Colorado State University

Seminar/Workshop on

WIND ENGINEERING

THE PAST TO THE FUTURE

Proceedings, Issues and
Recommendations

Department of Civil Engineering
Colorado State University
Fort Collins, Colorado

June 4 - 6, 1987

TABLE OF CONTENTS

Session I: Seminar Chairman: A. G. Davenport

Session II: Seminar Chairman: K. C. Mehta

Invited Lecture: Introduction J. D. Nelson

Session III: Seminar Chairman: H. Liu

Section Description Page

Session IV: Seminar Chairman: R. A. Pielke

Invited Lecture: Introduction F. A. Kulacki

Session V: Workshop Chairman: J. E. Cermak

Session VI: Workshop

Invited Lecture: Introduction F. W. Smith

Section I:

FOREWORD

ACKNOWLEDGEMENTS

FOREWORD

Concept of a Research Agenda

The export of engineering design skills and construction technology is presently an important source both of U.S. technical reputation overseas and of a favorable trade balance. In 1983, the U.S. construction industry generated export revenues of $19.6 billion, with close to $11 billion flowing--directly and indirectly--into the domestic economy. There are approximately 400 U.S. firms directly engaged in international architectural engineering and construction projects. Exports of construction and design firm services supported $1.4 billion in contracts to subcontractors. In addition, 261,000 domestic jobs resulted from direct and indirect participation in overseas construction services. The vitality and credibility of this export of our technology depends upon our ability to provide constantly improving and efficient designs and construction techniques. This is especially important since other nations such as Japan and Korea are placing increased emphasis on developing and exporting their own design abilities to other countries. Distressing news is that there has been a sharp decline in contractors and architectural engineering exports between 1982 and 1984. Losses are estimated to be nearly 50,000 jobs and $2.8 billion in revenues. Between 1984 and 1985 the U.S. share of foreign construction market fell a further 9 percent. Yet using 1984 numbers as a percent of sales, the Japanese construction industry spent about 3 percent on research and the U.S. construction industry about 0.01 percent (ENR/July 31, 1986). The U.S. research expenditures on construction in 1984 was about equal to the amount of research on razor blades in that same year.

Among the areas where important design/construction improvements can be made is Wind Engineering. Development of wind engineering techniques promises very significant benefits both to quality of design within the U.S.A. and to the marketability of these services abroad. Recent developments in wind engineering have very often taken place overseas. Dr. N. P. Suh, Assistant Director for Engineering, NSF, recently observed that "most of the boundary layer wind tunnel facilities constructed in the world in the last five years have been constructed in Japan. Many of these have been constructed in Japan's private sector."

Wind Engineering is a relatively young interdisciplinary engineering area which was identified at Colorado State University and other leading universities as a separate engineering discipline only about twenty years ago. Wind Engineering deals with the interaction of the wind in the atmospheric boundary layer with man-made structures and activities, vegetation and forest cover, and natural topographical features. A rational and integrated treatment of such a wide spectrum of wind interaction effects is possible only by synthesizing knowledge from many branches of engineering, architecture, meteorology, mathematics, computer science, forestry, agriculture, economics, psychology, sociology, and other fields. This integration of many disciplines into wind engineering is a dynamic process of continuous growth as more applications emerge almost daily.

Wind Hazard Related Costs to Society

The Office of Emergency Preparedness reported in 1972 that the average annual loss resulting from windstorms in the United States during the preceding fifty years was $100 million. Friedman (1979) reported that this cost had risen to between $500 million and $5 billion a year between 1968 and 1978. Wiggins (1978) calculated that damages during the 1980s caused by windstorms would exceed $3.7 billion annually. Petak and Atkisson (1982) estimated that by the year 2000, losses from wind-related natural hazards will be $8.8 billion annually. Put in perspective, this means year 2000 wind losses will exceed the 1970 value of all building losses due to fires, all crime against property, all expenditures by state and local police departments, all losses from accidents at work, all air pollution effects on value of property, all air pollution-related morbidity and mortality, and nearly equal to the 1970 value of all auto liability insurance premiums! Sanders (1971) estimated windstorms and other meteorological phenomena caused 1,677 deaths and 18,285 injuries in the United States alone. Within the period 1963-1970 these estimates do not include the indirect costs caused by wind effects on air pollution, energy losses, human discomfort, or loss of agricultural productivity due to soil removal (Price-Waterhouse, 1985; Wiggins, 1978).

Since wind damage is also a major design concern in foreign countries, this conveys the importance of increasing our collective research efforts on wind engineering. This conclusion is further reinforced when one considers that probably half of the estimated damage can be avoided by the application of current and probable near-future knowledge. It also indicates a very high economic payoff in the international engineering marketplace from an increased investment in wind engineering research.

Goals of a Wind Engineering Research Program

The primary elements of the broad discipline of Wind Engineering are found in the areas of fluid mechanics, aerodynamics, meteorology, and structural mechanics. The impact of Wind Engineering on human endeavor can be determined through the interpretations of economics, psychology, and the social sciences. The analytic tools used by Wind Engineering depend on the application of mathematical, statistical, and computer engineering skills. A possible goal for Wind Engineering in the next decade is to integrate researchers from these disciplines, industry participants and students to accomplish the following four major tasks:

1. Identify and study the fundamental fluid mechanics problems which constrain the advancement of wind engineering science.
2. Anticipate, identify and respond to the wind engineering research needs of industry.
3. Provide unique experimental capabilities not available elsewhere.
4. Provide professionals, including graduate engineers, well educated in wind engineering.

Seminar/Workshop on Wind Engineering

The Wind Engineering Program at Colorado State University invited engineers from industry, government and academia to join in a celebration of 35 years of research and service in the field of Wind Engineering. The program was designed for engineers and scientists interested in the capabilities of fluid modeling and computational modeling of atmospheric boundary-layer phenomena and the potential for the modeling science to resolve important wind engineering problems.

The objective of the seminar portion of the program was to review the state of fluid and numerical modeling concepts about atmospheric simulation, structural aerodynamics, atmospheric transport, and wind-solar energy techniques. The objective of the workshop was to identify and prioritize wind engineering research problems of most importance to industry and government.

The proceedings which follow are divided into sections which correspond with the thematic emphases of the seminar and workshop agenda: wind loading on structures, atmospheric boundary layer characteristics, scalar transport, and energy production. This report also contains the deliberations and comments of the workshop sessions, research recommendations, and a participant list.

We share with the other participants in the Seminar/Workshop on Wind Engineering: The Past to the Future a sense of pride and accomplishment. We also share the conviction that Wind Engineering Science can contribute much to mitigate and ameliorate the effects of winds in our environment.

Organizing Committee:

Bogusz Bienkiewicz, Assistant Professor
Jack E. Cermak, University Distinguished Professor
Marvin E. Criswell, Professor
Jane H. Davidson, Assistant Professor
Jon A. Peterka, Professor
Willy Z. Sadeh, Professor
Virgil A. Sandborn, Professor

Robert N. Meroney, Chairman
Seminar/Workshop Organizing Committee
Director, Fluid Dynamics and Diffusion
Laboratory, Colorado State University

ACKNOWLEDGEMENTS

The Seminar/Workshop on WIND ENGINEERING: THE PAST TO THE FUTURE was organized by members of the Fluid Mechanics and Wind Engineering Program and the Structural Engineering Program Faculties from the Colorado State Civil Engineering Department. The organizing committee included Dr. Robert N. Meroney, Chairman, and Drs. Bogus Biekiewicz, Jack E. Cermak, Marvin E. Criswell, Jane H. Davidson, Jon A. Peterka, Willy Z. Sadeh, and Virgil A. Sandborn, Professors at Colorado State University. Dean Frank A. Kulacki and Associate Dean Fred W. Smith provided organizational and fiscal support from the College of Engineering. Ms. Janet Montera, Civil Engineering Conference Coordinator, assisted with conference administrative and planning details.

The quality of the program depended, of course, upon the quality of the presentations and the skills of the chairmen. Their contribution was critical to the success of the conference. Conference participants are recognized by name and association in the Seminar/Workshop program found in Section III. Workshop chairmen deserve special recognition for their discussion leadership and the preparation of post-conference workshop summaries found in Section IV.

The Organizing Committee also wish to recognize the Seminar/Workshop sponsorship by the Wind Engineering Research Council, Dr. Kishor Mehta, President, and the travel support provided to participants by the Engineering Directorate of the National Science Foundation. The advice and support of Drs. Mike Gaus and Nora Sabadell, National Science Foundation, during the preparation, presentation and post-conference periods are highly appreciated.

Section II:

A WIND ENGINEERING RESEARCH PROGRAM TO BRIDGE THE PAST TO THE FUTURE

Prepared by Fluid Mechanics and Wind Engineering Program
Colorado State University

TABLE OF CONTENTS

DESCRIPTION OF A PROPOSED WIND-ENGINEERING RESEARCH PROGRAM

NEED FOR A RESEARCH AGENDA

A Wind Engineering Research Program (WERP) for the next decade is proposed both to bring the benefits of better design practices to industry and to enhance U.S. competitiveness in wind-affected disciplines related to construction, transportation, agriculture, energy production, mining and materials, consulting engineering services, and equipment exports. Accounting for wind effects in these important areas represents an opportunity for improving our balance of trade as well as responding to our own domestic needs.

Wind Engineering is a relatively young interdisciplinary engineering area which was identified as a separate engineering discipline only about twenty years ago. Wind engineering deals with the interaction of the wind in the atmospheric boundary layer with man-made structures and activities, vegetation and forest cover, and natural topographical features. A rational and integrated treatment of such a wide spectrum of wind interaction effects is possible only by synthesizing knowledge from many branches of engineering, architecture, meteorology, mathematics, computer science, forestry, agriculture, economics, psychology, sociology and other fields. This integration of many disciplines into wind engineering is a dynamic process of continuous growth as more engineering applications emerge almost daily.

Wind Engineering Support to U.S. Construction Industry

The export of U.S. design skills and construction technology is presently an important source both of our technical reputation overseas and of a favorable trade balance. The credibility of U.S. engineering depends on up-to-date design information. But, in the increasingly important area of Wind Engineering, other countries are making a greater investment and are rapidly gaining in their level of expertise.

Engineering construction and design represent one of our most important exportable skills, and they contribute significantly to the U.S. trade balance. American design and construction firms are very active and well respected in the foreign construction market. Indeed, 43 American firms do 31.4 percent of the business of the top 250 international contractors for a yearly dollar volume of $28.2 billion out of $81.6 billion (1985 values). About 59 American firms do 32.0 percent of the business of the top 200 international design firms, or a dollar volume of $1.2 billion out of $3.6 billion. Currently, five of the ten top international design firms are U.S. owned. Foreign contracts constituted 36 percent of these firms' total business. Engineering services represent more than 60 percent of the nation's dollar export value of services to other countries, and about 8 percent of our total dollar export value in goods and services (Eng. News Record, 1986a, 1986b).

Distressing news is that during the last several years the U.S. design and construction industries have seen a sharp decline. Between 1984 and 1985 the U.S. share of the foreign construction market fell a further 9 percent. Even the U.S. domestic market is being penetrated by foreign firms. In 1985 the Japanese market share of U.S. construction jumped from 9.1 to 14.3 percent. Representative Sherwood Boehlert (R-NY) observed

"...the U.S. construction industry is entering a critical period that could either make or break it. New technologies hold the promise of building better and more profitably, but the growing number of foreign competitors threatens the viability of America's construction industry" (ENR, July 31, 1986).

Unlike most other basic industries, construction is composed of a myriad of often very small companies. Even the largest firms have a relatively small market proportion. Partly for this reason, construction companies historically have invested very little in research and development. In 1984, the American construction industry spent less than 0.01 percent of sales on research, compared to 3 percent by the Japanese construction industry, an industry more dominated by several very large firms. The usual U.S. division of responsibilities for providing facilities among the design and the construction industry is also a major problem - neither sector has a real huge profit motive to be more refined in the design process! U.S. construction firms do not finance research for architects and design engineers, and these designers do not have a high enough fee system to pay for the research. It is unlikely that the construction industry will automatically band together to address its research problems, any more than farmers in the early 1900s banded together to advance agriculture. In that case, the government responded effectively by establishing the Department of Agriculture. In the important construction subdiscipline of Wind Engineering, a clear Agenda for Wind Engineering Research could provide a needed focus.

Wind Hazard Related Costs to Society

Wind has always had an important influence on man and his activities. World-wide losses due to wind-related phenomena expressed in deaths, injury, property damage, and inconvenience have increased society's concern for better definition of wind loads on buildings and structures, attempts to control air pollution, desire to conserve energy resources, need to design for human comfort, and better control of wind erosion of soil. Within the last several decades recognition of the importance of allowing for wind effects in design has increased tremendously. The Office of Emergency Preparedness (1972) reported that the average loss in 1970 dollars resulting from windstorms in the United States during the preceding fifty years was $100 million annually. Friedman (1979) later reported that this cost had risen to between $500 million to $5 billion a year between 1968 and 1978. Wiggins (1978) calculated that damages during the 1980s caused by windstorms will exceed $3.7 billion annually. Petak and Atkisson (1982) estimate that by the Year 2000 losses from wind-related natural hazards will be $8.8 billion annually. Put in perspective, this means that these Year 2000 wind losses will exceed the combined 1970 value of all building losses due to fires, plus all crime against property, plus all expenditures by state and local police departments, plus all losses from accidents at work, plus all air pollution effects on property, plus all air pollution-related morbidity and mortality, and nearly equal to the 1970 value of all auto liability insurance premiums! Sanders (1971) estimated windstorms and other meteorological phenomena within the 1963-1970 period caused 1,677 deaths and 18,285 injuries in the United States alone. These estimates do not include the indirect costs caused by wind effects on air pollution, energy losses, human discomfort, or loss of productivity due to soil removal.

Losses from wind effects are expected to increase in magnitude because the percentage of land area occupied by people and structures continues to increase. The use of new structural systems and materials results in structures and buildings increasingly sensitive to wind effects because they are lighter in weight, are tall and slender or are of large areal extent, have low mechanical damping, and use glass and light-weight cladding over large surfaces. Other important factors stimulating the need for better wind-engineering-design procedures is the increased attention by architects, city planners and engineers to public safety and human comfort, as affected by phenomena such as wind-generated noise, buffeting of pedestrians by gusty winds, soil and snow drifting, and ventilation or heating problems. Another cause of the expected increase in damage is the increasing economic pressures to develop sites even known to be in extreme wind speed locations.

In many countries, the sparse or rudimentary information collected by public agencies or available through press reports on windstorm losses prevents effective accumulation of accurate loss statistics. Nonetheless, world-wide concentration on large engineering projects and the replacement of housing and commercial buildings will naturally lead to the integration of wind engineering into engineering design. Concentration of man and his structures in high density urban areas increases the potential loss from a single weather-related catastrophe; hence, design and construction firms will increasingly be chosen on the basis of their demonstrated expertise in wind engineering.

Historical Development of the Wind Engineering Discipline

In 1891 a wind tunnel was constructed at Askov, Denmark, by Professor Poul la Cour to systematically study windmill performance. Not only was this among the first wind tunnels ever built, the windmill work in it may represent the first wind engineering laboratory experiments. In the 1930s, scientists at the National Physical Laboratory, Teddington, England, used wind tunnels to study plume rise from smoke stacks and wind loading on bridges. Pagon (1934, 1935) published a series of papers titled "Aerodynamics and the Civil Engineer," in which he discussed the importance of wind effects on structures. During the early 1940s Theodore von Karman directed wind tunnel experiments of simulated atmospheric boundary layer flow over terrain models of prospective wind energy sites. Most early wind-related efforts were disconnected and intermittent, and in some cases the results were even misleading. This changed in the early 1950s as scientists in Europe and the United States realized that special facilities were necessary to simulate the behavior of the atmosphere near the ground. The earlier use of uniform-flow low-turbulence aerodynamic wind tunnels had led to incorrect wind flow patterns and erroneous wind pressures. In Europe this realization led to the establishment of a number of special laboratories and the identification of a new discipline called "Industrial Aerodynamics". In the United States only a few laboratories such as the Fluid Dynamics and Diffusion Laboratory at Colorado State University were developed to work specifically in wind engineering.

The First International Conference on Wind Effects on Buildings and Structures was held in Teddington, England, in June 1963. Only 7 of more than 300 participants were from the U.S., and only 2 of the 24 papers were authored by American scientists. Yet in 1963 Colorado State University had two boundary-layer wind tunnels operating, and Colorado State University was performing tests on World Trade Center models--the first use of a boundary-layer facility for building design.) A second international conference on the same subjects convened in Ottawa, Canada, in 1967. This conference was organized to bring together researchers interested in building aerodynamics and the establishment of wind-load criteria. Perhaps the first recognition of Wind Engineering as a distinct engineering discipline occurred at a NSF-sponsored conference on wind loads on structures held at the California Institute of Technology in 1970. The conferees, including four engineers from Colorado State University, identified needed areas of research in wind loads on structures and organized a Wind Engineering Research Council to be devoted to the promotion and dissemination of research results. This meeting was later designated the First U.S. National Conference on Wind Engineering Research.

During the last decade, wind engineering has grown rapidly in the United States, but not at the same vigorous and coordinated pace as in Europe, Canada, and Japan. The Third and Fourth International Conferences were held in Tokyo (1971) and London (1975). At the Fourth Conference the name of future meetings was changed from Wind Effects on Buildings and Structures to "Wind Engineering". This name change reflected the continuous expansion of interests to include the social and economic impact of windstorms, dispersion of heavy gases, airflow over complex terrain, siting of wind turbines, and wind effects on people and vegetation. An International Association for Wind Engineering was also formed at this meeting. This establishment of an international association reflects the world-wide impact of wind-related problems. The Fifth and Sixth International Conferences were held at Fort Collins (Colorado State University) in 1979, and jointly at the Gold Coast, Australia and Aukland, New Zealand, in 1983. The participation of American engineers and scientists from both universities and industry has increased continuously from one conference to the next as increased interest continues to evolve.

Increasing U.S. interest in wind engineering and the pressing need for exchange of information among researchers and practicing engineers led the Wind Engineering Research Council and the National Science Foundation to sponsor U.S. National Conferences on Wind Engineering Research. Four such conferences have taken place in addition to the initial meeting at California Institute of Technology in 1970. These were the Second in 1975 at Colorado State University, Fort Collins, the Third in 1978 at the University of Florida, Gainesville, the Fourth in 1981 at the University of Washington, Seattle, and the Fifth in November 1985 at Lubbock, Texas. The U.S. National Conferences are now highly recognized by both the research and the practicing industrial engineering communities as sources of information about wind engineering. Because of Wind Engineering's broad interdisciplinary character, most other wind engineering information sources are widely scattered among various journals, reports, laboratories and institutes and, thus, are not conveniently available to most practitioners.

Even though there is considerable activity in wind engineering in the United States, it has tended to lack coherence and adequate visibility. Practicing engineers seeking wind engineering information, advice or laboratory support often are at a loss as to where to find help. Since many foreign countries systematically support wind engineering at their universities and national laboratories, many U.S. firms and government agencies currently appeal to foreign laboratories in Canada, England, Holland, and Germany for advice. Foreign engineering firms often have an advantage in access to wind-related design skills and information. This state of affairs clearly indicates the pressing need for a coherent Wind Engineering Research Program in the United States.

GOALS OF THE WIND-ENGINEERING RESEARCH PROGRAM

Wind Engineering is a discipline which ranges broadly in basic subject matter and application. The primary elements of this discipline are found in the areas of fluid mechanics, aerodynamics, structural mechanics, and meteorology. The analytical tools used in Wind Engineering depend on mathematical, statistical, and computer engineering skills. The impact of Wind Engineering on human endeavor can be estimated by using the economic, psychological, and social sciences. An effective WERP must integrate staff in these disciplines as well as industry participants and university students to accomplish the following four major goals:

1. Identify and study the fundamental fluid mechanics problems which constrain the advancement of wind-engineering science.

2. Anticipate, identify and respond to the wind-engineering research needs of industry.

3. Provide unique experimental capabilities not available elsewhere.

4. Provide professionals, including graduate engineers, well educated in wind engineering.

RESEARCH TASK AREAS

Wind-related research may be divided into different basic engineering science and application areas. Basic engineering science research attacks those issues which represent constraints to advances in wind-engineering science. Wind-related design requirements result in the need for design philosophies, data needs, standards, and codification. Research Working Groups might be organized around the need to address the various topics found in Table 1. In the following paragraphs, timely research goals under each subtopic are discussed.

Wind Characteristics

Knowledge of wind characteristics such as boundary layer climatology, severe storm dynamics, local wind perturbations, and mixed layer behavior is required to estimate wind effects on man's engineering activities. For example, in a typical wind-load study the specification of wind speed probabilities represents one of the larger uncertainties in specifying structural loads, yet frequently design and construction are based on only crude estimates of the local behavior of strong winds. Wind climatology for definition of wind loads in the U.S. is currently based on analysis of fastest mile wind records obtained from the National Climatic Data Center (NCDC) without consideration of wind direction, even though high winds at many sites are generally known to be directional. This simplified approach is incorporated in the ANSI A58.1-1982 standard for recommended minimum wind loads. Recent research by NCDC has shown that the wind speeds predicted by analysis of fastest mile wind speed records vary substantially with wind direction. Unpublished analyses of fastest-mile winds, hourly wind records, and balloon data at Colorado State University have shown that additional analyses of these records are required to produce a consistent wind definition for extreme wind events. Rijkoort (1983) proposed a method for analyzing wind data which could provide a better definition of wind speeds at some or all recording stations. Additional methods of analysis for short data records would permit use of a wider data base than Weather Service

Table 1: Research Working Groups

Wind Characteristics
- Boundary layer winds and turbulence
- Severe storms
- Local wind environments

Fundamental Fluid Mechanics Issues
- Large Reynolds number flows
- Bluff body aerodynamics
- Aeroelastic phenomena

Wind Effects on Wind Loading and Structural Response
- Building cladding problems
- Building, bridge and tower dynamic problems
- Buildings and structures under construction
- Pedestrian comfort, wind-induced noise
- Water/rain penetration

Wind Effects on Energy Production and Consumption
- Wind power generation
- Natural ventilation
- Heat transfer and infiltration
- Heating and A/C performance, equipment degradation

Wind Transport and Particles and Pollutants
- Air pollution - stationary sources, transportation
- Public safety - hazardous releases, risk analysis
- Odor problems
- Insect and disease vectors
- Wind-blown sand, soil, and snow

Physical and Numerical Models
- Model laws
- Wind-tunnel facilities and techniques
- Integration of physical and numerical data
- Development of field test techniques

Socio-economic Factors
- Damage assessment
- Damage mitigation
- Risk-benefit analysis
- Emergency response procedures
- Legal and insurance considerations

Wind Engineering Practices
- Codes and standards
- Reliability-based designs
- Wind Engineering in the regulatory environment

first-order stations. Methods of analyses of short records would find applications to wind records in the U.S. and foreign countries, where existing data are often sparse and short.

The wind speed and turbulence characteristics of flow in the atmospheric boundary layer (up to 300 or 400 m) and the surface boundary layer (below 50 to 150 m) determine the loads on buildings and structures and the transport of pollutants. On the average the wind speed over homogeneous surface roughness during stationary wind events can be described by power-law or log-law relationships. Unfortunately, very little information exists for the more frequent situation where the wind is nonstationary and perturbed by changes in surface roughness, surface heating, and terrain undulation. Such wind conditions cause uncertainty in the transfer of wind statistics from anemometer sites to building sites and may result in higher ambient pollutant concentration levels, energy variation from windmills, transport of insects or sprays in vegetative canopies, etc. Because the phenomena are highly variable, it is unlikely that even a realistic ensemble of detailed characteristics can be measured in the field. However, a wind tunnel laboratory provides an opportunity to study such phenomena in detail.

