United States, and a complete listing of all stacks over 122 meters is given in Appendix B. Figure 3 demonstrates that a considerable increase in the size of the tallest stacks has materialized during the more recent past. This increase in stack height has accompanied a similar increase in individual generating unit size, as shown in Figure 4. This figure indicates that average unit size has more than doubled since 1960, demonstrating that in addition to increasing their productivity, fossil-fueled electrical generating facilities have become more concentrated in terms of individual output. This concentration has become possible in large part because of the use of tall stacks which promote more widespread distribution of the effluent material, thus permitting higher emission rates than would be acceptable otherwise.

From Figure 2 it is apparent that the total input of sulfur pollutants from fossil-fuel generation in the United States has increased from 9.2×10^9 kg/yr in 1960 to 1.7×10^{10} kg/yr presently. Assuming no emission controls will be incorporated, this level would increase to over 4×10^{10} kg/yr by the year 2000. These United States emission values for electrical utilities can be compared with estimates of world emissions from natural sources, which are in the neighborhood of 1.3×10^{11} kg/yr (Robinson and Robbins[13]).

It is apparent that tall stacks can influence the amounts and distribution of atmospheric pollution in two major ways. The first and most obvious of these is the tall stack's ability, by injecting its effluents at higher levels in the atmosphere, to cause significant changes in the transport and dispersion of pollutants. Often this results in a substantial advantage in producing lower ground-level concentrations near the source. The second effect of tall stacks is the indirect-tendency -- because of the advantages created by the first -- to increase the amounts of pollutant emitted to the atmosphere.

The first effect is important in increasing the spacial influence of individual sources. Typically, the effective spacial domain of a given pollution source is dictated both by its magnitude with respect to surrounding sources and by the lifetime of the pollutant in the atmosphere. In this context it is important to note the comparison of natural and fossil-fuel sulfur emission rates given above, and to note also that higher emission elevations tend to increase atmospheric residence times of pollutants. From this, it is not unreasonable to expect that these combined effects are creating a situation of regional or even global consequence from one that has previously been considered primarily local in scale.

While the second major influence of tall chimney use -- that of providing a tendency towards increased total emissions -- is rather indirect in nature, it is potentially of major importance. An example of this[17] is the intrinsic relationship between tall-stack performance and the operation of "intermittent control systems", which is a procedure for varying emission source strength with atmospheric conditions to produce acceptable ambient air quality levels[18]. This incentive has been reduced by legislation and recent court action[19] under the Clean Air Act, which places limitations on circumstances where increasing the height of a chimney is considered acceptable as an air pollution control measure.

Although tall stacks have been most frequently associated with SO_2-related problems and electric-power production, they are an important consideration in the context of additional industries and pollutants as well. A prime example is the smelter industry which, in fact, has pioneered in the application of tall stacks for air quality control (Smith [1966]†, Hill, et al[20]). Currently the world's tallest stack is associated with a smelting operation; this unit is owned by the International Nickel Company in Sudbury, Ontario, and has a height of 381 meters.

Despite the fact that the advanced fuel processing techniques of coal gasification, liquefaction, and shale-oil conversion are insignificant at the present time, these industries undoubtedly will become important in future years; and the advent of these processes with their noted emissions of nitrogen and sulfur gases will promote a strong tendency toward the increased use of tall stacks if emission control techniques for these substances are not developed to a significantly advanced state by that time.

† References denoted in this manner appear in the annotated bibliography in Appendix C. Those denoted conventionally are listed in Section VIII.

Emissions from both smelters and fossil-fueled power plants include metals and transition elements.[21] Although metals from smelters have been associated with measurable adverse health effects,[22] recent survey studies for power plants[23] indicate that direct adverse health effects from airborne metals in power plant effluents should be rather unlikely. Carbon monoxide and hydrocarbons, especially aldehydes and the polycyclics, have been observed in power plant effluents.[24] The associated concentrations, however, are sufficiently low to preclude expectation of any adverse effects on human health.

Oxides of nitrogen emitted from power plants are of some concern, although the quantities of NO and NO_2 typically emitted are substantially less than those of SO_2.[24] Cavender et al[25] show that the United States emissions of nitrogen oxides are increasing somewhat. This increase is partially a result of greater fossil fuel consumption and higher firing temperatures. It has been speculated recently by Davis et al[26] that ozone may be formed as a secondary pollutant in power plant plumes to an extent sufficient to exceed Federal Ambient Air Quality Standards. This speculation, however, was based primarily on aircraft plume measurements with fast-response instrumentation, and was not related to surface measurements over periods of time appropriate to the established standards. At the present time this speculation is not widely accepted by others in the field.

As a consequence of the above discussion it may be concluded that, while other pollutants and industries may be of some limited consequence, the tall-stack problem is related primarily to sulfur oxides and the smelting and electric power industries (cf. EPA[27]). Accordingly, the prime emphasis of the following text will focus on these specific areas.

CRITERIA FOR "TALL" STACKS

Because of extensive usage of the term, there is a tendency to expect that some set criterion exists to distinguish between a "tall" stack and one that is not. Despite this expectancy, however, and although several arbitrary standards have been applied in the past, no really obvious or satisfactory criterion of this type exists.

A somewhat useful index in this regard is the "2 1/2 times rule,"* which is often applied in stack-height determination. One could, for example, designate "tall" stacks as ones that exceed the 2 1/2 times rule, and "short" stacks as ones that do not. An alternative criterion that has been applied in the past by several authors (c.f. Thomas, et al., [1963]) is to state an arbitrary height (200 m, say) above which all chimneys are considered to be "tall". Some basis for this approach exists in a chronological analysis of stack-height trends, such as in Figure 3. In view of the fact that such a distinction says nothing about performance of chimneys, however, it's practical utility is marginal.

*The 2 1/2 times rule, often applied in both the United States and Great Britain, states that chimney heights 2 1/2 times the height of the tallest surrounding structure should be adequate to minimize downwash effects in the vicinity of a source. This rule is based primarily upon direct observations from existing facilities.

A third possible criterion of tallness is the relationship between stack height and some reasonably persistent, key feature of the atmosphere, such as the depth of the planetary boundary layer. Tall stacks, for example, could be designated as those whose plumes penetrate the top of the boundary layer under a majority of circumstances. Unfortunately, the large variability and rather poor definition of such atmospheric features makes such distinctions of relatively little value for present purposes.

Consideration of the above possibilities in the context of the objectives of this report leads to the conclusion that possession of a set criterion for "tall" stacks is unimportant. Accordingly, we shall focus primarily on variations of plume behavior with release height, and deemphasize any arbitrary demarkations between "tall" and "short" chimneys. Some of the more pertinent aspects of the interactions of high plumes in the planetary boundary will be presented in Section IV of this report.

SECTION IV

POTENTIAL CONSEQUENCES OF INCREASED STACK HEIGHT -- ATMOSPHERIC INTERACTIONS

PRELIMINARY ANALYSIS

Upon emission into the atmosphere from an elevated source, an effluent plume is transported and diluted into its surrounding environment by a variety of mechanisms. In addition to its lateral acceleration and advection by the prevailing mean wind, the effluent is transported vertically by virtue of its exit momentum and its buoyancy to an extent governed both by the effluent's exit properties and by those of the surrounding atmosphere. Pronounced velocity gradients and other perturbations which occur during this process promote turbulence, and this combined with local environmental turbulence leads to further dilution of the plume by diffusion.

Upon considering these features in the context of the highly variable and structured nature of the lower troposphere, it is immediately evident that increasing the height of an effluent's release may modify its subsequent atmospheric behavior in a number of ways. Specifically, and insofar as purely the effects of transport and dispersion are concerned, increasing an effluent's release height may be expected to:

- Provide a greater transport distance -- and therefore a greater time for atmospheric dispersion -- both vertically and horizontally between the release point and ground-level receptors. Ostensibly this should result in a lowering of ground-level concentrations to values below those resulting from the use of shorter stacks.

- Release the effluent in a region less affected by aerodynamic downwash, thus preventing high, local, ground-level concentrations that might otherwise be encountered.

- Emit the effluent in a region where wind shear, turbulence, and mean wind direction differ from those features below, thus modifying gross plume structure, concentrations and direction of travel.

- Release the effluent in a region where velocity and vertical temperature structure of the local atmosphere differ from those features below, consequently modifying plume-rise behavior and associated mixing phenomena.

Related to these purely transport-dispersion effects are numerous additional potential modifications of pollutant behavior. It seems obvious that atmospheric residence times of primary pollutants (i.e., those originating at the source) will be extended with increasing stack height, since many of the associated atmospheric natural-recovery processes (dry-deposition, for example), will be altered accordingly. Conversely, some modification of aerial deposition patterns, precipitation chemistry, and associated features should be expected to occur. Residence-time modification of <u>secondary pollutants</u> (those generated by reaction of the primary pollutants) is also expected. The combination of all of the above factors may be expected to result -- to a greater or lesser extent -- in modifying such atmospheric features as visibility, weather, and climate.

INTERACTIONS OF PLUMES FROM TALL STACKS WITHIN THE PLANETARY BOUNDARY LAYER

General Aspects

Because the effects of increased emission height are influenced so profoundly by vertical structure of the atmosphere, it is expedient at this stage to discuss briefly some of the more pertinent aspects of this structure prior to embarking on an analysis of literature in the tall-stack field. Such structural variability results from frictional and thermal interactions of the lower troposphere with the Earth's surface; it is typically most pronounced adjacent to the surface and tends to decay with altitude to approach "free" atmospheric conditions aloft. Such behavior has encouraged the concept of the existence of a well-defined "boundary layer", within which frictional effects influence atmospheric structure directly. This region, which is known as the friction layer or planetary boundary layer, may range from several meters to kilometers in depth, and is influenced by surface roughness and thermal exchange as well as by large-scale pressure gradients. Numerous publications pertaining to aspects of boundary-layer meteorology are available,[28,29,30,31,32,33,34,35] and the reader is referred to these works for a more detailed description than the qualitative treatment presented here.

Within the planetary boundary layer, momentum of the air aloft is transferred by turbulent mixing to the earth's surface, where it is dissipated by friction. Air turbulence necessary for this purpose can be generated by mechanical interaction of the atmosphere with the surface, or by thermal instability. Furthermore stable thermal conditions, when they exist, can act to dampen turbulence generated mechanically and thus discourage mixing processes that might occur under more neutral conditions. This range of possibilities suggests that significant differences should exist between planetary boundary layers in neutral, stable, and unstable environments, and that in addition substantial differences in character should occur with variations in the roughness of underlying terrain.

As indicated previously, vertical variations within the planetary boundary layer typically include the following:

- Variations of wind speed with altitude,
- Variations of wind direction with altitude,
- Variations of turbulence with altitude, and
- Variations of temperature with altitude.

The above variations and the atmospheric relationships leading to their existence have been studied in detail in the lower portions of the planetary boundary layer, and at the present time a great deal of practical knowledge exists pertaining to behavior in this region. Unfortunately, much less is known regarding behavior in regions beyond a few tens of meters from the surface; sufficient knowledge does exist, however, to provide at least a qualitative picture of behavior under more-or-less ideal circumstances, where reasonably uniform air masses and generally persistent synoptic conditions exist.

Idealized characterizations of boundary layer behavior under a variety of such conditions are represented in Figures 5-8, which indicate vertical variations in wind speed, wind direction and diffusivity for cases of neutral, stable, and unstable boundary layers over uniform terrain. These figures were prepared from sounding data published by Pasquill[31] and by Clarke,[36] and represent composite results of numerous measurements. Abscissas for the diagrams express ratios of actual to "free-atmosphere" wind velocities and directions (denoted by subscript G); diffusional behavior is depicted by dimensionless diffusivities $\hat{Km}$*. Three-hundred meter stacks are shown at the left of each diagram to provide some physical appreciation for vertical scale and expected plume behavior. One should note in this context that no corresponding longitudinal distance coordinate is furnished, and this must be implied visually from the vertical scale shown on the graphs.

*Diffusion coefficients are expressed in dimensionless form here using the Coriolis parameter, f and the friction velocity $u^* = \sqrt{\tau/\rho}$, where τ is the surface shear stress and ρ depicts air density. Use of the dimensionless diffusivities ($\hat{K}_M$) rather than their dimensional counterparts (K_M) is necessary because of the manner in which Clarke presented his published data.

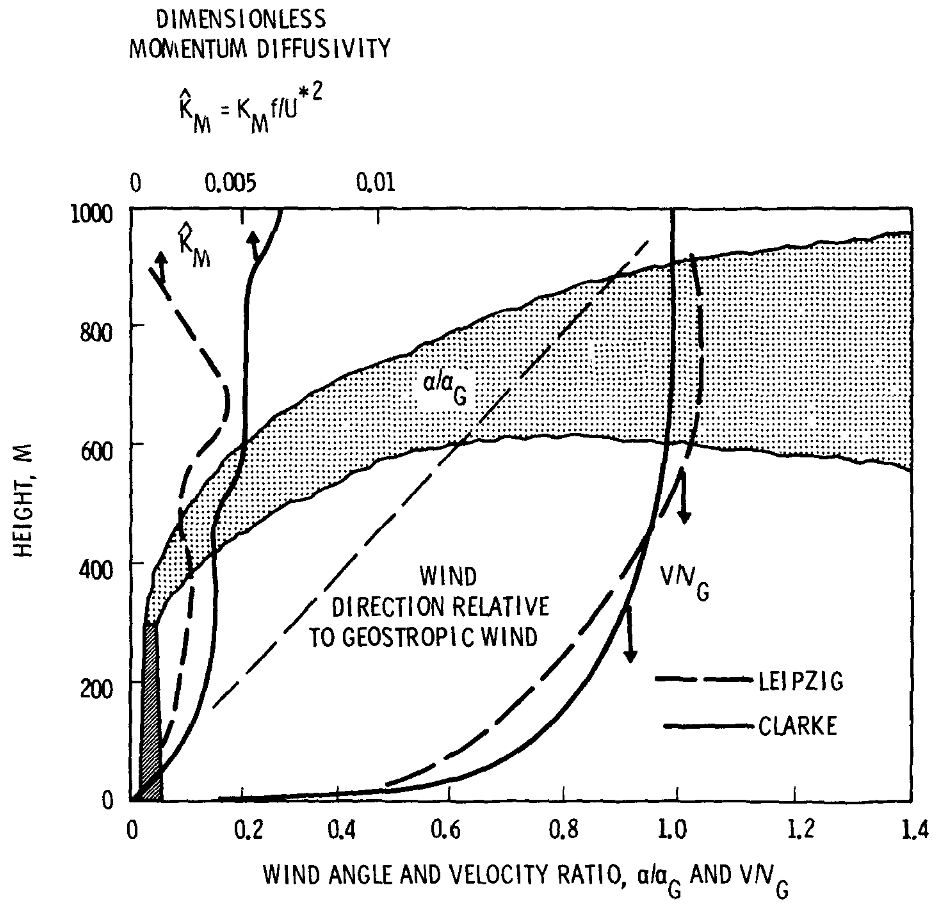

FIGURE 5. Characteristics of Neutral Boundary Layers

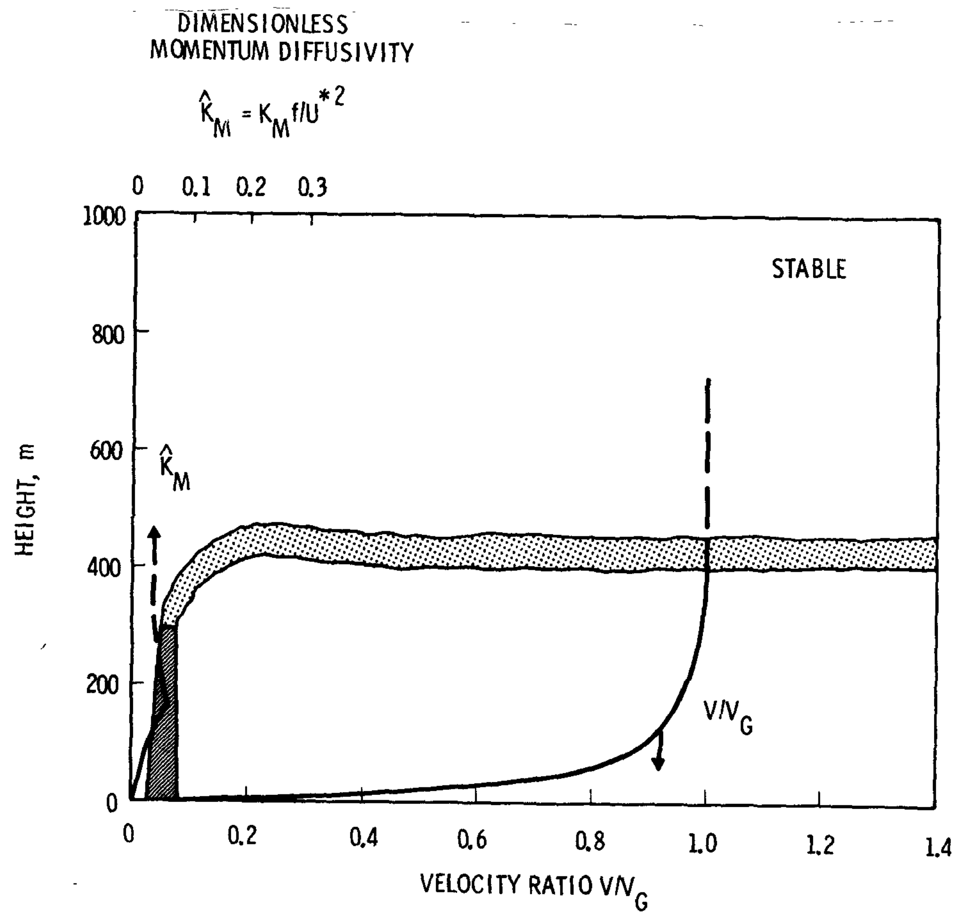

FIGURE 6. Characteristics of Stable Boundary Layers

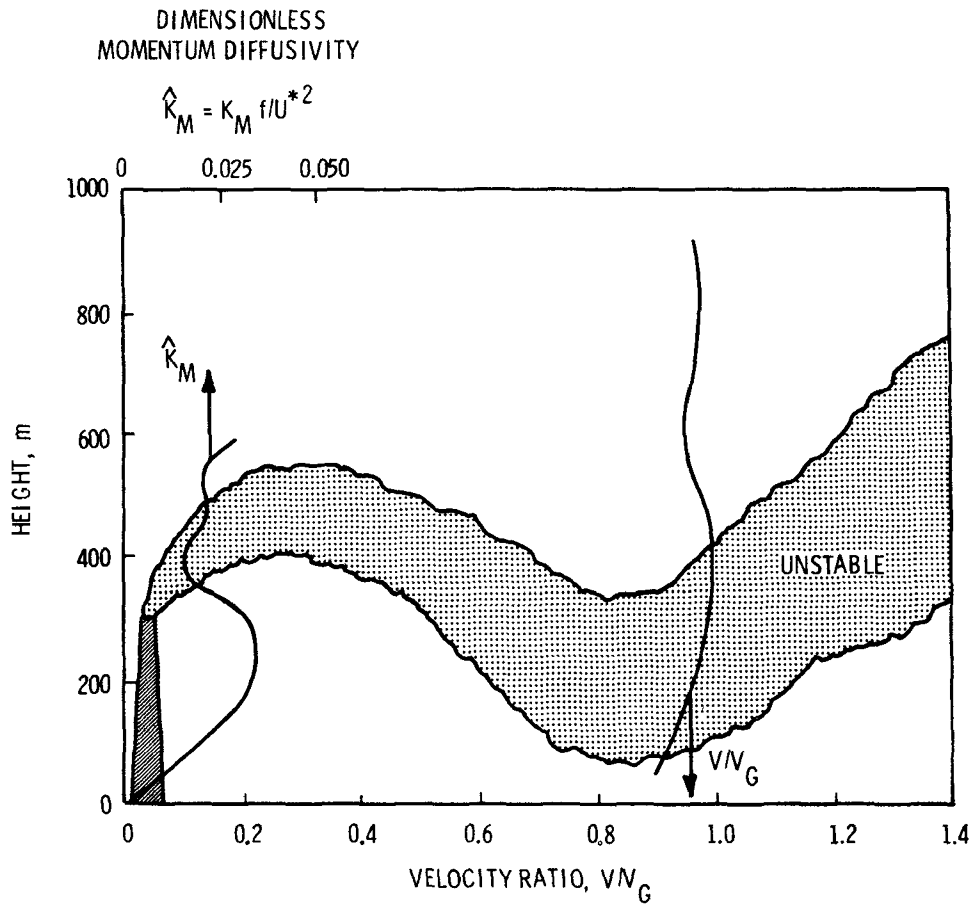

FIGURE 7. Characteristics of Unstable Boundary Layers

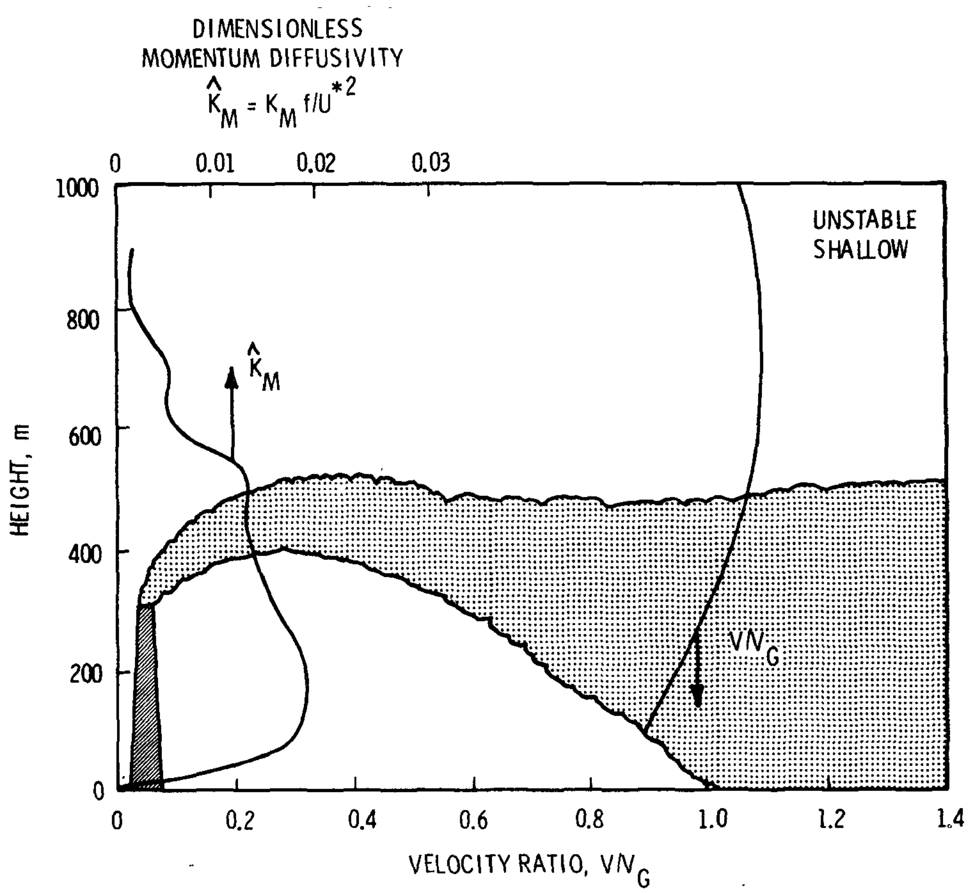

FIGURE 8. Characteristics of Shallow Unstable Boundary Layers; Note lateral compression of schematic plume (see text).

In neutral atmospheres the vertical temperature structure neither promotes nor discourages turbulence, and so the planetary boundary layer is dominated by mixing effects that are generated totally by mechanical interaction with the earth's surface. Such a situation is depicted in Figure 5 which shows results from two data sets: the well-known "Leipzig profile" and that generated by Australian researchers as reported by Clarke. Key points to note from this figure are the depth of the boundary layer relative to the plume height, the veering of the (Leipzig) wind with altitude, and the diffusivity profiles. The diffusivity profiles are particularly noteworthy owing to their direct relationship with plume dilution rates. In view of this importance, it is rather perplexing to observe the extremely poor agreement between the curves representing the German and Australian data in the upper portions of the boundary layer. As discussed by Pasquill[31], this lack of agreement reflects to some extent the general weaknesses in the procedure of applying velocity data as a means for obtaining diffusion parameters. It is also likely, however, that much of this disagreement arises from actual differences in transport behavior between the observed air masses, and provides some indication of variability exhibited by the atmosphere and of our current lack of understanding regarding processes that occur in the upper regions of the planetary boundary layer. This indication is supported also by noting that measurements of turbulence in these regions often have indicated a highly time-variant and rather unpredictable structure.[37,38] It is also supported to some extent by additional analyses of high-elevation diffusion measurements such as those by Shaffer[39] and by Zilitinkevich et. al,[40] who indicate a wide range of diffusional conditions can exist under apparently similar meteorological circumstances.

Under stable atmospheric conditions the change of temperature with height is such that any air parcel that is displaced vertically upward becomes more dense than its surroundings. Under such circumstances, therefore, all vertical displacements of air are discouraged and atmospheric mixing in the planetary boundary layer is minimized.

Stable conditions can be promoted in the atmosphere by a number of phenomena, and the vertical placement and extent of stable layers vary accordingly. Specifically, large-scale subsidence of upper air in high-pressure areas often leads to high-elevation temperature inversions where stable conditions are promoted aloft. Advection of warmer air masses over underlying cool air can also promote stable conditions. Finally, cooling of surface air by nocturnal radiation promotes the well-known radiation inversion, which is commonly associated with urban pollution phenomena.

Figure 6 provides a description of the planetary boundary layer under stable conditions, obtained from further composite balloon sounding data of Clarke. Important points to note here are the reduced vertical extent of the boundary layer as compared to that shown previously for neutral conditions and the low values of K_m near the gound. From these features, it is readily apparent that stacks sufficiently tall to clear such low-elevation, stable boundary layers benefit substantially from the fact that, owing to the low turbulence and favorable buoyancy, diffusion of effluent to the ground is minimized. Stable layers aloft such as those associated with subsidence inversions, however, may be expected to have somewhat the opposite effect, and have been noted (c.f. Montgomery [1968]) as conditions under which the value of tall stacks (up to any currently practical height, at least) is limited.

Under unstable atmospheric conditions the temperature decreases with height at a rate sufficiently large so that any air parcel displaced upward becomes less dense than its surroundings. Under such circumstances vertical displacements of air tend to occur spontaneously, with a subsequent high rate of mixing in the boundary layer. As noted by Plate[29], this case where mixing is dominated by thermally-generated turbulence can be considered as a situation opposite to that of neutral boundary layers (mixing induced totally by frictional effects).

Unstable conditions can be promoted by advection, by water condensation and precipitation phenomena, and by radiational heating of surface layers. A schematic diagram of the planetary boundary layer, under conditions where the unstable layer is large in vertical extent, is shown in Figure 7. Particularly noteworthy aspects of Figure 7 are the deepness of the planetary boundary layer, the disturbed nature of the vertical velocity profile, and the high level of turbulence (as reflected by $\hat{K}_M$).

Under conditions where unstable atmospheres occur close to the surface and are bounded by more stable layers aloft, the associated decay of turbulence with height limits mixing except in layers close to the ground. A composite schematic depicting the planetary boundary layer under such circumstances is shown in Figure 8. If stack height is sufficient to essentially prevent the effluents' contact with the underlying turbulent region, then mixing of pollutants to ground level will be minimized. On the other hand, if the vertical extent of the turbulent boundary layer is sufficient to envelope the plume, then high ground-level concentrations may occur as a consequence of the concentrated plume being rapidly transported downward. Typically, contact of the plume with the ground by this mechanism occurs only at moderately large distances downwind from the source. In this context one should note that the apparent downwind distance of the contact of the schematic plume in Figure 8 is unrealistic since, owing to the problem of presenting it on the graph, the schematic plume has been "compressed" in the longitudinal direction. This mechanism for promoting high ground-level concentrations has been cited as potentially one of the most disadvantageous for tall stacks (Pooler [1964]) and a number of field studies have been conducted to examine this effect.