Severe storms cause the majority of structural damage, soil erosion, snow drifting, and weather-related airplane accidents. Vortex-type strong winds such as hurricanes, tornadoes, and waterspouts may carry debris or missiles whose impact can lead to significant damage. The local structure of the wind flow may be different from that of a normal straight-wind boundary layer flow. Despite their importance only extremely crude fluid and mathematical models of their behavior exist, due mainly to the difficulty of measuring wind characteristics near the surface during these unpredictable events. The use of laboratory models of rotating flows, additional field measurement programs, and the development of analytical and numerical models should be encouraged and coordinated through a research agenda.

Local wind conditions are often determined by unique combinations of structures, terrain, and thermal or temperature effects. Low-level jets, down-slope winds, valley winds, leewaves, airflow channeling by street canyons or valleys, etc., all produce wind fields which cannot be described by simple formulae. These winds determine extreme air pollution episodes, the incidence of arrival of noxious odors, or the intensity of hazardous or flammable gases. Local winds around structures affect the re-entrainment of exhausts from fume hoods, the success of an outdoor cafe or recreation area, the accumulation of street debris, or even the safe use of entrances to buildings. Researchers should investigate these wind problems to select for study those that are most urgent (re-entrainment of exhausts, for example, has received little attention and current predictions are elementary at best).

Similarly, the design of a wind turbine requires an extensive knowledge and a data base for the wind input. Cost-effective production of electrical energy from a wind turbine requires detailed information on the spatial and temporal behavior of the wind. The behavior of the local wind largely determines the energy production of the wind turbine. The stochastic behavior of the wind plays a major role in the structural behavior of the machine. The ability to develop models of the local wind conditions as affected by local topography, atmospheric conditions, and other nearby wind turbines is available. Integration of these "wind models" with models which predict rotor performance are similarly in under development. What is needed is the continued establishment of the necessary wind characteristics databases and a mechanism for effective data retrieval.

Research Topics: Characterization of boundary layer, storm, and local winds is necessary before wind engineering can improve its response to industry's needs. Further research is necessary to establish both the general behavior of the wind in the surface layer and the magnitude of wind perturbations that special situations induce. Research on the following topics is needed:

1. Analysis of climatological data to determine the influence of wind direction, terrain features, storm type, data record length, location of data collection site relative to construction site, etc., on the reliability of methods for specifying maximum wind loads.

2. Characterization of wind and turbulence fields within hurricanes and tornadoes through laboratory, analytical, and numerical studies. Design of a rotating airflow facility should begin immediately.

3. Characterization of wind and turbulence variations with height over typical urban, coastal, mountain, and rural terrain situations for various high wind conditions.

4. Development of reliable physical and numerical models to predict microscale variations in wind and turbulence fields due to surface roughness, heating, and terrain inhomogeneities.

5. Dependence of the scales and indices of the power law and log law on combinations of magnitude and areal extent of surface roughness, surface heating, stratification, etc.

6. Measurement and classification of strong winds in special local wind situations, (i.e., gorge and valley winds, downslope winds, street canyon winds, structure induced winds) for wind-engineering applications.

7. Development of data analysis methods to economically characterize the meteorology of a building or wind-energy site using offsite climatological data.

8. The development of a design-oriented database and a data retrieval system which effectively ties all wind related research and technology development resource organizations together.

Fundamental Fluid Dynamic Issues

Wind engineering is a relatively new discipline that is based on knowledge accumulated from many established fields of engineering and natural sciences. Problems addressed by wind engineers typically refer to complex, real-life situations. These are usually analyzed through investigation of idealized situations with stress on the governing physical mechanisms involved. Some of the mechanisms are of fundamental nature and they occur in a variety of engineering problems. Thus, a full understanding of such phenomena is critical in establishing strong foundations for the discipline of wind engineering.

The fundamental problems of wind engineering are related to wind and its interaction with the natural and man-created environments. Typically, the wind is a fully developed high Reynolds number flow, usually of boundary-layer nature, with a turbulent structure. In some cases its equilibrium conditions are perturbed by changes in surface roughness, the presence of flow-disturbing obstacles, or strong large-scale vortex structures. Such disturbances result in development of internal boundary layers, boundary-layer unsteadiness, and swirling flow, respectively. These flow phenomena are not fully understood at the present time and systematic studies of corresponding idealized flow situations are needed.

Man-made structures of interest in wind engineering usually are single or multiple bluff bodies. The description of wind effects on such structures is referred to as bluff body aerodynamics. Of interest are local and global aerodynamic effects on bluff bodies with curved and sharp-edged surfaces. Related problems involve the not fully understood phenomena of separated flows, effects of turbulence, Reynolds number effects, effects of boundary-layer shear, and surface conditions. Theoretical analyses of such problems are usually of limited scope. Instead, physical (an in some cases numerical) modeling is used. Some modeling techniques need further refinements.

Dynamic wind effects on structures are usually evaluated using methods of random vibrations. Some structures exhibit nonlinear behavior and require appropriate nonlinear analysis. Although limited studies of nonlinear deterministic and probabilistic responses to wind loading have been reported, comprehensive studies of typical representatives of different wind-prone classes of structures are needed.

Studies of dynamic response of structures have recently been extended to include reliability and safety analyses. Attempts have been made to use elements of fuzzy set theory and artificial intelligence to construct expert systems capable of analyzing the performance and safety of elementary civil engineering structures. Further work is needed to advance such systems to a level required for analyzing more complex problems. Wind engineering problems are multidisciplinary and complex, and they seem to be well suited for analysis using expert systems. However, more research is needed to build higher level systems capable of analyzing wind engineering problems.

<u>Research Topics</u>: A comprehensive research effort is necessary both to improve understanding of the fundamental problems, and to advance the methods of wind engineering. Some of the research topics recommended are listed below:

1. Study of large-Reynolds-number boundary-layer flows perturbed by surface roughness changes; internal boundary layers; boundary-layer unsteadiness; and control of boundary-layer separation and reattachment.

2. Investigation of the interaction of boundary-layer flow with large- and small-scale rotational flow perturbations.

3. Evaluation of the distortion of boundary-layer flow by a single bluff obstacle and a group of obstacles.

4. Determination of the effects of approach flow characteristics on separated shear layers, on shear-layer kinematics and on stability, on pressure fluctuation and control.

5. Study of aerodynamics of flow and vortex-motion-induced response for bluff bodies with curved and sharp-edged surfaces.

6. Development of an "expert" (knowledge-based) system for wind engineering applications: wind loading, air pollution prediction; structural response, reliability, safety and human comfort analysis; overall effects (including socio-economic and fiscal) of extreme wind events and natural disasters.

7. Study of effects of freestream turbulence upon the pressure distributions and separation in flow about one or two a cluster of bluff bodies.

8. Investigation of coupled aeroelastic effects, including vortex-induced response, galloping, and flutter.

9. Study of the effects of nonlinearity on stochastic dynamic response and reliability of a generic class of wind-prone structures.

Wind Effects on Wind Loading and Structural Response

Wind pressure on building exterior surfaces causes steady and unsteady loadings that can result in significant damage and affect the comfort of occupants. Strong winds can cause damage to curtain walls, exterior glass breakage, rupture and dislocation of thin cladding panels and interior walls, and even damage to the main structural system. Severe winds also cause unacceptable building movement (sway and rotation); airflow, water infiltration and dust movement through cracks; and inefficient operation of ventilation, cooling and heating systems. Small buildings, low-rise buildings, and mobile homes are also sensitive to strong winds. Yet wind loads are usually considered only very approximately during design and construction, especially for small and low-rise buildings. Other structures sensitive to wind forces include tall towers, chimneys, cooling towers, long-span bridges, membrane roofs, off-shore structures, utility lines, wind turbines and their supporting structures, and others. Dramatic damage, loss of life, and many injuries have been caused by structural collapse due to severe wind loading associated with strong winds, hurricanes and tornadoes. Buildings under construction may be especially vulnerable, because structural supports are usually incomplete at this stage, and materials such as concrete may not have reached full strength.

External and internal pressures from winds on tall buildings often form the bases for definition of the controlling lateral design loads on buildings even in earthquake-prone areas. Code definitions of wind loads are based on data obtained for idealized structures investigated in idealized environments. Most wind-tunnel studies of buildings in their design stage have, for economic reasons, concentrated on model testing of a particular large or complex shaped building in one wind environment and locale. These tests are not representative of the large volume of small or intermediate sized buildings which are the bulk of buildings constructed. Testing of typical building shapes in different surroundings is needed to establish general relationships between the wind and corresponding wind loading. Such data can be used to improve code definitions of wind loading. During these studies, the effects of nearby structures upon the loading can be addressed in a more systematic manner. Similar studies can be extended for other wind-sensitive structures. Recent observation of wind damage indicates that internal pressure variations in buildings play an important role during wind damage incidences, but only a limited amount of data exists regarding this aspect of wind loading.

As buildings and other structures become more cost effective and make use of new materials, they also tend to become lighter and often more flexible. The dynamic response of buildings, bridges, wind turbine rotors, and towers to wind loading has become an increasingly important part of design for wind loads. Although sand theoretical models for structural dynamics exist, they need to be integrated with rather sparse existing field data and improved future data concerning the wind loading on structures. A need exists to describe the response of typical structures to wind loads and to develop approximate methods which would permit structural engineers to perform better wind load dynamic analyses quickly, without highly specialized knowledge or training. Such methods should be disseminated to design professionals, and evaluated in cooperation with them.

The recent trend in architecture has been to more irregular, multiple-sided shapes with often severe departures from symmetry. A better definition of local mean and fluctuating wind pressures in critical regions and the development of techniques to better predict the pressure distribution over the building facade would be very beneficial in allowing better and more economic design of windows and exterior walls. Efficient structural configurations for highly asymmetrical buildings need to be developed. Information on local pressures and structural system efficiency could affect the selection of initial building configurations and overall building economy, if it is well understood by architects and design engineers.

Numerous buildings, generally large or unusually shaped, have been tested in boundary-layer wind tunnels prior to their construction to determine cladding pressures and frame loads. These studies have not attempted to investigate the details of the wind flow around the buildings to understand the mechanisms by which the pressure loading is developed. Consequently, these studies are of limited value in developing conceptual models of wind/structure interaction that could in turn lead to effective load prediction models. However, the existing model studies do have great value as a data base against which to test a prediction model. A significant effort should be devoted to basic research to identify and quantify flow characteristics, and the ways they load the structure.

A limited data base exists to full-scale load measurements for comparison to wind-tunnel measurements. Unfortunately, much of the local pressure data is flawed and unreliable. It is desirable to add to the current full-scale database by undertaking new measurement programs, supporting on-going measurement programs (for example, the proposed field measurement program at Texas Tech) with wind-tunnel comparisons, and stimulating experiments by other organizations, especially building owners and private engineering firms, through guidance, equipment loans, and partial funding. Information most critically needed are local fluctuating pressures, area-averaged pressures (50 ft^2 to 1000 ft^2), mean and fluctuating frame forces, and building frame deflections (including floor-to-floor deflections which distort the cladding) and accelerations (which help control occupant perception of motion). Because field measurement programs are expensive, cooperative ventures must be used to the maximum extent possible in order to reduce costs.

There is a growing body of knowledge about psychological aspects of the wind environment (e.g., Cohen, et al., 1977; Jackson, 1977; Hunt, Poulton and Mumford, 1976). However, these preliminary studies have not been used fully to produce guidelines for city planners and architects. Additional research is needed to (a) establish improved criteria for wind and motion discomfort levels for pedestrians and building occupants, (b) provide information about human adaptation to wind environments around buildings, and (c) assess the relative importance of wind as a specific attribute in a setting. Methods exist for measuring perception of complex stimuli. For example, one approach based on signal detection theory has been applied successfully to complex assessment of sensory input (Loomis, et al., 1984). Similar psychological and social science approaches can be developed and tested in wind-engineering facilities when engineers and scientists form a multidisciplinary research team.

Research Topics: Data over a broader range of structural types, sizes, and flow conditions are needed for typical residential, industrial and commercial structures. Information of this type can give the U.S. construction industry a significant advantage in providing more economical designs. A program of study involving wind-tunnel modeling and field measurements will lead to new understanding of damage potential and serviceability of structures subjected to strong winds. Hence, the following research topics are recommended:

1. Systematic investigations of wind loading on low-rise, medium and tall typical buildings without and with adjacent structures. Emphasis should be placed on basic understanding of flow mechanisms, and how they produce structural loading.

2. Develop and implement plans to acquire selected full-scale data needed for verification of wind-tunnel load measurements.

3. Development of improved methodology for analysis of wind loads on structures which are usable by structural engineers without extensive specialized experience or training in wind engineering.

4. Development of improved methods to predict the magnitude of local and area pressures on various structural configurations to aid the design of glazing and exterior walls.

5. Evaluation of wind loads on typical structures in various stages of construction.

6. Development of efficient geometric shapes for buildings, bridges and towers, including local details, that minimize static and dynamic wind loads caused by severe winds.

7. Investigations of the dynamic and aeroelastic wind effects on tall, slender and flexible buildings and determination of criteria for when and how these effects should be included in design.

8. Continued development of tuned mass dampers and active techniques for minimizing structure motions.

9. Evaluation for aeroelastic effects (including galloping instability-vortex resonance interaction or ice effects) on light-weight and/or low-damped wind-sensitive structures, including wind turbine towers and "parked" rotors.

10. Investigation of turbulence effects on the aerodynamic stability of long-span bridges, and suspension and air-supported structures.

11. Detailed examination of turbulent flow about, and the induced pressures, forces and moments on sharp-edged and curved bluff bodies, including boundary layer formation, separation, reattachment, vortex shedding and wake structure, for various approach wind conditions.

12. Characterization of combined loads from wind, sea-wave and ice forces for coastal and off-shore structures.

13. Evaluation of the structural efficiency of various shelter or wind breaks for soil, snow, and evaporation control.

14. Preparation of guidelines for architects which maximize natural ventilation, reduce noise, and shelter occupants.

15. Experiments on human perceptions of wind speed, turbulence, humidity, and building motion during routine activities such as work, eating, and sleeping.

16. On-site evaluation of human reactions to wind environments associated with different building designs and construction features.

17. Evaluation of wind as an attribute in a setting such as a pedestrian mall or outdoor restaurant together with other factors such as amount of space, architectural aesthetics, safety, etc.

Wind Effects on Energy Production and Consumption

Nationally, up to one-quarter of all energy consumed is associated with heating and cooling of commercial and domestic buildings. Twenty to fifty percent of building energy losses are attributed to air infiltration. Surface convection of energy by wind over large glass areas or solar collectors also result in significant losses. Surface transfer may represent between 10 to 30 percent of the total load for such structures. Kusada (1978) remarked that:

> "Many inexperienced building heat transfer analysts have mistaken notions that the exterior surface or interior surface heat transfer coefficients as found in the heat transfer textbook or in the ASHRAE Handbook of Fundamentals are absolutely accurate.... In reality the surface heat transfer coefficient could differ from the published value as much as 100%, depending upon the local wind gusts and the irregularity of the surface geometry."

Arens and Williams (1977) reviewed the influence of wind on building energy conservation, and they concluded that wind influences energy consumption in four ways: (1) air infiltration and exfiltration; (2) surface heat transmission; (3) mechanical systems efficiency; and (4) the necessity for enclosing outdoor space.

Wind energy conversion systems (windmills) are considered by many to be the alternative energy resource most design-ready and cost-effective for immediate implementation. Unfortunately, the proper selection of a windy site remains one of the larger uncertainties in predicting the performance and useful lifetime of a wind energy system. Even with the best hardware, windmill performance, reliability, and cost-effectiveness are critically dependent upon the influence of local terrain, buildings, adjacent windmills, and the climatology of the area. With better information, designers could better tailor wind turbine models for sites with specific wind characteristics. This would allow the use of machines with reduced weight and cost in lower risk areas, while sturdier machines could be used in areas more turbulent.

Research Topics: U.S. firms sell a large amount of air-conditioning, heating, and ventilating equipment abroad. The market for this equipment depends upon reliable sizing and performance information for different wind environments. In particular, windmill manufacturers have great expectations for both domestic and foreign markets for their products, but they must respond intelligently to the wind characteristics at potential customers' sites. Such needs suggest that research should include:

1. Examination of wind effects on the natural and forced ventilation in a building by combined full scale measurements and model simulations.
2. Development of a practicable engineering means to predict wind-energy potential (i.e., high wind and turbulence characteristics for a particular locale) and the probable bounds of reliability of such data.
3. Determination of the influence on heat transfer and indoor air pollution of infiltration into multistory, multiroom structures.
4. Estimation of the magnitude of surface convection heat transfer over building facades, glass areas, and dynamic and passive solar collectors.
5. Identification of optimum landscaping and planting procedures to control building infiltration and surface heat transfer.

Wind Transport of Particles and Pollutants

Wind engineering includes many applications in which the transport and mixing of gaseous or particulate materials by the atmosphere can have a significant influence on overall planning, design details or operation of public and private projects. Ground-level concentrations of exhaust gases released from automobiles, stacks, hospital vents, chemical hoods and many other sources must be kept below levels harmful to man, animals and plants. An annual 1970 air pollution loss figure of $13.5 billion for the U.S. was quoted in The New Republic, October 31, 1970. Since this amount is nearly an order of magnitude greater than the annual 1970 amount for all other atmospheric sources of damage, wind transport of pollutants would appear to be of singular importance. The engineer is often called upon to predict dispersion consequences, often in a complex setting of building clusters, terrain features, or vegetation. The engineer must also consider the possibility of odors, flammable gases, and insect or disease vectors on an intermittent time scale.

The movement of wind-blown soil, sand, or snow can cause problems ranging from nuisance to life-threatening situations. The dust bowl conditions of the 1930's and the existence of large areas of wind deposited loess soil are graphic demonstrations of the impact of wind-blown soil movements on agriculture. Combined wind and surface condition effects on soil evaporation rates also impact agricultural production. Control of sand movement is of primary concern in many Middle-Eastern countries where dust and wind are persistent and dunes may encroach upon or cover large areas. The drifting of snow over roadways and rail lines, the weight of snow and ice on buildings, utility lines and structures, and visibility problems during blizzards are all important wind-related problems. Rain droplets may be blown by wind fields into cracks and ventilators on building facades. The intrusion of water through building cladding can result in expensive damage and the reduction of the lifetime of structures.

<u>Research Topics</u>: Atmospheric diffusion for the classical setting is understood sufficiently for many wind-engineering purposes. However, continuous fundamental research is needed to develop a formulation of transport in the complex setting of buildings, roadway cuts, and terrain. Research programs, design guidelines and manuals should be prepared to deal with:

1. Improving existing model capabilities and determination of model limitations for pollutant dispersion in the presence of buildings, complex terrain, stratified flow, elevated inversions, unsteady conditions, etc.

2. Development of instrumentation with sufficient spatial and temporal resolution to measure time-dependent pollutant concentrations in unsteady conditions, and concentration fluctuations both in the field and laboratory.

3. Snow and sand drifting around buildings, roadways, airfields, and their associated loads, and methods to mitigate drifting.

4. Methods to reduce soil transport and soil evaporation as affected by wind.

5. The influence of wind-related infiltration on indoor air quality. Because Americans spend about 90 percent of their time indoors, some research should address:

    a. Building design features that influence indoor air quality.

    b. Use of physical modeling to simulate indoor pollutant transport and removal, and

    c. Integration of building heating-ventilating-air conditioning and indoor air quality control techniques.

6. Dispersion of pollutants in coastal regions, mountain valleys, and urban street canyons which involve the effects of nonuniform solar heating of local surfaces on the wind field.

7. The dispersion of heavy, toxic, or flammable gases resulting from accidental spills during transportation or storage.

8. The transport of moisture, CO_2, crop sprays, insects, insect pheremones, and disease vectors over vegetative canopies. Optimization of spraying procedures in windy environments over agricultural and forest lands.

Physical and Numerical Models

Physical modeling of wind effects on buildings and atmospheric transport of pollutants has become one of the primary tools of wind engineering. The prominent role of physical modeling stems from its ability to provide immediate and realistic answers to designers' questions. While there have been major advances in numerical modeling, in many cases the local flow is so complex that only wind-tunnel modeling can provide the resolution necessary to specify fluctuating loads and pressures, or local wind variability.

Reliable information on mean and fluctuating pressures on building surfaces, forces, moments, deflections, dynamic response, local air circulation, and pedestrian discomfort can be obtained with proper wind-tunnel modeling. Safe, functional and economic design and operation of high-rise structures are contingent upon this type of information. For example, the wind problems of the John Hancock Tower in Boston (loss of windows, and subsequent replacement of all its 10,344 windows at a cost of $8.5 million, and loss of occupancy for nearly 2 years at $50 million) attest to the need for reliable modeling analysis, facilities, and instrumentation.

Physical modeling presumes similarity exists between the behavior of the atmosphere and the flow in a laboratory facility. In many cases structural and dynamic similarity must be obtained by adjusting model characteristics of mass, elasticity, and damping. Exact similarity is not generally achievable. Hence, compromise requires the use of "partial" similarity which attempts to reproduce in each situation the dominant force and motion scales. The various techniques proposed and used in different wind-engineering laboratories have resulted in some loss of wind-engineering credibility, and confusion among designers. Indeed, Lester E. Robertson, president of the structural engineering firm Robertson, Fowler and Associates (New York City) has encouraged the establishment of a monitoring body (or center) where qualifications of wind tunnels and testing methods can be standardized. Sharing of testing methods has "bogged down because of lack of research funds and the proprietary interest of labs" (ENR, 1985).

It has been some years since the U.S. has made a major investment in new or upgraded wind-engineering facilities. Meanwhile foreign governments have given major assistance in the construction and instrumentation of competitive wind-engineering laboratories. One program goal might be the development of a demonstration site for the latest techniques in wind engineering. The upgrade of existing facilities and the construction of new facilities (tornado simulators, low-speed dispersion tunnels, air-sea interaction flumes, etc.) would focus world attention on U.S. Wind-Engineering expertise.

The coupling of numerical and physical modeling can be a valuable tool in wind engineering. Mesoscale meteorological models do not incorporate the details of terrain, varying surface roughness, buildings, or vegetation needed in wind engineering. yet mesoscale and "large-eddy" numerical models can provide input conditions for laboratory studies which then concentrate on features of smaller resolution. In addition, laboratory measurements can provide data to test various numerical boundary conditions and closure concepts to aid in development of numerical simulations. For example, numerical models of the structural behavior of tall buildings, towers, membrane roofs, etc., require wind and pressure information to drive their load analysis. Techniques to use this information through admittance factors to the numerical analysis need to be developed by teams of wind engineers structural engineers, and atmospheric scientists. Furthermore, insight into physical flows can often be gained from numerical models of limited portions of a flow regime, e.g., a separated shear layer. Numerical models of limited portions of flow fields can be used to augment wind-tunnel measurements.

Research Topics: Continuing basic research is necessary to advance the methodologies of physical and numerical analysis. This research is most effective if combined with modern facilities and instrumentation. Research in physical and numerical modeling will provide better wind-engineering tools for the design engineer. Research should include:

1. Systematic study of similarity criteria and their limitations.

2. Development of laboratory, numerical, and field measurement concepts and techniques which permit realistic data comparison.

3. Development of standard calibration tests for wind-engineering facilities.

4. Comparison of various national and international wind-engineering laboratory facilities by means of standard calibration tests.

5. Study of the possible coupling of mesoscale numerical models and physical models by studying their mutual success in replicating features in overlapping domains.

6. Investigations using numerical models to predict complex wind flow fields about structures including comparison with field and wind tunnel data in both stationary and nonstationary situations.