Effects of Surface Roughness

Since turbulence in planetary boundary layers in neutral environments is generated by mechanical interaction with the earth's surface, it follows that the character of the boundary layer should depend strongly upon surface roughness. This effect is illustrated in Figure 9, which is a plot of velocity profiles in neutrally-stratified boundary layers over areas of different surface roughness. These profiles, calculated from empirical relationships given by Davenport (c.f. Plate[29]), show a dramatic change in boundary-layer depth with changes in terrain. Again the implications with regard to effects of stack height are obvious.

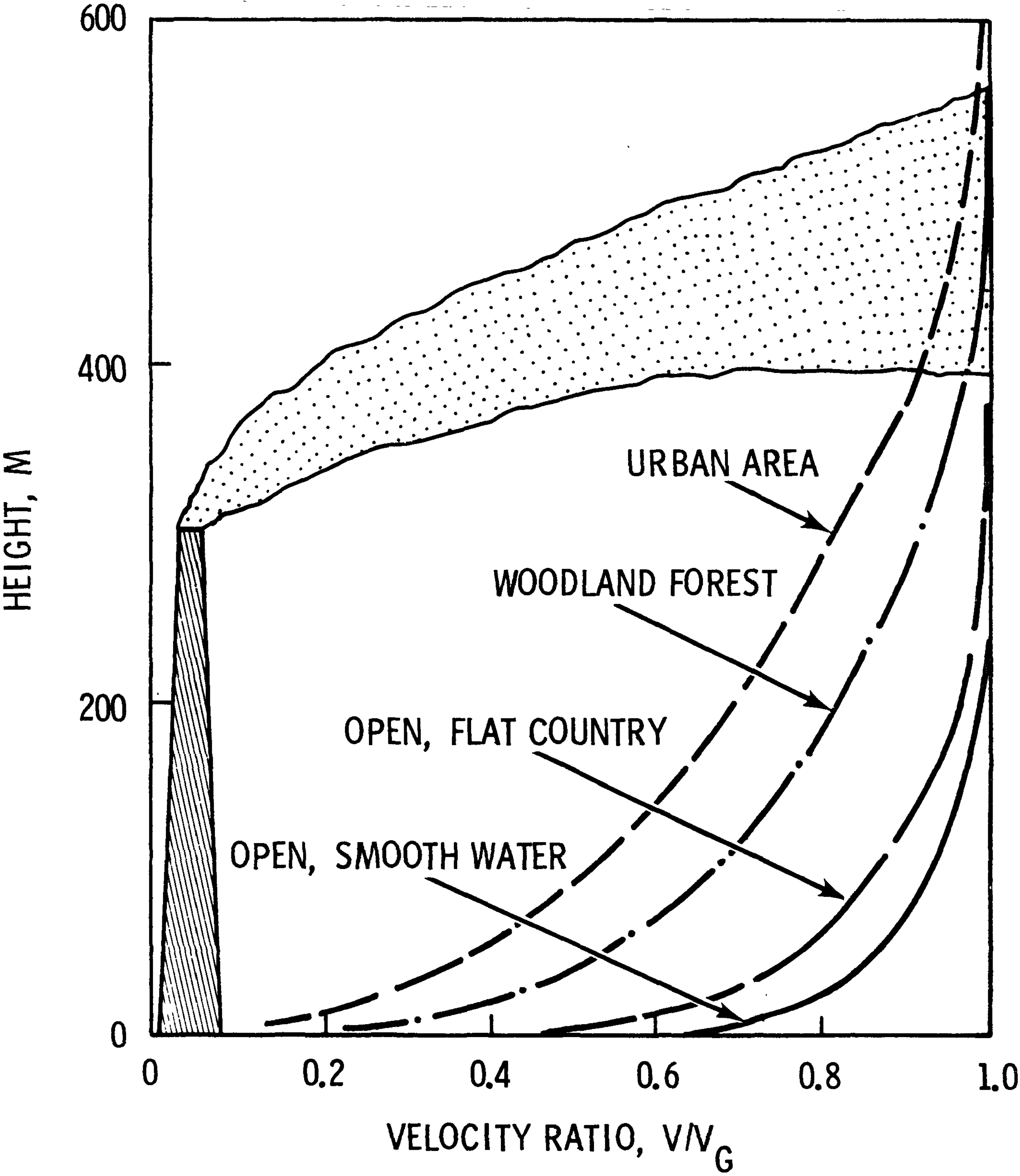

FIGURE 9. Effects of Surface Roughness on Neutral Boundary Layers

Under stable conditions, mixing in the boundary layer is constrained, and any perturbations induced by mechanical interactions will be dampened accordingly. Under highly unstable conditions the turbulence is dominated by thermal effects, and the effect of surface roughness will be attenuated from that experienced under neutral conditions.

Atmospheric Complexities and their Implications with Regard to Stack Height

The foregoing description of planetary boundary layers was presented in a rather idealized manner to portray some of the more pertinent aspects of plume interactions in the atmosphere and the associated significance of emission height. It is important at this point, therefore, to indicate some additional complications experienced in the atmosphere and to point out how these nonidealities could possibly affect the performance of all tall stacks.

The first point in this regard is the realization that the atmospheres considered in Figures 5-8 were taken essentially as steady-state, uniform air masses, far removed from any fronts or associated discontinuities. The exceedingly complex flows in frontal situations involving transients in wind fields, mixing, and stability, can be expected to influence plume behavior accordingly. In addition, the precipitation systems commonly associated with fronts pose an additional degree of complexity -- both in atmospheric dynamics and in the wet removal process. Little quantitative information is available concerning pollutant mixing and transport in frontal systems, although this subject is receiving increased research emphasis at the present time.[41,42]

The second area of non-ideality reflects the assumption of a steady-state process in the previous discussion. In real situations transients always exist and can appear through a number of phenomena. As indicated previously, it has been noted that upper boundary-layer turbulence can vary significantly with both time and space. The tacit assumption of stationary, isotropic, uniform turbulence at any given elevation used to derive the K_M values in Figures 5-8 is challenged accordingly.

Effects of Plume Rise

As indicated previously, plume-rise considerations are an important factor in determining both the transport and the dispersion of effluent material, especially at locations near the source. For any given source an increase in plume rise may modify plume behavior for the same variety of reasons cited previously in the context of increased stack height. Moreover, turbulence generated by a rising plume is often a predominant factor in determining mixing processes during its early stages. In noting these features, it is important also to observe that plume-rise behavior is influenced strongly by atmospheric conditions in the vicinity of the stack exit. Thus, increasing a stack's height may result in a combination of effects related to the plume-rise phenomenon.

Plume rise has been the subject of a number of comprehensive reviews during the recent past, and these have been summarized and extended by Briggs[43,44]. The reader is referred to these publications for a detailed quantitative examination of plume rise phenomena.

Applied Diffusion Modeling of Plume Behavior in Upper Regions of the Planetary Boundary Layer

During recent years, a substantial amount of mathematical modeling has been devoted to describing the behavior of effluent released from tall stacks. Models of transport and diffusion of plumes from both high and low sources have been summarized in a number of recent reviews[31,32,45,46,47,48,49,50] and Pasquill[45] has classified these efforts into individual categories, which include

- Statistical Theory
- Gradient Transfer Theory
- Similarity Theory, and
- Higher-Order Closure Theory.

Although efforts in the above areas have resulted in some highly sophisticated and/or complex new treatments, it is interesting to note that the overwhelming preponderance of applied models utilized for practical tall-stack analysis has occurred through direct or modified extension of simple traditional forms such as those advanced in the early works of Sutton and Pasquill. To account for such effects as directional shear and variations in diffusivity with height, these extensions have taken the approach of (1) applying modified dispersion parameters obtained from elevated-source data to existing formulae or (2) modifying the basic formulae themselves. Numerous examples of applications of this type appear in the literature review presented in the following section and in the annotated bibliography which appears in Appendix C.

SECTION V

THE AIR QUALITY IMPACT OF TALL STACKS AS ISOLATED SOURCES

INTRODUCTION

The purposes of this and the following section are to (1) review the published literature concerning tall stacks, and (2) utilize this information to indicate the effectiveness of tall stacks in achieving acceptable levels of ambient air quality. In accordance with the direction indicated in Section I, the present section addresses the question of tall-stack performance under the rather hypothetical "isolated-source" conditions wherein interactions of the plume with pollutants from other sources are assumed negligible. Section VI is concerned primarily with interacting plumes, and focuses more strongly upon aspects of long range transport. Literature discussed in the present section is presented in summarized form in the annotated bibliography appearing in Appendix C.

FIELD STUDIES OF TALL STACK PERFORMANCE

Following the pioneering investigations performed by Hewson and Gill[52] near the smelter at Trail, British Columbia, a number of field studies in the United States, Great Britain, and elsewhere have been conducted to assess transport and dispersion properties of plumes from tall stacks. Although pollution from other "background" sources was noted in several of these studies, these analyses were conducted basically to assess stack emissions as individual sources. While many pertinent measurements have been conducted privately and are not generally available at the present time, the open literature does contain a sufficient quantity of material for a reasonably complete evaluation insofar as pollution by SO_2 is concerned. Much less information is available concerning other pollutants, especially those such as sulfate which are formed by reaction of primary pollutants and are accordingly more difficult to evaluate.

Table 1 provides a summary of some of the more pertinent field investigations that have been documented in the open literature, and at the outset it should be noted that even in the simplified context of isolated-source conditions a concise presentation of this material is complicated by several factors. The first of these arises from the large number of physical variables in addition to stack height that influence air quality and are reported to varying degrees of completeness in the literature. These variables include firing conditions, fuel composition (especially with regard to sulfur content), topography, and meteorological circumstances. Although some consolidation of these features can be achieved with the use of dispersion models, they are difficult to treat in a concise manner that is totally satisfactory for the present analysis.

The necessity to intercompare air quality measurements arising from a large variety of sampling times and sampler arrays adds an additional degree of complexity, with sample averaging time being a particularly

TABLE 1.

SUMMARY OF PERTINENT FIELD INVESTIGATIONS OF TALL-STACK PLUME DISPERSION

Investigation	Location and Plant(s) (Mwe/s.h. (m))*	Period	Description of Measurements	Reference (in Appendix B)
Large Power Plant Effluent Study (LAPPES)	Western Pennsylvania Keystone (1800/244) Homer City (1280/244) Conemaugh (1300/305)	1967-1971	Helicopter SO_2, Ground Level Bubblers, Met. Support, LIDAR, Aerosols, Turbulence, Helicopter SO_2	Schiermeier (1970, 1972) Pooler and Niemeyer (1970) Niemeyer and Schiermeier (1969) Johnson and Uthe (1969, 1971) Johnson (1969) Niemann, et al. (1970) Proudfit (1970)
Full Scale Study of Inversion Breakup at Large Power Plants	Kentucky/ Tennessee Paradise (1908/183) Shawnee (1500/76) Johnsonville (1350/82, 122)	1966	Helicopter SO_2, Ground Level Monitors, Met. Support	TVA (1970) Montgomery, et al. (1973) Carpenter, et al. (1971)
Full Scale Study of Trapping at Large Power Plants	Kentucky/ Tennessee Paradise (1908/183) Bull Run (900/244)	1970	Helicopter SO_2, Ground Level Monitors, Met. Support	TVA (1970) Montgomery, et al. (1973) Carpenter, et al. (1971)
Full Scale Study of Plume Rise at Large Power Plants	Southern U.S. Paradise (1908/183) Gallatin (1256/152) Shawnee (1750/76) Johnsonville (691/123) Colbert (4824/91) Widows Creek (525/152)	1962-1965	Helicopter Soundings and Met. Support; Plume Photography	Carpenter, et al. (1968) Gartrell, et al. (1965) Thomas, et al. (1970)
Full Scale Study of Plume Dispersion at Large Power Plants	Alabama/ Tennessee Colburt (800/91) Gallatin (1256/152)	1958-1962	Helicopter SO_2, Met. Support	Gartrell, et al. (1965) Thomas (1969) Thomas, et al. (1963) Gartrell (1964)
Muskingum River Measurements	Ohio Muskingum River (1440/251)	1969-1973	Ground Level SO_2 Monitoring Network	Smith and Frankenberg (1975)
Cardinal Measurements	Ohio Cardinal (1200/251)	1965-1969	Ground Level SO_2 Monitoring Network	Frankenberg, et al. (1970)

*Denotes megawatts electrical output/stack height in meters.

TABLE 1. (Continued)

Investigation	Location and Plant(s) (Mwe/s.h. (m))*	Period	Description of Measurements	References (in Appendix B)
Clifty Creek/ Kyger Creek Measurements	Ohio Clifty Creek (1300/208) Kyger Creek (1100/163)	1952-1959	Ground Level SO_2 Monitoring Network	Frankenberg (1968)
Navajo Measurements	Arizona Navajo (2250/236)	1974-1975	Ground Level SO_2 Monitoring Network, Aircraft SO_2 Tracing, Met. Support	Navajo (1975)
CEGB Routine Surveys	England/ Wales Kingsnorth (2000/198) Fawley (2000/198) Pembroke (2000/213) Ratcliffe (2000/198) Eggborough (2000/198) Fiddler's Ferry (2000/198)	1966-1973	Ground Level SO_2, Monitoring Network	Clarke and Spurr, et al. (1975)
High Marnham/ West Burton Studies	England High Marnham (1000/137) West Burton (2000/183)	1963-1969	Ground Level SO_2, Monitoring Network, LIDAR, Elevated SO_2 Samplers	Martin and Barber (1967,1973) Stone and Clarke (1967)
Tilbury Study	England Tilbury (360/100) Northfleet (720/150)	1962-1966	Ground Level SO_2, Monitoring Network, Extensive Met. Support, LIDAR, Searchlight	Stone and Clarke (1967) Lucas, et al. (1967) Moore (1969, (1974) Scriven (1967), (1969)
Lake Michigan Studies	Illinois/ Wisconsin Oak Creek (s.h. up to 168 m) Waukegan (s.h. up to 137 m)	1970-1974	Ground Level/Airborne SO_2 and Particulate Met. Support, Turbulence	Lyons, et al. (1972), (1974)
ARL Studies	Utah Huntington Canyon (s.h. = 183 m) Garfield Smelter (s.h. = 122 m)	1973	Airborne and Surface SF_6 Measurements, Met. Support	Start, et al. (1974), (1975)
Sioux Study	Missouri (1050/183)	1968-1970	Ground Level SO_2, Monitoring Network, Met, Support	McLaughlin, et al. (1970)

important factor. Pollutant concentrations reported in the literature correspond to averaging times ranging from "instantaneous" to over 24 hours. Because of the complex nature of plume fluctuations, these values are difficult to intercompare on a meaningful and straightforward basis. Attempts to overcome this difficulty have generally followed a semiempirical statistical approach, and often have resulted in expressions relating "peak-to-mean" ratios to averaging time, i.e.,

$$\text{peak-to-mean ratio} = \frac{\text{maximum concentration observed at reference averaging time } t^*}{\text{concentration observed at any time } t > t^*} = f(t) \quad . \tag{1}$$

The substantial amount of material devoted to this subject in the literature[53-65] indicates in general that peak-to-mean relationships tend to be rather specific to given source and meteorological conditions. These relationships will be applied, when appropriate, in the following discussion.

A final complicating factor in the present analysis is the existence of essentially two basic types of field studies of tall-stack performance. The first of these types is composed basically of long-term monitoring studies involving the use of fixed samplers over extended periods of time. The second type of field study is that which is addressed primarily to the assessment of specific physical circumstances expected to be important in promoting high ambient pollutant concentrations. The following text is subdivided accordingly to provide a discussion of pertinent long-term monitoring studies, followed by consideration of the more specific investigations.

Field Studies of Tall Stack Performance:
Long Term Monitoring Studies

Although field studies involving long-term monitoring with fixed sampling networks lack some of the desirable features of the more specifically oriented investigations, they offer the distinct advantage of providing records over lengths of time sufficient to complete climatological assessments and relate directly to the longer term ambient air quality standards. Furthermore, their continuous nature obviously allows them to provide some indication of stack performance under specific, critical meteorological conditions even though their fixed placement precludes sampling in the most pertinent locations under all circumstances.

The most significant tall-stack monitoring studies that have been conducted within the United States and documented in the open literature thus far are those performed near plants in the American Electric Power (AEP) and Tennessee Valley Authority (TVA) networks. The first significant study of this type conducted within the AEP network was a comparatively limited investigation involving SO_2 sampling in the vicinity of two plants located in a comparatively low background area (Frankenberg (1968)). These plants (Clifty Creek s.h. = 208 m and Kyger Creek s.h. = 163 m) were surveyed between 1955 and 1959 by placing three monitors at locations near each plant. Analysis of the approximately four-year span of data revealed no hourly concentrations in excess of 1 ppm. There appeared to be a tendency for higher concentrations to occur during mid-morning hours and on a elevated plateau in the vicinity of the Clifty Creek plant. Concentrations measured by the monitors, however, tended to be lower than those predicted, especially in situations involving inversion-breakup conditions.

Following the Clifty Creek and Kyger Creek investigations, a somewhat more detailed field study was conducted at the Ohio River site of the then proposed Cardinal plant (Frankenberg, et al., (1970)). Somewhat in contrast to the previous situations, this site was characterized by rather high background SO_2 levels which were produced in part by contributions of two smaller, existing power plants (Windsor and Tidd), both having stacks less than 100 meters high. Accordingly, a primary objective of the Cardinal study was to assess SO_2 pollution levels before and after operation of the new plant to evaluate its contribution to total ambient concentrations.

The array of SO_2 monitors consisted of six units located at distances between about three and ten miles in the prevailing downwind direction from the plant. Average yearly, daily and hourly concentrations obtained prior and subsequent to plant operation were somewhat inconclusive with respect to the contribution of ground level SO_2 from the 251 meter stacks of the new

1200 Mwe facility. Although the SO_2 levels monitored by the stations were often higher than those allowed by present ambient air quality standards, it was apparent that most of the pollutant had originated from sources other than the Cardinal plant. The authors conclude that although long-term monitoring is necessary to establish the changes caused by the plant's presence, the data obtained to date suggest these effects to be minimal, even under adverse meteorological situations.

The results of a study reported very recently pertain to the measurement of ambient concentrations downwind from the Muskingum River plant (Smith and Frankenberg (1975)) during and after the period its stacks were being modified from 83 meters to 251 meters in height. The SO_2 emission rate from this plant is approximately 10 kg/sec. Data obtained from the four SO_2 monitors employed for this investigation indicate that a significant decrease in ground level SO_2 concentrations occurred after the new stacks were put into operation, and all National Ambient Air Quality Standards have been maintained since that time.

Monitoring studies conducted by the TVA have included extensive measurements in areas surrounding each of their major generating facilities. In general, these long-term monitoring results can be described most adequately in terms of the semiempirical dispersion relationships developed by the TVA for practical estimation purposes (cf Montgomery, et al.,(1973)). These will be discussed in greater detail later in the context of specific meteorological circumstances.

The results of a relatively short-term, but extensive, monitoring study in the vicinity of the new Navajo plant (s.h. = 236 m) near Page, Arizona have been documented, (Navajo (1975)). As with the TVA work, this monitoring was conducted concurrently with intensive support investigations to elucidate effects of specific meteorological and physical circumstances; accordingly, a more detailed discussion of this study will be deferred until later in this section.

Further studies along these general lines have been conducted outside of the United States, especially in Great Britain as a consequence of activities of the Central Electricity Generating Board (C.E.G.B.) which is a publicly-owned organization responsible for construction and operation of all major electric utilities in England and Wales. The earliest such investigation of significance to the present discussion is the High Marnham study, which was conducted during the period between 1963 and 1965, (Stone and Clark (1967), Martin and Barber (1966)). The relatively low (137 m) stacks of the High Marnham plant make this study of somewhat marginal interest in the present context, but it is significant in that it typifies the findings of all succeeding C.E.G.B. studies involving high stacks. Specifically, these findings are that air quality downwind from tall stacks in England generally is dictated primarily by low-elevation background sources, and that the contributions of high-elevation releases are difficult to ascertain under such circumstances. In the High Marnham survey a compilation of data obtained from the 16 SO_2 monitors located in the plant's vicinity indicated maximum hourly concentrations up to 0.5 ppm arising from the plant alone, while those from combined sources ranged up to roughly 0.7 ppm. The highest observed 24-hour concentration arising from the High Marnham power plant was 0.11 ppm, indicating that - as an isolated source - the plant should not have difficulty in maintaining primary Federal Ambient Air Quality Standards. In comparing these results with those obtained by the AEP and TVA networks, however, one should note that the 1-2 percent sulfur content of coal burned by the British plants is significantly lower than that typically burned in the eastern United States. This corresponds to emission rates that often are more than four times less than those from comparably sized eastern United States plants, and the resulting ambient SO_2 concentrations must be judged accordingly.

A composite set of investigations for six British power plants has been reported recently by the C.E.G.B. (cf Clarke and Spurr (1975)) which gives additional information on operation of tall stacks from some of the largest facilities now in existence in Great Britain. The plants chosen for this survey are each of 2000 Mwe output capacity, and are distributed widely throughout England and Wales providing a range of topographical and meteorological conditions. Included are the Kingsworth, Fawley, Pembroke, Ratcliffe, Eggborough, and Fiddlers Ferry plants; with the exception of Pembroke (s.h. = 213 m) the stack height on each of these plants is 198 meters. Full-load emission rates for these plants range from about 2 to 8 kg SO_2/sec.

Long-term monitoring was conducted using automatic SO_2 instrumentation at approximately twelve selected sites located around each plant at distances out to about 20 kilometers. Monthly and seasonal trends were analyzed, and statistical comparisons of daily results were obtained using upwind versus downwind data.

The common conclusion reached from an analysis of data from all six power plants was that, although a great deal of variability in surface SO_2 concentrations occurred in the vicinity of the plants, these levels were accountable almost totally to background sources. The authors state that "in all six cases studied it is not possible to detect an effect from the power station on the trends of monthly and seasonal averages of sulfur dioxide pollution levels". Insofar as daily averages are concerned, they estimate that contributions to the surface concentrations by the plants were less than about 0.01 ppm.

The indication of the long-term monitoring results presented thus far is that, insofar as SO_2 concentrations at ground level are concerned, considerable benefit is achieved by implementation of stacks with increased height. This indication may be criticized in part because, owing to the fixed locations of the pollutant monitors in these studies, they were limited in their ability to seek out regions of maximum concentration during specific conditions. Further studies using mobile samplers in attempts to resolve this difficulty are described in the following section.

Field Studies of Tall Stack Performance:

Specific Circumstances Leading to High Surface Concentrations

The previous text has indicated that a number of specific physical conditions have been identified as potentially important in promoting high surface concentrations of pollutants emitted from tall stacks. Several field studies have been conducted to assess the relative importance of these conditions, and in general it has been found that those most critical for a given plant depend primarily upon local climatology and topography, with stack height being an important deciding factor as well. As stack heights have increased, there has been a marked corresponding change in meteorological conditions associated with high ground-level concentrations in their vicinity.

Critical conditions most commonly discussed in the literature are summarized in Table 2. While the preceeding discussion has touched upon some of these conditions in its description of long-term monitoring studies, the present discussion is addressed more specifically to investigations pertaining directly to these categories.

TABLE 2.
SUMMARY OF OBSERVED AND POSTULATED CONDITIONS
FOR HIGH GROUND LEVEL CONCENTRATIONS
IN THE VICINITY OF TALL CHIMNEYS

Physical Conditions	Studies Of Plume Behavior Under Noted Conditions
High Wind, Neutral Conditions	Gartrell (1965), Carpenter, et al. (1971), Pooler and Niemeyer (1970), Thomas, et al. (1963)
Inversion Breakup	TVA (1970), Pooler (1965), Schiermeier (1970, 1972), Frankenberg (1968), Frankenberg, et al. (1968), Montgomery, et al. (1973), Johnson (1969), Carpenter, et al. (1971), Navajo (1975)
Shoreline/Urban Phenomena (Fumigations and Recirculation)	Van der Hoven (1967), Lyons, et al. (1972), Lyons and Cole (1973), Clarke (1969)
Thermal Instability - Looping Plumes	Schiermeier (1970, 1972), Martin and Barber (1967, 1973), Stone and Clarke (1967)
Trapping by High Inversions (Especially Under Stagnation Conditions)	Thomas (1969), Pooler and Niemeyer (1970), Johnson and Uthe (1969, 1971), Montgomery, et al. (1973), Carpenter, et al. (1971)
Complex Terrain	Schiermeier (1972), Start, et al. (1974), Navajo (1975)

Moderate Wind Speed, Neutral Conditions

Moderate wind speed, neutral conditions have been traditionally associated with high surface concentrations downwind from shorter stacks, and there has been some early concern (Gartrell (1965), Thomas, et al. (1963)) that such conditions may adversely affect the performance of tall stacks as well. The basic reason that such conditions are important is that, although greater wind speeds result in more efficient dilution of the plume, they also attenuate plume rise; and these two effects work counter to one another in establishing corresponding ground level concentrations. The expected result is that concentration should vary with wind velocity and maximize at some "critical wind speed", which is dictated by plant operating conditions and by meteorology (cf. Nelson and Shenfeld (1965)).

More recent field studies, however, (cf. Carpenter, et al [1973]), have indicated that surface concentrations downwind from tall stacks should be less dependent on this effect. While there is still some disagreement concerning this point at the present time[46], it appears that moderate wind-speed, neutral conditions are not usually of critical importance insofar as taller stacks are concerned.

Surface-Inversion Breakup

More recently the conditions of surface-inversion breakup have received considerable attention for their importance in promoting high ground level concentrations in the vicinity of tall stacks. The most important class of these conditions occurs when solar heating of the surface creates low-level instabilities in the nocturnal inversion layer. The rapid mixing thus induced causes the plume to be transported to ground level, as indicated schematically in Figure 8.

As a result of extensive monitoring and special studies in conjunction with its fossil-fuel fired power plants (note Table 1), the TVA (cf. Montgomery, et al. (1973)) has identified the inversion-breakup condition as one of the more disadvantageous insofar as high concentrations in the vicinity of tall stacks are concerned. These authors note that in the TVA regions nocturnal inversion-breakup conditions may occur on 200-300 days of the year. The magnitudes of the resulting ground level concentrations often are not significant, however, owing to limited vertical propagation of the mixed layers. In addition, high surface concentrations resulting from inversion breakup are of relatively short (30-40 min) duration, owing to the transient nature of the phenomena involved.

During the past decade two large federally-sponsored investigations have been conducted which have provided substantial information with regard to tall-stack performance under inversion breakup conditions. The first of these was the TVA "Full Scale Study of Inversion Breakup at Large Power Plants", which was conducted during 1966. The second was the NAPCA (now EPA) "Large Power Plant Effluent Study" (LAPPES), completed in 1971 (note Table 1). Both of these studies involved helicopter measurement of ground-level concentrations using relatively fast-response SO_2 instrumentation.

The TVA study focused upon three steam plants with the stack heights shown in Table 3. Helicopter measurements during this series included pre-breakup plume cross sections and longitudinal ground-level flights after inversion breakup was in progress. This study was limited to sixteen test days with helicopter operation.

TABLE 3. Power Plants Included in the TVA Full Scale Study of Inversion Breakup

Plant	Stack Height(s) m
Paradise	183
Johnsonville	122 and 82
Shawnee	76

Surface SO_2 measurements obtained by the helicopter were averaged with respect to time to arrive at the hourly concentrations shown in Table 4. Although averages over periods exceeding one hour were not presented, the TVA group (cf. Montgomery, et al. (1973)) suggests their estimation utilizing a peak-to-mean approach which involves multiplying the hourly values by 2/3 and 1/5 to obtain respective estimates of the 3- and 24-hour averages. Estimates obtained in this fashion are included in Table 4, along with lower-limit estimates computed on the assumption that the plumes were totally absent at times other than the original one-hour periods.