7. Evaluation of alternative admittance factor techniques in structural and reliability analysis.

Socio-economic Factors

Society has long accepted different levels of risk or discomfort for various activities or hazards -- consider the relative risks of smoking, automobile use, hang-gliding, skiing, and nuclear power. The implementation of improved wind engineering principles will depend both on careful documentation of the costs versus benefits and on the public's perception of the need for such changes. Hence, an important function of a problem-oriented research program will be to work with, educate, and learn from governmental and industry policy makers so that research produces information that can effectively impact construction and design practices.

An important step in better wind engineering and structures and other construction is to examine the lessons available from the exposure of such structures to severe winds. The failures of actual construction give the profession excellent guidance to define the primary problem areas and modes of damage. A number of effective disaster response teams exist in the U.S. to evaluate the effects of tornadoes and hurricanes (Committee on Natural Disasters of the National Research Council; the Institute for Disaster Research, Texas Tech University; etc.). Some types of storms are not as well observed (thunderstorms, downbursts, downslope winds, etc.), and some types of structures are not well documented (transmission lines, offshore structures, etc.). Damage information from other parts of the world where different building practices and components are used is nearly nonexistent.

Research Topics: The societal nature of wind engineering requires the involvement o an interdisciplinary team made up of engineers, meteorologists, economists, sociologists, insurance and law representatives, businessmen. Such a team could address needs such as:

1. Field collection and documentation of damage associated with large thunderstorms, chinook winds, ice storms, and storm surges.

2. Collection of world-wide loss information into a wind, snow and ice damage climatological library.

3. Establishment of a coordinating secretariat of the NAS/NAE/NRC wind damage inspection teams.

4. Development of mitigation measures to prevent or avoid the need for relief and reconstruction measures following a severe storm.

5. Linking of insurance and public reconstruction measures with the adoption of better building codes and rationale restrictions on the location of new structures.

6. Expansion and improvement of wind-engineering aspects of forecasting severe storms and their probable consequences. Design guides and codes should be prepared to prepare public safety officials and construction companies for wind hazards.

7. Development of a comprehensive program of training for practicing engineers, architects, builders, contractors, and code authorities to present updated knowledge for design and planning against natural wind-related disasters.

Wind Engineering Practices

Wind loading codes and standards form the principal tool for definition of wind loads on buildings and structures in the U.S. and in most foreign countries. Only a small percentage of design cases can afford a full wind-engineering study including wind-tunnel tests. However, current codes are based on data from simple, idealized geometries and are not capable of accurate load predictions for the wide range of geometries for which they are commonly used. The economics of current design and construction practice dictates that a better prediction of wind loads be available to the designer. In response to this need, England, Australia, Japan, and France have developed government-sponsored, wind-tunnel measurement programs whose purpose is to provide improved wind-load data on industrial and commercial building shapes. This information is often proprietary, but locally available to provide an international competitive advantage to industries in those countries seeking international markets. In the U.S., the metal buildings industry has sponsored a limited wind-tunnel study of metal buildings. However, a more extensive program in the U.S. is required to provide U.S. industry with wind-load data which will keep them competitive in international projects.

The U.S. is in the process of moving to a reliability-based structural design process. Critical to the successful implementation of this method is quantifying the uncertainties associated with the various elements of the design process. The uncertainties in wind speed definition and wind-load coefficients in current codes and standards are ill-defined.

A similar state of affairs exists within the U.S. Wind Energy Industry, in the sense that it also is moving toward the development of concensus standards for wind-turbine performance and reliability while competing with foreign products which have had the benefit of government supported standards programs. The American Wind Energy Association (AWEA) in joint effort with the wind energy industry and other technical bodies (e.g., ASME, ASTM, IEEE and others) have several draft standards pending within their respective approval processes. The establishment of testing facilities for certification testing development and verification would be of significant benefit to the U.S. industry.

Research Topics: Wind-engineering research teams have performed design-stage wind-tunnel studies on numerous of buildings. Similarly, load and performance data on wind-turbine behavior is available on file at DOE/WERC. This database is accessible on digital tape, and could form a basis for studies aimed at providing a more realistic wind code definition and for providing input to reliability-based design procedures. These data can be used along with other sources developed by a WERP to support research in the following areas:

1. Basic studies of wind speed probabilities and wind load coefficient uncertainties to provide the data required for proper use of reliability-based design.

2. Establishment of a data center, including the CSU wind-engineering digital-tape library and data from other institutions.

3. Translation of wind-tunnel and field data into codifiable design guidelines and standards.

4. Determination of the accuracy of wind-tunnel simulation so that cost-effective model studies maintain credibility among designers and during regulatory hearings.

5. Preparation of design guidelines that establish minimum standards for physical modeling of atmospheric diffusion of pollutants, hazardous spills of dense, toxic or flammable gases, etc.

6. Promulgation of wind-tunnel calibration procedures among wind-engineering laboratories to permit normalization and verification of test procedures and facilities.

NEEDED NEW FACILITIES

To reestablish a pre-eminent position in wind engineering, the United States must be prepared to invest in new and timely research as the demands of construction change. In the 1st 10 years unique new facilities in Japan (more than 25 new tunnels have been constructed including the Stratified Wind Tunnel at the National Institute for Environmental Studies), Germany (more than five new tunnels, including the Stratified Wind Tunnel at Bundesher Hochschule), France (Environmental Wind Tunnel at Nantes), and Canada (Meteorological Wind Tunnel at the University of Western Ontario), to mention just a few, have given unique advantages to foreign wind-engineering competitors. To maintain the U.S. Wind Engineering initiative, it is time for the United States to invest in new equipment. Based on our vast experience with older meteorological wind tunnels and current research in foreign facilities, recommendations can be made for a number of urgently needed new facilities. Typical of these facilities which are necessary to further our knowledge of wind effects are the following:

Wind Energy Facility: The 1986 Wind Turbine Aerodynamics Research Needs Assessment recommends that a first-rate wind tunnel with unsteady flow and turbulence-generating capability is needed. Also, a sophisticated data-processing center is required to permit accurate storage of data, generation of turbulence statistics, verification of analytical codes, and manipulation of large data sets. The report recommends that the wind tunnel should be in close proximity to a first-rate field test installation.

Tornado Simulation Facility: Tornadoes cause the majority of total structural collapse due to wind loads in the U.S. Although a number of small rotating tanks and miniature tornado simulators exist to study the fluid mechanics of tornadoes, none are large enough to study pressure distributions and dynamic loading upon model buildings.

Low-speed Diffusion Facility: Pollution problems associated with industrial stacks, transportation, vent hoods, odors, etc., are frequently associated with stratified flow atmospheric conditions. Simulation of stratified flows in the laboratories generally require speeds below 1 m/s. The wind tunnels now available in the U.S. were constructed to operate effectively at speeds above 3 m/s; hence, at low wind speeds they are extremely difficult to control and produce only marginally satisfactory flows. By using new construction concepts, wind-engineering researchers can construct a stratified facility capable of stationary and satisfactory operation down to 0.1 - 0.2 m/s.

REFERENCES

1. Arens, E. A. and Williams, P. B., "The Effect of Wind on Energy Consumption in Buildings," Energy and Buildings, Vol. 1, 1977, pp. 77-94.

2. Cermak, J. E., "Applications of Fluid Mechanics to Wind Engineering," Trans. ASME, J. Fluids Eng., Vol. 97, 1975, pp. 9-38.

3. Cohen, H., McLaren, T., Moss, S., Petyk, R., and Zube, E., Pedestrians and Wind in the Urban Environment, Amherst: University of Massachusetts, 1977.

4. Disaster Preparedness, Report to the Congress, Office of Emergency Preparedness, U.S. Government Printing Office, 3 Vols., Jan. 1972.

5. "Wind Tunnel Tests Criticized," ENR News: The McGraw-Hill Construction Weekly, McGraw-Hill, New York, November 14, 1985, pp. 15-16.

6. "ENR-The Top International Contractors, Foreign Contracts Inch Upward," ENR News: The McGraw-Hill Construction Weekly, McGraw-Hill, New York, July 17, 1986, pp. 39f.

7. "ENR-The Top International Design Firms, Foreign Billings Recover," ENR News: The McGraw-Hill Construction Weekly, McGraw-Hill, New York, August 7, 1986, pp. 26f.

8. Friedman, D. G., "Economic Impact of Windstorms in the United States," Wind Engineering, Proceedings of the Fifth International Conference, Fort Collins, Colorado, U.S.A., ed., J. E. Cermak, 1979, Vol. 1, pp. 47-60.

9. Hunt, J. C. R., Poulton, E. C., and Mumford, J. C., "The Effects of Wind on People: New Criteria Based on Wind Tunnel Experiments," Building and Environment, 1976, Vol. 11, pp. 15-28.

10. Jackson, P. S., The Evaluation of Windy Environments, Technical Report 3-77/4, Ministry of Works and Development, Central Laboratory, New Zealand, 1977.

11. Kusada, T., "Fundamentals of Building Heat Transfer," Energy Conservation in Heating, Cooling, and Ventilating Buildings, 1978, Vol. 1, (Hoogendoorn, C. J. and Afgan, N. H., eds.), pp. 321-338.

12. Loomis, R. J., Kiphart, M. J., Garnand, D. B., Malm, W. C., and Molenar, J. V., "Human Perception of Visibility Impairment," Conference on Air Pollution Effects on Parks and Wilderness Areas, Mesa Verde National Park, May 1984.

13. National Academy of Science, "Atmosphere-Biosphere Interactions. Towards a Better Understanding of the Ecological Consequence of Fossil Fuel Combustion," National Academy of Science Press, 1981.

14. Olienyk, J. P., Snyder, J. R., Skold, M. D., and Willis, W. O., "The Economic Benefits and Costs of Managing Windblown Snow in the Northern Plains of the U.S.," Wind Engineering, Proceedings of the Fifth International Conference, Fort Collins, Colorado, U.S.A., ed. J. E. Cermak, 1979, Vol. 1, pp. 37-46.

15. Pagon, W. W., "Aerodynamics and the Civil Engineer," Eng. News Record, 1934, Vol. 112, pp. 348-353; 1934, Vol. 113, pp. 41-43, 456-458, 814-818; 1935, Vol. 114, pp. 582-586, 665-668, 742-745; 1935, Vol. 115, pp. 601-609.

16. Petak, W. J. and Atkisson, A. A., Natural Hazard Risk Assessment and Public Policy: Anticipating the Unexpected, Springer-Verlag, New York, 1982, pp. 197-234.

17. Rijkoort, P. J., "A Compound Weibull Model for the Description of Surface Wind Velocity Distributions," Scientific Report W.R. 83-13, Koninklijk Nederlands Meteorological Instituut, 1983.

18. Sanders, F., "Toward Defining Human Needs: How Does the Atmosphere Hurt Us?" Bulletin of the American Meteorological Society, 1971, Vol. 52, pp. 446-449.

19. Wiggins, J. H., Building Losses from Natural Hazards: Yesterday, Today and Tomorrow, J. H. Wiggins Company, Redondo Beach, California, 1978.

20. "Wind Turbine Aerodynamics Research Needs Assessment," U.S. Dept. of Energy Report DOE/ER/30075-H1, January 1986, 126 pp.

21. Price-Waterhouse, "The Contribution of Architectural Engineering and Construction Exports to the U.S. Economy," Prepared for International Engineering and Construction Industries Council, April 1985, 22 pp.

Section III:

PROCEEDINGS OF SEMINAR ON WIND ENGINEERING

Extended Abstracts, Lecture Notes, and Viewgraphs

Seminar/Workshop on WIND ENGINEERING:
THE PAST TO THE FUTURE
June 4-6, 1987, Colorado State University

Date: **4 June 1987 (Wednesday)**
Place: **University Park Holiday Inn, Arizona Room**

Time	Program	Host
6:00	Registration	
	Ice Breaker	Cermak Peterka Petersen, Inc.
9:30 pm		

Date: **4 June 1987 (Thursday)**
Place: **Colorado State University**
Natural Resources Building, NR113

Time	Program	Speaker	Chairmen/Introduction
8:00	Registration		
8:30	Opening Remarks	R.N. Meroney, Seminar/Workshop Chairman Colorado State	
8:35	Welcome	Philip E. Austin President, Colorado State University	
8:45	Session I:		
	Wind Engineering - An Overview	J.E. Cermak Colorado State	A.G. Davenport Univ. Western Ontario
9:30	Discussion		
9:45	Coffee Break		
10:00	Session II:		K.C. Mehta Texas Tech Univ.
	Wind Loading of Buildings	J.A. Peterka Colorado State	
	Aeroelastic Structures	B. Bienkiewicz Colorado State	
	Wind Loading of Compliant Offshore Structures	A. Kareem Univ. of Houston	
	Wind Effects on Structures: A Probabilistic Viewpoint		
11:30	Discussion		
12:00	End of morning sessions		
12:15	Luncheon		
	Costs and Perspectives of Wind Engineering	John H. Wiggins Crisis Management Corporation	J.D. Nelson Colorado State

Time	Program	Speaker	Chairmen/Introduction
1:30	Session III:		H. Liu Univ. of Missouri
	Fluid Mechanics of Atmospheric Boundary Layers	S.P.S. Arya North Carolina State	
	Computational Aerodynamics	T. Yamada Los Alamos National Laboratory	
	Bluff Body Aerodynamics	W.Z. Sadeh Colorado State	
3:00	Discussion		
3:30	Coffee Break		
3:45	Session IV:		R.A. Pielke Colorado State
	Wind Transport of Scalars and Pollution	R. Thompson USEPA	
	Wind Transport of Odors and Hazardous Materials	R.N. Meroney Colorado State	
	Wind Energy Utilization	C. Hansen Univ. of Utah	
5:15	Discussion		
5:30	End of Seminar		
6:30	Open Bar - Reception (Lory Student Center, University Club)		
7:30	Dinner - (Cherokee Park Room, Lory Student Center)		
8:30	NSF Engineering Looks to the Future	C.W. Hall Directorate for Engineering, NSF	F.A. Kulacki Colorado State
	Recognition & Award Program		W.Z. Sadeh Colorado State

Date: **5 June 1987 (Friday)**
Place: **Natural Resources Building, NR113**

Time	Program	Speaker	Chairmen/Introduction
8:30	Session V: Workshop		
	Opening Remarks	R.N. Meroney, Seminar/Workshop Chairman Colorado State	
8:45	Futures Presentation	A. Davenport Univ. of Western Ontario	J.E. Cermak Colorado State
9:30	Coffee Break		
9:45	Session VI:	Co-chairmen	
	Industry Viewpoint	R.H. Scanlan, John Hopkins Univ. D.C. Perry, MBMA M.E. Criswell, Colorado State	
	1 Building Problems	E. Simiu, National Bureau of Standards	
	2 Structural Problems	C. Thornton, Lev Zetlin & Associates	
	3 Solar Systems	H.A. Franklin, Bechtel National, Inc.	
	4 Power Plant Dispersion	R. Claussen, Stearns Roger Division	
	5 Building Aerodynamics	R. McNamara, KKBNA	
	6 Hazard Problems	S.J. Wiersma, Gas Research Institute	
	7 Transmission Line Systems	P.F. Lyons, TLMRC, EPRI	
12:00	Luncheon		
	Education Futures	R. Dickeson Chief of Staff Governor of Colorado Cabinet and President, Univ. of Northern Colorado	F.W. Smith, Colorado State
1:30	Session VII:	Co-chairmen	
	Workshop Session Problem Definition		
	i) Wind loading	M. Gaus, National Science Foundation N. Isyumov, Univ. of Western Ontario J.A. Peterka, Colorado State	
	ii) Scalar transport	R.P. Hosker, ADTL, NOAA R.N. Meroney, Colorado State R.L. Petersen, CPP, Inc.	
	iii) Energy	N. Kelly, SERI A. Lewondowski, SERI V.A. Sandborn, Colorado State W. Z. Sadeh, Colorado State	
2:45	Coffee Break		

Time	Program	
3:00	Session VIII:	Co-chairmen
	Workshop Session Research Program	
	i) Wind loading	M. Gaus, National Science Foundation N. Isyumov, Univ. of Western Ontario J.A. Peterka, Colorado State
	ii) Scalar transport	R.P. Hosker, ADTL, NOAA R.N. Meroney, Colorado State R.L. Petersen, CPP, Inc.
	iii) Energy	N. Kelly, SERI A. Lewondowski, SERI V.A. Sandborn, Colorado State
4:30	Wrap up and Closing Program	
6:30	Trip to Estes Park, Dinner and Show at Ranch	

Date: **6 June 1987 (Saturday)**
Place: **Colorado State University, Engineering Research Center**

Time	Program	Host
9:00	Tour of Fluid Dynamics and Diffusion Laboratory	Fluid Mechanics and Wind Engineering Program Staff and Students

WIND ENGINEERING - AN OVERVIEW*

Jack E. Cermak

Wind in the lower atmosphere -- the atmospheric boundary layer (ABL) -- imposes both detrimental and beneficial effects on human activities and works. Increasing complexity and intensity of social, economic and technological interaction have been accompanied by new challenges and responsibilities for urban planners, developers, architects and engineers to minimize harmful effects and to derive benefits from mass transport by wind and wind energy. Wind effects on buildings and structures were the first wind effects to receive organized attention at an international conference in 1963 (1). A more comprehensive consideration of wind effects was initiated in 1970 (2) at a conference where the designation of "Wind Engineering" (WE) was adopted to identify the new discipline. International WE conferences in 1967, 1971, 1976, 1979, 1983 and 1987; U.S. National Conferences on WE Research in 1975, 1978, 1981 and 1985; the International Association for WE; the U.S. WE Research Council; the Canadian WE Association; the Japan Association for WE; the Australian WE Society; the Chinese WE Society; and the International Journal of WE and Industrial Aerodynamics all give evidence that efforts to meet the new challenges and responsibilities are in progress. The objective of this presentation is to delineate the current scope of WE and outline advancements in WE during the last decade (3) that have evolved (and some needed advancements) to meet the new challenges and responsibilities. The basic subject matter of WE is composed of wind characteristics, their statistics and their effects on various objects manifest through momentum, mass and heat transfer. Fluid dynamics (aerodynamics) constitutes the fundamental physical science that bridges meteorological aspects of WE with engineering and architectural practice (4). Relationships between various disciplines and how they merge to form the structure of WE are shown in Fig. 1.

Areas of WE practice can be classified according to national needs that have stimulated identification and development of the discipline. The primary needs and concerns are as follows:

1. Need for reduction of economic loss and improvement of performance for buildings and structures.
2. Increasing concern for human safety and comfort.
3. Increasing concern for environmental quality and safety.
4. Need to conserve energy, soil and water.
5. Need to increase energy production.
6. Need to improve agricultural production.

Some awareness of the potential benefits of good WE is realized by noting that economic loss by wind damage to buildings is projected to be approximately $8 billion for year 2000 (5). Economic and social benefits

---

*Extended Abstract

realizable by diligent efforts to achieve progress in areas two through six have not been estimated but will certainly increase with time.

Various WE applications associated with each of the foregoing six areas are presented in Fig. 2. These identify a broad spectrum of WE applications -- a range of subject matter too comprehensive to discuss in detail at this seminar. Accordingly, this presentation will focus on areas one, two and three.

REFERENCES

1. Proceedings of Conference on Wind Effects on Buildings and Structures (Redesignated as First International Conference on Wind Engineering), National Physical Laboratory, Teddington, England, 26-28 June 1963, Vol. I and II, H.M.S.O., 1965, 851 p.

2. Roshko, A. (editor), "Conference Report on Wind Loads on Structure" -- First U.S. National Conference on Wind Engineering Research, California Institute of Technology, Pasadena, California, December 1970, 137 p.

3. Cermak, J. E., "Advances in Physical Modeling for Wind Engineering," *Journal of Engineering Mechanics*, ASCE, Vol. 113, No. 5, May 1987, pp. 737-756.

4. Cermak, J. E., "Applications of Fluid Mechanics to Wind Engineering -- A Freeman Scholar Lecture," Transaction of the ASME, *Journal of Fluids Engineering*, Vol. 97, March 1975, pp. 9-38.

5. "Building Losses from Natural Hazards: Yesterday, Today and Tomorrow," J. H. Wiggins Company, Redondo Beach, California, 1978, 20 p.

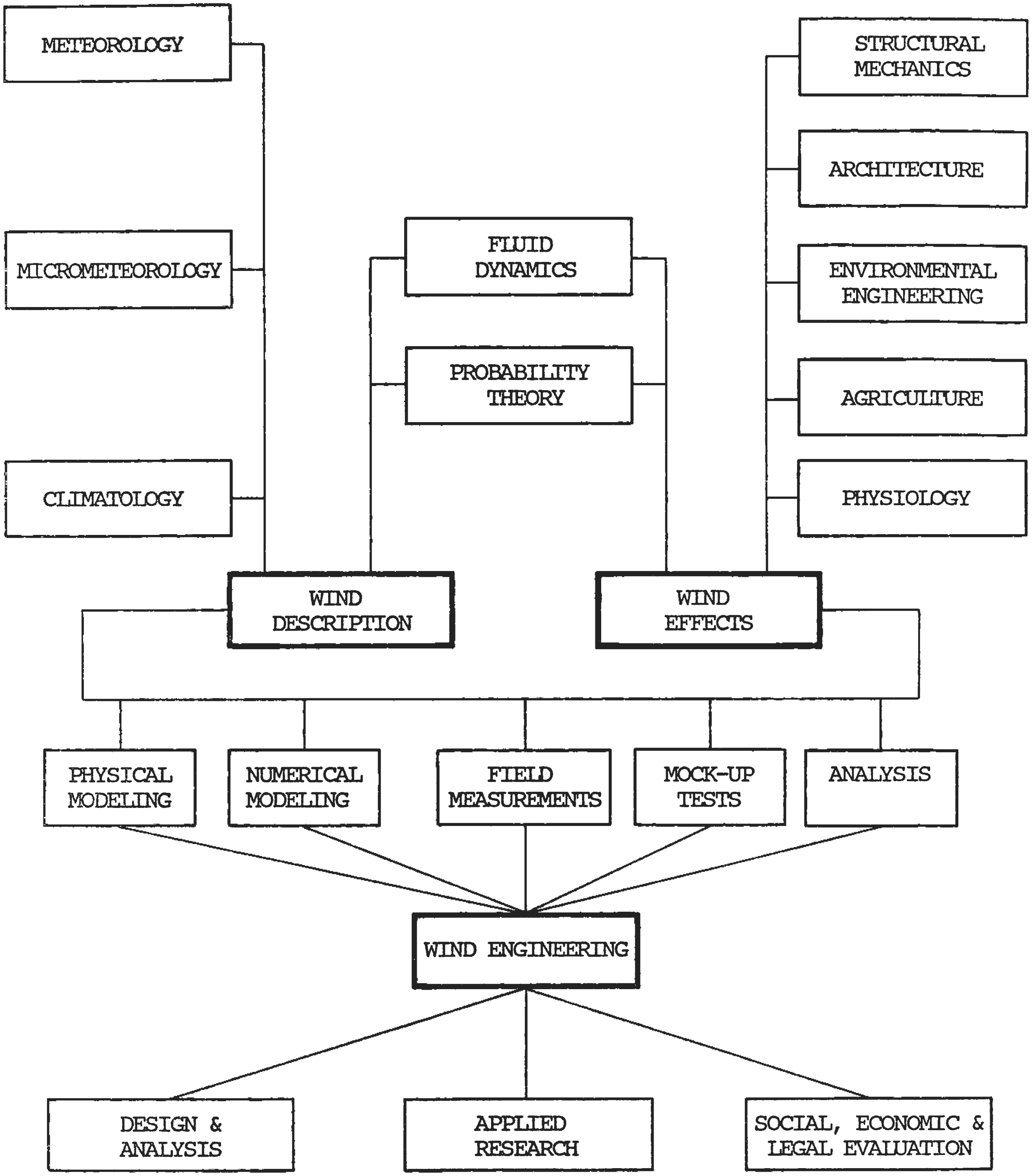


Figure 1. Relationship of traditional disciplines and information-generation methods to wind engineering.