Although limited to only a few sampling days, the data provided in this study are significant in the sense that they demonstrate that substantial portions of the plume from a tall stack such as that at the Paradise plant can be brought to ground level during the inversion breakup process. Furthermore there is strong evidence that even though observed instantaneous concentrations may be rather high, the persistence of the breakup process is of sufficiently short duration so that concentrations averaged over 3- and 24-hour terms are reduced appreciably.

The TVA has utilized the data in Table 4 to develop a correlation for ground-level concentration under inversion breakup conditions. This correlation applies only to situations where the plume is sufficiently low to be captured by the inversion breakup process, and the TVA researchers suggest that inversion-breakup conditions should serve to reduce ground-level concentrations in at least two ways. The first of these arises simply from the fact

TABLE 4.
SUMMARY OF TVA RESULTS FOR
INVERSION BREAKUP FUMIGATIONS

Date 1966	Plant	SO_2 Emission Rate kg/sec	Distance from Plant km	Average Ground Level, Centerline SO_2 Concentrations (ppm) Hourly	3-hr Estimates*	24-hr Estimates*
9/16	Paradise (s.h. = 183 m)	5.3	14	0.52	.35 (.17)	.10 (.02)
9/29		5.0	14	0.27	.18 (.09)	.05 (.01)
9/22		4.8	5	0.72	.48 (.24)	.14 (.03)
10/3		5.0	11	0.18	.12 (.06)	.04 (.01)
10/5	Shawnee	8.3	8	0.40	.27 (.13)	.08 (.02)
10/6		7.9	8	1.10	.73 (.37)	.22 (.05)
10/7		6.1	6	0.88	.59 (.24)	.18 (.04)
10/11		7.9	6	1.18	.79 (.39)	.24 (.05)
10/28	Johnsonville (s.h. - 122, 82 m)	5.3	16	0.74	.49 (.25)	.15 (.03)
10/25	- 82 m stack only -	4.6	24	0.57	.38 (.19)	.11 (.02)

*See Text

Note: National Ambient Air Quality SO_2 Standards are 0.50 and 0.14 ppm for 3-hr and 24-hr averaging times.

that an increase in the (effective) stack height serves to provide greater dilution of the effluent. The second effect, as indicated previously, occurs because an increasing emission height tends to reduce the number of circumstances under which the plume may be captured within the inversion-breakup process.

A simple example of predictions based upon the TVA correlation is shown in Figure 10. This plot gives expected maximum hourly SO_2 concentrations under inversion breakup conditions as a function of stack height, and is based upon assumed values of emission rate, plume rise and wind speed typical of those experienced with a large power plant.*

*These calculations may be performed conveniently using the TVA monograms (Montgomery et al. (1973)).

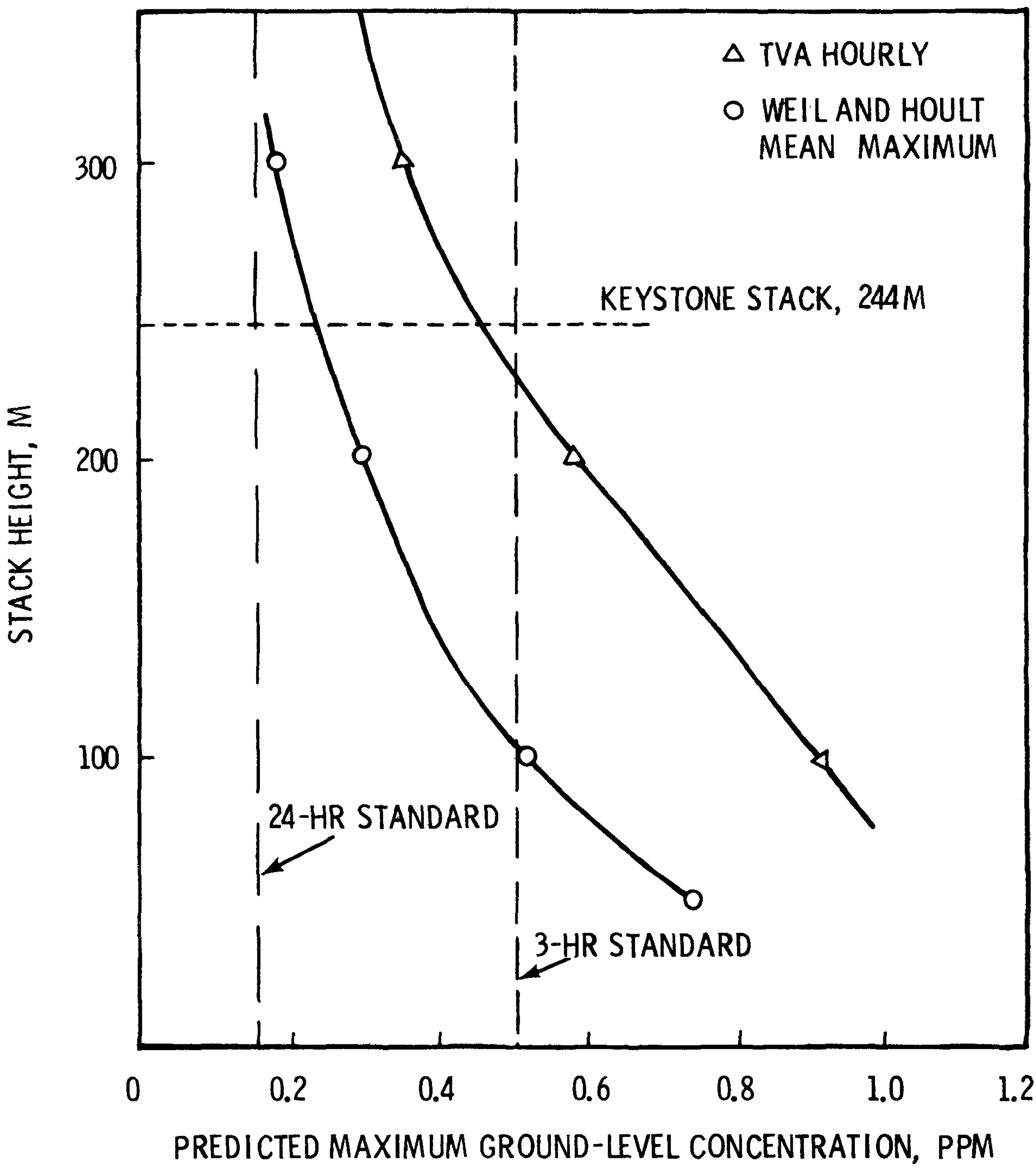

FIGURE 10. Calculated Ground-Level Concentrations During Inversion Breakup Based upon Q = 4 kg/sec, $\bar{u}$ = 5 m/sec, and Δh = 200 meters.

The Large Power Plant Effluent Study (LAPPES) helicopter measurements were conducted in a manner rather similar to those performed in the TVA study. These involved cross-sectioning of the plumes at various (4, 10, and 16 km) distances downwind from the source, as well as ground-level flights downwind along and normal to the plume centerlines. Stack heights and typical SO_2 emission rates of the three power plants included in the LAPPES program are given in Table 5.

TABLE 5.
POWER PLANTS INCLUDED
IN THE LAPPES INVESTIGATION

Plant	Stack Height(s)	Typical SO_2 Emission Rate at FULL LOAD kg/sec
	m	
Keystone	244	8.5
Homer City	244	5.9
Conemaugh	305	8.5

This series included a total of 170 experiment days in which helicopter flights were performed. Of these, 95 flight days were conducted in the Keystone plume, and 46 and 29 flight days were performed in the plumes of Conemaugh and Homer City, respectively. Although not limited to this aspect, special emphasis of the LAPPES project was placed in evaluating fumigations during the inversion-breakup process. During the total study period, which included flights in all weather conditions that permitted aircraft operation, measurable concentrations of SO_2 ($\geq$ 0.01 ppm) were observed at ground level via the breakup process on a total of (at least) 90 days. Instantaneous concentrations in excess of 0.3 ppm were experienced with fair regularity, with maximum observed values (under verified breakup conditions) in excess of 1 ppm.

Inversion-breakup fumigation data for the LAPPES program have been analyzed by Weil and Hoult (1973), who developed an expression for the height of the inversion-breakup layer on the basis of an energy balance. This was employed with an equation for plume loft to determine conditions under which fumigations would occur, and the result was subsequently correlated with observed instantaneous ground level concentrations .

It is important to note that the underlying basis for the Weil and Hoult analysis differs radically from that by the TVA, which visualized a vertically well-mixed plume beneath an inversion "lid". Weil and Hoult have the concept of a mixing plume which is looping to the ground, spending part of its time at ground level and the remainder aloft. An example of their prediction is compared to its TVA counterpart in Figure 10 for similar conditions of Δh, Q, and $\bar{u}$. It is interesting to note that the instantaneous concentrations predicted by Weil's and Hoult's analysis are less than the one-hour average values obtained from the TVA correlation.

Although a direct comparison of the instantaneous and one-hour concentrations shown in Figure 10 with 3- and 24-hour ambient air quality standards is difficult, the results do imply a great deal with regard to the effect of stack height on ground level concentration during inversion-breakup. This is tempered in part by noting that the curve pertains to average maxima, and observed values were often higher by a factor of two or more. Additionally, it should be emphasized that all of the data used in Weil's and Hoult's analysis were obtained from situations involving a single (244 m) stack height, and the use of their relationship to investigate the effects of varying stack height must be regarded as dubious. On the other hand it should be emphasized that one additional effect of increased stack height predicted by this model is not evident from the figure. This is the capability of the taller stacks to eliminate entrainment into breakup layers that entrain plumes from lower sources, and thus (according to the model) provide a larger number of circumstances when the plume does not approach the ground at all. In view of these features this analysis must be considered to provide considerable support to the proposition that, insofar as maintaining acceptable SO_2 concentrations downwind from isolated sources under inversion-breakup conditions is concerned, considerable benefit can be obtained from increased stack height.

Additional Mechanisms for Fumigation: Shoreline and Urban Phenomena

Although the inversion-breakup fumigation has received the majority of attention to date, it is important to note that additional mechanisms for fumigation exist which may be of considerable importance to the behavior of plumes from tall stacks. In contrast to the nocturnal inversion-breakup process, where the depth of the mixed layer is characteristically time variant and uniform in extent, these additional types of fumigations are typically caused by changes in planetary boundary layer thickness with position downwind. Such changes can be induced by thermal or surface roughness variations, which in turn can be generated by artificial (i.e., large cities) or natural causes.

The most important example of naturally induced fumigations of this type are associated with onshore flows under stable or neutral conditions. If, for example, stable air is flowing shoreward over smooth water, the mixed layer will be normally at most only a few meters deep (note Figure 6). Upon approaching the shore, however, a deeper boundary layer begins to build, owing to increases in surface roughness and, depending on conditions, to surface heating effects. Turbulence measurements of this effect have been obtained in the Chesapeake Bay experiments of Slade[65] and technical aspects of the problem have been analyzed by Van der Hoven (1967). Some limited tracer measurements of plume behavior under these conditions have been conducted by researchers at the Brookhaven Laboratories[66].

Several field measurements of this type of fumigation in power plant plumes have been conducted by Lyons and his coworkers (1972, 1973)[67]. The plants studied were located on the west shore of Lake Michigan. The investigations consisted of visual plume observations, airborne and surface SO_2 and particulate monitoring, and surface and elevated temperature measurements, with aircraft turbulence observations.

The meteorological situations during these studies involved onshore gradient flows of air from the east under clear conditions, where solar heating often raised surface air temperatures to levels as much as 15°C higher than the surface waters of the lake. This created growing inland boundary layers as shown in Figure 11, which effectively convected the plumes to the surface. Instantaneous surface concentrations from the (up to 168 m) stacks were observed to exceed 0.7 parts per million for sources having strengths in the area of 4 kg SO_2/sec. Owing to wide short-term fluctuations, however, no violations of the Federal Ambient Air Quality Standards were observed.

Lyons concludes that although onshore fumigations can result in high surface concentrations, factors such as wind shear and overall transient phenomena will tend to reduce this effect. Owing to the relative persistence of the meteorological phenomena (as compared to nocturnal inversion breakup), however, onshore fumigations are expected to be potentially capable of causing standards violations from power plants with tall stacks unless extreme care is exercised in siting and design. From the schematic in Figure 11 it is apparent that, in order to avoid the fumigation process totally, power plant stacks would have to be extended to unreasonable heights in many situtations.

An additional aspect of shore-lake breeze effects, also described at length by Lyons and his coworkers, is the appearance of local circulation patterns. Considering, for example, a warm land parcel adjoining a cooler body of water with air aloft moving toward the lake, such as shown in Figure 12, it is evident that because of the lake-breeze effect the lower air will tend to move landward where it will warm and rise, only to be drawn outward again with the prevailing flow. Once over the water this air will show a

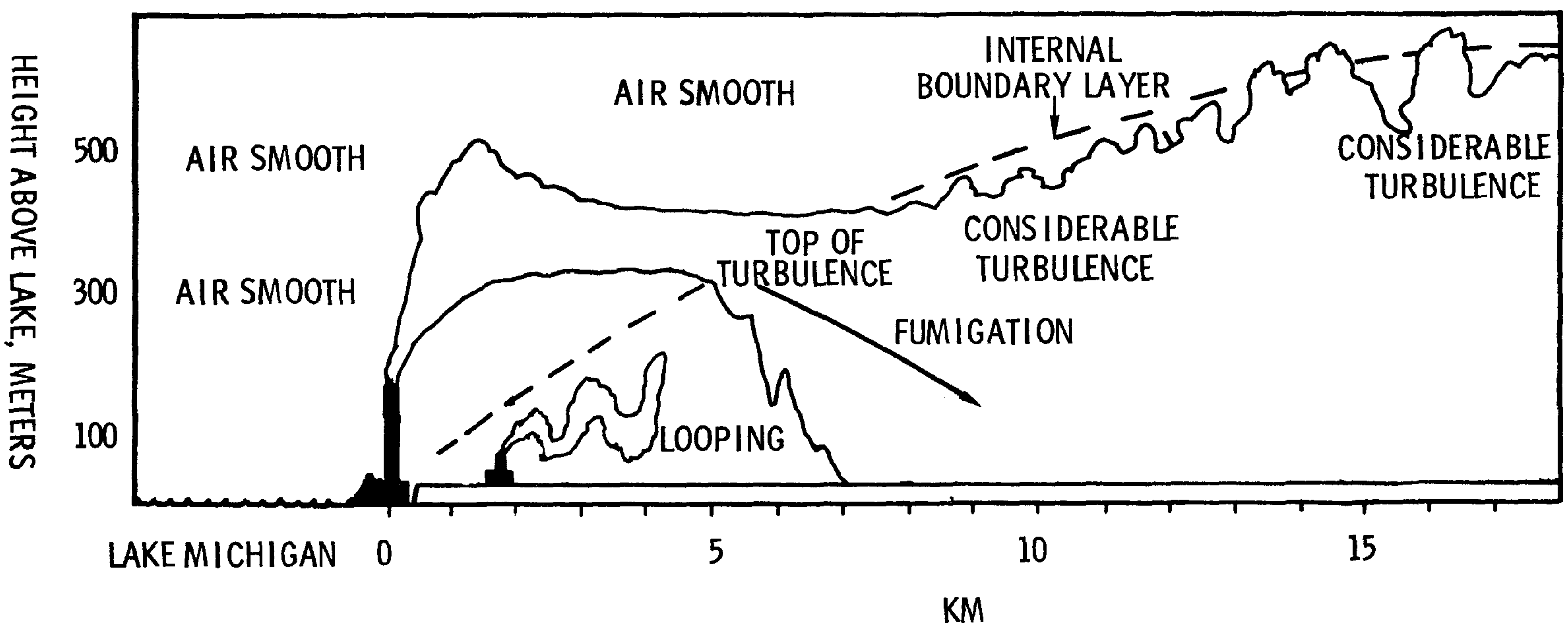

FIGURE 11. Schematic of Plume Interactions with Boundary Layer Induced by Onshore Flow - Adapted from Figure of Lyons.

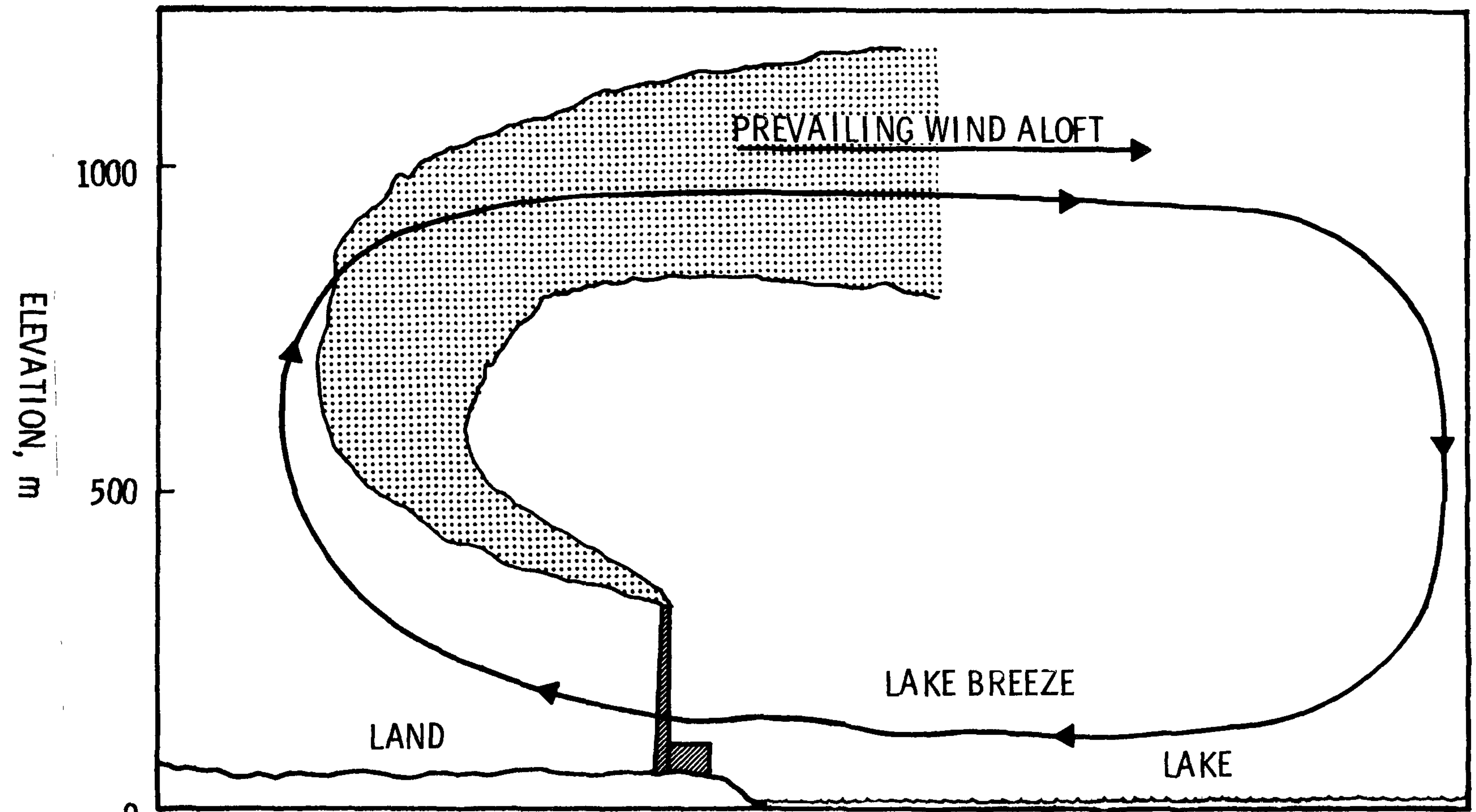

FIGURE 12. Schematic of Lake Breeze Circulation.

tendency to subside to satisfy the divergence of low-level air, and a circulation pattern is thus induced.

If a plume were entrained in such a circulation pattern, one would expect severe concentration buildups to occur. Lyons notes, however, that the lake-breeze flow pattern is rarely two-dimensional, but instead follows a helical pattern that progresses along the shoreline in one direction or the other. Because of this behavior, portions of the plume that actually come back upon the plant itself are usually diluted substantially. If a row of sources and receptors were to exist along the shoreline, however, this helical pattern could be capable of promoting substantial ground level concentrations through the additive effects of the sources.

The observation of fumigations from boundary-layer transitions over cities has been hampered by poorer definition of boundaries and by the multitude of sources usually existing in such areas. Accordingly, the most pertinent information that has been obtained thus far regarding the behavior of plumes from tall stacks under such conditions pertains to boundary-layer investigations.[67,68,69] Such studies have indicated that the combination of roughness and thermal release can increase the depth of the urban boundary layer several hundred meters over its rural counterpart, with obvious implications to the behavior of high plumes in the vicinity. It is expected that the Regional Air Pollution Study (RAPS), currently being conducted by the EPA in St. Louis, will generate significant new information in this regard.

Thermal Instability - Looping Plumes

The looping plume has been traditionally identified with thermally unstable atmospheres. Under such conditions convective exchange by large-scale vertical eddies transports portions of the plume virtually intact to lower levels of the atmosphere as indicated schematically in Figure 7.

At the present time there is some lack of agreement in the meteorological literature regarding the distinction between inversion-breakup fumigations and looping plumes. Weil and Hoult (1973) for example, have applied a looping-plume model to describe inversion-breakup fumigations. This has contrasted rather sharply with the uniform-mixing concepts applied to such cases by the majority of previous authors. Moore (1974) has recently treated this situation using a two-parameter model which assumes looping-plume conditions to occur as a consequence of unstable pockets of air imbedded in neutral or weakly stable surroundings. The observations of Lyons and Cole (1972) demonstrate that under appropriate conditions looping and fumigating plumes can coexist in the same locality. As seen from Figure 11, the plume from the larger power plant involved in their investigation had become entrained in the boundary layer from aloft, resulting in a fumigation situation. In contrast the plume from a smaller plant, by virtue of the placement of its release in the boundary layer, produced a classical looping plume.

It seems obvious that high instabilities and absence of overlying stable layers are conditions conducive to the existence of looping plumes. It is also apparent that during breakup of a nocturnal inversion a fumigating situation may evolve into one involving a looping plume if strong solar-radiation conditions persist for times sufficient to eliminate the inversion "lid", or at least raise it to a position appreciably above the emission height.

Martin and Barber (1967, 1973) have called attention to the importance of looping plumes in promoting high ground-level concentrations in conjunction with the British High Marnham-West Burton measurements. These authors have observed peak 3-minute average SO_2 concentrations as high as 0.9 parts per million at distances from about 0.8 kilometers to 5 kilometers from the High Marnham plant (s.h. = 137 m, 1.7 kg SO_2/sec) under thermally unstable conditions. Corresponding hourly averages were as high as 0.44 ppm. The relatively short residence time of the looping plume in any set location, however, resulted in a considerable lowering of values for longer-term averages. The maximum observed 24-hour average, for example, was about 0.06 ppm.

Further measurements of ambient SO_2 concentrations were conducted by Martin and Barber during periods when both the High Marnham and the new West Burton plants were in operation. These again showed relatively high concentrations to occur at close distances under thermally unstable conditions. Concentrations in the vicinity of the West Burton plant, however, were substantially less than those at High Marnham. This outcome was somewhat surprising because of the approximately doubled emission rate of the West Burton plant, and was attributed primarily to the increased stack height (183 m vs. 137 m for High Marnham) of this facility.

It is interesting to note that substantial disagreement appears to exist regarding the importance of the looping plume situation - disagreement that may be caused to a major extent by variations in local climatology. In apparent contrast to Martin and Barber, the TVA group has concluded that the looping plume situation is of sufficiently small significance so that it may be essentially disregarded as a critical stack-design factor. Smith and Frankenberg, on the other hand, suggest that this is probably the most important mechanism for raising ground level concentrations in the vicinity of the Muskingum River plant (s.h. = 251 m).

Additional data regarding the behavior of looping plumes from high stacks were obtained during the LAPPES series mentioned previously. Plume looping (aside from terrain effects) produced the highest surface SO_2 concentrations observed during this study, with instantaneous values exceeding one ppm on numerous occasions. In accordance with the High Marnham - West Burton observations, longer-term averages (as measured by bubblers) were substantially lower than the instantaneous values and indicated that current Ambient Air Quality Standards would not be exceeded under looping-plume conditions.

Trapping Beneath Elevated Inversions

During recent years the mechanism of trapping beneath elevated inversions has received considerable attention. It has been found to be quite important in promoting high surface concentrations in the vicinities of tall stacks.

Typically, high-elevation inversions are caused by subsidence of upper air under anticyclonic conditions. Adiabatic compression of this air during its descent from aloft results in heating, which promotes inversions whose bases range from thousands of meters in elevation to near ground level under some circumstances.

If such an inversion lies substantially above the effective release height of the plume, a "trapping" condition is promoted wherein the pollutant is prevented from mixing upward. Such conditions are significant considerations for stacks of all heights. They are especially pertinent to tall-stack design, however, since it is impractical to build stacks sufficiently tall to penetrate typical inversions of this type. The advantages that are enjoyed by tall stacks under other conditions, therefore, are largely precluded under these meteorological circumstances.

From its monitoring and analysis program the TVA (1974) has concluded that trapping beneath elevated inversions is the most restrictive meteorological circumstance under which to judge the performance of tall stacks - at least insofar as their own power plants are concerned. This conclusion resulted from an analysis of days when surface SO_2 concentrations in the vicinity of the Bull Run Plant (s.h. = 244 m) were substantially higher than predicted by the conventional coning plume model. Review of the meteorological conditions prevalent during these circumstances revealed that "in almost every case the region was dominated by a near stationary high pressure system with pronounced stability throughout the lower 1000-1500 m." This observation was substantiated by further studies at the Paradise Plant (s.h. = 183 m), and a corresponding dispersion model has been subsequently formulated.

Results indicate that maximum concentrations from this type of trapping may persist for two to four hours; thus this condition is viewed as more apt to result in air-quality standards violations than that of inversion breakup, which normally persists for appreciably shorter periods of time.

Plume trapping by elevated inversions was noted also in the LAPPES program (Pooler and Niemeyer (1971)), where half-hourly ground-level SO_2 concentrations as high as 0.3 ppm were observed. Lidar observations of the Keystone plume by Johnson (1969) and Johnson and Uthe (1969, 1971) supported the general concept of trapping beneath elevated inversions, although total plume behavior was noted to be complicated by tilting and shearing under such circumstances.

Simple diffusion models of the trapping process have been advanced by Healy and Baker (1968), Heines and Peters (1973), and Scriven (1967), which (in contrast to the TVA trapping model) consider the plume as a diffusing entity that is reflected downward from an elevated stable layer. The results of these models are in general agreement that while an inversion lid close to the effective release height may increase ground-level concentrations by factors of as much as two or more (depending on the model), the effect of the inversion decreases rapidly as its height increases. With inversions overlying neutral layers at elevations greater than twice the emission height the effect of the trapping process is negligible.

Effects of Complex Terrain

There is little disagreement at present that terrain of sufficient complexity can have severely detrimental effects on the performances of even the tallest of chimneys. Conjecture does exist, however, concerning several aspects of plume interactions with complex terrain. These include plume impingement on elevated surfaces, channeling effects and downwash phenomena.

One of the most well documented accounts of downwash of an elevated plume in complex terrain is the LAPPES investigation of the Conemaugh Plant (s.h. = 305 m) (Shiermeier (1972)). This power plant is situated approximately 6 km to the northwest of Laurel Ridge, which possesses peaks as high as 200 meters above stack top. With southeast winds under neutral conditions the Conemaugh plume was observed to approach the surface within a very short distance from the plant, yielding instantaneous SO_2 concentrations significantly greater than 2 ppm on some occasions. At greater distances the ground-level concentrations decreased rapidly, only to increase once again on the lee side of the second ridge, approximately 12 km northwest of the stacks. With wind from the opposite direction the plume was observed to rise well over Laurel Ridge and mix throughout a deep layer on the leeward side, with resulting low surface SO_2 concentration. The lee downwash effect at Conemaugh appears to occur only under neutral conditions. On days when sufficient radiation occurred to promote appreciable surface heating, the plume was observed to loft in its normal manner.