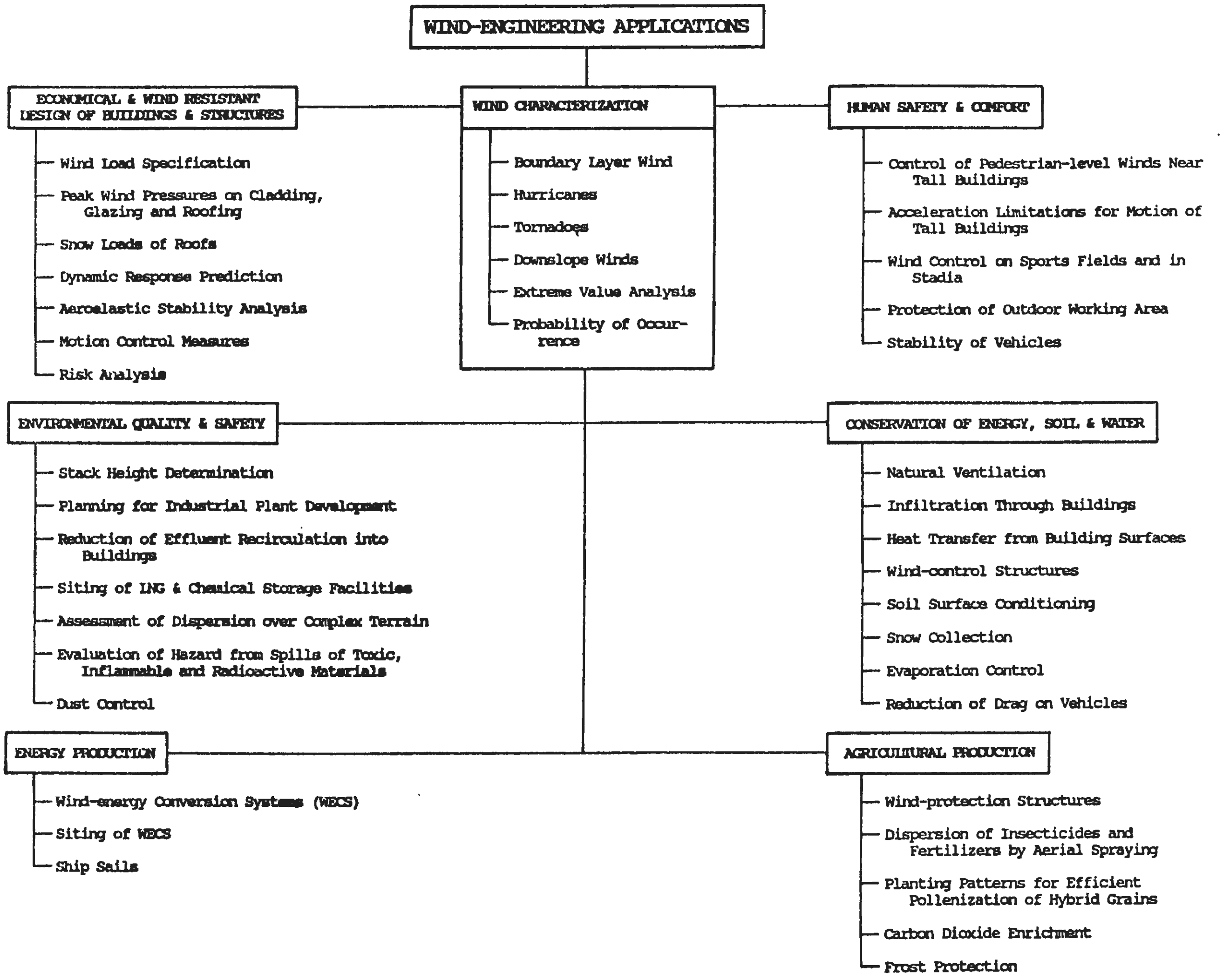


Figure 2. Major areas of wind-engineering practice.

WIND LOADING OF BUILDINGS

Jon A. Peterka
Colorado State University

Definition of wind loads on buildings and structures has had the benefit of boundary-layer wind-tunnel testing since the early 1960's. The first structures to be tested in a modeled boundary layer in the design stages were the World Trade Center Towers in New York City in 1962-1963. In the 25 years since that time, use of boundary-layer wind tunnels for definition of design loads has increased steadily with the total number of buildings tested to date exceeding 700 to 1000. Long-span bridges have been tested as section models for aerodynamic stability since the 1940's in uniform flow wind tunnels. By the 1970's, full bridge models were being tested in boundary-layer wind tunnels, and turbulence generators for turbulent flow for section models were under development. Wind loads on open truss structures were originally defined prior to 1940 in uniform flow. Tests in turbulent boundary layers have permitted an updating of those early results to include the effects of turbulence. The development of the boundary-layer wind tunnel during the 1950's has permitted a wide range of structure wind load problems to be attacked with realistic modeling during the past 25 years.

Wind load measurement techniques have developed also during the past quarter century. Digital data acquisition systems have permitted several orders of magnitude increase in data acquisition rates and have permitted data analysis capabilities which made possible experimental methods which could not be considered earlier. Current capability permits acquisition of multiple channels of fluctuating values of point pressure, area averaged pressures, forces, moments, flow velocities, temperatures, and fluxes of momentum and heat.

Current capabilities permit routine measurements of mean and peak pressures at 800-1200 pressure taps on a single model for 36 wind directions, integration of mean pressures into mean forces and moments, use of high frequency dynamic base balances for measurement of fluctuating forces and moments and calculation of load spectra for use in calculating response loads. Aeroelastic models are developed for single and multimode analysis of structure response. Tens of pedestrian velocity locations can be examined economically on each project.

With current capabilities, there is still need for additional accuracy in defining loads. For example, a recent project had a cost sensitivity in the structural frame alone of $150,000 for each percent of load increase or decrease. Finding ways to minimize loads while maintaining acceptable levels of risk are important. Significant benefits may accrue from refined wind statistics (cost sensitivity of $450,000 per mile per hour of fastest mile at 10 m for the same project), architectural shape modifications, structural framing efficiency, or other mechanisms.

Current wind load codes in the U.S. suffer from a lack of uniformity across the country. In addition, the codes often reflect early origins which were based on uniform-flow wind-tunnel tests and on simplified phenomenological models. Improved phenomenological models based on load tests in boundary layer wind tunnels will be incorporated more rapidly into codes if they can demonstrate significantly improved skill in prediction of loads.

Future improvements in wind load prediction capability can be made by key advances. Several of these are listed:

- systematic wind-tunnel studies of building geometries combined with appropriate analysis can provide phenomenological models tuned with empirical data which can in turn be used to improve code prediction of wind loads on structures.
- improvement in extreme wind statistics and microzonation will provide less uncertainty in resulting loads.
- improvement in knowledge of the inherent statistical variation and of measurement errors in load coefficients will contribute to decreased uncertainty in loads.
- increased use of risk analysis can provide a more uniform application of load requirements.
- increasing capability of desktop and minicomputers combined with improved solution algorithms provides computational fluid dynamics with the eventual potential to greatly improve the precision, economy, and time to availability of wind load predictions.
- improved methods of modeling phenomena such as wind loads on structures, stacks and other curved structures which are sensitive to Reynolds number, small structures, trussed or porous structures, and other special cases are needed.
- methods for simulating nonboundary-layer winds such as tornadoes and downbursts and their effects on structure wind loads can extend the range of current wind engineering practice.

AEROELASTIC STRUCTURES

B. Bienkiewicz
Colorado State University

Modern civil engineering structures are lighter, usually more slender and have lower inherent damping than their counterparts designed and erected in the past. As a result they are more prone to substantial dynamic response due to wind loading. By aerodynamics standards they are bluff bodies, causing the flow to separate and to form the wake with the flow characteristics different from, but usually affected by, those in the oncoming flow. The wake may range from being steady, dominated by small-scale eddies to being highly unsteady, with large periodic, coherent flow formations idealized as vorticies, shed from and convected downstream of the body. The aerodynamic loading fluctuations may be amplified by the wake unsteadiness and may result in substantial increase in the across-flow and torsional responses. Such responses belong to a class of vortex-induced oscillations.

The flow and the resulting aerodynamic forces acting on a structure are affected by the response of the structure itself. When the response-induced aerodynamic forces are noticeable, the aerodynamic loading and the response are coupled and form an aeroelastic problem. The response-induced forces are of a self-excited nature. They may result in an amplification of the structural response to a level bounded or not bounded by the aeroelastic mechanism involved. Depending on the geometry and structural properties of a body an idealized (dynamic) aeroelastic response may be classified as flutter, galloping, and motion-vortex-induced oscillation. Different aeroelastic mechanisms may sometimes interact simultaneously and clear classification into one of the listed groups may be difficult. Flow characteristics, including turbulence may attenuate or amplify some of the mechanisms and their interaction. Turbulence in oncoming flow will result also in additional, buffeting response.

Civil engineering aeroelastic structures are those structures that may exhibit aeroelastic response due to wind loading. Typically, they are slender, low-damping and line-like structures. They include slender towers and stacks, tall and super-tall buildings, long-span suspended and cable-stayed bridges, tension (membrane, cable and air-supported) roofs and structures, and power lines. Their analysis incorporates elements of low-speed aeroelasticity adapted for wind engineering applications and combined with deterministic and probabilistic structural dynamics, Dowell et al. (1), Scanlan (2), and Simiu and Scanlan (3).

Although the problem of separated flow about a fixed and oscillating bluff body remains theoretically unsolved even in a unidirectional flow, approximate methods have been developed to analyze aeroelastic responses. Different approaches have been applied for different structures and corresponding aeroelastic mechanisms. In general, most of the methods incorporate a few in number but restrictive in nature assumptions and some degree of empiricism based on full-scale observations, wind-tunnel testing and/or intuition. As a result of such an approach useful techniques were developed for the design analysis of common structures. As an example, one should mention a method for the estimation of the response of chimneys and towers, developed by Vickery and co-workers. A methodology for the aerodynamic stability and response analysis of long-span bridges, advanced by Scanlan, should be brought to attention as another example. (Both the methods are summarized in Simiu and Scanlan (3).)

Reliability of the existing methods for wind engineering analysis of aeroelastic structures varies from method to method and depends on the design situation analyzed. A method considered to be adequate in one situation (e.g. isolated structure) may not be appropriate in another situation encountered during design process (e.g. interference effects due to structures in close vicinity). Design situations often pose difficult questions regarding probability of occurrence and intensity of expected aeroelastic effects. At the present time some of the questions can not be answered without conducting wind-tunnel experiments. However, satisfactory agreement between the wind-tunnel aerodynamic stability data and recent results of the corresponding numerical experiments, reported by Sakata and Inamuro (4), lead to a proposition that perhaps in the near future some of the "aeroelastic" questions may be answered by numerical modeling.

Three-dimensional character of civil engineering structures makes sometimes the aeroelastic analysis quite cumbersome in view of a limited amount of aerodynamic data which is available or possible to acquire due to physical and/or fiscal constraints. Recently, Scanlan (5) showed how some of the difficulties can be overcome for long-span cable-stayed bridges, by incorporating "two-dimensional data" into aerodynamic stability analysis of the three-dimensional structure. It is believed that further advancements will be made in developing reliable methods for bridges and other aeroelastic structures, once our understanding of the aeroelastic aspects of the response of two-dimensional bluff bodies improves.

Two-dimensional aeroelastic effects should be investigated using experimental, numerical and analytical approaches. Experimental studies of vortex excitation and stability of prisms and other representative bluff bodies, and the effects of turbulence should be investigated taking into account findings of the massive, related research effort undertaken recently in Japan. Japanese experience in numerical simulations (two- and three-dimensional vortex method) should be helpful in complementing the experimental program. Analytical studies should incorporate recent developments in nonlinear aeroelasticity and fluid mechanics aspects of attached, separated and reattaching shear layers in flow about a bluff body.

REFERENCES

1. Dowell, E. H., Curtiss, H. C., Scanlan, R. H., and Sisto, F. A., "Modern Course in Aeroelasticity," Sijthoff and Noordhoff, Netherlands, 1978.

2. Scanlan, R. H., "Developments in Low-Speed Aeroelasticity in the Civil Engineering Field," AIAA Journal, Vol. 20, No. 6, June 1982, pp. 839-844.

3. Simiu, E., and Scanlan, R. H., "Wind Effects on Structures," 2nd Edition, John Wiley and Sons, 1986.

4. Sakata, H., and Inamuro, T., "A Study on Aerodynamic Instability of Structure by Numerical Flow Analysis," Proc. of the Fifth U.S. National Conference on Wind Engineering, Texas Tech University, Lubbock, Texas, Nov. 6-8, 1985, pp. 5B33-5B40.

5. Scanlan, R. H., "Interpreting Aeroelastic Models of Cable-Stayed Bridges," Journal of Engineering Mechanics, ASCE, Vol. 113, No. 4, April 1987, pp. 555-575.

WIND LOADING OF COMPLIANT OFFSHORE STRUCTURES

Ahsan Kareem
University of Houston

As the search for offshore oil and gas supplies moves into deeper water, the size of conventional fixed-leg platforms is approaching the economic limit. Several new structural systems have been proposed for enhancing the water depth capability of offshore structures. Some of the promising concepts are guyed or buoyant towers and tension leg platforms (TLP). These structural systems are known as compliant systems, inasmuch as they are designed to move with the environmental loads rather than resisting them rigidly. As a semisubmersible-type buoyant floating platform moored by several groups of tethers the TLP is expected to be more profitable in deep water due to its superiority over conventional platforms in terms of cot, mobility and operational capability. The wind load effects on TLPs have been recognized to be one of the significant environmental loading. An accurate assessment of the aerodynamic loads is, therefore, a prerequisite for the design of an economic and a reliable structure.

Wind effects on TLPs consist of a static and a dynamic component. The static effects result from mean wind force that can be computed from the mean wind velocity and an appropriate aerodynamic force coefficients (1). The dynamic component results from the buffeting action of wind gusts and/or flow-induced effects. Tension leg platforms, because of their compliance, are much more susceptible to the dynamic effects of wind loading than are conventional fixed-leg platforms. Thus, a procedure for estimating the dynamic response of a TLP should include both wind and wave load effects. Although the overall dynamic response is known to contain both relatively low and high frequency components (induced by the wind and wave fields, respectively), a simple linear superposition of the response due to these individual excitation phenomena may result in an unrealistic picture of the TLP motion. Indeed, it is recognized that wind gusts are typically broad-banded and have energy in the low frequency range which would excite the compliant surge mode of the TLP at the natural period. This motion is controlled by hydrodynamic surge damping. In recent years, several investigators have discussed these wind-induced oscillations utilizing either the assumption f a proportional damping or damping induced by linear nonchromatic waves (2,3,4,5). In a recent study by the author and his coworkers, both time and frequency domain simulations of the nonlinear dynamic response of a TLP subjected to random fluctuating wind field in the presence of depth varying currents and random ocean waves have been addressed (6). Simple models of TLP are also being examined ina wind-wave tank capable of simulating the action of random sea states and turbulent winds (7).

A simplified model of a TLP may be viewed as a rigid body with six degrees of freedom. In the horizontal direction, surge, sway and yaw, and in the vertical direction, heave, pitch and roll represents the respective degrees of motion. The natural periods of motion in the horizontal plane are high, whereas in the vertical plane the values are low. Generally, the surge motion is predominantly high due to the combined action of wind, waves and currents. However, due to coupling among various degrees of freedom and relatively low damping of hydrodynamic origin in the vertical modes of vibration a complete analysis of six degree-of-freedom system subjected to wind, waves, and currents is desirable.

At its simplest level the load effects due to wind and waves may be separated and the influence of hydrodynamic damping may be included in the analysis by way of a proportional damping approach. The basis of this approach is that the surge motion represents a linear system with an equivalent viscous damping term characterized by a nominal damping ratio. The effect of the nominal damping is postulated to be equivalent to the hydrodynamic viscous damping force. The determination of this damping term is given in References (4,6) for deterministic nonchromatic and random waves, respectively. The estimated values or the equivalent hydrodynamic damping have been generally found to be large which tend to suppress high levels of wind-induced dynamic amplification effects. The magnitude of the hydrodynamic damping is dependent on the drag coefficient used in the Morrison's equation to express the hydrodynamic forces. It is important to point out that the estimates of the drag coefficient corresponding to the high Reynolds numbers and low Keulegan-Carpenter numbers of interest in the analysis of TLPs with large circular legs are not available in the literature. Some data from laboratory experiments at low Keulegan-Carpenter numbers is available, but these are limited to relatively small Reynolds number (8).

The next level of analysis involves the solution of equations of motion of a TLP subjected to combined effects of random wind and waves, and currents. These equations have nonlinearity of both hydrodynamic and geometric origin which precludes a straightforward frequency domain analysis. Therefore, the time domain analysis remains the only convenient alternative means of solving the foregoing equations. The time domain analysis requires simulation of random wind and wave fields that it followed by a numerical evaluation of the response. This procedure involves considerable computational effort which is further increased if the TLP is modeled as a six-degree-of-freedom system. In the frequency domain a perturbation-based approach utilizing a spectral decomposition and convolution has been developed (6). In this approach, the loading and restoring forces have been decomposed into various orders of perturbation terms. For example, the aerodynamic loading term has been decomposed into the mean, first-, and second-order components, and the velocity dependent terms. Similarly, the wave induced loading has been expressed in terms of Hermitian Polynomials and then decomposed into the mean, first-, second- and third-order waves forces. The restoring force has been expanded in terms o Taylor Series. An iterative scheme has been employed to solve various components of response. The spectral convolution technique has been used to express the higher-order spectral descriptions. The decomposition of loading into several uncorrelated components facilitated a computationally efficient means of evaluating spectral density function of various response components. Further details of this formulation are available in Ref. (6).

In order to validate the preceding frequency domain approach, the results were compared to the time domain solution. First, the fluctuations in wind and wave fields were simulated by menas of an ARMA (Autoregressive Moving Averages) algorithm. Next, a discrete convolution model was utilized to generate time series of wave particle velocities and diffraction forces from simulated wave height fluctuations. The time histories of the wave particle accelerations were obtained from the associated velocity by means of discrete differentiation schemes. Discrete interpolation techniques are employed to interpolate between simulated data points in the parameter space. The dynamic response of the TLP was estimated utilizing a numerical integration scheme. The estimates of nominal equivalent damping values are also provided by the analysis. The results indicated a good comparison of the frequency domain approach with the results computed from the time domain analysis thus validating the computationally efficient frequency domain approach (6).

A comparison of the response estimates derived from the foregoing analytical procedures with the experimental studies currently under progress would permit a validation and/or improvement in our capability to solve this complex nonlinear probabilistic dynamics problem.

ACKNOWLEDGEMENT

The support for this research was provided by the NSF-PYI-84 award to the author by the National Science Foundation under Grant No. ECE 8352223 and matching funds provided by the Shell Oil Company, Conoco Inc., Chevron, USA, Brown and Root International, Inc., A.S. Veritas Research and Halliburton Foundation. Their support is gratefully acknowledged. Any opinions, findings, conclusions or recommendations expressed in this paper are those of the author and do not necessarily reflect the view of the sponsors.

REFERENCES

1. Kareem, A., et al., "Aerodynamic Loads on a Typical Tension Leg Platform," Ocean Engng., Pergamon Journals Ltd., 1987.

2. Kareem, A., "Wind Induced Response Analysis of Tension Leg Platforms," J. of the Struc. Div., ASCE, Vol. 111, No. 1, January 1985.

3. Salvesen, N., et al., "Computation of Nonlinear Surge Motions of Tension Leg Platforms," OTC Paper 4394, Proceedings, Offshore Technology Conference, Vol. 4, Houston, TX, May 1982.

4. Simiu, E., and Leigh, S. D., "Turbulent Wind and Tension Leg Platform Response," ASCE, J. of the Struct. Div., ASCE, Vol. 110, No. 4, April, 1984.

5. Kareem, A., "Non-Linear Dynamic Analysis of Compliant Offshore Platforms Subjected to Fluctuating Wind," J. of Wind Engng. and Ind. Aerodyn., 14, 1983.

6. Li, Y-S. and Kareem, A., "Stochastic Surge Response of a Tension Leg Platform: A Frequency Domain Approach," Department of Civil Engineering, University of Houston, Technical Report, 1987.

7. Vickery, P. J. and Davenport, A. G., "A Wind/Wave Tunnel Study of Combined Wind and Wave Loads on a TLP," Wind Effects on Compliant Offshore Structures, Editors, C. E. Smith and E. Simiu, ASCE, N.Y., 1986.

8. Bearman, P. W., et al., "The Loading on a Cylinder in Post-Critical Flow Beneath Periodic and Random Waves," Behavior of Offshore Structures, Elsevier Science Publishers B.V., Amsterdam, 1985.

WIND EFFECTS ON STRUCTURES: A PROBABILISTIC VIEWPOINT

Ahsan Kareem
University of Houston

The diversity of structural systems that are sensitive to the effects of wind and ever increasing need to improve the performance of constructed facilities that are economical has placed a growing importance on the problem of wind effects on structures. The wind effects range from factors affecting the structural integrity of constructed facilities to those factors influencing human comfort and serviceability requirements. A full description of the interdisciplinary area of probabilistic wind effects on structures covers diverse scientific fields such as micrometeorology, fluid dynamics, statistical theory of turbulence, structural dynamics and probabilistic methods. A rational treatment of the subject has been made possible by a synthesis of knowledge from the foregoing disciplines. A knowledge of wind climatology, turbulent atmospheric boundary layer, its interaction with structures, resulting unsteady load effects and the associated dynamic response, which on occasions may lead to aerodynamic instability are features of interest. The element of uncertainty inherent in the parameter space, e.g., wind speed and structural characteristics introduces variability in the estimates of wind effects that requires a probabilistic framework to assess structural performance and associated measure of structural reliability.

The following is a brief discussion on the probabilistic description of aerodynamic loads, dynamic response of structures, response of structures with uncertain parameters, and methods of structural safety and reliability.

AERODYNAMIC LOADS

Notwithstanding the improved knowledge of wind effects on structures over the past few decades, our understand of the mechanisms that relate the random wind field to the various wind induced effects on structures has not been developed sufficiently for functional relationships to be formulated. Not only is the approach wind field very complex, but the flow pattern generated around a structure is complicated by the distortion of the wind field, the separation of flow and the development of wake. These effects cause large pressure fluctuations on the surface of a structure which in turn impose large overall aerodynamic loads upon the structural system and lead to intense localized fluctuating forces over the envelope of the structure. Under the collective influence of these fluctuating forces, a structure may vibrate in rectilinear and torsional modes.

The aerodynamic loading in the alongwind direction may be adequately represented on the basis of strip and quasi-steady theories. A lack of a convenient transfer function, between the velocity fluctuations in the far-field turbulence and the pressure fluctuations on the side faces of a building, has prohibited any acceptable formulation, to date, of the acrosswind and torsional loads on structures. Physical modeling of fluid-structure interaction, therefore, provides the only viable means of obtaining information on the lateral and torsional loads.

The aerodynamic loads on structures may be obtained by mapping and synthesizing the random pressure fields acting on structures. The mapping techniques encompass measurement of the space-time correlation structure of the random pressure field through simultaneously monitored discrete multiple-point realizations of pressure fluctuations, and measurement of local averages of the space-time random pressure fields by means of spatial and temporal averaging. The spatial averaging procedure may employ local averaging of the random pressure field utilizing an electronic summation circuitry, a pneumatic manifolding device, or a pressure sensitive surface element like PVDF (1). Recently, high-frequency force balance techniques for determining the dynamic wind induced structural loads from scale models of structures have been implemented. The mode-generalized spectra obtained from a force balance study requires adjustments if the building mode shapes depart from those implied in the derivation of the force balance theory. A second generation of force balances promises to alleviate the preceding limitation (1).