The question of plume "impingement" on elevated surfaces was drawn into sharp focus by Van der Hoven[72] as a consequence of the Southwest Energy Study. This is of special significance to the operation of tall stacks near mountainous terrain, since much of a tall stack's benefit will be removed if its plume intercepts elevated surfaces in the surrounding area. Simple modeling efforts in this area have ranged between the extremes of assuming either that plume height rises directly with terrain features, or else that it does not rise at all. Compromise measures, such as assuming that the plume rises essentially one-half as rapidly as the terrain,[70,71] have also been employed.

Several wind-tunnel and tow-tank measurements of flows in complex terrain have been conducted [73,74] which provide some insight pertaining to the impingement problem. In general, these experiments have indicated that conformity of plume elevation with topographical features is stability dependent, and under stably stratified conditions high concentrations in the vicinity of elevated terrain should be expected. Lin and his coworkers performed tow-tank investigations of a simulated plume upstream from a mountain ridge bordered by two mountain peaks. Their results indicated a strong blockage of the plume by the ridge under stable conditions, which led to high surface concentrations on the upstream side. High concentrations on the lee side of the ridge were also experienced, owing to the lee-wave effect.

Prompted in part by the Southwest Energy Study, a recent field investigation of plume diffusion in mountainous terrain has been conducted by the NOAA Air Resources Laboratory. This study (Start, et al. (1974), (1975)) was centered in two locations in Utah where tall stacks were in operation. The first of these locations was Huntington Canyon, the site of a new power plant located in a valley with walls rising approximately 800 m above the 183 m primary stack. The second location was near Garfield on the south shore of the Great Salt Lake. This site was bordered by steep slopes of the Oquirrh Mountains directly to the south. The two principal stacks of the smelter at this location were 122 m high.

Basically, the experiments conducted in this investigation consisted of releasing halogenated tracer compounds from the stacks, and measuring their concentrations downwind with airborne and ground-level sampling facilities. In addition to other important results, these measurements demonstrated vividly that although rough terrain appears to enhance their dilution, plumes from the stacks impinge against the surrounding elevated terrain frequently. The bulk of the experiments involving high surface concentrations occurred under unstable conditions with a stable capping layer aloft. As indicated by the tow-tank experiments described earlier, however, even higher surface concentrations would be expected under pronounced stably stratified conditions.

A second major field program prompted by the Southwest Energy Study is the SO_2 monitoring project completed recently in the vicinity of the Navajo power plant (s.h. = 236 m) currently under construction near Page, Arizona. Two of the three 750 MWe units of this plant are presently in operation, with the third scheduled for service in mid 1976.

The Navajo site is located in typical desert terrain, with pronounced elevated areas located in several directions from the plant. An array of 26 SO_2 monitors surrounding the plant was utilized in conjunction with an aircraft SO_2 - analyzer system to assess plume behavior in the region. Particular efforts were made to determine the extent of the plume's impact on elevated terrain.

One area of particular interest in this regard was the Vermillion Cliffs, which rise approximately three hundred meters above the stack exits. The Navajo study demonstrated that plume impingement does indeed occur at this site, and results in relatively high surface concentrations. These concentrations were not judged sufficiently high, however, to warrant implementation of flue gas desulfurization at the plant, providing the sulfur content of the coal did not exceed 0.6-0.7 percent and the heat content of the coal was not less than 12,000 BTU. In agreement with the findings of previous studies, these measurements indicated that high local concentrations in the elevated regions occurred primarily under stable atmospheric conditions.

As a summary to this discussion on the effects of complex terrin, it may be concluded that highly complex topography will interfere strongly with a tall stack's ability to promote acceptable ground-level concentrations. Although the processes responsible for these interferences are not well understood at the present time, the preponderance of recent experimental evidence testifies strongly to the severity of these effects. Accordingly, any decision to site a tall stack in a topographically complex area always should be preceeded by a comprehensive meteorological analysis of the specific area in question.

Achieving Acceptable Sulfate Levels

The question of whether the tall stack, as an isolated source, is effective in achieving acceptable levels of sulfates is complicated by the fact that the majority of airborne sulfate is generated by chemical reaction in the atmosphere; that is, it is a secondary pollutant. Rate behavior of this reaction -- of prime importance for modeling calculations -- is poorly understood at the present time. Also, the relatively ubiquitous presence of sulfate in the atmosphere[75] renders the assumption of an "isolated" source of somewhat questionable value in the present application.

Recent epidemiological studies[27] have indicated that adverse health effects are associated with annual sulfate levels in the 10 $\mu g/m^3$ region. The significance of this level can be appreciated by considering a hypothetical situation where SO_2 existing at the 0.03 ppm (80 $\mu g/m^3$) annual standard is completely transformed to sulfate. The resulting sulfate concentration of 120 $\mu g/m^3$ would require a factor of twelve greater control to achieve an annual average sulfate concentration of 10 $\mu g/m^3$.

It is fortunate in this respect that the SO_2 - sulfate conversion occurs rather slowly in the atmosphere, and (close to the source, at least) the majority of airborne sulfur exists as SO_2. Although a wide range of reaction rates have been published[76] it is apparent that typical values are in the range of 1-5% per hour.[77] Standard diffusion calculations indicate that under normal meteorological circumstances the plume will be advected long distances before appreciable sulfate is formed. At such distances an isolated plume will be sufficiently dispersed to preclude exceeding any reasonable standard. Obvious exceptions to this are return-flow and stagnation conditions, and possibly extended trapping and/or fumigation. When acceptable annual average concentrations are considered, however, such circumstances are not normally expected to weigh into the average to a significant extent.

It is important to note that the consideration of plume-borne sulfate refocuses concern at much greater distances from the source. This is significant in that most plume-modeling efforts to date have concentrated on the regions of maximum surface concentrations of primary pollutants, and modeling of plumes at extended distances is still at a relatively early stage. This extended range of the problem increases the probability for interaction of the plume with plumes from other sources, and once again suggests that the concept of an "isolated" plume is of doubtful utility in this context.

Finally, a first-order analysis of the problem indicates that, since the effects of stack height become less pronounced with increasing downwind distance, increases in stack height should be of relatively little benefit insofar as sulfate is concerned. A more detailed analysis including the effects of dry deposition suggests that tall stacks may be even detrimental in this respect. This can be demonstrated by performing computations based on the simple depositing plume model of Horst[78] using appropriate values of deposition velocity and dispersion parameters. Choosing for an example a 5 m/sec wind speed under neutral conditions with a 0.01 m/sec deposition velocity (roughly appropriate for SO_2), this model predicts amounts of material remaining in depositing plumes relative to nondepositing plumes as a function of distance as shown in Figure 13.*

The curves in Figure 13 pertain to a nonreactive, primary pollutant, and thus do not relate directly to a secondary pollutant such as sulfate. Taking the primary pollutant as SO_2, however, and recognizing that depletion of this substance by dry deposition must ultimately result in reduction of reaction-product sulfate, provides some insight regarding the influence of stack height on sulfate levels.

Figure 13 also indicates rather dramatically the influence that deposition may have on concentrations at large distances from the source. This points to the fact that consideration of removal terms, while relatively unimportant in assessing local plume effects, can be critically important as distances from the source become large. These effects will be considered within the discussion of interacting sources that appears in the following section.

*Other models have been applied for similar analyses with rather varied results (cf. Smith[79]).

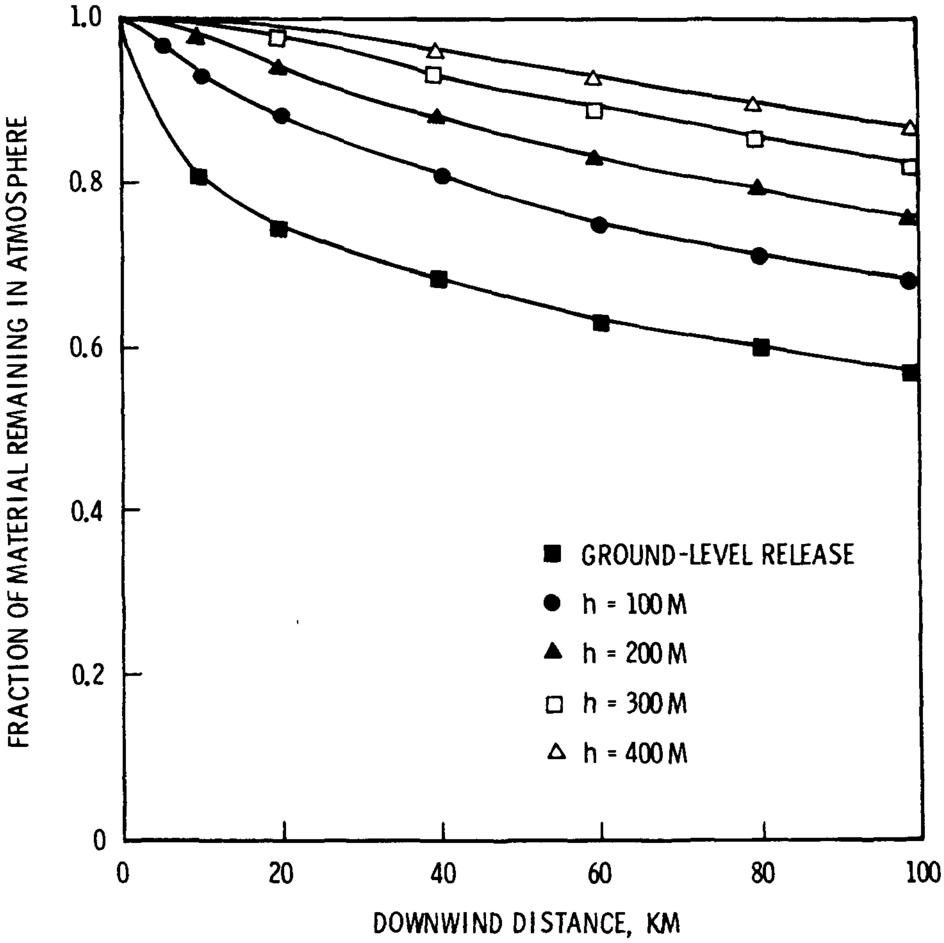

FIGURE 13. Calculations of Plume Depletion by Dry Deposition Using Horst's Model.

Conclusions Pertaining to Tall Stacks as Isolated Sources

From the survey in this section it is readily apparent that in the proximity of an isolated source, the tall stack provides an attractive means for minimizing the impact of emissions on ground-level air quality. This is not to say that such standards are not violated by effluents from tall stacks in specific situations, nor that simply providing a tall stack will permit unlimited release of pollutants into the atmosphere. The available information does indicate strongly, however, that elevating the point of release without increasing the effluent, will usually be accompanied by considerable lowering of ground-level concentrations of primary pollutants.

Exceptions to this finding are circumstances involving onshore flows, lake-breeze circulations, highly complex terrain, and elevated inversions. It is imperative that detailed meteorological analyses for sites experiencing any of these conditions be performed prior to deploying tall stacks in these areas.

It may be expected also that an isolated source able to satisfy existing SO_2 standards would also be capable of achieving acceptable levels of sulfate. This finding, which is based on the assumption that in-plume oxidation processes for SO_2 are rather slow, is tempered somewhat by the tall stacks' discouragement of deposition processes. It is tempered also because of the expected long transport distance for sulfate, which renders the concept of an "isolated source" generally inapplicable for this purpose.

SECTION VI

THE AIR QUALITY IMPACT OF TALL STACKS AS MULTIPLE SOURCES

INTRODUCTION

The preceding text has indicated strongly that, when considered as isolated sources, tall stacks are highly effective in promoting low surface concentrations in the immediate regions of emission. One of the secondary effects of increasing stack height, however, is to extend the downwind range of concern, and along with it the probability for interaction of plumes from other sources. Depending upon rates of removal, these effluents may become of regional or even global significance. In considering such aspects it becomes progressively naive to retain the concept of an isolated point source.

A simplified visual example of potential plume interactions on a regional scale is given in Figure 14. This figure shows results computed from a Lagrangian "puff" model of Wendell[80] corresponding to several sources located in the eastern United States and Canada, whose plumes were advected by wind fields obtained from historical weather data. Although the modeling procedures utilized to create Figure 14 are rather approximate, the indication that plumes on a regional scale interact strongly in a highly complex fashion cannot be escaped.

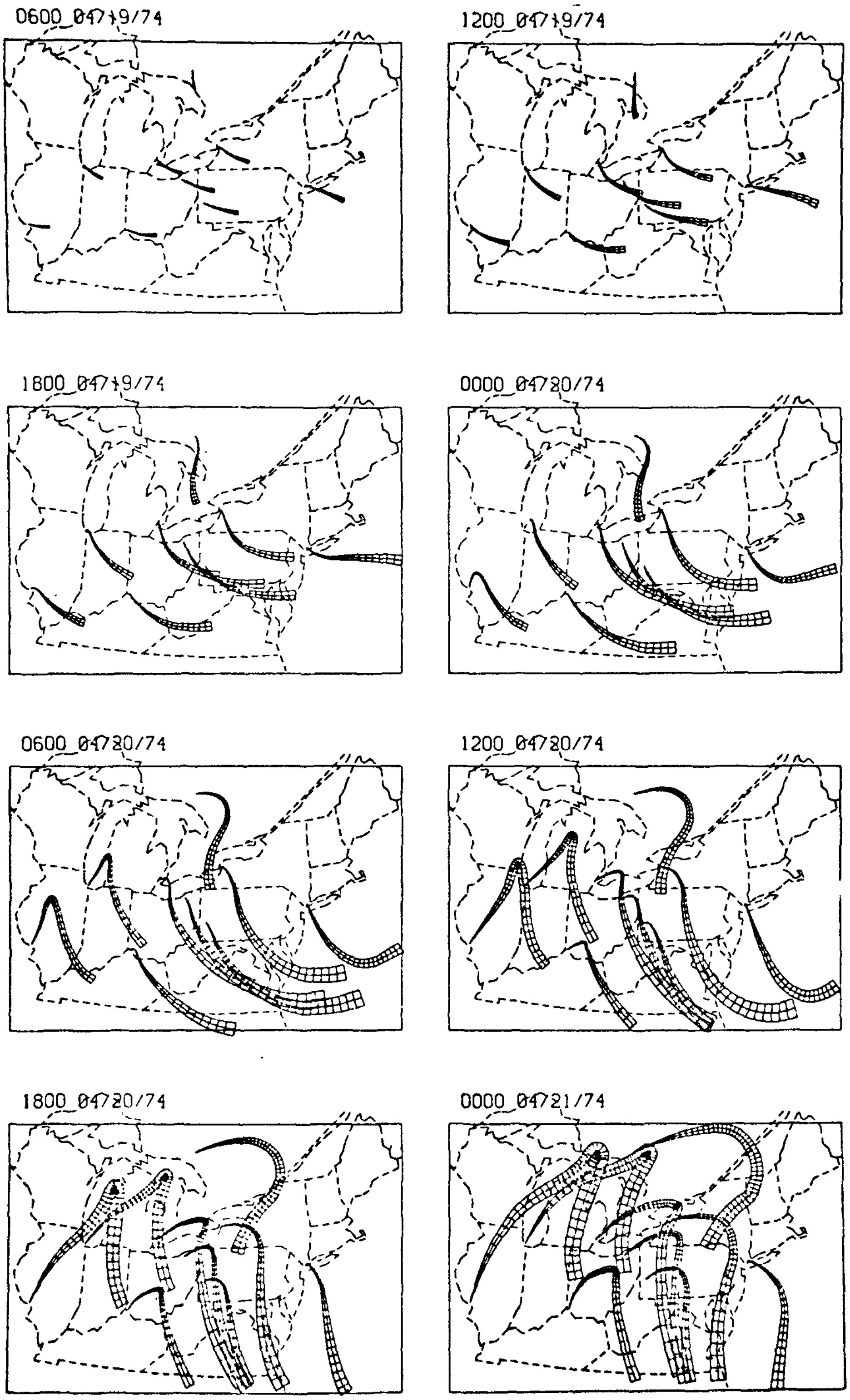

FIGURE 14. Six-hourly plume plots for continuous releases from nine cities, beginning at 0000 GMT 4/19/74. Wind data used for advection were from 850 mb NMC analyses. Plume widths are σ_y. The lines across a plume indicate positions of points leaving the source at 1 hour intervals. (From "puff" model of Wendell.)

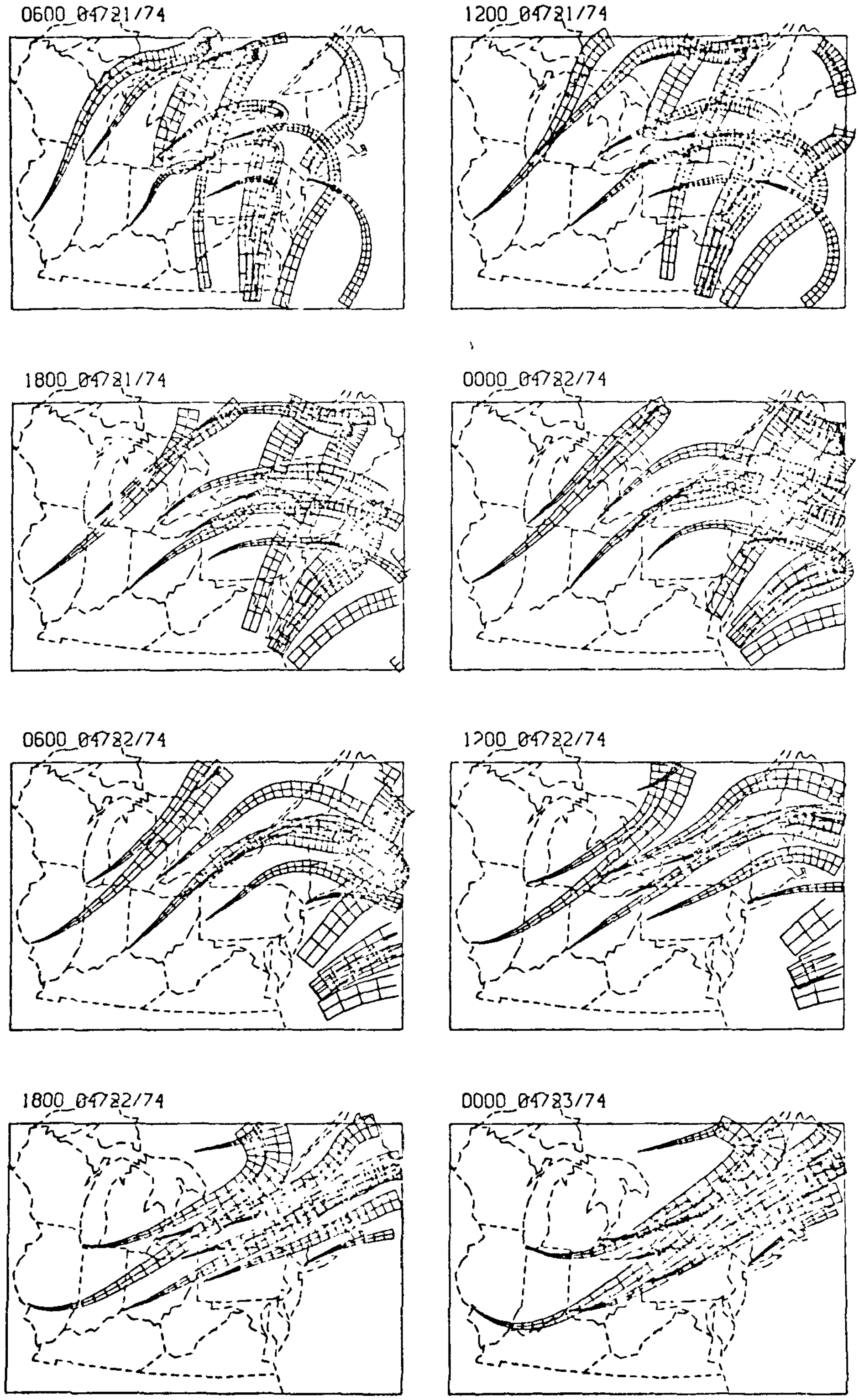

FIGURE 14. (Continued)

The present section deals with the problem of plume interaction and long-range transport by first considering some simple examples of overlap of two plumes. This is followed by a discussion of pertinent work in the multi-source, long-range transport field. Individual effects, such as scavenging, deposition, and transformations are included intrinsically in much of this work, and these accordingly will be incorporated in the context of this discussion when appropriate. An individual discussion of these separate effects is given in the following section of this report.

OVERLAPPING PLUMES

Although the overlapping of two plumes from separate sources is obviously a common occurrence, lack of plume definition at the distances involved usually precludes a vivid observation of the interactions. Two-plume interactions have been included in modeling calculations for a number of scoping studies. A comprehensive analysis of State Implementation Plan strategy performed by the Walden Corporation (1973), for example, utilized a simple Gaussian, straight-trajectory approach, which included overlap of plumes from multiple sources under conditions when these sources were in close proximity to one another.

During the LAPPES investigation, Schiermeier(1970) observed interactions between the Keystone and Homer City plumes. Such interactions were noted also in the High Marnham-West Burton plumes by Martin and Barber (1967, 1973). These authors point out, however, that plume interaction is less persistent than one would expect on the basis of linear trajectories owing to the normal meandering and curvature from shear effects. They emphasize in addition that while actual mixing of the two plumes was not highly persistent, long-term concentration measurements in general distinctly reflected the overlay of the two plumes.

MULTIPLE SOURCES AND LONG-RANGE TRANSPORT: MODELING INVESTIGATIONS

For longer distances and larger numbers of sources, individual plumes rapidly lose their identity. Furthermore, scavenging, deposition, and transformation processes begin to dominate, and accordingly these features must be incorporated into related modeling efforts in a realistic fashion.

Despite the above-noted tendency for plumes to lose their individual identities as they interact downwind with emissions from other sources, it is often convenient to visualize single or multiple discrete plumes for modeling purposes. This is the approach taken by Wendell (note Figure 14), and also by Hefter et al.[81] These authors employ a normal dispersion model along a wind-dictated trajectory and provide for deposition, scavenging, and/or transformations for each discrete parcel. A striking feature of these models is their indication that ambient air concentrations become extremely sensitive to the deposition and scavenging parameters as the transit times grow large.

A number of detailed analyses devoted specifically to long-range sulfur transport have been published during recent years. Scriven and Fisher,[82,83] for example, present a two-part analysis which initially considers SO_2 from an area source which has drifted sufficiently far downwind so that a uniform concentration is established vertically between the surface and some given mixing-layer height. Deposition and washout are incorporated into the model using a deposition-velocity and washout-coefficient approach, and resulting mean transport distances prior to deposition are estimated.

For the case of SO_2 removal solely by dry deposition, Scriven and Fisher estimate mean transport distances of 100-1000 kilometers prior to removal. Under typical rain conditions washout is estimated to reduce this mean distance to about 50 kilometers. On this basis the authors conclude that washout of SO_2 dominates dry deposition under rain conditions, but on a long-term basis these two effects are of about equal significance. They also conclude that much of the airborne SO_2 is removed by rain before it can be converted to sulfate.

The SO_2 washout calculations of Scriven and Fisher can be criticized because of the fact that they employ washout-coefficient theory to a gas, which has been demonstrated previously[84] to disobey such behavior. In view of these more recent findings it is probably preferable to assume that the rain approaches the surface saturated with SO_2 at its ambient ground-level concentration. Following this approach one can estimate that actual SO_2 washout is about three orders of magnitude less than that predicted by Scriven and Fisher and that certain of their above conclusions should be reversed accordingly.

Although they do not deal extensively with the sulfate formation and removal problem, Scriven and Fisher note that deposition velocities for sulfate aerosol are probably an order of magnitude less than for SO_2 and accordingly the washout process is expected to dominate removal of this substance both during rain periods and on the long-term basis.

Scriven's and Fisher's initial analysis, in general, presumes complete vertical mixing, and aside from noting that pollutant from high sources may not enter into the mixing layers considered in their model, the effect of stack height is largely ignored. In their subsequent paper[83], however, these authors employ a K-theory approximation to assess the effects of vertical profiles caused both by elevated release points and by the dry-deposition process. In general, these results indicate that increasing the height of release increases the mean transit distance and residence time of SO_2. An example calculated for typical nonrain conditions suggested that extending the release height from ground level to 200 meters would result in an increase in the mean transit distance from 500 to 680 kilometers. These authors also indicated that SO_2 concentrations in the vicinity of the surface should be attenuated by virtue of the diffusion-deposition process.

In a similar, but more emission-height oriented analysis, Lucas (1975) has presented results of calculations of SO_2 concentrations downwind from area sources of assumed emission elevation. Sutton's dispersion equation was employed for these calculations, and cases involving neutral conditions and inversion heights ranging from 200 to 1000 meters were considered. The emissions from these sources were assumed to be uniform over the extended areas of release, and typical meteorological parameters (5 m/sec wind speed, and Pasquill-type mixing categories) were employed.

Typical results from Lucas' analysis, presented as plots of ambient SO_2 concentration versus downwind distance, indicate that the increase of emission height promotes a marked lowering of ground-level concentrations in the area-source vicinity. For limited mixing-layer conditions this effect of source elevation becomes negligible at large downwind distances, the model's results reducing asymptotically to those of simple, well-mixed ventilation models such as those suggested by Holzworth.[85]

Lucas' calculations indicate that for metropolitan sources with expected ranges of emission rates, ground-level SO_2 concentrations can be maintained at acceptably low levels simply by raising the effective release height a reasonable distance. Similar results are indicated for larger geographical areas such as the continental United States, although it should be emphasized that at such large downwind distances stack height has little relevance to the predictions, which are comparable to those of the simple ventilation models. An example calculation of this type using as assumed wind speed of 5 m/sec, mixing height of 1000 meters, and SO_2 emission flux of 0.16 $\mu g/m^2$ sec results in an ambient ground-level SO_2 concentration of approximately 30 $\mu g/m^3$ at a point 1000 km downwind, assuming that none of the emitted SO_2 is removed or oxidized to sulfate enroute. If all of the SO^2 is assumed to be converted to sulfate by this point, the corresponding sulfate concentration is 45 $\mu g/m^3$.

The deficiencies of this simplistic type of calculation should be emphasized. The neglect of removal processes in the latter examples have been compensated to some degree by choosing an emission rate value characteristic of the average United States and by limiting the downwind extent of the calculation (1000 km) to a distance that can be associated with a reasonable estimate of the transit range of airborne sulfur. Idealizations of the source distribution and meteorology are further points for criticism; bearing these difficulties in mind, however, such an application has some value as a scoping exercise.

Comparison of the sulfur oxide concentrations estimated above with present and suggested standards (cf. Appendix A) in this manner indicates that, while SO_2 does not appear as a significant problem in this context, that of sulfate may indeed be critical. This indication is underscored by the fact that measured sulfate levels in excess of 45 $\mu g/m^3$ are not uncommon at some points in the United States today.[25] As pointed out by Trijonis[86] this situation can be expected to worsen significantly in the future as sulfur emissions from tall stacks, or indeed from any other type of source, increase.

Bolin and Persson[87] have utilized a somewhat more sophisticated approach to the modeling of long-range sulfur transport which employs a statistical description of transport and sink mechanisms. This is essentially a climatological trajectory model which incorporates reasonable parameterizations of dry-deposition and washout phenomena. In its simplest form it ignores chemical conversion by treating all sulfur species as if they existed as a single compound.