DYNAMIC RESPONSE

The equations of motion of a structure represented by a discretized lumped-mass system may be solved by means of modal superposition, direct frequency, time domain and recursive techniques employing z-transform. The modal superposition referred to as mode-displacement approach permits decoupling of the coupled system of equations of motion by utilizing undamped eigenvectors. An alternate format generally known as mode-acceleration technique permits a reduction in errors introduced by conventional modal truncation in a mode-displacement method. In the event that the damping matrix is not classical, it gives rise to complex-valued mode shapes, for which commonly used modal superposition is not directly applicable. The stochastic dynamic equations of the system may be expressed in terms of state-vector which provides a convenient solution. The response cross-spectral density matrix may be obtained directly in the frequency domain without resorting to normal mode approach which involves an inverse of the matrix of system transfer function. This approach neither requires the evaluation of eigen properties nor the damping matrix to be classical.

In the time domain the equations of motion may be integrated directly using a numerical step-by-step procedure. For the implementation of integration schemes the time histories of loading function are required as opposed to the description of the load spectral density function. The sample functions may be generated by utilizing FFT-based techniques, are ARMA (Autogressive and Moving Averages). The ARMA representation involves weighted recursive relations that connect the random quantity being simulated at successive increments. This procedure utilizes recursive relationship in which the coefficients are ascertained from the given covariance of the random field. The theory of stochastic differential equations has also been utilized to estimate the response of a multidegree-of-freedom system to multicorrelated random wind loads.

The response of structures to evolutionary loading functions such as nonstationary large gusts may be obtained in the framework of random vibration theory utilizing a classical frequency domain approach, or a state-space formulation. A computationally efficient procedure for calculating the response of a multidegree-of-freedom system to nonstationary nonwhite vector-valued random excitation has been developed utilizing a modal time-domain approach (2). This procedure is being used to estimate the response of structures to modulated excitation representing gusts in a hurricane wind field.

DYNAMIC RESPONSE OF UNCERTAIN SYSTEMS

Besides the parametric uncertainties associated with aerodynamic loading, uncertainties related to the structural properties impart variability in the prediction of the overall response. Uncertainties in the system parameters such as mass, stiffness its fabrication, or its mathematical idealization, for example, the contribution of partition walls and some cladding components of high-rise buildings, introduces uncertainty in the overall system stiffness estimates. The influence of uncertainty in the parameters is propagated in accordance with the functional relationship that relates them to the structural response. The propagation of uncertainty may be accomplished by employing one or a combination of the following approaches: perturbation techniques; probabilistic finite element methods; Galerkin-based weak form discretization; Monte Carlo Simulation; and Second-Moment techniques (3).

STRUCTURAL RELIABILITY UNDER WINDS

Traditionally, wind excited structures have been designed based on the equivalent static aerodynamic forces. Uncertainties associated with various parameters due to insufficient data or lack of knowledge are included in the design procedure by implementing safety factors to acknowledge these short comings in the information. Assurance of structural safety and serviceability requires assessment of various uncertainties in the design procedure and associated probability of failure.

The structural reliability analysis is accomplished by examining the limit state equation that describes the condition that renders a structure unfit for one of the intended roles due to one or a combination of load effects. The limit state equation is generally expressed in terms of the structural resistance and load effects. The probability of failure is equal to the volume integral over the failure region involving the joining PDF for the n-dimensional vector. The evaluation of the above integral involving a multiple numerical quadrature is formidable, with the exception of a few simple cases, and the description of the joint PDF is generally not available. This has led to alternative algebraic techniques involving linearization of the limit state surface, direct Monte Carlo simulation and in conjunction with variance reduction schemes (4).

The readers are referred to recent literature in probabilistic methods for further details to expand on the discussion presented in this paper.

ACKNOWLEDGEMENTS

The support for the research summarized herein was provided by the NSF-PYI-84 award to the author by the National Science Foundation under Grant No. ECE 8352223 and matching funds from several industrial sponsors.

REFERENCES

1. Kareem, A., "Mapping and Synthesis of Random Pressure Fields," University of Houston, Department of Civil Engineering, Research Report No. UHCE 86-16, 1986.

2. Sun, W-J. and Kareem, A., "Coupled Lateral-Torsional Response of MDOF Systems to Nonstationary Random Excitation," 3rd U.S. National Conference on Earthquake Engineering, Charleston, South Carolina, 1986.

3. Kareem, A., and Sun, W-J, "Probabilistic Response of Structures with Parametric Uncertainties," Fifth International Conference on Applications of Statistics and Probability in Soil and Structural Engineering, Vancouver, B.C., Canada, 1987.

4. Kareem, A., "Reliability Analysis of Structures under Dynamic Wind Loads," Journal of Structural Engineering, SERC, Vol. 12, No. 4, January 1986.

COST AND PERSPECTIVE OF WIND ENGINEERING

John H. Wiggins
Crisis Management Corporation
Redondo Beach, California

The cost of natural hazards in the United States have been receiving more and more attention since 1974 when the J.H. Wiggins Company concluded the first study identifying the direct losses to buildings resulting from earthquake hazards. In 1977, a similar study was completed which included eight other natural hazards: landslide, expansive soil, hurricane wind, tornado wind, general severe wind, riverine flood, storm surge and tsunami. Secondary losses in addition to primary losses were included in the 1977 study. In 1978, a national loss forecast was also concluded which added urban headwater flooding to the list of natural hazard culprits which ravage our nation every year, some much worse than others.

Even with the increased attention, I will show in the following discussion that natural hazards take a back seat in the nation's lit of priorities. In 1977, the Earthquake Hazards Reduction Program was funded by a special act of Congress which has been continued over the last 10 years (1978 through 1987); it is projected to last another five years at least. Yet the $70 million per year budget in 1978 has not been changed in the last 10 years despite the doubling of the consumer price index during those same years. In effect, the Congress is saying that the earthquake program is worth one half as much as it was in 1977; considering further that federal expenditures since 1977 have tripled, then the earthquake program is considered to be worth one third the value it was in 1977. This reduced interest is accentuated even more when one considers that the Mexico City earthquake of 1985, which caused the country of Mexico severe economic hardships, was barely considered by Congress.

Wind research and loss mitigation has no external mandated program as does the earthquake program. Flood, on the other hand, is mitigated and studied by the Corp of Engineers, while landslide and expansive soil is dealt with primarily by professional engineers and geologists as well as the U.S. Geological Survey. There is however, no universal program on natural hazards research and reduction as a common, unified entity. This is a sad state of affairs when one recognizes that every state in the union suffers losses from natural hazards, with Florida and Louisiana leading the list of states in dollar loss per capita, and the District of Columbia suffering the least in per capita losses. Perhaps the low rate projected for the District of Columbia explains why Washington has not paid attention to natural hazards in general and the wind problem in particular.

The public seems to perceive natural hazards as inevitable acts of God, when actually losses are the result of acts of men, for the most part. It is hard to be the practical pig and build our houses of "brick" when people only want to pay for houses of "straw" or "sticks". When the "wolf" wind blows them down, they simply go to their insurance agent and rebuild the houses and the buildings in the same old way.

In the following discussion, I shall give some perspectives and comparisons about the wind-loss problem with respect to six other natural hazards and with respect to man-made hazards as well as expenditures that are made by Congress to treat those man-made hazards. In this way, we are able to see just how poorly Congress perceives the civil structural engineer's domain of interests.

Wind losses from hurricane, tornado and severe winds are different from losses caused by other natural hazards in that, on the average, 72 percent of wind losses result from severe damage of collapse situations, whereas, on the average, tsuman, earthquake and storm surge cause only 6 percent of the losses to occur in the severe or the collapse columns. As a result, the severity of losses from wind is greater than the severity of losses from tsumani, earthquake and storm surge when considered together.

Another way of comparing wind losses to losses from other natural hazards is to examine the extreme events. Earthquake by far, can cause the greatest single loss scenario of all of the major natural hazard sources (earthquake, hurricane wind, tornado wind, storm surge, riverine flood and tsumani). One single earthquake can cause about $63 billion in first loss damage, that is, the cost of replacing or repairing structures that are damaged. It is estimated that one hurricane can cause a maximum of about $10.5 billion; a tornado, $4.8 billion; storm surge, when considered alone, $2.4 billion and riverine flooding, about $3 billion. A tsumani would cause only about $1 billion in primary structure losses.

On the other hand, if one takes all of the hurricane losses that have been recorded and actuarially scale them to 1987 exposure and CPI conditions and then statistically plot this information on probability paper, one can hypothecate the losses that hurricanes might pose in any one single <u>year</u>. Recognizing that it is much more likely that multiple hurricanes hit our populated regions than multiple maximum critical earthquakes occurring in any one year, we have actuarially computed the potential for hurricane losses and find them to be about two-thirds of the single scenario, maximum earthquake loss. That is to say it is not unlikely that hurricanes could cause first losses on the order of $40 billion due to wind only within a one year time frame within the United States. This loss expectancy has the same likelihood as the $63 billion earthquake loss expectancy.

Another way to examine losses that may accrue from natural hazards is to consider not only fist losses, but also the deaths and injuries that might take place. On the average, wind is expected to cause about 400 deaths per year, which is about 35 percent of the deaths that might result from natural hazards. On the other hand, all accidents, that is man-made accidents, will cause in 1987 about 100,000 deaths. Thus, from death rate comparisons, we see that all natural hazards cause about 1/100 the death rate generated by man-made accidents.

Comparing hurricane wind losses with potential mitigation effects, in order to derive some idea and appreciation for what could be done through research, engineering and applicable code development and enforcement, we have projected from the year 1970 through 2000, loss differences if certain mitigations were enacted in the year 1980. It can be shown that if all structures built after 1980 were designed to 3 times the strength that current code allows where wind was concerned, losses could have been reduced in the year 2000 by about 27 percent. This could mean a savings of primary losses only of about $1.3 billion per year. If, on the other hand, all new structures built after 1980 were designed to be 50 percent greater than current code allowances, a 17 percent savings could be recognized in the year 2000.

To get an idea of the number of people and wealth at risk to the hurricane wind hazard in the United States, rates and computations were mae and it was found that about $4.4 trillion and 71 million people are exposed to the hurricane wind hazard. This is a significant number when one considers the same kind of situation in the case of earthquake. Fewer than 50 million people are exposed to potentially severe earthquake conditions in the United States.

In rank ordering, the nine natural hazards that I have mentioned earlier, in terms of expected annual losses per capita, we find that in 1970, the wind exposure situation was not as great as say, riverine flooding. However, by the year 2000, due to the fact that populations are moving to the seashores in the northeast and south, tornado, hurricane wind and general severe winds are expected to increase in loss percentages by more than three times the increase in riverine flooding. This is due in part to the fact that barrier construction and land control along major rivers is continually being accomplished by the Corp of Engineers, thus resulting in the lower increase in riverine flooding changes.

We have also examined losses that are secondary in nature to primary losses, which result from damage to structures. For example, contents, income loss and social loss in terms of death and injury, housing loss and unemployment, all come into play. Even these secondary losses are not all of the losses that can accrue to the nation from severe natural hazard conditions. For example, tax base can be affected; mortgagors can be affected; banks, due to failure of computers, can be affected, and so forth. It is very difficult though not impossible to include the higher order losses in a total economic study. Yet the National Science Foundation and other agencies who are responsible for natural hazards research have failed to sponsor research efforts aimed at identifying qualitatively if not quantitatively, the magnitude of secondary and higher order losses due to natural hazard situations. I believe that only when such identification is made, can the interested bodies in Congress, State assemblies, and other funding bodies understand the implications of natural hazards and their severe costs to the constructed wealth base of the nation. Damage to our constructed wealth adds to the costs of all products produced in the nation and therefore affects our ability to compete internationally.

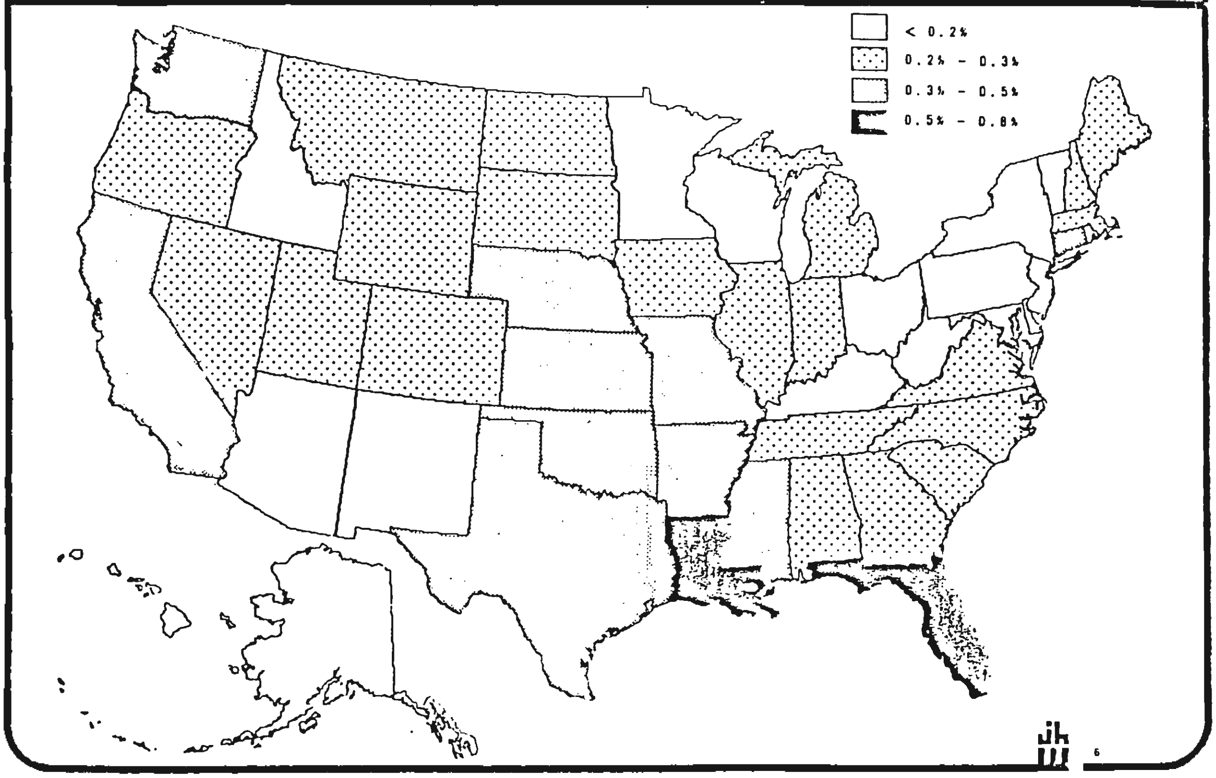
I have made comparisons of the costs of natural hazards with the costs of the wind hazard. Natural hazards costs and wind costs can be compared with other costs which are treated with great interest by political bodies. For example, all property tax collections by state and local governments amount only to about four times the first loss expectancy from all natural hazards. Wind accounts for about one-third of the losses from the nine natural hazards, which I have cited earlier. All accidents are about three times the costs of natural hazards. The total economic losses caused by air pollution are about twice the losses from natural hazards, whereas pollution control costs for air, water and solid wastes are about the same as those from all natural hazards. On the other hand, all crimes against properties, investments in water pollution control facilities, business losses due to six types of various criminal activities, range from one-third to one-half the cost of natural hazards. Finally, building losses due to fires equal wind losses and are about one-third the costs of all natural hazards combined. Fire department costs equal about one-third the costs of all natural hazards and equal the losses that are expected from wind hazards.

Even though the costs of these other expenditures are comparable with those losses from natural hazards, the amount of research and control that goes into mitigating hazards are minuscule compared to these other areas which interest the Congress and state legislative bodies.

One final comparison can be made regarding research and development funding for safety. It has been found that in general, the amount of money spent by Congress to control and mitigate facilities from various transportation modes is about 1/20 the R&D funding that is provided natural hazards. This fact indicates that natural hazards, wind included, are considered to be acts of God, as opposed to transportation modes, thus deserving greater proportionate share of R&D funding. As I have indicated earlier, wind hazard losses are basically the act of man not the act of God. This idea has not been sold to the Congress or the public.

In conclusion, we see that wind costs the nation about one-third of all the costs from natural hazards. At equal probability levels, hurricanes and tornados generated by them, can cause at equal probability levels about two-thirds the losses of a single severe earthquake. Finally, the Congress does not perceive wind and other natural hazards to be important from a safety or national loss point of view as they do hazards created by various transportation modes, air pollution and fires. It seems to this investigator that our priorities are not in balance with regard to research and development funding and hazard control when it comes to natural hazards. In this time where international competitiveness is stressed and with the recognition that the building stock in this country causes overhead costs that influence the cost of products we might well abroad, it is necessary for the Congress to re-evaluate their position on treating natural hazards collectively and the wind hazard in particular.

RANKING FOR EACH STATE FOR THE NINE NATURAL HAZARDS ANNUAL LOSSES AS A PERCENTAGE OF THE BUILDING ASSETS IN EACH STATE FOR 1970 CONDITIONS

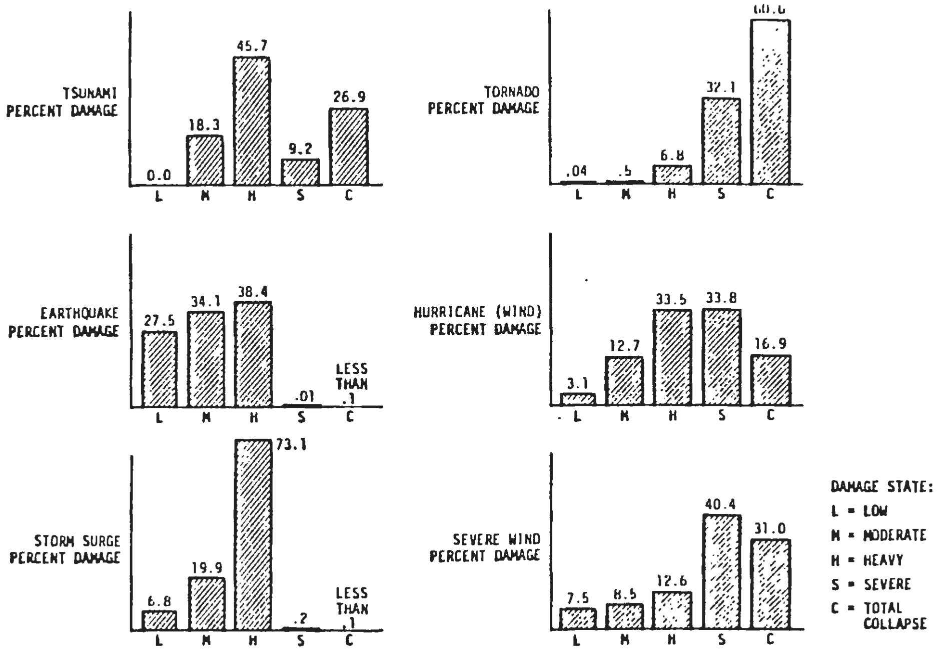


EXPECTED ANNUAL NATIONAL PER CAPITA DOLLAR LOSSES FROM NATURAL HAZARD EXPOSURES IN THE UNITED STATES, BY TYPE OF HAZARD, 1970 AND 2000

	HAZARD	EXPECTED ANNUAL PER CAPITA AFFECTED LOSS FOR INDICATED YEAR (1987$)		CHANGE
		1970	2000	
1.	RIVERINE FLOODING	$ 40.52	61.24	51%
2.	TORNADO	24.24	60.85*	151%
3.	EXPANSIVE SOIL (DWELLING)	16.63	31.89	92%
4.	HURRICANE WIND	15.52	41.11*	165%
5.	EARTHQUAKE	11.44	18.09	58%
6.	STORM SURGE	9.43	27.32	190%
7.	LANDSLIDE	3.13	5.85	87%
8.	TSUNAMI	0.21	0.48	129%
9.	SEVERE WIND	0.18	0.57*	217%
	ALL HAZARDS	$ 121.30	$ 247.40	104%

* Wind hazards combined = $102.53 which exceeds riverine flooding, $61.24.