In a simplified example Bolin and Persson utilize gridded emission data over western Europe in conjunction with historical wind data to estimate wet and dry sulfur deposition as a function of location. Using this approach, they estimate that significant amounts of sulfur deposited in Sweden have originated from outside the country. Between five and twenty percent of the total deposited sulfur in Sweden, for example, was calculated to originate from the British Isles.

For their simplified calculations Bolin and Persson have assumed an average emission height of 85 meters. They note that lower heights will tend to increase the relative importance of dry deposition and decrease the transit distance of airborne sulfur. Somewhat in contrast to some of the previous authors, however, they indicate that increasing emission height above this level will have little effect on subsequent behavior of the emitted material.

The indication by the above modeling programs that sulfur is transported over comparatively large distances prior to its removal from the atmosphere is supported, in general, by a number of measurement programs that have been conducted during the past decade. Many of these programs have consisted essentially of observing air and/or rainborne sulfur concentrations and then utilizing trajectory analyses in attempts to establish the pollutants' origin.

Numerous studies of this type have been conducted by Scandinavian researchers.[88] In addition to noting that high sulfate concentrations in Scandinavia often are associated with air trajectories that have passed over the industrialized regions of Great Britain and northern Europe, several of these investigators (cf. Prahm et al.,[89] Brosset et al.[90]) have obtained data demonstrating that the chemical composition of sulfate aerosol can differ markedly depending upon its origin. Similar results have been obtained within the United States by Charlson and his coworkers,[91] who have utilized sulfate aerosol concentration and composition measurements in conjunction with trajectory information to indicate that sulfate in the St. Louis, Missouri, area originates primarily from distant sources.

In addition to these primarily receptor-oriented measurements, a number of experiments involving tracking of pollutants from mixed area sources have provided substantial evidence on behalf of the long-range sulfur transport concept. Particularly noteworthy in this regard are the simultaneous SO_2, sulfate, lead-212 and radon-222 measurements conducted onboard ship off the French Mediterranian coast by Cuong and his coworkers.[92] These studies provided strong evidence that, while near-surface SO_2 was depleted rapidly by dry deposition to the sea surface, sulfate aerosol was advected over considerable distances prior to removal.

Although an assessment of vertical diffusion of SO_2 was attempted using the lead and radon measurements, this study suffered the drawback that depletion of SO_2 aloft could not be measured directly. This handicap was largely overcome in the aircraft plume tracking experiments performed by Smith and Jeffrey[93] off the English coast. These authors employed carefully gridded SO_2 emission inventories in conjunction with their aircraft measurements of SO_2 and sulfate, and using a back-trajectory technique with an integral material balance were able to infer rates of SO_2 transformation and dry deposition. In accordance with the previous authors, the work of Smith and Jeffrey provides substantial evidence that sulfur compounds, especially those emitted from elevated sources, are transported substantial distances downwind prior to their removal.

CONCLUSIONS PERTAINING TO TALL STACKS AS MULTIPLE SOURCES

The conclusion regarding multiple arrays of tall stacks and their ability to promote acceptable ambient SO_2 concentrations under a majority of conditions is similar to that determined for isolated sources. It is evident that elevating the release points will be effective in reducing the collective concentrations at ground-level points downwind until uniform vertical mixing in the boundary layer is attained. For typical mixing-layer depths it is apparent that sufficient ventilation air is usually available to dilute the emissions to levels below the existing standards beyond that point.

The above conclusion is, of course, qualified by the special constraints of complex topography, land-sea effects, and elevated inversions. In particular, widespread stagnation in conjunction with a capping inversion would appear to be particularly disadvantageous in this respect, and in some instances the current air quality standards may be exceeded under these conditions.

In contrast to the conclusions for SO_2 and other pollutants for which standards currently exist, it is apparent that the widespread utilization of tall stacks in lieu of sulfur emission control may pose a serious problem insofar as achieving acceptable ambient sulfate concentrations is concerned. It is safe to conclude that airborne sulfate is typically advected over long distances prior to removal. This fact, combined with rough ventilation calculations, leads to the reasonable conclusion that sulfate in the atmosphere originating from composite source patterns is likely to constitute a significant problem, particularly in future years if increasing emission trends continue.

In making this conclusion, however, it is important to note that even with emission limitations in force the tall stack is a useful and important factor in maintaining ground-level air quality. This is true both because of the stack's role in dispersing pollution not retained by the control process, and because of its capability to reduce the consequences of temporary failures in emission control systems. From these considerations, it is probable that many situations may require both tall stacks and reduction in order to achieve optimal control.

SECTION VII

TALL STACKS AND ADDITIONAL ASPECTS OF AIR QUALITY

Previous sections of this report have primarily addressed the analysis of tall stacks and their relation to ground-level pollutant concentrations. This is a subject of principal importance to the question of existing and anticipated ambient air quality standards. In contrast, this final section will consider briefly some aspects of air quality not directly related to these standards. These additional aspects generally reflect total atmospheric loading more than they do surface concentrations, and include wet and dry removal processes, visibility, and weather modification.

Comparatively little has been published which directly addresses the question of tall stacks and their influence on these additional features, and because of this the present section will not be devoted to a prolonged discussion of published literature. Rather, this section will present a brief examination of the individual mechanisms for the specific interactions and will utilize this information to assess related consequences of increased emission height.

WET-REMOVAL PROCESSES

The fact that natural precipitation has a cleansing effect on air polluted from both low and elevated sources has been well established. Early experimental investigations such as those by Chamberlain[94] and May[95] determined approximate relationships between aerosol particle size, rainfall rate, and washout rates for below-cloud processes. Both below-cloud and in-cloud removal processes (cf. Figure 15) have been the subject of extensive continued research up to the present time.

Following Chamberlain's and May's original suggestions, below-cloud scavenging of aerosols may be analyzed most conveniently utilizing the washout coefficient approach. This method of analysis is based essentially on the assumption that falling raindrops capture aerosol particles with some given collection efficiency. Once captured, these particles are carried to the ground with no chance of subsequent release from the raindrop. A typical plot of washout coefficient versus aerosol particle size is shown in Figure 16.

From a knowledge of the washout coefficient and the areal distribution of pollutant, one can proceed to calculate removal rates and deposition fluxes in a straight-forward manner. It is sufficient for the purposes of this discussion, however, to note simply that the washout coefficient, Λ (units of fraction of material/t), is a direct measure of the fractional removal rate from the plume. Thus, if one considers a small parcel, or "puff", of plume as it drifts downwind, the fractional change in the mass of this material owing to washout in a short time period Δt is given simply by $\Lambda \Delta t$.*

*In more exact terms, we may express this relationship as $dQ/dt = -\Lambda Q$, where Q is the amount of pollutant in the puff at any given time. This may be integrated to give the relationship $Q = Q_0 e^{-\Lambda t}$, where Q_0 is the initial value of Q.

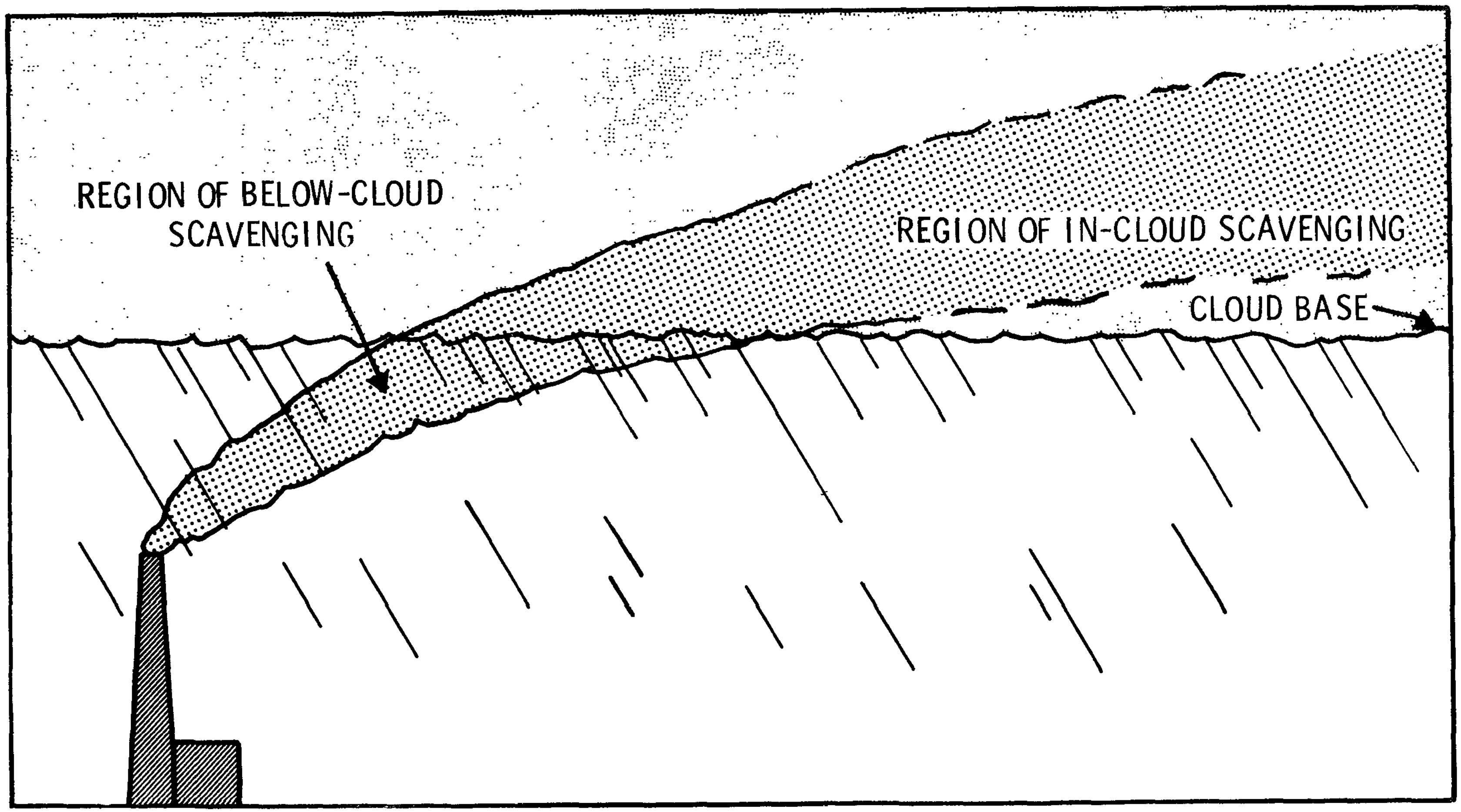

FIGURE 15. Schematic representation of in- and below-cloud scavenging.

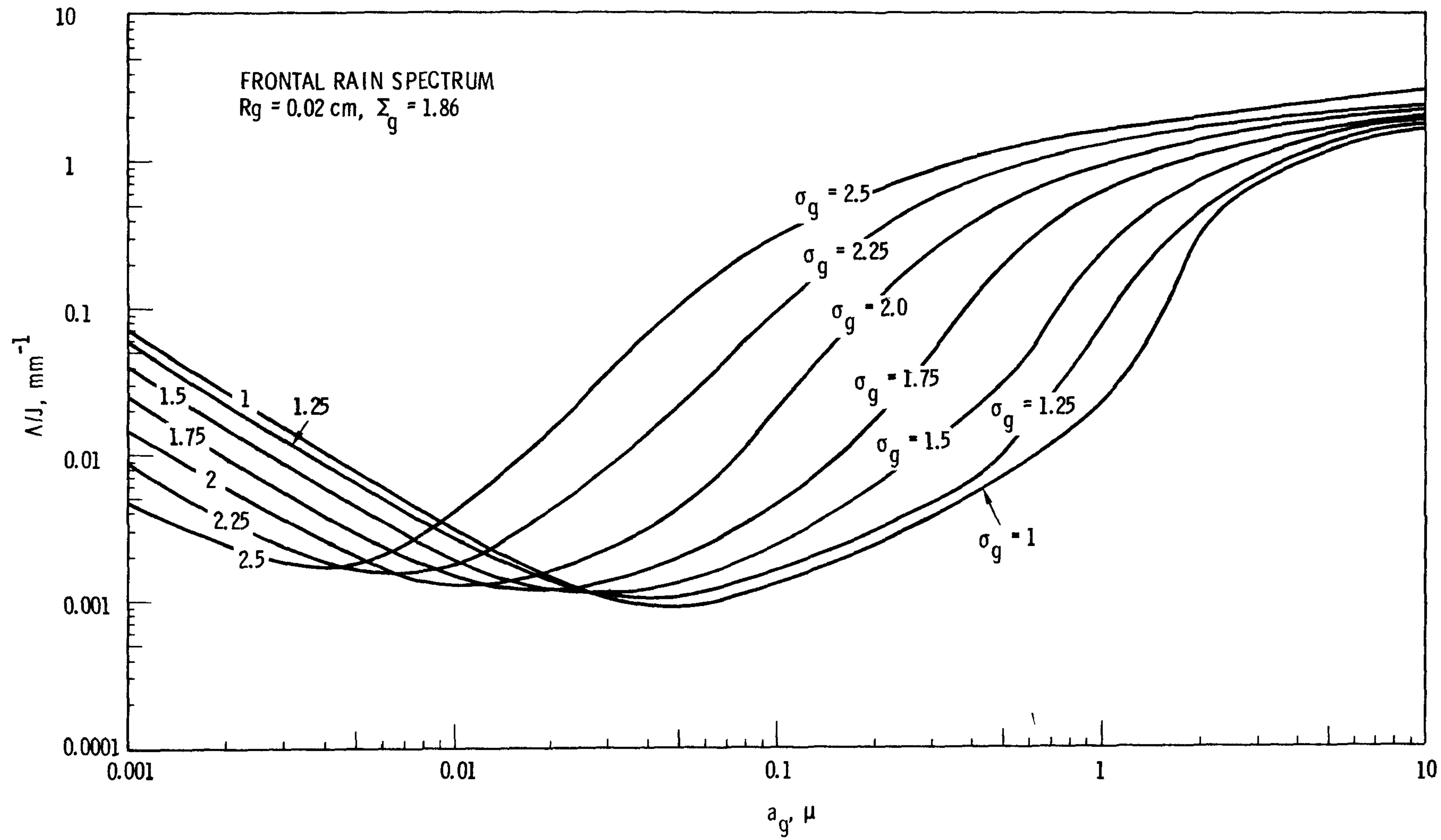

FIGURE 16. Washout coefficients* for size-distributed aerosols of geometric mean diameters a_g and standard deviations σ_g for a typical rain spectrum. From Dana and Hales.[86]

*Normalized to unit rainfall rate, J.

Two important features of this analysis should be emphasized. The first of these is the prediction that, as a first approximation, below-cloud scavenging of aerosols is independent of release height. The second important feature, as noted from Figure 16, is that under moderate rain conditions the times for aerosol plume depletion by below-cloud scavenging can be relatively long. A one percent removal of a homogeneous 1-micron aerosol by a 1 mm/hr rain, for example, ($\Lambda \cong 0.01\ hr^{-1}$ from $\sigma_g = 1$ curve in Figure 16) would take about one hour to occur. If the plume in question were drifting with the wind at 5 m/sec this would correspond to a distance of 18 kilometers. From this analysis, therefore, it is apparent that if below-cloud scavenging were the only process active in depleting the plume, the distance scales of interest are typically of the order of hundreds of kilometers under rain conditions. If the plume were emitted under nonrain conditions, and subsequently encountered precipitation, these time and distance scales would be altered accordingly.

Although there is considerable doubt that the scavenging of sulfate from power-plant plumes occurs through a simple aerosol-capture process such as that depicted here, it is still of interest to compare these values with actual field measurements of sulfate washout from power-plant plumes. These have fallen in the range between zero and about three percent per minute, corresponding to a Λ between zero and 1.8 hr^{-1}.[96-99]

The below-cloud scavenging of gases such as SO_2 does not adhere to the irreversible behavior implied by washout-coefficient theory. This fact was demonstrated vividly in washout measurements beneath the Keystone plume where observed SO_2 concentrations in rain were found to be as much as three orders of magnitude lower than those predicted on the basis of washout-coefficient theory[97]. Under some conditions "negative" washout even occurred; that is, background SO_2 existing in the rain prior to its contact with the plume was released back to the gas phase after its encounter.

The experiences at the Keystone plume were verified by later experiments[98-100] and a generalized theory of gas scavenging is now available.[84,101,102] As a consequence of this development it is now accepted that, if vertical concentration gradients are sufficiently small, the amount of SO_2 (or any other gas) existing in precipitation at ground level depends soley on the ambient, ground-level pollutant concentration and the solubility of the gas in rain.

Two important features emerge as a consequence of this behavior. The first of these is that, in contrast to aerosol scavenging which depends upon a vertically-integrated exposure of the raindrop to the pollutant, gas scavenging depends strongly upon near-surface concentrations. Thus stack height, while an unimportant consideration for aerosol scavenging, is extremely important to the scavenging of gases. Tall stacks, in general, discourage gas scavenging and thus tend to extend deposition by this process over greater areas. This behavior forms the basis for the earlier criticism of Scriven's and Fisher's analysis, which treated SO_2 washout in terms of washout-coefficient theory.

The second important feature arising from the reversible nature of gas scavenging is that it often introduces a nonlinear response to increased emission rates. It has been demonstrated, for example,[103] that SO_2 solubility varies with concentration in a manner that leads to proportionately less removal for greater SO_2 concentrations. On this basis one would expect disproportionately large increases in airborne pollutant concentration with increasing emission rates. Conversely, a rollback in SO_2 emissions would tend to effect a more than linear reduction in ambient air concentration.

In-cloud scavenging of pollutants is understood more poorly than its below-cloud counterpart, and depends in general upon the type and intensity of the precipitation process, the nature of the pollutant, and its location within the precipitating system. Basically, the in-cloud scavenging process can be considered to occur as a consequence of three consecutive steps, each of which may be important as a rate-limiting factor in the overall phenomenon. These are:

1) Transport of pollutant into the precipitating system,

2) Mixing of pollutant within the system, and its attachment to the precipitation elements, and

3) Transport of the pollutant-laden precipitation elements from the cloud to ground level.

Approximate scavenging relationships based upon this sequence of steps have been formulated[104,105] and detailed storm dynamics models currently are being applied for the analysis of in-cloud scavenging processes.[106,107] For present purposes, however, it is sufficient to note that the three-step in-cloud scavenging process described here implies that little direct relationship exists between source height and in-cloud removal. Potentially, step 1 could reflect emission height to some extent, but because of the large differences between the elevations of typical in-cloud phenomena and tall-stack release heights, this effect should be minimal. This lack of influence is underscored by noting that most frequently plumes encounter in-cloud systems only at large distances downwind, where most of the source-height dependence of the plume's distribution has been removed.

In contrast to <u>direct</u> effects, source-height related factors of an <u>indirect</u> nature may have significant influence on the processes and amounts of in-cloud scavenging. These effects include the shift in pollution loadings "in-cloud" that will tend to occur as a consequence of the less effective dry deposition and below-cloud gas scavenging* associated with tall stacks. In addition to these features, weather modification effects arising from tall-stack related shifts in atmospheric loadings may be of some consequence to the nature and extent of the in-cloud scavenging process. This aspect will be examined in greater detail in a following subsection of this report.

*This assumes that a typical removal pathway for a gas (SO_2, say), is its reaction to form a nonvolatile species with subsequent in-cloud removal.

DRY REMOVAL PROCESSES

Although some aspects of the dry-deposition process are poorly understood at the present time, there is little argument that it is influenced strongly by the airborne pollutant concentration adjacent to the ground. Accordingly, the dry-deposition process is most commonly represented in terms of the equation

$$F_D = V_D \chi_0 \quad , \qquad (1)$$

where F_D $(m/\ell^2 t)$ is the deposition flux to the surface, $\chi_0 (m/\ell^3)$ is the ground-level concentration, and $V_D (\ell/t)$ is known as the <u>deposition velocity</u>.

Equation (1) is rather unsatisfactory for a number of reasons, the most important of which is its implication of irreversible deposition, a stipulation which may be violated by resuspension of aerosols or by reemission of deposited gases. A second difficulty of the deposition "velocity" approach is that it tends to give the impression that all deposition occurs solely through some deterministic "fallout" process, and thus accounts for diffusional transport only in a rather artificial manner. Much of this difficulty can be removed, conceptually at least, by expressing deposition flux in terms of the alternative form

$$F_D = k_D (\chi_0 - \chi_s) \quad , \qquad (2)$$

where $\chi_s (m/\ell^3)$ is an equivalent concentration from the reemitting surface substrate and $k_D(\ell/t)$ is a mass-transfer coefficient.*

Under conditions where the predominant mechanism for deposition is diffusional transport, one can apply a momentum-mass transfer similarity assumption (cf. Pasquill) to obtain the result

$$k_D = \frac{u^{*2}}{\bar{u}}$$

$$(= V_D \text{ when } \chi_s = 0) \quad , \tag{3}$$

where $\bar{u}$ (ℓ/t) is the wind velocity at some reference height above the ground (where χ_o is measured -- 1 meter, say) and u^* (ℓ/t) is the previously defined friction velocity. Equation (3) predicts values of k_D in the range of 1 cm/sec, a region where many measured deposition velocities have been observed.

Regardless of the exact form for expressing deposition flux, it is evident that increasing emission height will tend strongly to reduce the amount of material deposited at downwind locations close to the source. This has been discussed previously in the context of Figure 13, from which it can be noted that changes in stack height between 50 and 300 meters might be expected to

*One should note that k_D and V_D possess the same units, and are, indeed, equivalent in cases when $\chi_S = 0$. Use of k_D is preferable, however, because it contains no false implications regarding deposition mechanism and has been utilized extensively for diffusion-drift applications in the past (cf. Bird, et al.[108]).

result in as much as a 25 percent increase in the amount of material existing in the plume at points downwind.

Since precipitation scavenging mechanisms (aside from gas scavenging) tend to reflect emission height only weakly, one expected result of increasing release height will be a decrease in the relative amount of material removed by dry processes. Various current estimates of the relative importance of dry and wet removal processes for tropospheric emissions indicate that dry deposition is of somewhat greater importance at the present time. The extensive utilization of tall stacks may change this situation appreciably.

MEASUREMENTS OF LARGE-SCALE IMPACTS FROM WET AND DRY DEPOSITION

Trends in the chemical composition of precipitation have been monitored on a rather widespread basis for several years using various precipitation chemistry networks.[109] By far the most extensive of these is the European network, which has been in existence since the late 1940's. From this network it has been determined that sulfate deposition in rain is currently increasing at a rate of 2-3 percent per year, roughly in parallel with emissions over northern Europe.[110] As noted previously, various Scandinavian researchers have analyzed these data in conjunction with historical meteorological records and have concluded that much of the sulfate in Scandinavian precipitation occurs as a consequence of long-range transport from British and continental-European sources. Since the acidity associated with sulfate deposition is considered to have a pronounced adverse effect on Scandinavian soils and surface waters, this conjecture poses a strong argument against the use of tall stacks rather than absolute emission controls -- even in localities such as the British Isles where the extent of the surrounding land mass is limited.

Corresponding measurements of precipitation-chemistry trends throughout the United States have been hampered by the discontinuance of networks and by their limited coverage. Nisbet[110] has utilized data from networks in existence during 1955-56 and 1965-66 to demonstrate that a 60-65 percent increase in the sulfate content of precipitation has occurred during this ten-year period. This increase, which shows signs of continuing after a leveling off during the five-year period ending 1970, is reflected by a decrease in rain pH levels throughout the country.[111] A comparison of the measured sulfate levels with U.S. emission inventories suggests that 30-40 percent of emitted sulfur returns to the land surface as rain-borne sulfate.

Although there is some argument to the contrary,[112] strong evidence supports the suggestion that increases in precipitation acidity in the United States are largely the result of increased fossil-fuel consumption. Specifically, the fact that observed changes in precipitation chemistry closely parallel trends in fossil-fuel consumption would seem to indicate this relationship strongly. Furthermore, the observation that geographic areas of deposition coincide with those of emission makes any argument to the contrary extremely difficult.

Nisbet has combined an assumed relationship between sources and precipitation chemistry with fuel-utilization projections to estimate sulfate content and pH of rain in the United States by the year 1980. From his analysis, Nisbet calculates that if absolute source controls are utilized extensively, the United States sulfate deposition from rain will not change appreciably from its estimated 1972 level of 5.7 million tons per year. If tall stacks are chosen as an alternative to absolute emission control, the precipitation input rate will increase to 8.2 million tons per year, 3.9 million tons of which will exist essentially in the form of sulfuric acid. This corresponds to approximately two kilograms of sulfuric acid delivered, on the average, to each acre of surface per year.

Obviously, the surface impact of increased dry and wet deposition rates of sulfates and other acid-forming materials depends strongly upon the buffering capabilities of soils and surface waters. Given strong buffering conditions, the deposition of these materials may be largely inconsequential or even beneficial in some cases. On the other hand, severe adverse impact of sulfate deposition has been demonstrated in a number of cases. Aside from the well-known Scandinavian situation, the most dramatic example of this phenomenon is the locality near the Sudbury, Ontario, smelter area. Here a number of lakes have become acidified to pH values below 4.0. This has resulted in loss of fishery, marked changes in both zoo- and phytoplankton, and decreases in biomass and productivity by over one order of magnitude.[113]

WEATHER MODIFICATION AND VISIBILITY

Atmospheric pollutant materials can be expected to influence climate and the weather in at least three basic ways:

1) by changing the earth's albedo either locally or globally,
2) by changing the absorptive character of the atmosphere with regard to solar and terrestrial radiation, and
3) by modifying in-cloud evaporation-condensation phenomena, which in turn affects (1) and (2) above, in addition to modifying storm dynamics and precipitation phenomena.

Since most of these influences are related strongly to light-transmission characteristics, they are of key interest to the question of visibility as well. This subsection is addressed to a brief analysis of these aspects on global and local scales to assess the impact of tall stacks on these additional features of the atmospheric environment.

Several comprehensive documents have been published on the subject of inadvertent weather and climate modification,[114,115,116] and the reader is referred to these publications for a more detailed account of the subject. Insofar as global climatology is concerned, these analyses have generally concluded that natural variations in the earth's climate have precluded any definite measurement of trends in mean temperature attributable to the impact of man. On the other hand, trends have been identified in more specific areas. Notably, a continuous drop in solar radiation incidence at ground level arising from increased turbidity has been identified in the northern hemisphere at latitudes above about 30°N. These observations are supported by similar trends in atmospheric conductivity measurements, which are an indirect indication of aerosol loadings.

Although it is largely evident that anthropogenic aerosol is responsible for the observed decrease in solar incidence, the question of its effect on climatic temperature trends is not immediately obvious. Machta and Telegadas[116] emphasize that atmospheric aerosol both absorbs and scatters incoming solar radiation; whether the presence of additional particles will result in a warming or cooling trend depends upon several factors, including vertical placement of the aerosol in the atmosphere, surface albedo, and the ratio of absorbed to scattered energy.

In view of our current inability to measure or predict reliably the anthropogenic impact on climatic temperature variations, it is extremely difficult to anticipate any effect of tall stacks in this regard. From the discussion presented in previous sections, however, it is evident that tall stacks tend to increase the amount of aerosol in the atmosphere by several direct and indirect mechanisms:

- increasing the atmospheric residence times of primary particulates by discouraging deposition processes,

- increasing the amounts <u>and</u> residence times of secondary particulates (e.g., sulfates, nitrates) by discouraging deposition of both, and
- indirectly increasing the amounts of both primary and secondary particulates by discouraging the use of absolute emission control techniques.

Any prediction of additional particulate loadings arising from the above mechanisms is extremely tenuous, owing to the host of uncertainties involved. From a semiquantitative assessment of information regarding

- fossil-fuel trends,
- source terms for aerosol precursor gases (NO_x, SO_2),
- source-height-deposition relationships,
- source terms for primary aerosol, and
- background sources,

however, an estimate of a two-fold anthropogenic aerosol increase by the year 2000 does not seem unreasonable for remote locations through much of the northern hemisphere if a widespread utilization of tall stacks without source control is implemented. From current trends in atmospheric turbidity this increase could correspond to a further turbidity increase of twenty percent or more.

On smaller scales of distance, anthropogenic influences on climate and the weather become less difficult to verify. Turbidity trends in cities, for example, in general show distinct increases over long periods and pronounced weekly cycling. The enhancement of precipitation from both frontal and convective storms by urban effects has been documented in several instances, although extensive conjecture about measurement, interpretation, and cause-effect relationships continues.[117,118] Somewhat in contrast to urban locations, few results have been obtained regarding the influence of isolated sources on weather, although Hobbs and Shumway[119] have shown evidence of increased rainfall downwind from the stack of a kraft mill (large primary particulate sulfate source) in Washington State. However, since a majority of the particulate expected to be active in cloud and precipitation formation is secondary aerosol in the case of smelters and power plants, the most significant weather-modification effects from such sources may occur at comparatively large distances downwind, where they are extremely difficult to identify.

Insofar as cities themselves are concerned, local ground level sources undoubtedly contribute to turbidity to an extent where the effect of a remote elevated source typically will have negligible additional impact. Elevation of sources located within or near to the urban area, on the other hand, will certainly improve local horizontal visibility and (through confinement of the plume) will tend to reduce solar attenuation as well.

CONCLUSIONS RELATED TO THE INFLUENCE OF TALL STACKS ON ADDITIONAL ASPECTS OF AIR QUALITY

As a consequence of this analysis of the impact of tall stacks on aspects of air quality not directly related to Federal Ambient Air Quality Standards, it is concluded that evidence exists to indicate that a significant downward trend in the quality of the atmospheric environment will occur if widespread tall stack usage is implemented in lieu of source emission control. Some positive aspects of tall stacks emerge in this regard. They are effective, for example, in preventing intolerably high SO_2 deposition rates at short distances from sources. This positive effect, however, is offset by the collective impact of multiple sources at long distances. It is also limited to some extent by the fact that limitation of removal processes close in are necessarily accompanied by higher atmospheric loadings, residence times, and (on a collective basis) concentrations.

Insofar as weather and climate modification are concerned, no really conclusive statement can be made with regard to the influence of tall stack usage on gross aspects such as mean temperature and precipitation. In contrast to other weather-related aspects, trends in visibility can be estimated in a relatively straightforward manner. Accordingly, decreases in this parameter in the northern hemisphere probably will be the most evident weather-related effect of a widespread implementation of tall stack policy during future years.

SECTION VIII

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APPENDIX A

AMBIENT AIR QUALITY STANDARDS

National primary and secondary ambient air quality standards that exist at the present time are summarized in Table A-1. The primary standards define levels of air quality necessary to protect the public health with an adequate margin of safety. National secondary standards define levels of air quality necessary to protect the public welfare from any known or anticipated adverse effects of a pollutant. Recent reviews conducted by the National Academy of Sciences, the EPA, and independent groups have essentially supported these standards as they currently exist.[16] As noted in the previous text, the sulfur dioxide standards are at present the most significant in the context of tall-stack performance, and are followed in importance by the oxides of nitrogen.

TABLE A-1. SUMMARY OF EXISTING FEDERAL AMBIENT AIR QUALITY STANDARDS

Pollutant	Type of Standard	Sampling Time	Concentration of Standard
Sulfur Dioxide	Primary	1 year	80 $\mu g/m^3$ - 0.03 ppm
	Primary*	24 hr	365 $\mu g/m^3$ - 0.14 ppm
	Secondary*	3 hr	1,300 $\mu g/m^3$ - 0.5 ppm
Nitrogen Dioxide	Primary and Secondary	1 year	100 $\mu g/m^3$ - 0.05 ppm
Total Particulate	Primary	1 year†	75 $\mu g/m^3$
	Primary*	24 hr	260 $\mu g/m^3$
	Secondary**	1 year†	60 $\mu g/m^3$
	Secondary*	24 hr	150 $\mu g/m^3$
Photochemical Oxidants	Primary and Secondary	1 hr	160 $\mu g/m^3$ - 0.08 ppm
Carbon Monoxide	Primary and Secondary*	8 hr	10,000 $\mu g/m^3$ - 9 ppm
	Primary and Secondary*	1 hr	40,000 $\mu g/m^3$ - 35 ppm
Hydrocarbons (non-methane)	Primary and Secondary***	3 hr	160 $\mu g/m^3$ - 0.24 ppm

*Not to be exceeded more than once per year
**As a guide to be used in assessing implementation plans to achieve the 24-hour standard
***As a guide in devising implementation plans for achieving oxidant standards

†Geometric means

APPENDIX B

1974 SUMMARY OF U.S. STACKS TALLER THAN 122 METERS

The summary of stack heights given in the following table was prepared by accessing the computer files of the NOAA office of Aeronautical Charting and Cartography, and applying this information in conjunction with 1972, Federal Power Commission Form FPC-67 data and further information from the EPA document Steam Electric Power Generating Point Source Category, EPA 440/1-74 029-a, 1974. The author expresses his sincere appreciation to staff members of NOAA and the EPA, who have contributed significantly to the creation of this table.

1974 SUMMARY OF U.S. STACKS
TALLER THAN 122 METERS

Plant Name	Location	Height (type)* (meters)
	Alabama	
Gorgas	Gorgas	229 (P)
E. C. Gaston	Wilsonville	229 (P)
Barry	Bucks	183 (P)
Brown's Ferry Nuclear	Decatur	183 (N)
Widows Creek	Stevenson	152 (P)
Colbert	Pride	152 (P)
	Arizona	
	Hayden	305/183 (S)
Navajo	Page	236 (P)
	Morenci	236 (S)
	Douglas	171 (S)
	San Manuel	168 (S)
Mohave	Clark Co., Nev.	153 (P)
	Arkansas	
Ritchie	Helena	137 (P)
	California	
Moss Landing	Moss Landing	152 (P)
	Benicia	142 (R)
Contra Costa	Antioch	137 (P)
Morro Bay	Morro Bay	137 (P)
Pittsburg	Pittsburg	137 (P)
	Colorado	
Comanche	Pueblo	152 (P)
Cherokee	Denver	122 (P)

TABLE 1. (contd)

Plant Name	State Location	Height (type)* (meters)
	Connecticut	
Middletown	Middletown	152 (P)
Bridgeport Harbor	Bridgeport	151 (P)
	Delaware	
	Delaware City	152 (P)
	Florida	
Crystal River	Red Level	154 (P)
Anclote #1	Tarpon Springs	153 (P)
Manatee	Port Manatee	152 (P)
Big Bend	Tampa	149 (P)
Fort Meyers	Fort Meyers	137 (P)
Crist	Pensacola	127 (P)
Cape Kennedy	Cocoa	122 (P)
Turkey Pt.	Florida City	122 (P)
Sanford	Lake Monroe	122 (P)
	Georgia	
Bowen	Bartow County	305 (P)
Wansley 1 & 2	Carrollton	305 (P)
Harlee Branch	Milledgeville	305 (P)
McDonough	Cobb County	253 (P)
Yates	Newnan	251/244 (P)
Hammond	Floyd County	229 (P)
Arkwright	Bibb County	177 (P)
Mitchell	Daugherty County	152 (P)

TABLE 1. (contd)

Plant Name	Location	Height (type)* (meters)
	Illinois	
Baldwin	Baldwin	185 (P)
Joliet	Joliet	168 (P)
Powerton	Pekin	161 (P)
Coffeen	Coffeen	152 (P)
E. D. Edwards	Bartonville	152 (P)
Kincaid	Kincaid	152 (P)
Waukegan	Waukegan	137 (P)
Will County	Lockport	137 (P)
Fisk	Chicago	137 (P)
	Indiana	
Clifty Creek	Clifty Creek	208 (P)
E. W. Stout	Indianapolis	172 (P)
Breed	Sullivan	168 (P)
Petersburg	Petersburg	168 (P)
Tanners Creek	Lawrenceburg	168 (P)
Gallagher	New Albany	168 (P)
Cayuga	Cayuga	152 (P)
Gibson	Princeton	152 (P)
Michigan City	Michigan City	152 (P)
R. M. Schafer	Wheatfield	152 (P)
Warrick	Newburgh	152/122 (P)
State Line	Hammond	140 (P)
Bailly	Dune Acres	124 (P)
	Iowa	
Neal #1 & 2	Salix	122 (P)
	Kansas	
La Cygne	Linn County	213 (P)

TABLE 1. (contd)

Plant Name	State Location	Height (type)* (meters)
	Kentucky	
Big Sandy	Louisa	252 (P)
Ohio River #1	Maysville	245 (P)
J. M. Stuart	Aberdeen, Ohio	244 (P)
Paradise	Drakesboro	244 (P)
Ghent	Ghent	201 (P)
Elmer Smith	Owensboro	198 (P)
Mill Creek	Louisville	183 (P)
E. W. Brown	Burgin	172 (P)
Cane Run	Louisville	152 (P)
	Louisiana	
	Chalmette	154 (A)
	Maryland	
Morgantown	Newburg	213 (P)
	Luke	183 (P)
Chalk Point	Aquasco	122 (P)
Dickerson	Dickerson	122 (P)
	Massachusetts	
Mystic	Everett	152 (P)
Salem Harbor	Salem	152 (P)
Brayton Point	Somerset	152 (P)
Canal	Sandwich	152 (P)

TABLE 1 (contd)

Plant Name	State Location	Height (type)* (meters)
	Michigan	
Monroe	Monroe	244 (P)
B. C. Cobb	Muskegon	198 (P)
Weadock	Essexville	198 (P)
St. Clair	E. China Township	183 (P)
Trenton Channel	Trenton Channel	172 (P)
	White Pine	154 (S)
Karn	Essexville	152 (P)
River Rouge	River Rouge	130 (P)
Campbell	West Olive	123 (P)
	Minnesota	
King	Oak Park Hts.	239 (P)
Sherbourne	Becker	198 (P)
Black Dog	Minneapolis	183 (P)
High Bridge	St. Paul	174 (P)
Riverside	Minneapolis	145 (P)
Boswell	Cohasset	122 (P)
	Mississippi	
G. Andrus	Greenville	152 (P)
Jack Watson	Gulfport	122 (P)
	Missouri	
Labadie	Labadie	216 (P)
Rush Island	Crystal City	216 (P)
Sibley	Sibley	213 (P)
Sioux	West Alton	183 (P)
Hawthorne	Kansas City	183 (P)
New Madrid	New Madrid	183 (P)
Thomas	Randolph County	123 (P)
Asbury	Asbury	122 (P)

TABLE 1. (contd)

Plant Name	Location	Height (type)* (meters)
	Montana	
	McGill	230 (S)
	Anaconda	178 (S)
	Great Falls	157 (S)
Colstrip #1-4	Colstrip	154 (P)
	New Hampshire	
J. O. Newington #1	Newington	127 (P)
	New Jersey	
Hudson	Jersey City	152 (P)
	Woodbridge	122 (S)
	New Mexico	
	Hurley	192 (S)
	Animas	183 (S)
	New York	
Oswego	Oswego	213 (P)
Northport	Northport	183 (P)
Ravenswood	New York	152 (P)
59th & 74th Sts.	New York	152 (P)
Authur Kill	New York	152 (P)
Waterside	New York	142 (P)
Port Jefferson	Port Jefferson	130 (P)
	Upton	129 (N)

TABLE 1. (contd)

Plant Name	State Location	Height (type)* (meters)
	North Carolina	
Roxboro	Roxboro	244 (P)
Belews Creek	North Winston	182 (P)
L. V. Sutton	Wilmington	168 (P)
Cliffside	Cliffside	155 (P)
	North Dakota	
Leland Olds	Stanton	152 (P)
	Ohio	
Gavin	Cheshire	335 (P)
W. H. Sammis	Stratton	305/259/154 (P)
Burger	Shadyside	259 (P)
Cardinal	Brilliant	251 (P)
Muskingum River	Beverly	252 (P)
Conesville 5 & 6	Conesville	245 (P)
J. M. Stuart	Aberdeen	244 (P)
Miami Fort	North Bend	244 (P)
Toronto	Toronto	198 (P)
Avon Lake	Avon Lake	183 (P)
East Lake	East Lake	183 (P)
Kyger Creek	Cheshire	163 (P)
W. C. Beckjord	New Richmond	145 (P)
Conesville 1-4	Conesville	137 (P)
Ashtabula	Ashtabula	122 (P)

TABLE 1. (contd)

Plant Name	State Location	Height (type)* (meters)
	Pennsylvania	
Homer City	Homer City	366/244 (P)
Conemaugh	Indiana County	305 (P)
Bruce Mansfield	Shippingport	289 (P)
Cheswick	Springdale	244 (P)
Keystone	Shelocta	244 (P)
Hatfield's Ferry	Masontown	244 (P)
Seward	Seward	184 (P)
Martins Creek	Martins Creek	183 (P)
Shawville	Shawville	183 (P)
Montour	Washingtonville	183 (P)
Brunner Island	York Haven	183 (P)
	Langloth	152 (S)
Peach Bottom Nuclear	Peach Bottom	151 (P)
	Morgantown	122 (S)
Portland	Portland	122 (P)
Susquehanna Nuclear	Tunkhannock	122 (P)
	South Carolina	
Georgetown	Georgetown	123 (P)
	South Dakota	
Big Stone	Grant	152 (P)
	Tennessee	
Kingston	Kingston	306 (P)
Cumberland	Cumberland	305 (P)
Bull Run	Clinton	244 (P)
Gallatin	Gallatin	152 (P)
T. H. Allen	Memphis	132 (P)
Johnsonville	Johnsonville	123 (P)

TABLE 1. (contd)

Plant Name	State Location	Height (type)* (meters)
	Texas	
	El Paso	251/186 (S)
	La Porte	147 (R)
	Amarillo	125 (S)
	Port Arthur	123 (R)
Big Brown	Fairfield	122 (P)
	Monticello	122 (R)
	Utah	
Huntington Canyon #1 & 2	Huntington	183 (P)
	Murray	139 (S)
	Salt Lake City	138 (S)
	Garfield	122 (S)
	Virginia	
Yorktown	Yorktown	149 (P)
Clinch River	Carbo	138 (P)
Glen Lyn	Glen Lyn	134 (P)
Chesterfield	Chesterfield	129 (P)
	Washington	
	Tacoma	181 (S)
Centralia	Centralia	144 (P)
	West Virginia	
Mitchell	Moundsville	366 (P)
Harrison	Haywood	306 (P)
Amos	St. Albans	274 (P)
	Ravenswood	187 (S)
Kammer	Captina	183 (P)
Philip Sporn	Graham	183 (P)
Mt. Storm	Mt. Storm	183 (P)
Ft. Martin	Maidsville	168 (P)

TABLE 1. (contd)

Plant Name	Location	Height (type)* (meters)
	Wisconsin	
Alma	Alma	213 (P)
South Oak Creek	Oak Creek	168 (P)
Genoa #3	Genoa	152 (P)
Columbia	Portage	152 (P)
Port Washington	Port Washington	152 (P)
Valley	Milwaukee	122 (P)
	Wyoming	
Bridger	Rock Springs	154 (P)

State

*Symbols: P - power plant
S - smelting or metals processing
N - experimental nuclear reactor
R - refinery

APPENDIX C

ANNOTATED BIBLIOGRAPHY OF PERTINENT LITERATURE ON TALL STACKS

This section presents an annotated bibliography of selected articles and reports related to the subject of transport and dispersion of plumes from tall stacks. The material presented here was selected on the basis of its direct relationship to dispersion from tall stacks, its technical merit, and its general accessability. It is restricted primarily to publications in the English language.

It should be noted that primary emphasis is given to the more recent literature , and that there are two basic reasons for this. The first of these is that stack-height trends necessarily restrict literature pertaining to the taller stacks to a relatively late period. Secondly, much of the early work has been discussed previously in detailed publications by Slade,[50] Pasquill,[31] and Csanady,[48] to mention but a few. The reader is referred to these refrences for a more thorough examination of the earlier work.

Finally, it is emphasized that, in order to obtain a more objective presentation, the abstracts have been written to reflect the original authors' intents as much as possible. To help accomplish this, the wording of the abstracts has been chosen to reflect the time period when the article was published. This material does not necessarily reflect a viewpoint of anyone other than the original authors.

The references appear in reverse chronological order, except in cases where continuity of series of reports demands grouping otherwise.

NAVAJO

Navajo Generating Station Sulfur Dioxide Field Monitoring Program. Volume I, Final Program Report, Rockwell International, Meteorology Research Incorporated, Systems Applications Incorporated (1975).

The purpose of this program was to determine the amount of flue gas desulfurization necessary to satisfy ambient SO_2 standards in the vicinity of the Navajo generating station. This facility currently has two 750 Mwe units in operation; a third unit of similar size is scheduled for operation in April, 1976. Effluent from each unit passes through individual, 236 m stacks.

The primary impetus for this program was the previous Southwest Energy Study, which indicated that without SO_2 source control, air quality standards would be violated. A particularly important aspect of this study - open to considerable debate - was the behavior of pollutant plumes as they encountered elevated surfaces. In addition to this question of plume impingement, meteorological situations involving plume looping, fumigation, and limited mixing received special emphasis. The air monitoring component of this program consisted of an array of 26 fixed SO_2 monitors, used in conjunction with aircraft plume measurements to determine dispersion behavior downwind from the Navajo plant. The data obtained in this manner were utilized in conjunction with a dispersion model to predict the expected frequency of occurence of surface concentrations in excess of the 1300 $\mu g/m^3$ three-hour standard.

The principal conclusion of the program is that the expected frequency of occurrence of SO_2 concentrations above the three-hour standard is less than twice per year. The implementation of flue gas desulfurization at the Navajo plant is therefore judged to be unnecessary.

Situations leading to highest observed ground-level concentrations were those involving impingement of the plume on elevated terrain, and fumigation conditions. Particular emphasis was placed upon impingement at the Vermillion Cliffs area, where the terrain rose abruptly of the order of one thousand feet above the stack exit. In general impingement was observed to occur principally under conditions involving light, steady winds in stable atmospheres.

Clarke, A. J., and G. Spurr.

Routine Sulfur Dioxide Surveys Around Large Modern Power Stations Part I - Summary paper. Central Electricity Generating Board (1975).

This series of papers describes sulfur dioxide measurements at six of the Central Electricity Generating Board's more modern power plants. These include Kingsworth, Fawley, Pembroke, Ratcliffe, Eggborough, and Fiddler's Ferry. With the exception of Pembroke (s.h. = 213 m) the stack height of all of these 2000 MWe plants is 198 m.

Sampler locations for these surveys were such that uniform distributions around each power station were achieved. In addition to SO_2 monitors, more sophisticated plume detectors such as Lidar were employed.

Natural diurnal, seasonal, and long-term variations in ground level SO_2 concentrations have precluded detection of contributions by any of the plants insofar as monthly and seasonal averages are concerned. Comparisons of daily upwind and downwind measurements provides more sensitivity in this regard, but the effects of the plants' contributions have not been detected even with this method. On the basis of these results it is concluded that contributions by the plants to daily mean SO_2 levels is less than 7 $\mu g/m^3$. This almost complete absence of a measurable power station contribution is surprising since an occasional effect on the daily mean SO_2 concentration is expected on the basis of diffusion theory. This suggests that "some hitherto unaccounted process is assisting in the dilution of the plumes."

These results are unequivocal in their finding that SO_2 pollution can be controlled effectively by tall stacks. It is emphasized, however, that these measurements do not consider other aspects of power-plant air pollution, such as SO_2 reactions, or its ultimate fate.

Parts II-VI of this report follow this summary section, and are authored by various individuals as follows:

Part II: Fawley and Pembroke - R. T. Jarman and C. M. deTurville
Part III: Kingsworth - A. W. Powell and P. A. Tatchell
Part IV: Ratcliffe-on-Soar - F. R. Barber and A. Martin
Part V: Eggborough - D. L. Dolman and P. M. Owens
Part VI: Fiddler's Ferry - F. Dale

Start, G. E., C. R. Dickson, and L. L. Wendell.

Diffusion in a Canyon Within Rough Mountainous Terrain. JAM, 14, 333-341 (1975).

A field test was conducted to assess the effect of complex terrain on the dispersion of airborne effluents. Specifically, the project had two primary goals: 1) to evaluate plume "impaction" on elevated terrain and 2) to assess diffusion in the complex areas as compared to that over flat terrain.

The site of the study was the Huntington Canyon area where a 183-meter power-plant stack was utilized to disperse oil-fog and SF_6 tracers. The stack was situated in the trough of a narrow valley with steep walls, which possessed a number of sizeable feeder canyons along its length. Measurement techniques included helicopter and ground-level SF_6 sampling in addition to plume photography. Under daytime lapse conditions little deviation between measured dispersion and expected flat-terrain values was observed. Under neutral and stable conditions, however, observed mixing rates were several times higher than flat-terrain values. Frequent occurrences of impaction of the plumes on elevated terrain were observed.

Lucas, D. H.

The Effect of Emission Height in Very Large Areas of Emission. Atm. Env. 9, 607-622 (1975).

Calculations have been performed to determine the effects of emission height on ground level air concentrations in and downwind from uniform area sources. The calculations employed Sutton's plume equation for typical atmospheric conditions, which included neutral and isothermal cases, as well as stable stratifications at elevations of 200, 400 and 1000 m. The pollutant (SO_2) was considered to act as an inert substance, and zero background concentration was assumed.

Graphs of concentration versus distance based on these calculations gave the following indications:

- large chimneys reduce the maximum ground-level concentrations of pollutants under all meteorological conditions
- the required chimney height to promote acceptable ground-level concentrations increases with increasing size of the area source, and such concentrations can be achieved with chimney heights currently practical
- raising the height of emission above the bottom of stable layers essentially eliminates the possibility of pollutant diffusing to ground level
- while sufficiently tall stacks can reduce concentrations substantially in the area of emission, they do not increase downwind concentrations as a result.

Further calculations indicate that a 90% reduction in the sulfur emissions from high-elevation sources would result in less than ten percent reduction in ambient ground-level concentrations inside even moderately large cities. This is because low elevation sources contribute disproportionately to ground-level concentrations.

This paper does not deal with the problem of sulfate formation; it is noted, however, that in view of the U.S. Environmental Protection Agency's position that flue gas desulfurization is preferable to the use of tall stacks, the burden of proof that tall stacks are unacceptable is on this agency. Accordingly, the EPA should utilize their resources to "demonstrate the relative effects of emission control and stack-height control in real situations."

Smith, M. E., and T. T. Frankenberg.

Improvement of Ambient Sulfur Dioxide Concentrations by Conversion from Low to High Stacks. JAPCA 25, 595-601 (1975).

During the last twenty years the stacks of the Muskingum River Power Plant have increased in height from 83 m to 251 m. Because of this increase and also because of the rural, unpolluted environment of the plant, an excellent opportunity to assess the true effects of stack height has been provided.

This study began with a monitoring program in 1969 when the plant was operating with 133 m stacks. It consisted of a monitoring program that extended through 1973, when only the 251 m stacks were employed.

Plume concentrations were predicted for this study utilizing ASME standard procedures which had been modified to account for directional shear and variation of velocity with elevation. SO_2 monitoring was conducted with automatic instrumentation at four sites, located between 4 and 20 km from the plant.

Comparison of concentrations predicted for situations with the 133 and 251 m stacks indicated that an approximately two-fold decrease in ground-level concentration should result from the use of the taller chimneys, and this prediction is borne out by the actual measurements. Further analysis of the measurements indicate that, in contrast to the case with shorter stacks, the predominant mechanism for promoting high ground level concentrations is downward mixing under daytime conditions, where unstable conditions exist in a relatively deep layer.

Although EPA primary and secondary standards were exceeded on occasion with the shorter stacks, there have been no observations of SO_2 in excess of standards since the 251 m stacks were implemented.

Miller, S.

The Building of Tall (and Not So Tall) Stacks. Envi. Sci. Tech. 9, 523-527 (1975).

The purpose of the tall stack is high-level dispersion of pollutants to reduce concentrations at ground level. Several aspects make the subject of tall stacks especially pertinent today:

- in 20 years SO_2 emission to the atmosphere will have nearly doubled;
- the number of tall stacks is increasing at a rapid pace; and
- additional effects not directly related to ground-level concentrations, such as acid rain, are currently being associated with industrial air pollution.

Proponents of tall stacks point out that such units are able to reduce ground level concentrations of SO_2, and can document such claims with data from monitoring networks. These proponents, however, fail to recognize that material vented must ultimately come back to the surface despite the height of release.

Early indications are clear that SO_2 emissions from tall stacks can penetrate through inversion layers. There are strong indications, however, that such emissions convert to sulfates and are removed as "acid rain" at some distance from the source. Increases in rain acidity within the U.S. have been noted during recent years, and some specialists are now proposing that such increases are directly associated with changes in anti-pollution technology.

Dunlap, R. N.

Control of Ambient Sulfur Dioxide Concentrations with Tall Stacks and/or Intermittent Control Systems. Air Quality and Stationary Source Emission Control NAS/NAE (1975).

The advantages of particular meteorological conditions for maintaining high air quality suggest that control systems for power plants need only be operated intermittently, under adverse conditions. Intermittent Control Systems (ICS) are often closely associated with tall stacks, owing to the latter's enhanced dispersion capability. The TVA estimates, for instance, that ICS requirements for the Kingston plant would be reduced from 55 to 0 days per year if the stacks were extended to 1000 feet.

Proposed EPA regulations do not accept increases in stack height beyond levels of "good engineering practice" as acceptable air quality control measures, unless this is accomplished as a part of an ICS program. An acceptable ICS program, in addition, must adhere to several stringent guidelines. The suggestion that tall stacks be used for meeting ambient ground-level SO_2 standards is a controversial one. The sizable amount of evidence indicating that they are often effective for this purpose is tempered by the fact that, over an extended period of time, they result in only a negligible reduction in the amount of pollutants emitted. This is the major reason for limitations on the use of tall stacks by the EPA, which contends that the use of emission limitations in preference to dispersion-enhancement techniques is required by the Federal Clean Air Act. The limits of acceptable flue-gas-desulfurization (FGD) measures in conjunction with ICS programs is currently being debated in several court cases, with results which are largely conflicting at the present time.

A few tall-stack ICS programs are now operating, but few data exist to indicate their performance. Data for TVA's Paradise Steam Plant are most extensive, and indicate that the ICS (which has included substantial stack-height increases) is resulting in compliance with Federal Ambient Air Quality Standards (AAQS). Similar results have been observed with the ASARCO Tacoma smelter, although more stringent local AAQS have been continued to be violated. ASARCO's El Paso smelter (828' and 611' stacks) demonstrated an improvement in ambient air quality upon initiating an ICS. The success of this program was limited by problems associated with the complex terrain in the area, however. In summary, the results to date indicate mixed results from ICS tall stack application, with terrain effects being a major complicating factor.

Aside from maintaining primary Federal AAQS's, much controversy has arisen over other effects. These include the biological impact of sulfate aerosol, precipitation chemistry, visibility effects, and climate and weather modification. Unfortunately most of these impacts are not well understood qualitatively, rendering most related decisions with regard to tall stacks rather subjective in nature. The EPA has suggested that sulfate levels above 6-10 $\mu gm/m^3$ are associated with adverse health effects, and has concluded that use of tall-stack-ICS control systems will aggravate the sulfate problem. An opposing viewpoint (by the FEA, the TVA, and the AEP Service Corporation) suggests that if sulfate is indeed a problem, appropriate AAQSs should be set. If information is insufficient to issue a criteria document, then tall-stack-ICS technology should not be rejected on this basis.

This NAS/NAE study suggests that a compromise position can be identified where ICS-tall-stack technology could be accepted for carefully defined situations as an interim control technique on the basis of the need to:

1. select suitable interim techniques during large scale implementation of FGD technology, and

2. reduce the clean fuels deficit while complying with AAQSs (for SO_2 if not for SO_4).