DISTRIBUTION OF ANNUAL U.S. LOSSES BY DAMAGE STATE



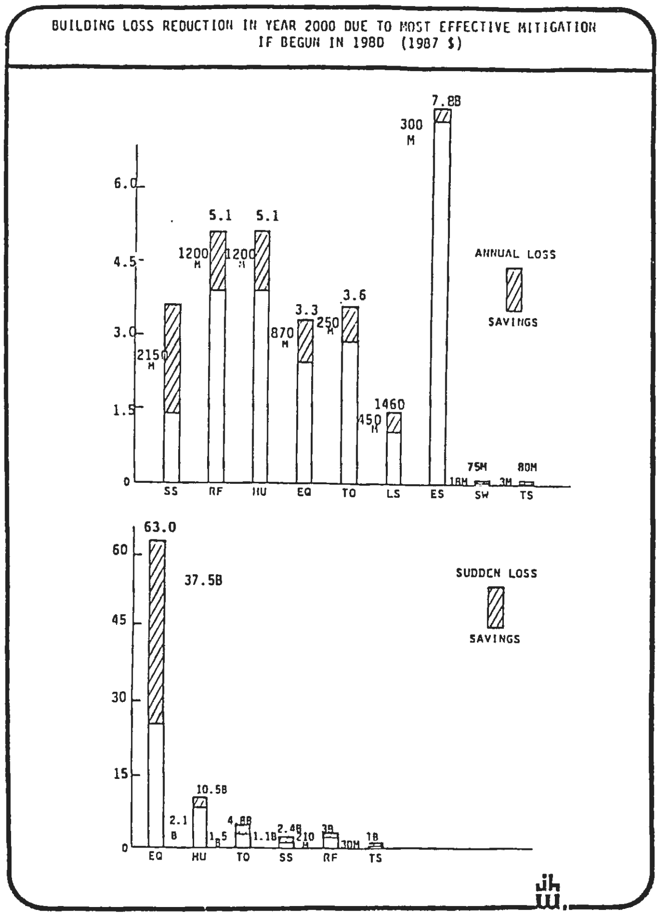
HURRICANE WIND LOSSES AND MITIGATION EFFECTS

A. EXPECTED NATIONAL ANNUAL LOSSES IN $ MILLIONS (1987)

MITIGATION	1970	1980	1990	2000
BASELINE - EXPECTED LOSSES ARE ALL DUE TO WINDS ONLY FROM HURRICANE (GREATER THAN 73 MPH IN TROPICAL CYCLONE)	2030	2800	3880	5080
(1) ALL NEW STRUCTURES BUILT AFTER 1980 MUST BE DESIGNED TO UNIFORM BUILDING CODE X3.0	(0%)	(0%)	(-13%)	(-27%)
(2) ALL NEW STRUCTURES BUILT AFTER 1980 MUST BE DESIGNED TO UNIFORM BUILDING CODE X1.5.	(0%)	(0%)	(-8%)	(-17%)
(3) ADVANCED WARNING ALLOWS FOR BOARDING ALL WINDOWS SO NO WINDOW DAMAGE OCCURS AFTER 1980	(0%)	(0%)	(-1%)	(-1%)
(4) ALL STRUCTURES STRENGTHENED SO LIGHT DAMAGE IS ELEMINATED AFTER 1980	(0%)	(0%)	(-3%)	(-3%)

B. SCENARIO EXPECTED LOSSES IN $ MILLION (1987)

HURRICANE CAMILLE OF 14-22 AUGUST 1969 STRUCK MISSISSIPPI COAST NEAR BAY ST. LOUIS. WIND OVER 175 MPH.	2150	2690	3580	4780
(1) ALL NEW STRUCTURES BUILT AFTER 1980 MUST BE DESIGNED TO UNIFORM BUILDING CODE X3.0	720 (0%)	900 (0%)	1000 (-14%)	1100 (-28%)
(2) POPULATION GROWTH IN HURRICANE-PRONE STATES CEASES AFTER 1980	720 (0%)	900 (0%)	1200 (-4%)	1400 (-8%)


BUILDING LOSS REDUCTION IN YEAR 2000 DUE TO MOST EFFECTIVE MITIGATION IF BEGUN IN 1980 (1987 $)

	TYPE OF LOSS OR EVENT	VALUE IN 1975 (BILLIONS OF 1987$)	NATURAL HAZARD COST MULTIPLIER
1.	ALL PROPERTY TAX COLLECTIONS BY STATE AND LOCAL GOVERNMENTS	75	4
2.	ALL ACCIDENTS	60	3
3.	TOTAL ECONOMIC LOSSES CAUSED BY AIR POLLUTION	35	2
4.	INCREASE IN ANNUAL EXPECTED LOSSES FROM NATURAL HAZARDS, 1970 - 2000	29	2
5.	POLLUTION CONTROL COSTS (AIR, WATER, SOLID WASTES)	21	1
6.	EXPECTED ANNUAL NATURAL HAZARD LOSSES TO BUILDINGS (1/3 WIND)	18	1
7.	EXPENDITURES BY ALL STATE AND LOCAL POLICE DEPARTMENTS	10	1/2
8.	ALL CRIMES AGAINST PROPERTY	9	1/2
9.	INVESTMENTS IN WATER POLLUTION CONTROL FACILITIES	7	1/3
10.	BUSINESS LOSSES DUE TO SIX TYPES OF CRIMINAL ACTIVITIES	7	1/3
11.	FIRE DEPARTMENT COSTS	7	1/3
12.	BUILDING LOSSES DUE TO FIRES	5	1/4

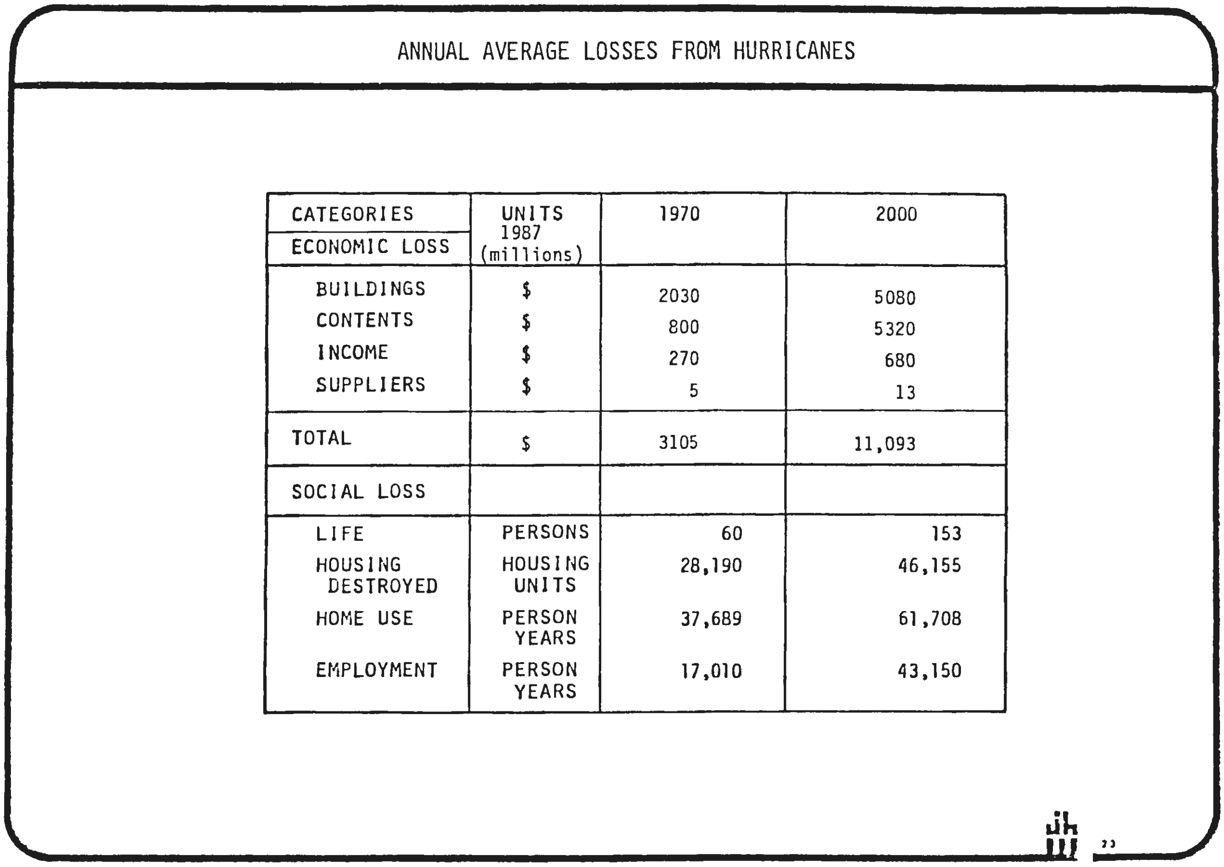
EXPOSURE (VALUE AT RISK) TO THE HURRICANE WIND HAZARD IN THE UNITED STATES BY REGION

REGION	WEALTH-AT-RISK (BILLIONS OF 1987 $)	PEOPLE-AT-RISK 1987
NORTHEASTERN	2740	40.21
NORTHCENTRAL	0	0
SOUTH	1680	30.95
WEST	0	0
TOTAL* UNITED STATES	4420	71.16

*Various totals may differ slightly from other tables because of round-off error.

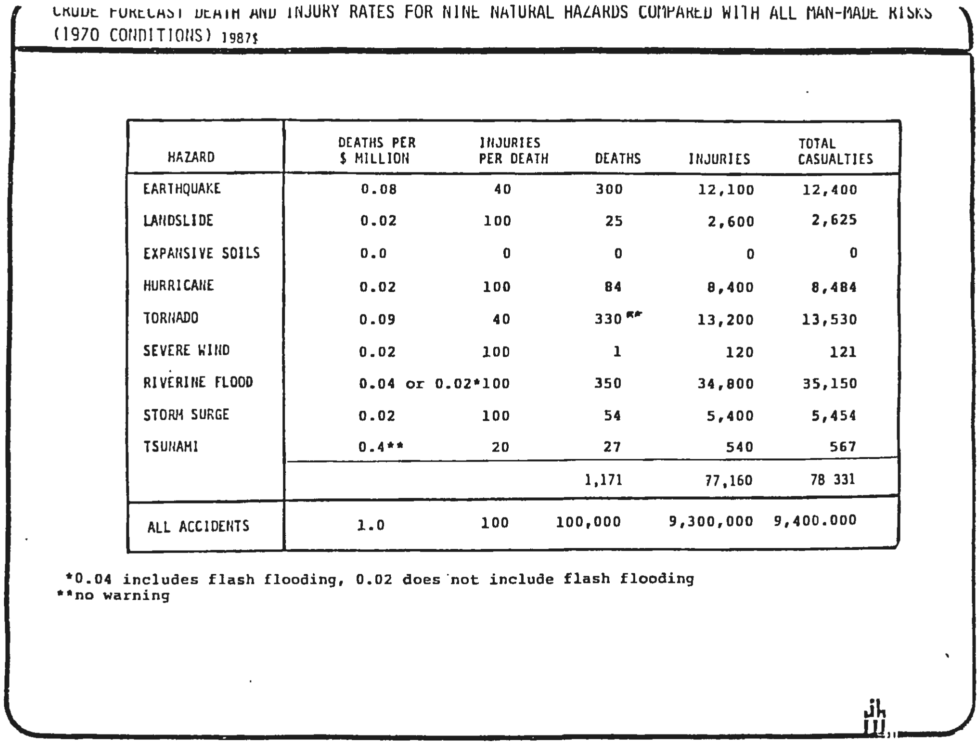
LOSSES

- WEALTH LOSS
  - STRUCTURES
    - RESIDENTIAL
    - COMMERCIAL & INDUSTRIAL
    - PUBLIC
  - CONTENTS
    - CONSUMER DURABLES
    - PRODUCER CAPITAL
    - INVENTORIES
- INCOME LOSS
  - DIRECT
  - INDIRECT
  - MARKET EFFECT
  - TAX LOSS
    - LOCAL
    - STATE
    - FEDERAL
- SOCIAL LOSS
  - LIFE LOSS, INJURY
  - HOUSING LOSS
    - HOMELESSNESS
    - TOTAL LOSSES
  - UNEMPLOYMENT



ANNUAL AVERAGE LOSSES FROM HURRICANES

CATEGORIES ECONOMIC LOSS	UNITS 1987 (millions)	1970	2000
BUILDINGS	$	2030	5080
CONTENTS	$	800	5320
INCOME	$	270	680
SUPPLIERS	$	5	13
TOTAL	$	3105	11,093
SOCIAL LOSS			
LIFE	PERSONS	60	153
HOUSING DESTROYED	HOUSING UNITS	28,190	46,155
HOME USE	PERSON YEARS	37,689	61,708
EMPLOYMENT	PERSON YEARS	17,010	43,150

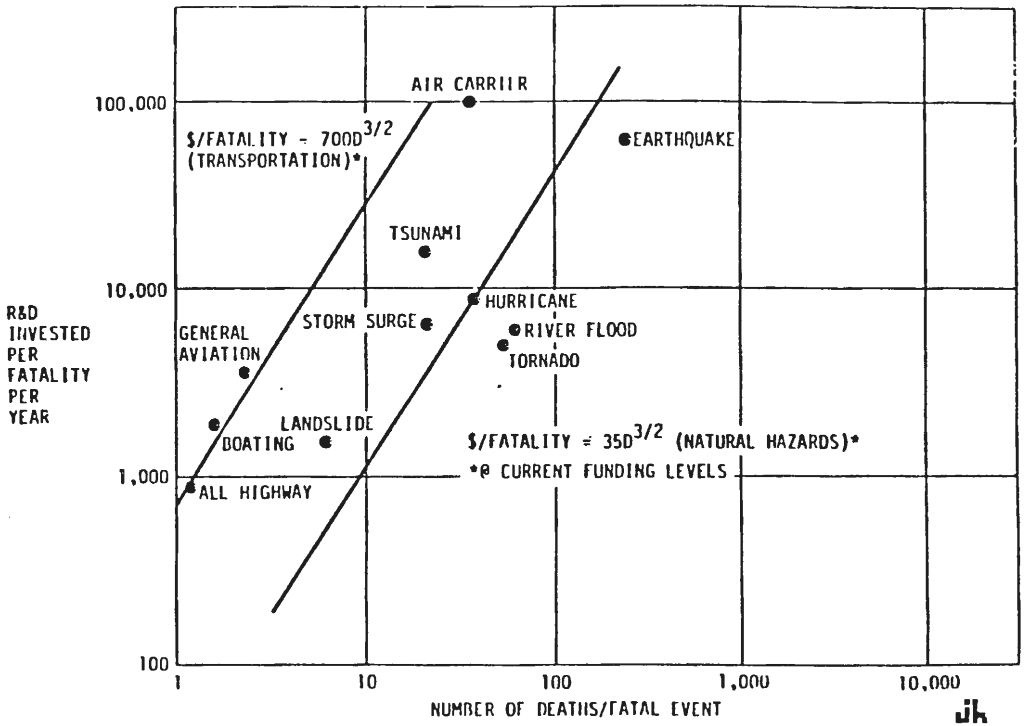


CRUDE FORECAST DEATH AND INJURY RATES FOR NINE NATURAL HAZARDS COMPARED WITH ALL MAN-MADE RISKS (1970 CONDITIONS) 1987$

HAZARD	DEATHS PER $ MILLION	INJURIES PER DEATH	DEATHS	INJURIES	TOTAL CASUALTIES
EARTHQUAKE	0.08	40	300	12,100	12,400
LANDSLIDE	0.02	100	25	2,600	2,625
EXPANSIVE SOILS	0.0	0	0	0	0
HURRICANE	0.02	100	84	8,400	8,484
TORNADO	0.09	40	330**	13,200	13,530
SEVERE WIND	0.02	100	1	120	121
RIVERINE FLOOD	0.04 or 0.02*	100	350	34,800	35,150
STORM SURGE	0.02	100	54	5,400	5,454
TSUNAMI	0.4**	20	27	540	567
			1,171	77,160	78 331
ALL ACCIDENTS	1.0	100	100,000	9,300,000	9,400.000

*0.04 includes flash flooding, 0.02 does not include flash flooding
**no warning

R & D FUNDING FOR SAFETY (DE FACTO UTILITY)



FLUID MECHANICS OF THE ATMOSPHERIC BOUNDARY LAYER

S. P. S. Arya
Department of Marine, Earth and Atmospheric Sciences
North Carolina State University, Raleigh, NC 27695-8208

EXTENDED ABSTRACT

Almost all the wind engineering activities, including release of pollutants take place in the atmospheric planetary boundary layer (PBL) which refers to the lowest part of the atmosphere directly affected by turbulent mixing and heat, mass and momentum exchanged with the earth's surface. A complete understanding of physics and fluid mechanics of the PBL under a wide range of conditions encountered in nature is therefore essential in wind engineering applications. A brief review of our current state of knowledge of the PBL will be presented and significant gaps and missing links in the same will be pointed out as indicators of future research needs and directions.

The various factors influencing the atmospheric boundary layer are: (1) horizontal pressure and temperature gradients giving rise to geostrophic and thermal winds, which provide external forcing for the PBL motions; (2) the surface roughness which influences the mean flow and turbulence in the surface layer, as well as the surface drag; (3) the diurnal heating and cooling of the surface which give rise to important stability, stratification or buoyancy effects in the PBL; (4) the earth's rotation which causes wind direction to change with height; (5) the presence of capping inversion and entrainment of a free-atmospheric air into the PBL which determine the PBL thickness; (6) the generation and possible breaking of gravity waves in a stably stratified environment which influence the turbulence structure of the stable boundary layer (SBL); (7) horizontal advections of momentum, heat and moisture which are important in nonhomogeneous and internal boundary layers; (8) rapid evolution of the PBL during the passage of storms and fronts; (9) the presence of fog, stratus and other clouds within the PBL; and (10) the presence of complex topography and surface structures. Quantitatively, the influences of only the first four or five factors listed above are well understood, i.e., we have achieved a fairly good, if not thorough, understanding of the "ideal" horizontally-homogeneous, quasi-stationary nonentraining, fair-weather atmospheric boundary layer (1-7). For wind engineering applications, however, we also need to know more about the real-world PBL which is often influenced by the complicating factors (6) - (10) mentioned above.

Equations for the conservation of mass, momentum and heat in the PBL will be reviewed with their possible simplifications and approximations. These conservation equations form the basis for different types of mathematical models (2,4,6), such as integral or slab models, eddy viscosity and mixing length models, higher-order closure models and large eddy simulations, of the PBL. Usefulness and limitations of these models will be discussed. For example, none of the existing models can simulate the episodic or intermittent generation and suppression of turbulent patches in stable boundary layer, and adequately consider the important effects of gravity waves, advection and radiation observed in the same. Large-eddy simulation appears to be most promising in this regard. Urgency and need for more reliable numerical simulations of the PBL in complex terrain

situations, in the presence of strong thermal stratification and wave motions, and in disturbed weather (stormy) conditions will be emphasized.

For the simpler, horizontally-homogeneous and quasi-stationary PBL, similarity theories and scaling have proved to be very useful in obtaining certain general or universal similarity relationships. Examples of successful similarity theories are: (1) the Monin-Obukhov theory for the stratified surface layer (1,2); Deardorff's mixed-layer similarity theory for the convective boundary layer (6,7); and (3) the local similarly scaling for the stable boundary layer (8,9). All of these have certain limitations and restrictive conditions for their validity, e.g., stationarity, horizontal homogeneity and barotropy. Sometimes, additional effects of baroclinity, terrain slope and horizontal advection are also included in more generalized PBL similarity theories, but the number of independent dimensionless parameters in them become too large and the similarity functions of those parameters are not easy to determine empirically from observational studies.

Observations and experiments have also largely focussed on quasi-stationary, fair-weather boundary layers over relatively homogeneous and smooth sites (e.g., Great Plains, Wangara, Koorin, Kansas, Minnesota and Cabauw experiments). Here too the observed range of stability conditions has been limited and there is little information on the PBL structure in extremely unstable (convective) and extremely stable condition. There have been a few case studies of the changes in mean flow and turbulence parameters in the PBL, following sharp changes in surface conditions (e.g., rural to urban and sea to land contrasts), and also a few case studies of the PBL under weakly disturbed weather conditions. But, comprehensive, systematic studies of atmospheric boundary layers over complex topography and under very disturbed weather (e.g., during the passage of a strong front, thunderstorm, hurricane, or cyclone) are still lacking, primarily due to the severe logistical and instrumental problem encountered in such studies. The largest concerted effort in observing complex terrain flows has been made under the ASCOT (Atmospheric Studies in Complex Terrain) program whose primary focus was on slope and valley drainage flows during nighttime stable conditions. Some aspects of the PBL under highly disturbed weather conditions have been studied during the 1979-STREX (Storm Transfer Experiment) and the 1986-GALE (Genesis of Atlantic Lows Experiment) projects. The latter was carried out over several thermally contrasting surfaces (e.g., piedmont, coastal plain, coastal shelf waters, the Gulf Stream and the Sargasso Sea). Observational systems of the GALE boundary layer program will be briefly reviewed to bring out the logistical difficulties of observing complex flows.

Based on experimental data and similarity considerations, useful parametric relations have been suggested for specifying (parameterizing) the mean wind and temperature profiles in the PBL, the vertical fluxes of momentum, heat and moisture, the variances of velocity fluctuations, scales of turbulence, the PBL thickness, etc., for possible use in wind engineering and other applications (e.g., atmospheric circulation models and air quality models). Some of the better-known PBL parameterization will be reviewed.

There are a number of situations in which the PBL structure needs to be further studied. The mechanism and role of entrainment in modifying the structure of the upper part of the convective boundary layer should be investigated in the laboratory, as well as in the atmosphere. The role of gravity waves and their interaction with turbulence in the stable boundary layers (SBL) should be investigated. Also, the intermittency and patchiness of turbulence in the SBL should be studied both experimentally (e.g., through the use of remote sensors) and theoretically (e.g., through large-eddy simulations (11)). There is still great need for studying topographical effects on PBL flow and dispersion. Here, physical modeling studies may provide valuable guidance for systematic field studies. There is, of course an urgent need for PBL studies during highly disturbed weather especially during strong winds and severe gusts. Laboratory simulations of such conditions would also be useful.

REFERENCES

1. Monin. A. S., and Yaglom, A. M., Statistical Fluid Mechanics: Mechanics of Turbulence, Vol. 1, The MIT Press, Cambridge, 1971, p. 769.
2. Haugen, D. A. (Ed.), "Workshop on Micrometeorology," American Meteorological Society, Boston, 1973, p. 392.
3. McBean, G. A. (Ed.), The Planetary Boundary Layer, World Meteorological Organization, Geneva, 1979, p. 201.
4. Wyngaard, J. C. (Ed.), "Workshop on the Planetary Boundary Layer," American Meteorological Society, Boston, 1980, p. 322.
5. Plate, E. J. (Ed.), Engineering Meteorology, Elsevier, Amsterdam, 1982, p. 740.
6. Niewstadt, F. T. M. and van Dop, H. (Ed.), Atmospheric Turbulence and Air Pollution Modeling, Reidel, Dordrecht, 1982, p. 358.
7. Panofsky, H. A., and Dutton, J. A., Atmospheric Turbulence, Wiley, New york, 1984, p. 397.
8. Nieuwstadt, F. T. M., "The Turbulence Structure of the Stable Nocturnal Boundary Layer," J. Atmos. Sci., Vol. 41, 1984, pp. 2202-2216.
9. Lacser, A., and Arya, S. P. S., "A Numerical Model Study of the Structure and Similarity Scaling of the Nocturnal Boundary Layer (NBL)," Boundary-Layer Meteor., Vol. 35, 1986, pp. 369-385.
10. Arya, S. P. S., "Parametric Relations for the Atmospheric Boundary Layer," Boundary-Layer Meteor., Vol. 30, 1984, pp. 57-73.
11. Wyngaard, J. C. (Ed.), Large-Eddy Simulation: Guidelines for its Application to Planetary Boundary Layer Research, U.S. Army Research Office, Research Triangle Park, 1984, p. 122.

COMPUTATIONAL AERODYNAMICS

T. Yamada
Los Alamos National Laboratory
P.O. Box 1663, Los Alamos, NM 87545

ASCOT (Atmospheric Studies in Complex Terrain), a program supported by the U.S. Department of Energy, has been investigating atmospheric transport and diffusion of airborne materials over complex terrain. A series of extensive observations were made during the summers of 1979, 1980, and 1981 over the Geysers geothermal energy development area in northern California. High concentrations of pollutants were expected to occur during nocturnal periods since turbulent mixing was suppressed, and the drainage flows that frequently develop were shallow. Therefore, the majority of experiments were conducted during the nighttime. The objectives of the experiments were to investigate the structure of nocturnal drainage flows and the behavior of trace gas released over the sloping terrain. The ASCOT data provided an excellent opportunity to test performance of three-dimensional numerical models for transport and diffusion of pollutants over rugged terrain.

In the fall of 1982, the ASCOT project moved the study area to Brush Creek, Colorado, approximately 50 km north of Grand Junction, and conducted extensive meteorological and tracer experiments. The objectives of the experiments were to examine applicability and transferability of the knowledge obtained in the Geysers area and to investigate the structure of the atmospheric boundary layer during not only the nocturnal but also the morning transition periods.

In this presentation, the 1982 ASCOT Brush Creek data are used to test performance of a three-dimensional hydrodynamic model HOTMAC (Higher Order Turbulence Model for Atmospheric Circulations) and a random-particle statistical diffusion model RAPTAD (RAndom Particle Transport And Diffusion), for tracer simulation.

HOTMAC, also referred to as a "second-moment turbulence-closure model," is based on a set of second-moment turbulence equations closed by assuming certain relationships between unknown higher-order turbulence moments and the known lower-order variable. The model output variables are winds, potential temperature, mixing ratios of water vapor and liquid water, turbulence second-moments, a turbulence length scale and turbulence transport coefficients (eddy viscosity and eddy diffusivity). These results are used as inputs to pollutant dispersion models. The model is time dependent and three-dimensional in space.

HOTMAC can be used under quite general conditions of flow and thermal stratification since methods for turbulence parameterization are more advanced than those in simple eddy viscosity models. The present model, combined with a statistical cloud model, has simulated interaction between water phase changes and basic dynamic variables.

The present model assumes hydrostatic equilibrium and uses the Boussinesq approximation. Therefore, in theory, the model applications are limited to flows where the local acceleration and advection terms in the equation of vertical motion are much smaller than the acceleration due to gravity (hydrostatic equilibrium), and temperature variations in the horizontal are not too large (Boussinesq approximation).

The model has been used for a variety of fluid problems: atmospheric boundary layer, ocean boundary layer, and airflow over complex terrain, and the results have been used in dispersion simulations.

Three major improvements were added recently to the HOTMAC/RAPTAD model system. The first improvement is the nested grid which enables us to address a specific area in finer detail with only a moderate increase in computational cost. The nested grid technique is also found to be an excellent way to provide proper lateral boundary values to the inner grid. A simulation without nesting produced large perturbations along the lateral boundaries which quickly deteriorated the wind field in the inner computational domain.