The study concludes with the finding that "tall-stack-ICS technology is a potentially important technological option for control of ambient sulfur dioxide." Much disagreement exists with regard to the question of sulfate aerosol, however.

Walden Research Corporation

Modeling Analysis of Power Plants for Compliance Extensions in 51 Air Quality Control Regions. Summary Report to EPA contract 68-02-0049, (1975).

This report summarizes individual reports covering modeling analysis of power plants in a number of Air Quality Control Regions (AQCR's). Its purpose is to determine the extent that variances could be granted for certain plants to relieve the aggregate low-sulfur coal deficit.

Input data for the model (Gaussian with Briggs' plume rise) were taken from the Federal Power Commission (FPC Form 67), in conjunction with measured meteorological data for the year 1964. Terrain effects are compensated by adjustment of the virtual emission height in the Gaussian model. An additional short-term model for valley terrain was also employed. Interaction of plumes from individual plants was considered when warranted by their proximity.

The report concludes that a power plant variance strategy appears to offer a viable approach to reducing the low-sulfur coal deficit without jeopardizing attainment of primary Federal Ambient Air Quality Standards.

Start, G. E., C. R. Dickson, and N. R. Ricks

Effluent Dilutions over Mountainous Terrain and Within Mountainous Canyons. Proc. Symposium on Atmospheric Diffusion and Air Pollution. AMS, Santa Barbara Conf. (1974).

A field study was conducted to evaluate the effects of complex terrain on plume dilution and to determine the extent of impingement of plumes on elevated surfaces. The study involved helicopter and ground-level sampling of plumes emitted from the surface and from stacks in two different locations. The first of these was a 183 meter stack in the Valley of Huntington Canyon; in the second was the 122 m stack located near Garfield, Utah, on the south shore of Great Salt Lake.

These measurements showed that centerline concentrations of plumes that flowed over complex terrain were significantly more dilute than those predicted using Pasquill categories and the Gaussian plume model. These deviations became increasingly pronounced with increasing stability, reflecting the relative importance of mechanically-induced mixing under these conditions.

Four physical mechanisms are suggested as important in enhancing dilution in complex terrain. These are: mechanical mixing, overshoot from slope winds, wake turbulence, and vertical directional shear.

There was no question that the plumes impacted the terrain, but generally impaction was only a few minutes in duration at any given location.

Lucas, D.

Pollution Control by Tall Chimneys. New Scientist, 790-791 (26 Sept 1974).

An evaluative technique which is based on the concept of an elevated area source has been employed to determine the consequences of increasing release height in areas of concentrated SO_2 emission. The results of this analysis indicate that increasing release height should reduce downwind SO_2 concentrations appreciably; and this result is used as a basis to argue against United States EPA source control policy, which emphasizes removal of SO_2 at its source.

Moore, D. J.

The Prediction of the Mean Hourly Average Maximum Ground Level Concentration of Sulfur Dioxide. Atm. Env. 8, 543-554 (1974).

Previously-derived equations for the hourly, maximum ground-level concentration in a power plant plume, developed from measurements at the Northfleet plant, were applied for analysis of results from Tilbury. These equations had the form

$$C_m = [(M/H)^2 + (C/U^2)^2]^{1/2}(Q/H^2) \qquad \text{(unstable conditions)}$$

and

$$= [(M/H) + (C/U^2)^2](Q/H^2) \qquad \text{(all other conditions),}$$

where

$$H = 100 + 475\, Q_h^{1/4}/U,$$

Q_h = heat release, U = wind speed, and M and C are stability-dependent parameters.

The physical basis for the above equations rests in the fact that downward diffusion from sources above about 150 m takes place through an environment that is always stably stratified to some degree. Observations of instability arise from local inhomogeneities (i.e., thermals) which are always embedded in a slightly stable environment. The observed diffusivity thus can be considered to consist of two terms: M, which depends upon mechanical stirring of the boundary layer, and C, which reflects convective activity.

Application of the above equations using M and C determined from the Northfleet measurements to the Tilbury data demonstrates excellent agreement.

Start, G. E., N. R. Ricks, and C. R. Dickson.

Effluent Dilutions over Mountainous Terrain NOAA TM ERL ARL-51 (1974).

A tracer sampling program was undertaken at Garfield, Utah to determine the effect of complex terrain on the behavior of plumes. Specifically, the objectives were (1) to determine the dilution attributable to rough terrain, (2) to examine the "impaction" of plumes against elevated surfaces, and (3) to establish a modest data base to aid in diffusion analysis at this and similar sites.

The Garfield smelter (s.h. = 122 m) is located near the south shore of Great Salt Lake immediately north of the steep slopes of the Oquirrh Mountains. The experiments consisted primarily of releasing SF_6 tracer from the smelter stacks and performing airborne and ground level measurements of this substance at points downwind. These plus visual plume observations verified the fact that plumes often came in contact with mountain surfaces. These occurrences were strongly influenced by atmospheric stability, with the most pronounced contact occurring under stably-stratified conditions.

Measured Pasquill plume-spread parameters indicated that plumes that flowed over the rough terrain experienced as much as four times the dilution expected from similar plumes flowing over flat surfaces.

Moore, D. J.

Observed and Calculated Magnitudes and Distances of Maximum Ground Level Concentration of Gaseous Effluent Material Downwind From a Tall Stack. Adv. Geophys. 18B 201-221 (1974).

A revised approach to a previously-derived method was utilized to predict the distance of maximum ground-level concentration downwind from an elevated source. This revision incorporated a provision to account for early stages of plumes, where mixing is dominated by plume-generated turbulence.

The starting point for this analysis was the plume model of Moore, which assumes a normal distribution with mixing dictated by separate thermal and mechanical components. This model expresses maximum ground-level concentration in terms of two fitted parameters A and C, which respectively reflect mechanical and thermal turbulence. The model also can be utilized to calculate a downwind distance of the maximum concentration, but this is an inappropriate value, owing to the model's tacit neglect of plume-generated turbulence during its early stages.

To remedy this situation an expression for the virtual location of the source (the location of the source of an imaginary plume possessing no plume-generated turbulence) was derived. Predictions based upon this expression were compared with observations from the Tilbury and Northfleet Plants, where acceptable comparisons were obtained except under light wind, unstable conditions, stable situations, and conditions involving high winds.

Moore, D. J.

Comparison of the Trajectories of Buoyant Plumes with Theoretical/Empirical Models. Atm. Envi. 8, 441-57 (1974).

Many attempts to describe plume rise are based upon a two-dimensional concept of plume behavior. This concept is only partially applicable in early plume stages, owing to the "lumpy" nature of the plume under such conditions, suggesting that a more three-dimensional characterization might be more appropriate. Parameterized two- and three-dimensional approaches can be force-fit to data from moderate-sized stacks and power plants with approximately equal success. The results of this study, however, indicate that for stack heights greater than 120 m, the three-dimensional-based form

$$\Delta h = 2.4\, Q^{0.25}\, x^{*\,0.75}/U$$

describes the data in a more satisfactory manner.

Martin, A., and F. R. Barber.

"Further Measurements Around Modern Power Stations" Atm. Env. 7, 17-37 (1973).

Beginning in 1966 a program was conducted to assess ambient sulfur dioxide levels from the West Burton Power Station (s.h. = 183 m). Measurements were also taken in the vicinity of the High Marnham Station (s.h. = 137 m), which is located some 15 km to the south. Measurements included those taken from arrays of ground-level SO_2 instrumentation, elevated (tower) measurements, and Lidar.

The highest concentrations at ground level were observed during looping-plume conditions. Fumigation from inversion break-up processes were no more severe than concentrations observed during steady state conditions with similar wind speeds and lapse rates. Ambient SO_2 levels caused by the plants are less than one tenth those contributed by background sources. Despite its approximately doubled firing rate, ambient SO_2 concentrations from the West Burton Plant are somewhat less than those from High Marnham. This is attributed to the higher stack of the West Burton facility.

Weil, J. C., and D. P. Hoult.

A Correlation of Ground-Level Concentrations of Sulfur Dioxide Downwind of the Keystone Stacks. Atm. Env. 7, 707-721 (1973).

A partial energy balance is employed to obtain an expression relating meteorological variables and solar radiation to the heights of unstable mixing layers developing below overlying stable air. This expression is fit empirically to observed mixing heights in the Keystone plant area, and combined with plume-rise estimates to predict the incidence of plume interception by the mixing layers.

A relatively simple plume dispersion expression, relating ground-level concentration under plume interception conditions to the effective emission height, source strength, and wind velocity is then fit empirically to surface measurements to obtain a means for estimating ground-level concentrations under these conditions.

Lyons, W. A., and H. S. Cole.

Fumigation and Plume Trapping on the Shores of Lake Michigan During Stable Onshore Flow. J. Appl. Met., 12, 494-510, (1973).

Fumigation and plume trapping can occur under conditions of onshore, gradient flow owing to the associated perturbations in the boundary layer. When air flowing onshore from a cooler lake environment progresses inland surface heating and roughness creates a developing turbulent boundary layer. Plumes emitted into the overlying stable air may be drawn into the deepening turbulent boundary layer causing fumigation to occur.

This paper discusses field observations of power plant plume behavior under such circumstances, and describes models developed to calculate associated ground-level concentrations.

Heines, T. S., and L. K. Peters.

The Effect of a Horizontal Impervious Layer Caused by a Temperature Inversion Aloft on the Dispersion of Pollutants in the Atmosphere. Atm. Env. 7, 39-48 (1973).

A Laplace-transformation technique was used to obtain solutions to a continuity equation for pollutants having diffusion coefficients obeying a power law. The solutions pertained to line and point sources, and were constrained by zero flux boundary conditions at the surface and at some elevated height $z = H^*$.

For a point source the effect of rising H^* was to decrease ground level concentration.

For inversion heights beyond two-thirds higher than the stack height the effect of the inversion was negligible.

Allen, R. G.

Facts to Consider when Evaluating Stack Height. Power 117, 30-31, (1973).

Tall stacks are effective and economical devices for reducing ground-level pollution. Downwash caused by local terrain features may hinder the performance of a tall stack, but the solution in such circumstances is an even taller stack. Other nonideal features such as sea-land breeze circulations are more difficult to estimate. Fortunately the associated problems are often solved automatically using conventional analyses for tall stacks.

Montgomery, T. L., W. B. Norris, F. W. Thomas, and S. B. Carpenter.

Simplified Technique Used to Evaluate Atmospheric Dispersion of Emissions from Large Power Plants, JAPCA 23, 388-394 (1973).

Nomograms corresponding to predictions from three atmospheric dispersion models are presented. The model types include those for coning, inversion breakup, and trapping, and are intended for use in predicting ambient concentrations resulting from large power plants.

Inversion breakup and trapping dispersion processes have been identified with the highest observed ground-level concentrations in TVA's experience, and have generally been associated with the newer plants having tall stacks (75 m or more). The coning model is most closely associated with critical conditions for plants with shorter stacks. Inversion breakup results in high surface concentrations which are of relatively short duration (30-45 min). In the TVA region inversion breakup may occur on 200-300 days per year; the resulting magnitudes of surface concentrations, however, normally do not reach high levels at any single location more than a few times a year, owing to the variable sector of the plume and dependence on initial inversion height.

Plume trapping, identified with rapid vertical mixing below an inversion layer, can result in high concentrations for periods of 2-5 hours. The trapping condition is found to apply to large power plants on about 30-40 days per year in the TVA region.

Schiermeier, F. A., and L. E. Niemeyer.

Large Power Plant Effluent Study [Lappes] Volume 1 - Instrumentation, Procedures, and Data Tabulations (1968), USPHS National Air Pollution Control Administration APTD 70-2 (1970).

Considerable debate is presently underway regarding the use of tall stacks for air pollution management. Accordingly, the National Air Pollution Control Administration is conducting a 5-year comprehensive field study to determine the behavior of plumes from tall stacks. Centered in Western Pennsylvania in the vicinity of three new large power sources, the specific objectives of the study are:

1. To develop and validate transport and diffusion models with which to calculate ground-level concentrations resulting from tall stacks,

2. To measure the magnitude, frequency, and spatial distribution of ground-level concentrations from large power plants with tall stacks, singly and in combination, and to compare the observed data with calculated predictions, and

3. To evaluate the effects of sulfur compounds and other effluents from a large power plant complex on vegetation.

The three power stations of primary significance to this study are Keystone (1800 MWe, s.h. = 244m), Homer City (1280 MWe, s.h. = 244m), and Conemaugh (1800 MWe, s.h. = 305m).

The primary measurements of plume concentration in this study are conducted with a helicopter, instrumented for SO_2, altitude, temperature, and wet-bulb depression measurements. Support measurements include portable bubblers for ground-level SO_2 measurement, and radiosonde and pilot balloon facilities.

Typical observational days consist of two helicopter flights, about 150 minutes in duration. The first flight is conducted near dawn while the plume is normally isolated from the surface by low-level stable layers, and consists of three cross sections at 4, 10, and 16 km preceded and followed by 1000 meter temperature soundings just upwind of the stacks. The second helicopter flight is begun during normal inversion breakup conditions to assess concentrations attained under circumstances when the plume may be brought near the ground. This includes treetop-level mapping of the plume distribution as well as additional temperature soundings.

This volume presents results obtained from this program during March, May, July, and October of 1968. Maximum ground-level SO_2 concentration measured in the Keystone plume by the helicopter in this series was 1.39 ppm. Maximum half-hour bubbler sampler concentration was 0.3 ppm.

Schiermeier, F. A.

Large Power Plant Effluent Study [Lappes] Volume 2 - Instrumentation, Procedures, and Data Tabulations (1967 and 1969). USPHS National Air Pollution Control Administration APTD-0589 (1970).

This report includes the descriptive material given in Volume 1, and presents Lappes SO_2, climatology, and meteorology data as well as plant (Homer City and Keystone) operating data for operations conducted during 1967 and 1969.

During these series helicopter measurements were conducted in both the Homer City and Keystone plumes. Maximum ground-level concentrations observed by helicopter were 1.62 ppm for the Keystone plume and 1.39 ppm for that of Homer City. Maximum half-hourly bubbler sampler concentrations were 0.23 ppm for Keystone and 0.14 ppm for Homer City.

Schiermeier, F. A.

Large Power Plant Effluent Study [Lappes] Volume 3 - Instrumentation, Procedures, and Data Tabulations (1970). Environmental Protection Agency APTD-0735 (1972).

This report includes the descriptive material given in Volumes 1 and 2, and presents Lappes SO_2, climatology, and meteorology data as well as plant (Conemaugh and Homer City) operating data for operations conducted during 1970.

During this series helicopter measurements were conducted in plumes of the Homer City and Conemaugh plants. Maximum ground-level concentrations observed by helicopter were above 2.2 ppm for both plants. Maximum half-hourly bubbler-sampler concentrations were 0.15 ppm for Homer City and 0.21 ppm for Conemaugh.

Schiermeier, F. A.

Large Power Plant Effluent Study [Lappes] Volume 4 - Instrumentation, Procedures and Data Tabulations (1971) and Project Summary. Environmental Protection Agency APTD-1143 (1972).

This report includes the descriptive material given in Volumes 1 and 2, and presents Lappes SO_2, climatology, and meteorology data as well as plant (Conemaugh and Keystone) operating data for operations conducted during 1971. Helicopter SO_2 measurements in this series were conducted primarily in the Conemaugh plume, where the maximum ground-level concentration observed was 2.09 ppm. The maximum half-hourly bubbler-sampler concentration was 0.19 ppm.

The report summarizes the total Lappes project, and describes contractor support, which includes the following:

- Stanford Research Institute - Lidar plume studies
- Sign-x Laboratories - Plume rise studies
- Meteorology Research, Incorporated - Aerosol and turbulence studies
- IITRI - Cooling tower plume studies
- Battelle-Northwest - Precipitation scavenging and dry deposition studies.
- French Meteorological Services - Water tunnel modeling
- Brookhaven National Laboratory - Isotopic SO_2 conversion studies.

Montgomery, T. L., S. B. Carpenter, W. C. Colbaugh, and F. W. Thomas.

Results of Recent TVA Investigations of Plume Rise. JAPCA 22, 779-784 (1972).

The loft of plumes from power-plant stacks has been investigated in a number of previous studies. The progressive trend of increasing unit sizes and stack heights, however, has necessitated further investigation. TVA has collected plume-rise data from three of its power plants - Bull Run (950 MWe, s.h. = 244 m), Paradise (2558 Mwe, s.h. = 244 m), and Gallatin (1255 MWe, s.h. = 152 m) for this purpose.

Evaluation of these data indicated that plume loft was not primarily dependent on stack height, although correlated variables such as vertical temperature structure were highly important. Separating into three stability classes, three equations were obtained, which pertain to neutral, moderately stable, and very stable conditions. At any particular distance from the stack the data for all stabilities can be correlated in terms of a single expression containing the potential temperature gradient.

Lyons, W. A., and L. E. Olsson.

Mesoscale Air Pollution Transport in the Chicago Lake Breeze. JAPCA, 22, 876-881, (1972).

A two day program was conducted during the summer of 1967 to elucidate the behavior of lake-breeze circulation patterns in the Chicago area. Observations included the use of pibals, tetroons, and surface SO_2 monitors in conjunction with aircraft state and aerosol measurements.

On the two observation days light northeasterly gradient winds prevailed aloft. The inflow layer caused by the lake breeze was observed to grow in depth to a level of about 800 m. It protruded several tens of kilometers inland and was capped by an outflow layer, which induced a distinct circulation pattern. Constant density-level tetroons were used to track the trajectories of the circulation patterns, and indicated helical trajectories parallel to the lake shore.

Plumes from ground-level and elevated sources entrained in such circulation patterns can result in high ground-level concentrations if the sources are positioned so that the cycling process creates additive effects.

Carpenter, S. B., T. L. Montgomery, J. M. Leavitt, W. C. Colbaugh, and F. W. Thomas.

Principal Plume Dispersion Models: TVA Power Plants. JAPCA 21, 491-495 (1971).

The provision of higher stacks at TVA generating plants has partially compensated for higher SO_2 surface concentrations. This trend toward higher stacks and larger generating units has been accompanied by a change in plume dispersion models applied.

Plume dispersion models include those considering coning, fanning, and inversion breakup, looping, and trapping. TVA experience indicates that high surface concentrations may result from inversion breakup, but the durations associated with this condition are short. Looping conditions have not, in general, resulted in severely high ground-level concentrations from tall stacks. Trapping conditions, however, have resulted in some persistent, adverse conditions. These were first noted with the Bull Run Plant (s.h. = 244 m), and later verified with similar measurements at the

Paradise facility. Trapping is associated, in most circumstances, with deep stable layers caused by high-pressure subsidence. Under these conditions stack height is a minor determinant of plume height, and tall stacks therefore lose much of the effectiveness that they have under other meteorological conditions.

Johnson, W. B., and E. E. Uthe.

Lidar Study of the Keystone Stack Plume. Atm. Env., 5, 703-724 (1971).

A Lidar study of the plume from the Keystone Power Plant was conducted in May and October, 1968. This study provided a number of measurements of plume dispersion phenomena and plume rise, and indicated that the following factors were particularly important in determining plume behavior:

- fanning and tilting due to wind shear with height,
- plume trapping by elevated stable layers, and
- fumigation.

A comparison between predictions of the Briggs/ASME plume rise formula and 17 different Lidar measurements gave a mean absolute difference of 30 m in effective stack height.

Thomas, F. W., S. B. Carpenter, and W. C. Colbaugh.

Plume Rise Estimates for Electric Generating Stations. JAPCA 20, 170 (1970).

The "Full-Scale Study of Plume Rise at Large Electric Generating Stations" involved investigation of plume rise from six TVA generating plants, which possessed stacks ranging from 76 to 183 meters in height. Extensive plume photography and support measurements were employed to determine plume rise, which was subsequently compared with numerous predictive formulae, including those of Holland, Bosanquet, et al., Csanady, Davidson, Lucas, et al., and CONCAWE.

Of these formulae, the CONCAWE and Csanady expressions were optimized to conform with the observed TVA data. The resulting expressions were as follows:

$$\Delta h = 133(F/J^3)^{.27} \qquad \text{Csanady}$$

$$\Delta h = 0.414 \frac{Q_H^{.444}}{J^{.694}} \qquad \text{CONCAWE}$$

where F and Q_H are the "buoyancy flux" and heat emission rate, respectively. Plume rise can also be expressed by a 2/3-law relationship as

$$\Delta h = 114CF^{1/3}/J \quad ,$$

where C is a stability parameter given by the equation

$$C = 1.065 - 6.25\frac{\Delta\theta}{\Delta Z} \quad ,$$

where $\frac{\Delta\theta}{\Delta Z}$ is the potential temperature gradient in °C/M. Although the Csanady and CONCAWE formulae provide good estimates of plume rise, the 2/3-power equation is recommended for use whenever sufficient meteorological information is available.

Clarke, A. J., D. H. Lucas, and F. F. Ross.

Tall Stacks - How Effective Are They? Proc. 2nd Int. Clean Air Cong. Wash.,D.C. (1970).

The information in this paper is directed toward facilitating a fair assessment of the capabilities of the tall stack. The benefits of tall stacks often are taken for granted in industrial circles, but have not been largely accepted elsewhere.

Tall chimneys are effective in reducing "total pollution", and lower concentrations at all distances from the source. "It is unlikely that tall stacks cause greater increases in the acidity of rainfall at greater distances than at lesser distances."

The high chimney is a cheap, reliable, and indispensible means of reducing pollution by gases, and their criticism has been largely misguided.

Periano, A.

The Tall Stack - Technical and Social Aspects. Proc. 2nd Int. Clean Air Cong., Wash.,D.C. (1970).

This paper is presented as an example of how not to proceed in designing and constructing a large power plant with regard to air pollution control. The case in point is the Reading station in north Tel Aviv, which was constructed near the shoreline of the Mediterranean Sea to the west of a growing, populated area.

Evaluations of the stack height necessary to achieve acceptable ambient SO_2 levels were performed by several expert groups who, under various assumptions, specified stack heights ranging from 38-861 m. Calculations performed by the author indicate several deficiencies in the approaches utilized. The resulting state of affairs suggests that an emission standard, if present, would have precluded much of the turmoil experienced in siting the plant.

Niemeyer, L. E., R. A. McCormick, and J. H. Ludwig.

Environmental Aspects of Power Plants. IAEA Symposium on Env. Aspects of Nuclear Power Stations, New York (Aug 1970), p. 10-14.

Assuming no source control is imposed, the emissions of SO_x, NO_x, and optically active particulates are estimated to increase in the U.S. 5, 3.5, and 4 times, respectively. This indicates that anthropogenic SO_2 sources will soon exceed natural sources globally. Tall stacks have been applied in increasing numbers to lower ground-level concentrations of these effluents. Because of differing meteorological circumstances at higher elevations, however, the standard dispersion formulae, developed for smaller stacks, cannot be expected to apply.

New experiments for evaluating tall-stack behavior have been funded by the NAPCA. These are the LAPPES and TVA studies, the second of which is presently complete. Although these studies are in apparent agreement regarding several aspects of plume behavior, our knowledge in this area is highly incomplete. Our lack of knowledge of diffusion and transport is compounded by a similar lack regarding transformation and removal processes. Although tall stacks are effective in some respects, the accumulation of scientific evidence combined with the fact that energy production is increasing enormously indicates the prudence of preventing emissions, rather than relying on procedures that are directed only toward the reduction of ground-level concentrations.

Tennessee Valley Authority

Report on Full-Scale Study on Inversion Breakup at Large Power Plants. T.V.A., Muscle Shoals, Alabama (1970).

The trend toward increasing stack height in the electric utility industry has been accompanied by a corresponding shift in meteorological conditions associated with maximum ground-level pollutant concentrations. For plants with 200-400 ft stacks maximum ground-level concentrations often are identified with moderate-to-high wind speeds under near-neutral stability conditions. With higher stacks, however, the inversion breakup situation may be more significant. Accordingly, this study has been conducted to assess surface SO_2 concentrations in the vicinity of large power plants under inversion-breakup conditions.

Three TVA plants were included in this study. These were: Paradise (1400 MWe, s.h. = 183m), Shawnee (1500 MWe, s.h. = 76m) and Johnsonville (750 MWe, s.h. = 122m, 82m). Basic measurements were performed with an instrumented helicopter (SO_2, temperature, humidity, and altitude). Support measurements included pilot balloon measurements and data from stationary SO_2 instrumentation. In addition to the three principal plants, data from stationary SO_2 monitors at the Widows Creek and Kingston plants are reported.

Helicopter measurements were performed before and during inversion breakup. Before breakup temperature soundings were made to approximately 300m, and plume cross sectioning - usually at 5 and 10 miles from the sources - was performed. During breakup low-level flights were made to assess surface concentrations, and additional cross sections and soundings were performed. Maximum observed surface concentrations were as follows: Paradise 0.90 ppm; Shawnee 1.78 ppm; Johnsonville 2.04 ppm. Maxima were observed at relatively large downwind distances, ranging up to 20 miles from the sources.

Under stable conditions the elevated plumes were found to follow quasi-Gaussian behavior, and Gaussian plume parameters were obtained for these conditions by adjustment to fit the measured data. Under inversion-breakup conditions this same treatment indicated a relatively large spread along the y axis.

Stationary SO_2 sampler data analysis indicated that most of the stationary samplers were sited too near the source to adequately reflect surface inversion breakup conditions.

Niemann, B. L., M. C. Day, and P. B. MacCready.

Particulate Emissions, Plume Rise, and Diffusion from a Tall Stack. Final Report to National Air Pollution Control Administration contract CPA 22-69-20 METEOROLOGY RESEARCH, Inc. (1970).

Airborne turbulence and aerosol measurements, as well as plume photography were performed at the Keystone Power Plant (1800 MWe, s.h. = 244m). Typical sampling flights were initiated by performing a sounding to obtain meteorological conditions and background aerosol concentrations to altitudes of 5000 ft msl. Five or six horizontal plume traverses were then performed at distances of two, five, and ten miles downwind, after which a second sounding was performed and an along-plume traverse was flown back to the power plant.

Estimates of the surface shear stress (τ_0) and surface roughness (Z_0) were performed assuming a constant-stress relationship. Measurements of plume and environmental turbulence exhibited wide scatter, but show a tendency to conform to previous basic predictions regarding the initial decay of plume turbulence.

Aerosols collected on a moving slide impactor were sized using optical and scanning electron microscopes. High variability, however, cast much doubt upon the exact size distributions of the airborne flyash.

Pooler, F., and L. E. Niemeyer.

Dispersion from Tall Stacks: An Evaluation Proc. 2nd Int. Clean Air Cong., Wash., DC (1970).

The Large Power Plant Effluent Study was initiated with the following objectives:

- to develop and validate transport and diffusion models with which to calculate ground-level concentrations from large power plants with tall stacks,
- to measure in the field the magnitude, frequency and spatial distribution of these concentrations, and
- evaluate the associated effects on vegetation.

Primary emphasis in this study has been given to high-wind, neutral stability regimes, and low-wind regimes.

In addition to meteorological measurements, SO_2 concentration measurements were obtained by cross-sectioning the plume with an instrumented helicopter, and these data were used to calculate plume dispersion and rise. Observed plume rise was found to agree with Briggs' formula within experimental error. Horizontal spreading of the plume was observed to be closely related to directional wind shear, and measurements of tilt and horizontal spread were employed in attempts to quantify this relationship.

There appears to be sufficient turbulence within early stages of the plume to cause substantial vertical diffusion. This conclusion stems both from the plume cross-section observations and from actual turbulence measurements. Beyond 10 km downwind, however, this turbulence is suspected to be attenuated substantially.

Attempts to calculate plume dispersion from a high plume through a growing, surface mixing layer indicate that maximum ground-level concentrations will occur at distances greater than 60 km from the plant. The few ground-level SO_2 measurements obtained at comparable distances (0.2 - 0.36 ppm) are in fair agreement with calculated values. If the surface mixing layer envelopes the plume, it is carried to the ground within a few kilometers from the stack. Both looping and trapping of the plume are of concern in this respect.

Other than for general observations of higher SO_2 concentrations at high points and in the lee of hills, no discernable topographic effects were noted at the Keystone Plant. The Conemaugh Plant, however, is located adjacent to a high (400-450 m) ridge, and experiences radical downwash when the plant is in the lee of the ridge.

Tall stacks are concluded to help reduce, or in some cases eliminate, occurrences of ground-level concentrations that might be found with shorter stacks. This is particularly true for neutral, high-wind conditions and during inversion breakup. On the other hand, increasing the stack height (within reasonable limits) will not reduce significantly the concentrations associated with the trapped-plume, limited mixing layer situation. In addition, the effect on precipitation chemistry is expected to be significant regardless of stack height. Additional areas where tall stacks are expected to be of little or no value are those of large-scale transport, with multiple source overlap, and the effects of pollutants in weather modification, visibility, and associated phenomena.

McLaughlin, J. F., M. E. Smith, and I. A. Singer.

Survey of Ground-Level SO_2 Concentrations Near Alton, Illinois. Proc. 2nd Int. Clean Air Cong. Wash., DC (1970).

A network of five SO_2 monitors with meteorological support information was implemented in the vicinity of the new Souix generating plant between 1968 and 1970. The Souix plant (1050 MWe, s.h. = 183 m, SO_2 emissions = 3.3 kg/sec), began operations prior to network installation. Thus, the data reflect the influence of the plant during this 1 1/2 year study.

The five monitors were located at distances ranging between 4 and 12 km from the plant site. Above-standard SO_2 concentrations were observed most often with moderate winds from the southeast, indicating that the major source of ground-level SO_2 in the area is not the plant, but a complex of emissions lying to the southeast of the sampler array. Ground-level concentrations of SO_2 originating from the plant, itself, were consistently below those estimated by standard dispersion formulae.

Frankenberg, T. T., I. Singer, and M. E. Smith.

Sulfur Dioxide in the Vicinity of the Cardinal Plant of the American Electric Power System. Proc. 2nd Int. Clean Air Cong. Wash., D.C. (1970)

A pollution study in the vicinity of the Cardinal Power Plant (s.h. = 252 m) was initiated with the primary objective of measuring ground-level SO_2 concentrations before and after operation of this new facility. Developing a functional sampling network for this purpose was complicated by the existence of other SO_2 sources and the difficult terrain in the region.

The sampling network contained six SO_2 monitors, some of which were sited primarily to evaluate contributions from other sources and others for the purpose of assessing pollution levels at sites expected to be most severely affected by the Cardinal Plant. Most of these latter sites were at elevations substantially higher than plant grade, in highly complex terrain.

From the resulting data it is apparent that no trend in SO_2 level occurred at any of the stations, either before or after plant startup. If present, the additions caused by the Cardinal Plant are largely masked in the variability of pollution arising from other sources.

Proudfit, B. R.

Plume Rise From Keystone Plant. Sign-X Labs. Report to USPHS National Air Pollution Control Administration, contract PH-86-68-94 (1970).

A helicopter, instrumented for SO_2, temperature, and charged aerosol was used to measure plume rise from the chimneys of the Keystone (1800 MWe, s.h. = 244m) generating plant. The measurement procedure involved performing an initial temperature sounding immediately upwind of the plume, and then flying traverses through the plume itself.

Approximately 60 hours of flight data were obtained, and 20 cases were selected for analysis. The analysis indicates that a single formula will not accurately predict plume rise for all conditions of stability and wind speed. By introducing the concept of the maximum potential temperature difference that can be penetrated by the plume, however, one can utilize diagrams to estimate rise relatively quickly and easily.

Fortak, H.

Comparison of Calculated and Measured Maximum Ground Level SO_2 Concentrations Downwind from Strong Emission Sources (Power Plants). Staub 29, 14-20 (1969).

A simple Gaussian plume equation, adjusted for averaging time, was utilized to model maximum hourly surface concentrations in the vicinity of the High Marnham, Paradise, Bull Run, and Keystone plants. Modification of the plume rise equation utilized by this model subject to the observed data resulted in a direct expression to calculate the minimum stack height necessary to promote acceptable ground-level concentrations downwind from large power plants.

NAPCA

Tall Stacks, Various Atmospheric Phenomena, and Related Aspects. National Air Pollution Control Administration Document PB 194 805 (1969).

This document is a compilation of abstracts of articles dealing with tall stacks. It is true that under any given set of meteorological conditions the increase of emission height will result in a decrease of ground-level concentration. This source-receptor relationship, however, is dictated by a number of variables, and specific critical conditions exist under which ground-level concentrations are expected to reach peak values.

Although the usefulness of tall stacks in reducing pollution in the vicinity of a plant is acknowledged, they do not reduce the amount of pollution emitted to the atmosphere. Other means must be found to prevent over-burdening the atmosphere with pollution.

Clarke, A. J.

The Application of Air Pollution Research to Power Station Design. Phil. Trans. Roy. Soc. London A 265, 269-272 (1969).

The concentration levels of pollutant arising from emissions from power plants depend upon two controllable variables: the amount released and the emission height. The Central Electricity Generating Board has taken the approach of controlling the source term for particulates; for gaseous emissions, however, control at present is effected by maintaining a suitably large emission height. Trends in chimney design have been to consolidate all effluents into a single chimney to take advantage of enhanced plume rise.

Moore, D. J.

The Distribution of Surface Concentrations of Sulfur Dioxide Emitted from Tall Chimneys, Phil. Trans. Roy. Soc. A 265, 245-259 (1969).

Hourly SO_2 concentration measurements at the Tilbury (s.h. = 100 m) and Northfleet (s.h. = 120 m) plants for the period November 1964 - May 1966 are reported. Mean hourly surface concentrations were observed to fall in the range between 0 and $\sim$25 pphm, and were found to agree well with predictions of a simple Gaussian plume model for high wind speed conditions. The model was found to over-predict under low to moderate wind speed conditions. An empirical correction factor can be applied to enhance agreement between experiment and theory in all cases.

Cumulative frequency distributions for hourly ground level concentrations are presented for segments of the data, which permit estimates of variability about the mean values.

Cross-wind integrals of surface concentrations indicated that the downwind point of maximum concentration is only weakly dependent on wind speed, except possibly under light wind conditions. Crosswind spread also seems to be relatively independent of wind speed, the expression $\sigma y = 0.08x$ fitting most of the data for distances out to about 12 km.

It is concluded that while the semiempirical relationships provided in this paper correlate well with the Tilbury-Northfleet measurements, they are probably invalid for stacks much below 100 m. This is because lower stacks are likely to vent their effluents into the lower, mechanically-stirred boundary layer, where different mixing mechanisms prevail.

Klug, W.

Determination of Industrial Stack Heights. Phil. Trans. Roy. Soc. A-265, 205-208 (1969).

A technique is described for selecting appropriate stack heights for a proposed plant on the basis of source, topographic, and wind and diffusion information. To apply this technique, a stack height must be chosen, and resulting isopleths of ground-level concentrations are generated for evaluation.

Thomas, F. W.

TVA's Air Quality Management Program. Proc. Am. Soc. Civil Engrs., J. Power Div., Paper 6483:131-143, March 1969.

TVA has sought to prevent deleterious effects from SO_2 emission principally through the use of high stacks. Stack heights have increased with increasing plant size, with the largest current stack being 244 m high. The stack at the Cumberland City plant will be 305 m. With a few exceptions this approach has permitted ground-level air quality criteria to be met.

Research operations under the TVA Air Management Program have included studies of diffusion, plume rise, and inversion breakup. Fumigations resulting from inversion breakup conditions in the vicinity of stacks greater than 150 m tall are substantially less severe than estimated by standard formulae.

While more definitive studies are needed, the limited data to date indicates that the critical situation for relatively tall stacks involves limiting mixing layers generally associated with high-pressure meteorological systems. Under such conditions the plume might be expected to rise until it is entrained into a layer of moderate stability. Subsequent downward mixing from solar-induced turbulence can then cause fumigations lasting several hours.

Williams, David H., Jr., and John T. Dowd.

Design and Construction Features of the 1600 MW Mitchell Plant. Combustion, 41, 19-23, August 1969.

Determination of the stack configuration for the Mitchell plant arose from several considerations, including:

- local terrain out to 20 miles from the plant
- local, state and federal air pollution regulations
- the growing body of literature regarding dispersive properties of tall stacks
- properties of the fuel to be used, and
- data from the existing Kammer Plant.

These considerations were combined with model calculations, and a single, 366 m stack was ultimately specified. The plant is not yet operational, but is scheduled to begin operations in June, 1970.

Johnson, W. B.

Lidar Observations on the Diffusion and Rise of Stack Plumes. J. Appl. Meteor, 8, 443-449 (1969).

Several general features of the Keystone (s.h. = 244 m) plume are apparent from the results of a lidar study performed there during the spring and fall of 1968. Maximum particulate concentrations are usually found near the top of the plume, owing to enhanced buoyancy. In addition, the tilting and fanning of the plume arising from wind shear under stable conditions is highly evident. Some evidence of terrain-channeling effects is also present under special conditions.

Fumigation with resulting high concentrations at ground level was observed in one of the four cases considered. This was apparently caused by rapid vertical mixing below an inversion at 900-1000 m.

Frankel, R. J.

Problems of Meeting Multiple Air Quality Objectives for Coal-Fired Utility Boilers. JAPCA, 19, 18-23 (1969).

Methods for controlling sulfur oxides from power sources include desulfurization of fuels, fuel substitution, and the use of tall stacks. It has been demonstrated that desulfurization cannot reduce the sulfur content of coal to meet proposed fuel standards in most cases.

The use of ambient air standards for SO_2 will allow better utilization for tall stacks. Although they do not eliminate the overall quantity of wastes discharged, such units reduce ground-level SO_2 concentrations by promoting greater dispersion and providing longer airborne periods for chemical decay.

Johnson, W. B., Jr. and E. E. Uthe.

Lidar Study of Stack Plumes. (Final Report) Stanford Research Inst., Menlo Park, CA, Contract PH 22-68-33, Proj. 7289, (1969).

This study established the feasibility of lidar analysis for tall-stack plume studies. The test site was the Keystone Plant (s.h. = 245 m), where some 3800 lidar observations were recorded during the study. From these observations the following conclusions, which relate primarily to tall stacks, were made:

- directional shear, which is important in promoting plume tilting and fanning, requires reconsideration in the definition of plume rise
- fanning is a very common feature of plumes from high stacks, and must be included in any realistic diffusion theory.
- effects of elevated inversions and other levels of increasing stability with height were observed frequently in the Keystone plume
- plume fumigation occurs often, probably more frequently than previously expected.

Niemeyer, L. E., and F. A. Schiermeier.

Tall Stack Study Underway. Power Engineering, 27, 42-51 (1969).

Considerable debate is underway regarding the effectiveness of tall stacks. It is obvious that increasing stack height will result in lower ground level concentrations, but it must be noted that tall chimneys do nothing to limit the total amount of pollution released to the atmosphere.

A study by the National Air Pollution Control Administration (NAPCA) is currently underway in western Pennsylvania to assess the performance of tall chimneys. This study focuses upon three large power stations: Keystone, Homer City, and Conemaugh. NAPCA has contracted SRI to perform lidar observations, and Sign-X to measure plume rise using airborne instrumentation. Additional airborne and ground level pollution and meteorological measurements are being conducted by NAPCA personnel. Data collected in this program will be used to develop and test plume rise dispersion theories applicable to tall stacks.

Scriven, R. A.

Variability and Upper Bounds for Maximum Ground Level Concentrations. Phil. Trans. Roy. Soc. Lond. A 265, 209-220 (1969).

Results from the Tilbury-Northfleet tests were analyzed using a similarity approach combined with solutions to the diffusion equation including variable wind and diffusivity profiles. The results of this more rigorous treatment provide a basis for the previous finding that simple formulae tend to show good agreement with measured mean concentrations. Three cases were considered: boundary-layer flow, flows in the unbounded atmosphere, and effects arising from stable layers aloft. In these examinations it is apparent that different factors acting in opposing directions act to lower errors in the mean ground-level concentrations.

Thomas, F. W., S. B. Carpenter, and W. C. Colbaugh.

Recent Results of Measurements. Plume Rise Estimates for Electric Generating Stations. IV. Phil. Trans. Roy. Soc. Lond. A 265, 221-243 (1969).

The objective of this NAPCA-sponsored work was to compile and analyze data for definition of plume rise from six TVA power plants, whose stacks ranged in height from 76 to 183 m. Plume photography, plus extensive meteorological measurements composed the bulk of the study. Plume rise data obtained in this manner were compared with the models of Holland, Bosanquet, et al., Davidson-Bryant, Csanady, CONCAWE, and Lucas, et al. Of these the Csanady and CONCAWE formulae generally showed the best conformity with experiment. These formulae were "optimized" with the data to provide improved forms for applied estimation.

Carpenter, S. B., J. M. Leavitt, F. W. Thomas, J. A. Frizzola, and M. E. Smith.

Full-Scale Study of Plume Rise at Large Coal-Fired Electric Generating Stations. JAPCA, 18, 458-465 (1968).

Limited plume rise information has been obtained during the USPHS/TVA "Full-Scale Study of Dispersion of Stack Gases", conducted over the five-year period 1957-62. Starting in 1962 a second research project, the "Full Scale Study of Plume Rise at Large Electric Generating Stations' was begun. The objective of this study was to collect data on and assess the nature of plume rise from power plants over a wide range of conditions. Stack heights on the power plants selected for the study ranged from 76 to 182 m.

Data included photography, transit readings, and helicopter measurements. In all, 133 composite plume rise measurements were made. These results were plotted as a function of values predicted by various plume rise equations.

McLaughlin, J. F., Jr.

Progress in Meeting Power Plant Air Pollution Problems. EEI Bull., 36, 155-159 (1968)

Fly ash from power plants is not a problem if high-efficiency electrostatic precipitators and tall stacks are employed. Sulfur dioxide is the most difficult problem area at the present time, because there is no way of collecting oxides of sulfur.

In any meaningful discussion of control measures, an objective treatment of the tall stack is essential. British experience with tall stacks leads them to state definitely that such units are an effective technique for SO_2 control. Such an acceptance is not evident in the U.S., however; reasons for this hesitancy are a noted reluctance to accept small, but finite increases in ambient SO_2 levels, concern for behavior under "unusual" meteorological conditions, and lack of knowledge pertaining to SO_2 reaction products.

Frankenberg, T. T.

High Stacks for the Diffusion of Sulfur Dioxide and Other Gases Emitted by Electric Power Plants. Am. Ind. Hyg. Assoc. J., 29, 181-185 (1968).

Despite strong evidence to the contrary, there is a tendency to ignore the major role that the tall stack can play in reducing ground level concentrations of SO_2 resulting from the combustion of fuel. The purpose of this paper is to describe the experience gained from measurements taken in the vicinity of the Clifty Creek (s.h. = 224 m) and Kyger Creek (s.h. = 127 m) steam plants, which supports the tall stack concept.

In this experiment, SO_2 monitors and dustfall collectors were placed primarily in regions in the predominant downwind direction from the sources. An analysis of the data reveals that no hourly mean concentrations in excess of 1 ppm were observed, and the dispersion models generally over-predicted actual conditions. The analysis demonstrates also that these tall stacks "completely eliminate ground-level concentrations during inversions."

Moroz, W. J. and E. Koczkur.

Plume Rise and Dispersion Near the Shoreline of a Large Lake when Flow Patterns are Dominated by the Lake Breeze. Proc. USAEC Meteorological Meeting, C. A. Mawson, ed. AECL-2787 (1967).

An observational study was conducted near the power plant on the north shore of Lake Ontario to assess the effects of the lake breeze on diffusion and rise of the plume from the 152 meter stacks.

During this study aircraft temperature soundings were conducted three times daily inland as well as over the lake. These were supported by bi-hourly pibal observations and surface measurements. Actual plume measurements were made using a photographic technique, in conjunction with subsequent densitometer analyses.

From these results it was suggested that vertical dispersion of the plume for onshore flows under near neutral conditions could be represented by the form

$$\sigma_Z = X^{0.44}.$$

If the plume were to avoid the lake circulation patterns under such conditions it would have to rise to a level 500 to 750 m above the surface.

McLaughlin, J. F., Jr.

Atmospheric Pollution Considerations Affecting the Ultimate Capacity of a Thermal-Electric Power Plant Site. JAPCA, 17, 470-473 (1967)

At the present time adequate means are available to predict stack heights required to provide acceptable ground-level pollutant concentrations in the vicinity of power plants. Tall stacks are presently the only method for controlling the sulfur oxide problem. These units will, in most cases, enable construction of power plants at any given site and permit successful operation from the standpoint of air pollution. On the other hand it may be necessary at some sites to place a limitation on maximum capacity.

Determination of an appropriate stack height depends upon a number of factors, including topography, meteorology, land use planning, and source conditions.

Stone, G. N., and A. J. Clarke.

British Experience with Tall Stacks for Air Pollution Control on Large, Fossil-Fueled Power Plants. American Power Conference, Illinois Inst. Tech., April 27, 1967.

With increasing demands for power generation, there has been a strong trend within the Central Electricity Generating Board complex to increase both the sizes of generating units and the heights of chimneys. There has also been a tendency to incorporate single - rather than multiple - chimneys, and to limit efflux velocities to those sufficient to minimize downwash in all but exceptionally high winds.

For more than fifteen years it has been standard practice to monitor SO_2 and dustfall around each new power station with six to eight field stations. The principal conclusion that has emerged from these studies is that a modern power station with tall stacks does not materially increase the general pollution levels which already existed before the plant was built.

In 1963 a major pollution survey was begun at the High Marnham Power Plant (s.h. = 137 m), and it was continued until 1965 when the monitoring instrumentation was redeployed to the West Burton Plant area. Twenty-four SO_2 recorders were located around the plant at distances out to approximately 10 km. The data obtained indicated that hourly SO_2 levels from the plant did not exceed 0.5 ppm, and that pollution from other sources was much more significant than that from the plant itself.

Following the High Marnham study, a more comprehensive investigation - aimed at examining causal relationships - was initiated at the Tilbury Plant (s.h. = 100 m). Here twenty-two SO_2 monitors were employed at distances out to approximately 12 km from the plant. Although still continuing at the present time, useful preliminary results are available. Specifically, there is substantial support for a maximum plume rise formula of the form

$$Z_{max} = \alpha QH^{1/4}/U$$

where α is a constant for a given chimney and site. It is also apparent that plume rise is dependent on stack height, owing to decreasing turbulence aloft - thus a plume emitted at a greater height will experience a greater rise.

The question of whether the power industry significantly affects SO_2 concentrations can be examined by comparing trends in emission rates with those in concentration. Although SO_2 emissions by power production have nearly tripled between 1951 and 1966, ambient ground-level SO_2 concentrations have decreased. Thus it may be concluded that "all the power plants over a large geographical area can collectively operate without any detectable influence on the trend of ground-level SO_2 concentrations in the area."

Lucas, D. H.

> SO_2 Concentration Measurements Near Tilbury Power Station. Atm. Env., 1, 389-410 (1967) also p. 421-424.

This paper discusses reliability of data obtained from the Tilbury experiment, and summarizes some of the more important findings, including derived expressions for maximum ground level concentration and plume rise.

Bender, R. J.

Tall Stacks, A Potent Weapon in the Fight Against Air Pollution. Power, 111, 94-96 (1967)

Tall stacks for public utilities and industrial plants are an effective remedy for gaseous pollution. While they obviously do not prevent pollution from escaping into the atmosphere, they do reduce contamination at ground level. There is little doubt that tall stacks provide a significant remedy to the problem of ground-level contamination while alternative methods - such as flue gas desulfurization - are under development.

Martin, A. and F. R. Barber.

Sulphur Dioxide Concentrations Measured at Various Distances from a Modern Power Station. Atmos, Env., 1, 655-677 (1967).

SO_2 measurements in the vicinity of the West Burton power station, still under construction, were obtained to assess effects of background contributions. One source of background was the High Marnham station (s.h. = 137 m), approximately 14 km to the south.

Six-month average SO_2 concentrations ranged from .011 to .072 ppm, and little difference between sites in the High Marnham and West Burton areas was observed. Most of the pollution was suspected of originating from low-level urban sources. Ground-level SO_2 originating solely from High Marnham showed six-month averages peaking at .005 ppm, at distances within 5 km from the stacks. In addition to the six-month averages, 3 minute maxima are presented, along with hourly, daily, and monthly means.

Maximum concentrations coming from High Marnham were higher than those predicted by dispersion models about 16 percent of the time. Thermal instability conditions (strong sunshine, light winds) gave rise to relatively high (0.90 ppm in one case) concentrations near the source. The absence of larger concentrations at higher sampling stations indicated that the plume essentially rises with topographical contours.

Scriven, R. A.

Properties of the Maximum Ground Level Concentration from an Elevated Source. Atm. Envi., 1, 411-419 (1967).

Often high ground-level concentrations are associated with atmospheric situations involving stably stratified air above the stack, with well-mixed conditions below. Such situations are more appropriately treated with two-layer models, rather than the conventional one-layer versions.

The simple two-layer model described in this paper indicates, as expected, that ground level concentrations are highly sensitive to the height of the stable layer, if this layer is below 1-1/4 source heights from the ground. They are also sensitive to small changes in mixing in the stable layer. This model can be applied with statistical data pertaining to inversion height frequency to provide frequency distributions of the correction factors required to adjust single-layer models to account for layered conditions.

Van der Hoven, I.

Atmospheric Transport and Diffusion at Coastal Sites. Nuclear Safety, 8, 490-499 (1967)

Atmospheric diffusion over wide expanses of water is expected to be reduced owing to two factors: the decrease of mechanically-generated turbulence arising from the relatively smooth surface, and the normally cooler water surfaces with their resultant low thermal turbulence. Such expectations have been borne out with measurements taken over the past decade, which show substantial decreases in plume spread below those that would be expected under similar conditions over land.

Transitions of surface roughness and heating accompanying on-shore flows can cause fumigation under some conditions, where a confined plume suddenly experiences rapid mixing conditions. Diurnal effects involving land-sea breeze conditions can cause extremely complex flows, which again can result in high ground-level concentrations.

Smith, M. E.

Reduction of Ambient Air Concentrations of Pollutants by Dispersion from High Stacks. Proc. Third Nat. Conf. on Air Poll., Wash. D.C. (1966).

In the past 15 years the tall stack has become symbolic of good industrial air pollution practice; and, led by the smelting industry, there is a distinct trend toward the use of taller stacks in the utilities industry at the present time. Under any meteorological conditions, a tall stack located in open, uncomplicated terrain will produce dramatic reduction in ground-level pollutants compared to the same emission released at lower levels. It is also important to note that a tall stack in open terrain converts the least favorable meteorological conditions into the most favorable, that is if a stack is sufficiently high to penetrate an inversion layer, then its effluent is essentially prevented from mixing to the ground, rather than the converse for shorter stacks. Tall stacks are also effective in eliminating effects from local circulation patterns that tend to result in high ground-level pollutant concentrations.

It is emphasized that tall stacks possess no magic power to eliminate a pollutant, but simply distribute it differently in the atmosphere. This is the basis for a criticism of tall stacks which is valid as long as the pollutant does not change to a less objectionable form while airborne. Airborne SO_2 is estimated to decay with a half-life of 12 hr. or less, and thus tall stacks have the effect of actually reducing pollutant amounts.

The previous predictions of others concerning the importance of inversion breakup in promoting high ground-level concentrations appears to have doubtful support in the field results obtained to date. Specifically, measurements in the vicinity of the Clifty Creek and Kyger Creek plants as well as those in the TVA region have not resulted in concentrations nearly as high as predicted.

Nonhebel, G.

British Charts for Heights of Industrial Chimneys. Int. J. Air, Water Poll., 10, 183-189 (1966).

The Memorandum on Chimney Heights was published by the Ministry of Housing and Local Government in 1963, subsequent to the issuance of an advisory report by a working party of the Department of Scientific and Industrial Research. This memo applys only to smaller industrial power plants, as larger plants and public power supply stations are covered under the inspection of the Alkali Inspectorate. The values of chimneys height estimated using this guide reflect the requirement that it is necessary to vent effluents at least 2-1/2 times higher than surrounding obstructions.

Pooler, F.

Potential Dispersion of Plumes From Large Power Plants. USPHS Document PB 168790 (1965).

Estimates of plume dispersion from power plants in the 1000-5000 MWe category currently rely on extrapolations from existing data for smaller plants. Assuming that the stack is constructed so as to minimize downwash effects, however, the analysis of worst-case dispersion is expected to be reduced to a few specific cases. These include: 1) high wind fumigations, 2) inversion breakup, and 3) limited mixing, light-wind situations.

Inversion-breakup fumigations are expected to produce the highest ground level concentrations, but will be confined to a relatively small area at any given time. Limited mixing layer fumigations are potentially more troublesome owing to the more widespread nature of the effect and the relative lack of influence of stack height in promoting low ground-level concentrations.

Ground level SO_2 concentrations in the vicinities of hypothetical 1000 MWe and 5000 MWe generating plants were estimated from specific formulae derived for the three critical circumstances. For high-wind neutral conditions these estimates were based on Sutton's equation in conjunction with Holland's plume rise formula. For inversion breakup the estimates were obtained from an independent estimate of plume height, assuming complete mixing between the inversion and ground level. A similar expression was employed for limited mixing conditions, with the inversion height determining the vertical extent of the plume.

Gartrell, F. E.

Monitoring of SO_2 in the Vicinity of Coal-Fired Power Plants - TVA Experience. Proc. Am. Power Conf. (Presented at 27th Annual Meeting of the American Power Conference, Chicago, IL, Apr. 27-29, 1965).

This paper presents results of the extensive appraisal program conducted by TVA with regard to air pollution in the vicinity of its fossil-fuel electricity generation plants. It is observed that plots of frequency of occurrence versus SO_2 concentration on semilog paper exhibit reasonably straight lines. Limited data to date indicate that such plots for 183 m stacks may be somewhat different than those for lower stacks, with a trend toward lower SO_2 frequency at ground level.

Under stagnation conditions, ambient air quality measurements in the vicinity of the Kingston Steam plant (s.h. = 91 m) have indicated that no significant buildup of pollution occurs. Under such circumstances, it appears that air pollution potential forecasts need to consider power plants as a special case for which the meteorological criteria normally employed may not be applicable.

Nelson, F., and L. Shenfeld.

Economics, Engineering, and Air Pollution in the Design of Large Chimneys. JAPCA, 15, 536-539 (1965), (Presented at the 58th Annual Meeting, Air Pollution Control Association, Toronto, Canada, June 20-24, 1965, Paper No. 65-144).

The present state of SO_2 removal technology has led technical men in the power industry to the general opinion that SO_2 pollution from generation sources is still best handled by dispersion from tall stacks.

Selection of an appropriate chimney height can be performed using standard formulae in conjunction with source and climatological data. The paper illustrates the application of such an approach for large power stations.

stack heights from an extrapolation of plant and environmental data obtained from existing facilities. Diffusion analysis is also applicable for this purpose using dispersion parameters compiled by previous authors. Stack design for neutral meteorological conditions generally provides for acceptable performance under all other commonly encountered conditions. Higher heat emissions from larger plants may provide sufficient bouyant lift to prevent trapping by inversions. In addition, they are often capable of inducing "thermals" under unstable conditions which elevate the plume thousands of feet. Stack exit velocity is of questionable effectiveness in promoting plume rise, and for this reason, velocities above the 50-60 fps needed to eliminate stack downwash are not recommended.

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16. ABSTRACT

The question of the effectiveness of tall stacks has become an increasingly important subject for several reasons, which are keyed strongly to the rapidly growing energy demands in the U.S. and abroad. This report addresses this subject by presenting a review of literature pertinent to tall stacks, and by assessing the potential effects of their large-scale implementation. A comprehensive annotated bibliography is included as an appendix to the report.

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