The second improvement is the inclusion of terrain shadows in HOTMAC. Steep side walls and orientation of the Brush Creek canyon presented a unique problem which may not be encountered in most mesoscale modeling where a horizontal grid spacing is much larger than the present one (500 m). The sun rise on August 4, 1982, was shortly before 5:30 a.m., but the side canyons on the slope facing southwest in Brush Creek remained in shadow until close to 8 a.m. The modeled tracer plume without terrain shadows moved much too far to the west compared to the observations. When shadows are included, the modeled plume compared much better with the observations.

The third improvement is about the way the concentration is estimated from the particle distribution modeled by RAPTAD. A kernel density estimator is used where each particle represents a center of a puff. The concentration level at a given time and space is determined as the sum of the concentration each puff contributes. The kernel method produced a smooth concentration distribution with a much smaller number of particles than required for a method counting the number of particles in an imaginary sampling volume. The modeled tracer concentrations at a typical site are slightly underestimated, but are within a factor of two of the observations.

BLUFF BODIES AERODYNAMICS

Willy Z. Sadeh
Colorado State University

Man-made structures and buildings of interest in wind engineering consist primarily of single or multiple bluff bodies without or with sharp corners. Most of the high-rise buildings are essentially bluff bodies with sharp corners as their cross sections are either square or rectangular. Flow about bluff bodies and the associated flow forces exerted on them have been subjects of research for the pat 200 to 250 years; however, the basic fluid mechanics of this flow is not yet fully understood and amenable to detailed analytical and/or numerical modeling. Even the knowledge, understanding, and modeling of the apparently simple flow about a circular cylinder, that has been the subject of extensive research for almost a century, is far from complete.

The aerodynamics of structures depends upon the characteristics of the wind in the surface layer. Flow about a three-dimensional bluff body in a turbulent shear flow involves complex nonlinear interactions between the nonhomogeneous nonuniform turbulent approaching wind and the three-dimensional boundary layers along the body, the separated flow, the vortex shedding and the wake. The flow separation, wake and vortex shedding characteristics of two-dimensional bluff bodies with sharp edges and even of a circular cylinder in a uniform flow are not yet completely understood, and even less is known on the flow about a three-dimensional bluff body. Another aspect of interest related to buildings and structures are exterior architectural features and details (e.g., mullions, parapets, setbacks, any architectural discontinuity, to mention a few) that induce local flow situations characterized by specific three-dimensional turbulent boundary layers and vortex generation which, in turn, interact with the overall flow and boundary layer on the body.

Flow about a bluff body can be divided into three distinct but highly interdependent regions. These three regions are: (1) the oncoming turbulent shear wind; (2) the three-dimensional turbulent boundary layers on the body including localized effects; and, (3) the separated flow including reattachment along the side walls (for a bluff body with sharp edges) followed by separation from rear edges, the wake and the vortex shedding. Most of the present knowledge concerning this compounded flow has been obtained through experimental studies in wind tunnels using small-scale models. Analytical studies on the evolution of approaching uniform turbulent flow resulted in advancing the rapid distortion theory and the vorticity amplification theory. Both theories, whose predictions have been qualitatively reasonably verified experimentally, indicate that amplification of oncoming turbulence at selected scales induces the development of highly turbulent boundary layers along the forward face of a bluff body, affects the separation and the reattachment, the wake and the vortex shedding.

The characteristics of the three-dimensional turbulent boundary layers are not yet known with sufficient depth to provide information other than general features and to enable the formulation of analytical and/or numerical models despite the large number of experimental studies that have been performed. It should be pointed out that most of the experimental studies have been conducted for specific bluff bodies, each being characterized by its own peculiar boundary layer. The details of forwarding edges separation, separation region (or cavity), reattachment, rear edges separation, wake and vortex shedding are even less known than those of the boundary layer. Moreover, little is known on the interaction among the three flow regions.

Wind forces exerted on a bluff body consist of the sum of the mean and fluctuating forces. Both force components depend on the characteristics of the turbulent oncoming wind, the bluff body geometry (width-to-depth ratio and aspect ratio), the separation and the extent of the separated region, the occurrence of reattachment and the wake. Additional factors to be considered are vortex shedding, galloping and buffeting which may occur separately or in combination. The present knowledge on the mean and fluctuating forces and moments is fully based on experimental data as neither theoretical nor numerical models have yet been advanced. Particularly, little is known on the dependence of the fluctuating forces upon the turbulence in the flow and in the body boundary layer.

Significant advances in the knowledge and understanding of the aerodynamics of bluff bodies can be achieved by conducting systematic research for two basic geometric shapes characteristics of the bluff bodies, i.e., (1) circular cylinder; and, (2) bluff body with sharp edges and of varying width-to-depth and aspect ratios. The key areas of research are listed below:

1. systematic wind-tunnel studies of the evolution of the oncoming turbulent shear wind and amplification of freestream turbulence in the presence of the bluff body;

2. systematic wind-tunnel studies of the boundary layer development and characteristics for selected freestream conditions (e.g., low and high wind, low and high turbulence);

3. systematic and detailed wind-tunnel studies of the forward edge separation, separated region, reattachment, rear edge separation;

4. systematic wind-tunnel studies of the wake and vortex shedding;

5. systematic wind-tunnel studies of the local effect of external architectural features upon the boundary layer;

6. development of mathematical and numerical models based on wind-tunnel data;

7. standard field studies in order to validate the wind-tunnel data and predictions of models.

WIND TRANSPORT OF SCALARS AND POLLUTANTS

Roger S. Thompson
Meteorology and Assessment Division
Atmospheric Sciences Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

The release of radioactive materials in April of 1986 from the accident at the Chernobyl power plant in the U.S.S.R. made the world aware of the importance of the wind transport of pollutants (1). Measurements of radiation at monitoring sites in Scandinavian countries were used in conjunction with meteorological data to help locate the radiation source. This long-range transport of a hazardous material affecting the health and welfare of hundreds of thousands of people is a dramatic example of how knowledge of the atmosphere and wind transport is important.

An understanding of the transport of scalars and pollutants in the atmosphere is essential in many engineering applications, from the protection of the nation's health through enforcement of the Clean Air Act to military applications of gas warfare and smoke camouflage. The role of the wind in atmospheric transport has been studied by theoreticians and experimentalists at an increasing rate through this century. Many full-scale field experiments have been conducted to provide measurements necessary to evaluate the various theories. Laboratory study of the atmosphere in wind tunnels and water tanks has become quite popular over the last thirty or so years. The rapidly increasing power of computers (in terms of memory size and speed) has made them modern tools for the study as well as prediction of atmospheric transport.

Studies of atmospheric transport can be categorized by a variety of factors: the material being transported (dust, passive gas, chemically reactive gases, dense gas, nuclear reactive matter, heat), the source type (point, area, moving), the condition of the atmosphere (neutral, stably stratified, convective), the transport distance of interest (short range of a few hundred meters to long range across countries or continents), the terrain or obstacle type (flat terrain, an isolated three-dimensional hill, a two-dimensional hill, complex terrain consisting of several hills, single buildings, building complexes, urban areas) and the method of study (theoretical, field, laboratory, numerical). Most combinations of these factors have been considered in various studies.

The Gaussian plume model (2) has been the workhorse for predicting pollutant concentrations. The model is based on empirical values of the standard deviations of the horizontal and vertical plume spread as functions of distance from the source and atmospheric stability. Originally derived from field data collected over flat terrain at fairly close proximity (1 km or so) to a point source, the model has been applied with many adjustments to a variety of terrain and source configurations. Virtual sources and "enhanced" or modified sigmas to account for terrain types or building influence have been used, most often based on very limited data.

Field studies have been performed to provide data bases for transport model development, testing and evaluation. The Complex Terrain Model Development Project (3,4,5,6) being performed by Environmental Research and Technology, Inc. (ERT) under contract to the Environmental Protection Agency is a good example. The ultimate goal of this effort is to provide a regulatory computer model for prediction of concentrations from sources located near or within complex terrain situations. Three full-scale field experiments were conducted: one at Cinder Cone Butte, Idaho, an isolated, 100 m high, three-dimensional hill; one at Hogback Ridge, New Mexico, a long, 80 m high ridge; and on at the Tracy Power Plant near Reno, Nevada, located in a mountainous region. The data bases from these studies, along with data from the EPA Fluid Modeling Facility, have been used in the development work.

Fluid modeling of the atmosphere in wind tunnels and water tanks has become an important research and engineering method. Snyder (7) has prepared a comprehensive guideline for the application of fluid modeling to the study of atmospheric diffusion. The EPA has published specified guidelines (8) for the use of fluid modeling in the determination of "good engineering practice" stack heights to be used with EPA's stack height regulations (40 CFR 51). An example of the type of information that can be obtained from fluid modeling studies is the establishment of an integral formula for the prediction of the dividing-streamline height for stratified flow over a terrain obstacle. The formula, originally proposed by Sheppard (9), has been shown to be applicable to the flow over a wide variety of three-dimensional hills and fences in both stratified wind tunnels and towing tanks (10). It was found to accurately predict the dividing boundary between flow passing over the top of the hill and that moving around the hill in nearly horizontal planes. The formula was applied quite successfully in tactical planning of the above mentioned field experiments by ERT and measurements showed it to be a valid indicator.

Numerical modeling of the wind transport of scalars and pollutants has developed nearly as rapidly as the required computer technology. Early computer models were mostly direct applications of a Gaussian plume formula for some particular situation or averaging time. As interest in diffusion from sources near complex terrain features and near buildings increased, the need for more sophisticated models has led to models which predict the mean flow field. The mean flow may be calculated from a potential flow model (11) or by numerical solution of the Navier-Stokes equations (12). Then diffusion about the mean streamline through the source may be calculated, using a Gaussian plume or a Monte Carlo statitical formulation.

There are several future research projects that will benefit the theoreticians and modelers of the wind transport of pollutants. The wakes of buildings and hills are not yet sufficiently well understood to predict flow separation and the size of the resulting wakes. Techniques have become available to measure reverse flows (pulsed-wire anemometers) and fluctuating concentrations (fast-response flame-ionization detectors and computer-aided video analyses) to facilitate studies of diffusion in wake flows. Interest in dense-gas diffusion is increasing. The disaster at Lake Nios last August, with many deaths caused by a carbon dioxide cloud moving down a mountain valley, indicates a need for a better understanding of dense-gas transport. Fluid modeling in neutral and stable flows is fairly well established; however, there is much to be learned about diffusion in the convective layer that can be modeled in the laboratory in convective tanks by continuing the work of Deardorff (13). The combined effort of theoreticians, experimentalists (both field and laboratory) and modelers is required for the future development of the understanding and prediction of wind transport of scalars and pollution.

REFERENCES

1. Elliott, L., "Deadly Winds: One Year after Chernobyl," Reader's Digest, May 1987, pp. 129-133.

2. Turner, D. B., "Workbook of Atmospheric Dispersion Estimates," Office of Air Programs Pub. No. AP-26, Envir. Prot. Agcy., Res. Tri. Pk., NC, 1970.

3. Lavery, T. F., Bass, A., Strimaitis, D. G., Venkatram, A., Greene, B. R., Drivas, P. J., and Egan, B. A., "EPA Complex Terrain Modeling Program: First Milestone Report - 1981, 1982," Rpt. No. EPA-600/3-82-036, Envir. Prot. Agcy., Res. Tri. Pk., NC, 304 p.

4. Strimaitis, D. G., Venkatram, A., Greene, B. R., Hanna, S., Heisler, S., Lavery, T. F., Bass, A., and Egan, B. A., "EPA Complex Terrain Model Development: Second Milestone Report - 1982, 1983," Rpt. No. EPA-600/3-83-015, Envir. Prot. Agcy., Res. Tri. Pk., NC, 375 p.

5. Lavery, T. F., Strimaitis, D. G., Venkatram, A., Greene, B. R., DiCristofaro, D. C., and Egan, B. A., "EPA Complex Terrain Model Development: Third Milestone Report - 1983, 1984," Rpt. No. EPA-600/3-83-101, Envir. Prot. Agcy., Res. Tri. Pk., NC, 271 p.

6. Strimaitis, D. G., Lavery, T. F., Venkatram, A., DiCristofaro, D. C., Greene, B. R., and Egan, B. A., "EPA Complex Terrain Model Development: Fourth Milestone Report - 1984, 1985," Rpt. No. EPA-600/3-84-110, Envir. Prot. Agcy., Res. Tri. Pk., NC, 319 p.

7. Snyder, W. H., "Guideline for Fluid Modeling of Atmospheric Diffusion," Rpt. No. EPA-600/8-81-009, Envir. Prot. Agcy., Res. Tri. Pk., NC, 1981, 200 p.

8. EPA, "Guideline for Determination of Good Engineering Practice Stack Height," (Technical Support Document for the Stack Height Regulations), Rpt. No. EPA-450/4-80-023R (Revised June 1985), Envir. Prot. Agcy., Res. Tri. Pk., NC, 1985, 102 p.

9. Sheppard, P. A., "Airflow over Mountains", Quart. J. Roy. Meteorol. Soc., Vol. 82, 1956, pp. 528-529.

10. Snyder, W. H., Thompson, R. S., Eskridge, R. E., Lawson, R. E., Jr., Castro, I. P., Lee, Hunt, J. C. R., and Ogawa, Y., "The Structure of Strongly Stratified Flow over Hills: Dividing-Streamline Concept," J. Fluid Mech., Vol. 152, 1985, pp. 249-288.

11. Bass, A., Strimaitis, D. G., and Egan, B. A., "Potential Flow Model for Gaussian Plume Interaction with Simple Terrain Features," Rpt. under Contract No. 68-02-2759, Envir. Prot. Agcy., Res. Tri. Pk., NC, 1981, 201 p.

12. Mason, P. J., and Sykes, R. I., "Three-Dimensional Numerical Integrations of the Navier-Stokes Equations for Flow over Surface-Mounted Obstacles," J. Fluid Mech., Vol. 91, 1979, pp. 433-50.

13. Deardorff, J. W., "Laboratory Experiments on Diffusion: The Use of Convective Mixed-Layer Scaling," J. Clim. Appl. Meteorol., Vol. 24, 1984, pp. 1143-1151.

WIND TRANSPORT OF ODORS AND HAZARDOUS MATERIALS

Robert N. Meroney
Colorado State University

Three major hazards to life -- fire, explosion and toxic release -- usually involve the emission of material from containment followed by vaporization and dispersion. Toxic and flammable materials are characterized by hazards over short time scales as opposed to air pollutants assumed to cause long-term health, corrosion or environmental deterioration. Such materials include noxious or odorous compounds, flammable gases, asphyxiates, and toxic chemicals. Often a hazardous phase is proceeded by odors which are detectable at levels below hazard concentrations. At one time an accepted engineering strategy was to identify hazards by building one chemical facility and waiting to see what happens. This approach was based on the idea "every dog is allowed one bite." But it no longer seems reasonable to keep dogs as big as Flixborough or Bhopal!

The number and consequence of major chemical spills has increased steadily for the last twenty years. A bypass failure released Cyclohexane at Flixborough, England, in 1974 causing 28 deaths; a Proylene release from a pipeline rupture at a refinery in Beek, Netherlands, in 1975 killed 14; a runaway reaction scattered toxic Dioxin over several square kilometers in Seveso, Italy, in 1976; a tank truck crash in San Carlos, Spain, in 1978 caused a Propylene explosion which killed more than 200; the natural gas explosion in Mexico City left 450 dead; and during the Spring of 1984 in Bhopal, India, toxic fumes killed over 2500.

Buckley and Wiener (1978) examined over 15,000 incidents which occurred in the early 1970's to identify the type, cause, operational area and severity of hazardous releases. They concluded the primary spill causes were tank rupture or puncture; tank overflow; hose or transfer system failure; and non-tank related ruptures (ie. cans, drums, bottles). The most hazardous releases primarily occurred from chemical plant storage or process areas followed by transportation and loading/unloading accidents. But most accidents occurred during transit (57 percent) and loading/unloading (25 percent). The most frequently released chemicals were sulfuric acid, ammonium nitrate fertilizer, sodium hydroxide, hydrochloric acid and ethyl parathion. The materials with highest hazard potential reported were anhydrous ammonia, toluene, nitric acid, phenol, methyl alcohol, and xylene. Lees (1980) also summarized the details of an extensive list of hazardous chemical accidents.

Concern over the extent of hazards associated with material spills or process releases has led to a number of field-scale experiments since 1966. Most of these studies involved the release of relatively small quantities of fluid (< 3 m^3 or liquid/test); however, since 1980 spills of ammonia, propane, LNG, and Freon-air mixtures have considered liquid quantities from 5 to 40 m^3 (Puttock et al., 1982; McQuaid and Roebuck, 1985) which can generate undiluted gas clouds up to 24,000 m^3 in size! Unfortunately, only a limited subgroup of these tests exhibited the strong negative buoyancy effects which act to accentuate hazards in space and time. These tests have provided some valuable information about the effects of cloud density, release configuration, vapor barrier fences and background atmospheric turbulence on dilution rates. Further information is need concerning terrain effects, the effectiveness of mitigation devices, chemically reactive clouds, and the initial dilution which occurs during explosive decompression of tank containers and pipelines.

Laboratory scaling of the dispersion of hazardous gas clouds has contributed valuable information about the statistical character of instantaneous releases (Hall, et al., 1974, 1975, 1982; Meroney and Lohmeyer, 1983; Davies and Inman, 1986), the interaction of clouds with barriers and fences (Kothari and Meroney, 1981, 1982), and the efficacy of mitigation devices (Meroney, et al., 1984). Meroney (1985) and Davies and Inman (1986) compared data from laboratory simulations of some 60 separate field tests to prototype measurements. They achieve generally "good to excellent" model/full-scale comparisons. They concluded that wind-tunnel simulations of gas cloud dispersion, and simulations of the reduction in concentrations due to vapor fences, sprays and other obstructions provide reliable design and guideline information.

Validation experiments specifically found that:

- Model and field experiments produced clouds which are very similar in appearance, spread and travel at correct rates, produce comparable concentrations and model peak concentrations are predicted to within a factor of two or better.

- Field/fluid model comparisons suggest that LFL (lower flammability distances) for cryogenic spills released over land or water are predicted within a standard deviation of 23 percent with a 90 percent confidence level.

- Field/fluid model comparisons suggest that suddenly produced gas clouds which undergo strong initial gravity slumping showed no effective lower threshold of Peclet/Richardson number ratio below which fluid-model concentrations predictions become nonconservative.

- For trials involving sharp-edged mixing elements there was no evident lower validity threshold of the simulation Reynolds number.

A variety of numerical and analytical models have been proposed to predict the life-history of hazardous gas clouds. Blackmore, et al. (1982) suggested that these models may be broadly classified into K-theory and slab models. Meroney (1984) suggested five categories of increasing sophistication and plume physics: a) modified Gaussian plume formulae, b) gravitational spread models for pre-entrainment shape, c) volume-integrated box models, d) depth- or cross-section averaged slab models, and e) direct solution of the full three-dimensional conservation equations by finite difference or finite element methods. Wheatly and Webber (1984) considered some 45 numerical models designed to predict dense gas dispersion. They found all-to-often that the models failed to include correct or consistent fluid physics for all physical effects of importance within the range of scales being considered. Recently, Havens and Spicer (1985) proposed a validated cross-section averaged slab model to predict idealized releases of dense gas. Havens (1986) also reported on the performance of the most sophisticated finite-difference and finite-element codes available. Even the most elaborate codes can make excessive numerical-diffusion errors. Only one or two of the most complex models attempt to consider terrain or heat transfer effects. Meroney (1986) compared fluid- and numerical model predictions of Burro Spill Tests 8 and 9. They produced comparable predictions of the cloud concentration patterns.

Substances which only produce noxious odors are considered to be noncriteria pollutants by the U.S. Environmental Protection Agency since no direct physiological harm can be found due to the odors themselves. Nonetheless, odors can be a mental irritant and one can develop symptoms, such as nausea, headache, irrational behavior, and loss of appetite, caused by the shear unpleasantness of the odor. In addition, since the perceived intensity of an odor decreases less sharply than the absolute concentration, odor control often requires the largest ventilation rates and dominates equipment choice even over threshold toxic levels!

Odorants, flammable gases and toxic gases all interact with life forms over short time intervals; thus, they involve similar transport and mixing characteristics. Models proposed by Meroney (1984) or Wilson (1982) concerning the statistical character of plumes released from fume-hood exhausts or short-stacks on building roofs are equally useful for each source gas. Unfortunately, statistical models for the intermittent behavior of plumes are based on very limited data taken with instruments of limited time and spatial resolution.

Future improvements in the prediction of the consequences of hazardous gas cloud release will be dependent upon advances made in several key areas. These areas include:

- systematic field and laboratory studies of the internal character of gas clouds, the correlation of gas cloud concentration with eddy size, and the connectivity of regions exceeding LFL levels within gas clouds

- improved understanding of the physics of the mixing process across stratified shear layers, which result in improved turbulence models to include in numerical programs

- improvement in the understanding of near-source dilution mechanisms such as the interaction of supersonic decompression with source geometry, water and steam spray curtains, and the influence of two-phase or reactive gases.

- improvement in the manner in which terrain effects are incorporated into numerical models, and validation of these models.

REFERENCES

1. Blackmore, D. R., Herman, M. N., and Woodward, J. L., "Heavy Gas Dispersion Models," J. of Hazardous Materials, Vol. 6, Nos. 1 & 2, 1982, pp. 107-128.

2. Buckley, J. L. and Wiener, S. A., "Hazardous Material Spills: A Documentation and Analysis of Historical Data," EPA-600/2-78-066, Factory Mutual Corporation, 1978, 243 p.

3. Davies, M. E. and Inman, P. N., "Wind Tunnel Modeling of the Thorney Island Heavy Gas Dispersion Trials," British Maritime Technology, Gas Research Institute Report GRI-86/0264, 1986, 204 p.

4. Hall, D. J., Barrett, C. F. and Ralph, M. O., "Experiments on a Model of an Escape of Heavy Gas," Warren Springs Laboratory, Report LR 217 (AP), Stevenage, UK, 1974, 24 p.

5. Hall, D. J., "Further Experiments on a Model of an Escape of Heavy Gas," Warren Springs Laboratory Report LR 312 (AP), Stevenage, UK, 1979, 47 p.

6. Hall, D. J., Hollis, E. J., and Ishaq, H., "A Wind-Tunnel Model of the Portion Dense Gas Spill Field Trials," Warren Springs Laboratory, Report LR 394 (AP), Stevenage, UK, 1982, 103 p.

7. Havens, J. A. and Spicer, T. O., "Development of an Atmospheric Dispersion Model for Heavier-than-Air Gas Mixtures," Vol. 1, Final Report, Dept. of Transportation Contract DT-CG-23-80-C-20029, 1985, 191 p.

8. Havens, J. A., "Evaluation of 3-D Hydrodynamic Computer Models for Prediction of LNG Vapor Dispersion in the Atmosphere," Gas Research Institute Report, Contract No. 5083-252-0788, 1985, 224 p.

9. Kothari, K. and Meroney, R. N., "LNG Plume Interaction with Surface Obstacles," Colorado State University, Gas Research Institute Report GRI80/0095, 1981, 156 p.

10. Kothari, K. and Meroney, R.N., "Accelerated Dilution of Liquefied Natural Gas Plumes with Fences and Vortex Generators," Colorado State University, Gas Research Institute Report GRI 81/0074, 1982, 222 p.

11. Lees, F. P., Loss Prevention in the Process Industries: Hazard Identification, Assessment and Control, Volume 1, Butterworths, London, 1980, 1250 p.

12. McQuaid, J. and Roebuck, B., "Large Scale Field Trials on Dense Gas Dispersion," Final Report to Sponsors on the Heavy Gas Dispersion Trials at Thorney Island 1982-84, Safety Engineering Laboratory Report, HSE Sheffield, UK, 1985.

13. Meroney, R. N., Transient Characteristics of Dense Gas Dispersion, Part I: A Depth-averaged Numerical Model," J. of Hazardous Materials, Vol. 9, 1984, pp. 129-157.

14. Meroney, R. N., "Guideline for Fluid Modeling of Liquefied Natural Gas Cloud Dispersion: Volume II: Technical Support Document," Colorado State University, Gas Research Institute Report GRI86/0102.2, 1986, 266 p.

15. Meroney, R. N. and Lohmeyer, A., "Statistical Characteristics of Instantaneous Dense Gas Clouds Released in an Atmospheric Boundary Layer Wind Tunnel," Boundary-Layer Meteorol., Vol. 28, 22 p.

16. Meroney, R. N., Neff, D. E. and Heskestad, G., "Wind-tunnel Simulation of Field Dispersion Tests (by the UK Health and Safety Executive) of Water-spray Curtains," Boundary-Layer Meteorol., Vol. 28, 1984, pp. 107-119.

17. Puttock, J. S., Blackmore, D. R., and Colenbrander, G. W., "Field Experiments on Dense Gas Dispersion," J. of Hazardous Materials, Vol. 6, Nos. 1 & 2, 1982, pp. 13-42.

18. Wilson, D. E., "Predicting Risk of Exposure to Peak Concentrations in Fluctuating Plumes," Pollution Control Division, Alberta Environment, Canada, 1982, 90 p.

WIND ENERGY UTILIZATION

A. C. Hansen
University of Utah

In the past decade the wind energy industry has evolved from a collection of small, struggling companies to an industry with 1986 energy sales of approximately $84 million. Wind energy use is now economically viable in areas of the U.S. that have favorable winds, energy costs and regulatory environment. Wind Engineering technology has made a significant contribution to the evolution and success of U.S. manufacturers of wind turbines. But advancements in the technology will be required before use of wind energy will become economically feasible over widespread areas. This paper will discuss the current state-of-art in wind energy conversion, concentrating on wind engineering aspects of the technology. In highlighting current problem areas it will also suggest topics requiring additional research or development.

There are currently over 15,000 wind turbines operation in the United States. The overwhelming majority of these turbines are installed in "wind farms" in California. The wind farms are investor-owned cogeneration facilities that sell energy to the California utilities. 1986 annual energy production was 1.2 billion kWh and the cumulative energy production to the end of 1986 was approximately 4 million barrels of oil equivalent. There is no longer doubt that wind turbines can produce energy at a cost which is competitive with conventional sources if maintenance costs can be controlled. Research has shifted from addressing primarily questions of efficiency and energy yields to the more difficult questions of hardware lifetime expectancy and maintenance costs.

Wind Engineering techniques have been applied to the wind energy discipline primarily in two ways. Estimation of wind loads upon the structure is paramount. Experience has shown that "overdesign" of all structural elements not only makes costs prohibitive, it also is no assurance of structural integrity. Wind Engineering technology has also been employed in site evaluation and selection. Mean wind speed distributions are obviously important to energy production and turbulence characteristics of a site are important to the fatigue life of the turbine system.

Progress has been made in developing designs which are relatively insensitive to wind loads and in using computer codes to predict operating loads during the design of a turbine. Compliant, lightweight structures have offered both lower installed costs and reduced static and dynamic operating loads. There is additional technical risk in these designs, however, that has slowed their acceptance among designers and customers. Methods are available for accurate prediction of steady operating loads and power output. (There is one notable exception, airfoils exhibit stall at angles of attack greater than those observed in wind tunnel testing of 2-D models. This delayed stall results in higher mean loads and power output than predicted for normal operation in high winds.)

The state-of-art in prediction of unsteady loads is unfortunately not so advanced. Effects of turbulent inflow to the rotor are just beginning to be understood and predictions of cyclic loads typically may be in error as much as 50 percent to 100 percent in normal operation and more during extreme wind events. This is clearly unacceptable for prediction of fatigue life of the structures. Blade rotation through large-scale turbulence causes cyclic loads at multiples of the rotor speed. Thus, even though there is little energy in the approach flow turbulence at frequencies of interest to turbine designers (typically 0.5 to 5 Hz), there is significant periodic aerodynamic forcing of the structure by "rotationally sampled" high frequency turbulence.

Dynamic loading in extreme wind conditions is also not fully understood. This is the most complex and difficult situation because the wind characteristics are not well known and models predicting the response of a rotor to severe turbulence or very high wind speeds are not accurate enough for design purposes. Much research is needed in this area.

Effective siting of wind turbines requires means of estimating wind speed duration curves and turbulence characteristics at a potential site. Often measurements of wind speed duration curves are available from nearby locations and in most cases simple extrapolation has been adequate for estimation of energy yield of a site. But it has been found that significant energy yield variations (greater than 20 percent) can be observed among identical turbines within a few hundred meters of one another on a site. These variations are due to terrain effects but often the magnitude of the variations surprises even the most experienced site selection engineers.

When multiple turbines are located in an array or wind farm then wake effects become important. It is important to maximize the energy output of a given parcel of land and this obviously requires spacing turbines in an optimum pattern. Much investigation of this problem has been completed and the wakes are quite well characterized in homogeneous terrain. But the wakes of turbines in complex terrain are not adequately predicted.

Experience has shown that "turbulent" sites have higher maintenance costs than "smooth" sites. Turbulence causes excessive loads on turbines directly through dynamic loading of the structure and indirectly by causing more yaw motion, more frequent start-ups and shut-downs, and more control activity. However, the specific characteristics of turbulence that are most damaging are not known. It is beginning to appear that turbulence intensity, longitudinal integral scale and stability (Richardson number) are the most important factors. But work in this area is in its infancy.

In summary, much progress has been made, helped considerably by wind engineering methods. The wind energy industry is viable and looking forward to a long period of gradual growth and development. However, many technical problems remain. If these problems can be resolved the result will be more widespread usage of wind power and a greater contribution to our world's energy demands.

NSF ENGINEERING LOOKS TO THE FUTURE

by
Carl W. Hall
Deputy Assistant Director for Engineering
National Science Foundation
Washington, DC 20550

SEMINAR/WORKSHOP ON WIND ENGINEERING
Colorado State University
Fort Collins, CO
June 4, 1987

NSF RESPONSIBLE FOR

ASSURING BASIC RESEARCH AND

PREPARING QUALITY MANPOWER

TO MEET FUTURE NEEDS -- CIVILIAN AND DEFENSE

NATIONAL SCIENCE FOUNDATION
DIRECTORATES

ADMINISTRATION (ADM)

BIOLOGICAL, BEHAVIORAL, AND SOCIAL SCIENCES (BBS)

COMPUTER AND INFORMATION SCIENCE ENGINEERING (CISE)

ENGINEERING (ENG)

GEOSCIENCES (GEO)

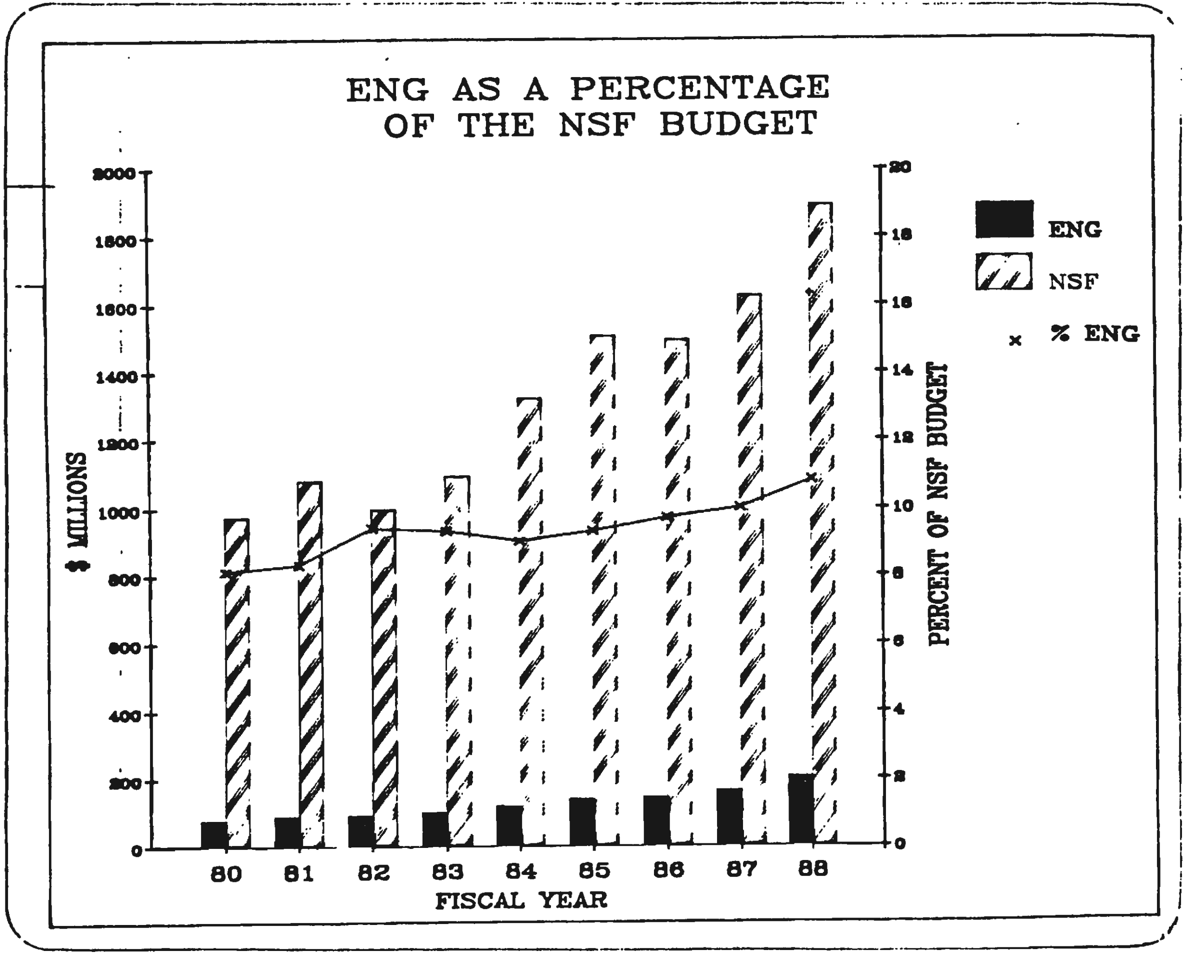
MATHEMATICAL AND PHYSICAL SCIENCES (MPS)

SCIENCE AND ENGINEERING EDUCATION (SEE)

SCIENTIFIC, TECHNOLOGICAL, AND INTERNATIONAL AFFAIRS (STIA)

BRIEF HISTORY

1950	NSF INITIATED ENG AS PROGRAM SECTION DIVISION
1981	ENG DIRECTORATE FORMED
1983	NSB STUDY ON ROLE OF ENG
1984	NSF ORGANIC ACT CHANGED
1985	NSF ENG REORGANIZATION



SOME ASPECTS OF ENGINEERING ACTIVITIES:

- NEED FOR MORE CROSS-DISCIPLINARY ACTIVITIES
- INVOLVE STUDENTS IN TEAM RESEARCH
- SUPPORT MORE WORK AT INTERFACE OF DISCIPLINES
- UTILIZE INDUSTRY EXPERTISE AND SUPPORT TO STRENGTHEN ENG
- RECOGNIZE THAT FUNDAMENTAL RESEARCH IS PREVALENT IN CROSS-DISCIPLINARY ACTIVITIES
- INCREASE EFFORTS FOR TIMELY TRANSFER OF KNOWLEDGE TO USERS

WHICH TELLS US THAT

- WHAT WE HAVE BEEN DOING IS NOT ENOUGH
- EXPECTATIONS FROM ENGINEERING RESEARCH AND EDUCATION ARE NOT SAME AS SCIENCE
- THE INDIVIDUAL INVESTIGATOR APPROACH ALTHOUGH NECESSARY IS NOT SUFFICIENT TO MEET GOAL
- ENG HELPS IDENTIFY AND SOLVE PROBLEMS
- ENG MORE RESPONSIBLE FOR ECONOMY
- ADDITIONAL MECHANISMS NEEDED

ROLE OF GROUPS

- NURTURE NEW FIELDS AT INTERFACES OF DISCIPLINES
- STIMULATE SYNERGY BETWEEN INVESTIGATORS
- PROBLEM-FOCUSED EDUCATION
- DEVELOP INDUSTRY/UNIVERSITY COLLABORATION

ROLE OF CENTERS

- CROSS-DISCIPLINARY TEAMS
- GENERIC PROBLEM-FOCUSED
- SYSTEMS VIEW OF AN AREA
- LARGE-SCALE SHARED INSTRUMENTATION
- INDUSTRIAL/STATE COLLABORATION
- ENHANCED TECHNOLOGY TRANSFER
- ADMINISTRATIVE STRUCTURE

RESPONSE

DEVELOP OTHER MECHANISMS FOR CARRYING OUT GOALS

- ENG RESEARCH CENTERS (ERC)
- INDUSTRY/UNIVERSITY RESEARCH CENTERS (IURC)
- GROUP SUPPORT OF INVESTIGATORS
- PARTNERSHIPS WITH INDUSTRY

CENTERS AND GROUPS IN ENG
BUDGET PROJECTIONS

CENTERS	FY 1987	FY 1988	FY 1992
FUNDS	$38.0	$56.5	$110.0
NUMBERS			
ERC	(14)	(18)	(25)
IUC	(39)	(45)	(60)
EQ	(1)	(1)	(1)
GROUPS			
FUNDS	$ 5.8	$ 7.4	$ 35.0
NUMBERS	(22)	(27)	(100)
TOTAL C & G	$43.8	$ 64.	$145.0

PARTNERSHIPS WITH INDUSTRY

- INDUSTRIAL REVIEWERS
- BOARD OF INDUSTRIAL ADVISORS TO ERC
- INDUSTRIAL COLLABORATORS IN I/UCRC
- LIAISON TO STATE S&T, FOUNDATIONS, ETC.
- INDUSTRY-UNIVERSITY COOPERATIVE RESEARCH PROJECTS

ORGANIZE NSF ENG TO CARRY OUT GOALS

- SCIENCE-BASED DIVISIONS
- TECHNOLOGY-DRIVEN SCIENCE BASE DEVELOPMENT DIVISION
- EMERGING ENGINEERING TECHNOLOGY DIVISION
- CRITICAL ENGINEERING SYSTEMS DIVISION
- CROSS-DISCIPLINARY RESEARCH DIVISION
- ENGINEERING INFRASTRUCTURE DEVELOPMENT OFFICE

OPERATIONAL

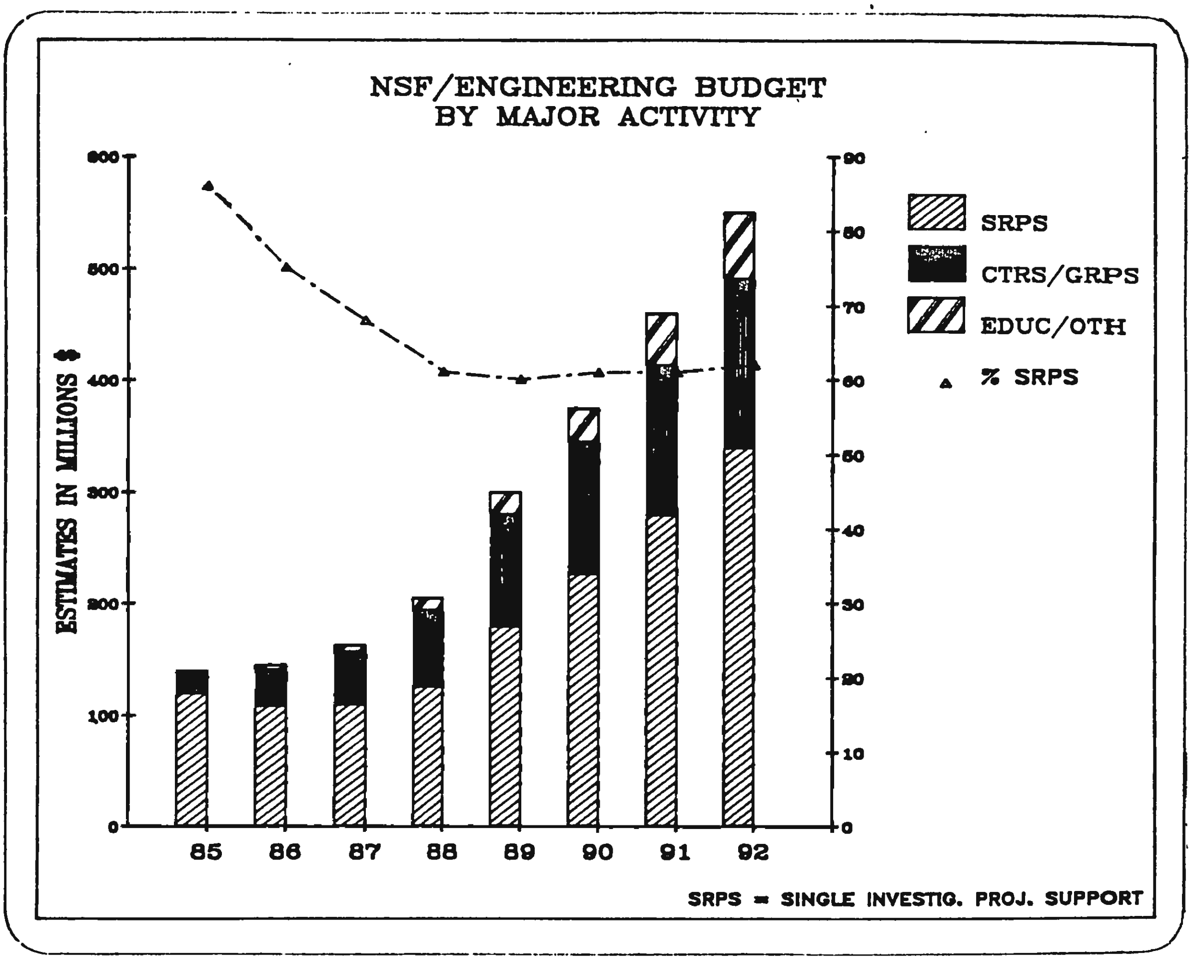
- PANELS FOR CROSS-DISCIPLINARY PROJECTS
- INCREASE INDUSTRY PARTICIPATION IN REVIEW PROCESS
- INCORPORATION OF INDUSTRY PARTICIPATION IN INDIVIDUAL PROJECTS WHERE PERTINENT
- MINIMIZE USE OF PROPOSAL PRESSURE AS BASIS OF RESOURCE ALLOCATION
- WORKSHOPS TO IDENTIFY FUNDAMENTAL RESEARCH ISSUES
- MEETINGS WITH USERS OF RESULTS
- EXCHANGE OF PEOPLE

STATUS

- INCREASE IN BUDGET; LARGER BASE, LARGER PERCENT INCREASE
- 40 I/URC
- UNDERGRADUATE EDUCATION RECOGNIZED AS RESPONSIBILITY
- UNIVERSITIES MODIFYING ENGINEERING INFRASTRUCTURE

PLANS (5 YEAR)

- BUDGET TO INCREASE FROM $163 M TO $450-$550 M
- FUND 25 ERC
- INCREASE IN GROUP ACTIVITIES
- MORE EMPHASIS ON MEETING EQUIPMENT NEEDS
- ACCESSIBILITY TO LARGE LABORATORY FACILITIES
- GET NEW PEOPLE, NEW PROPOSALS INTO SYSTEM
- INCREASE OF SUPPORT FOR UNDERGRADUATE ENGINEERING ACTIVITIES
- COORDINATE WITH OTHER ORGANIZATIONS



LONG RANGE GOALS FOR SUPPORT OF ENGINEERING RESEARCH EQUIPMENT

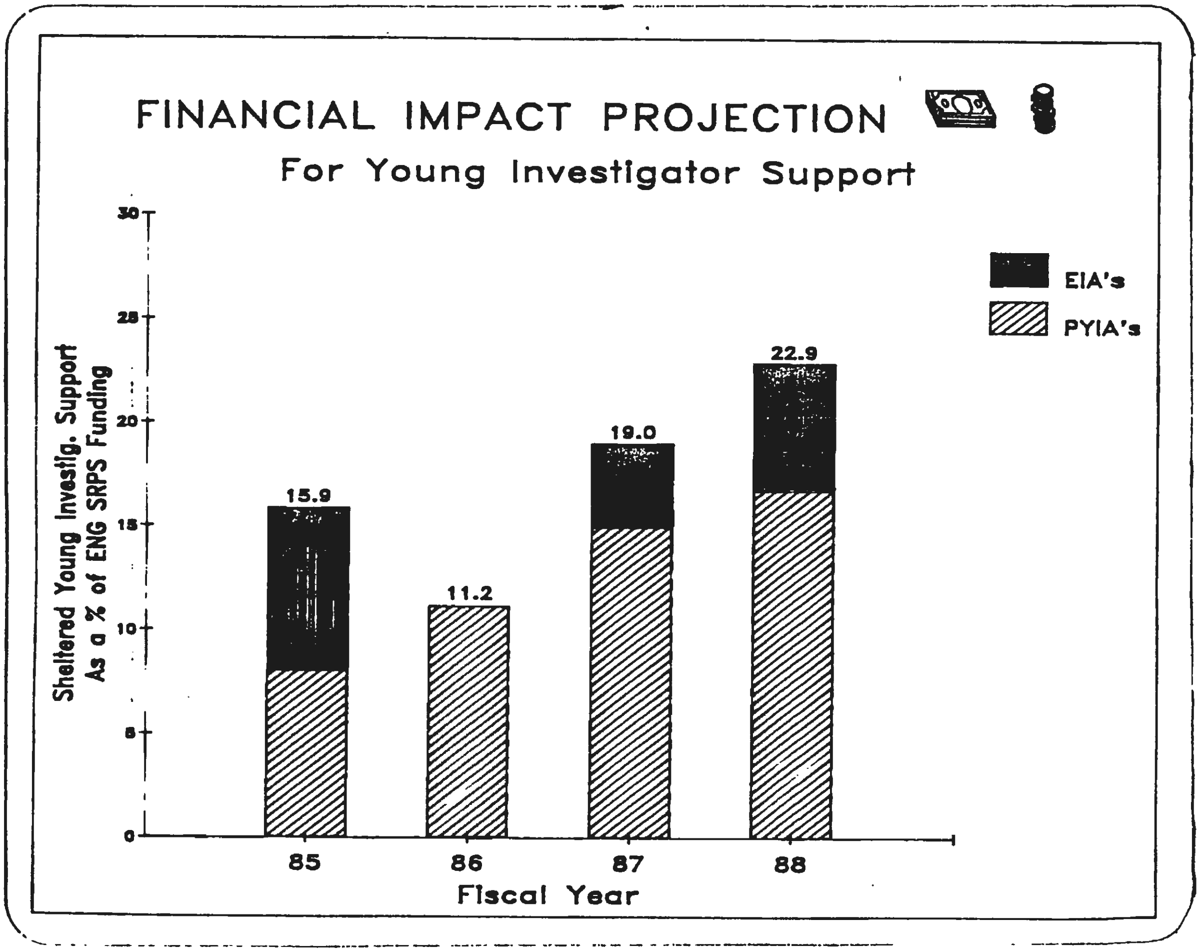
- INCREASE PERCENTAGE OF SRPS GRANT FUNDS GOING FOR EQUIPMENT FROM 10 TO 15 PERCENT

- DOUBLE THE ENG RESEARCH EQUIPMENT PROGRAM FROM $5 MILLION TO $10 MILLION

- USE THE ERC PROGRAM AND GROUP GRANTS TO MEET THE NEED FOR "BIG TICKET" ITEMS

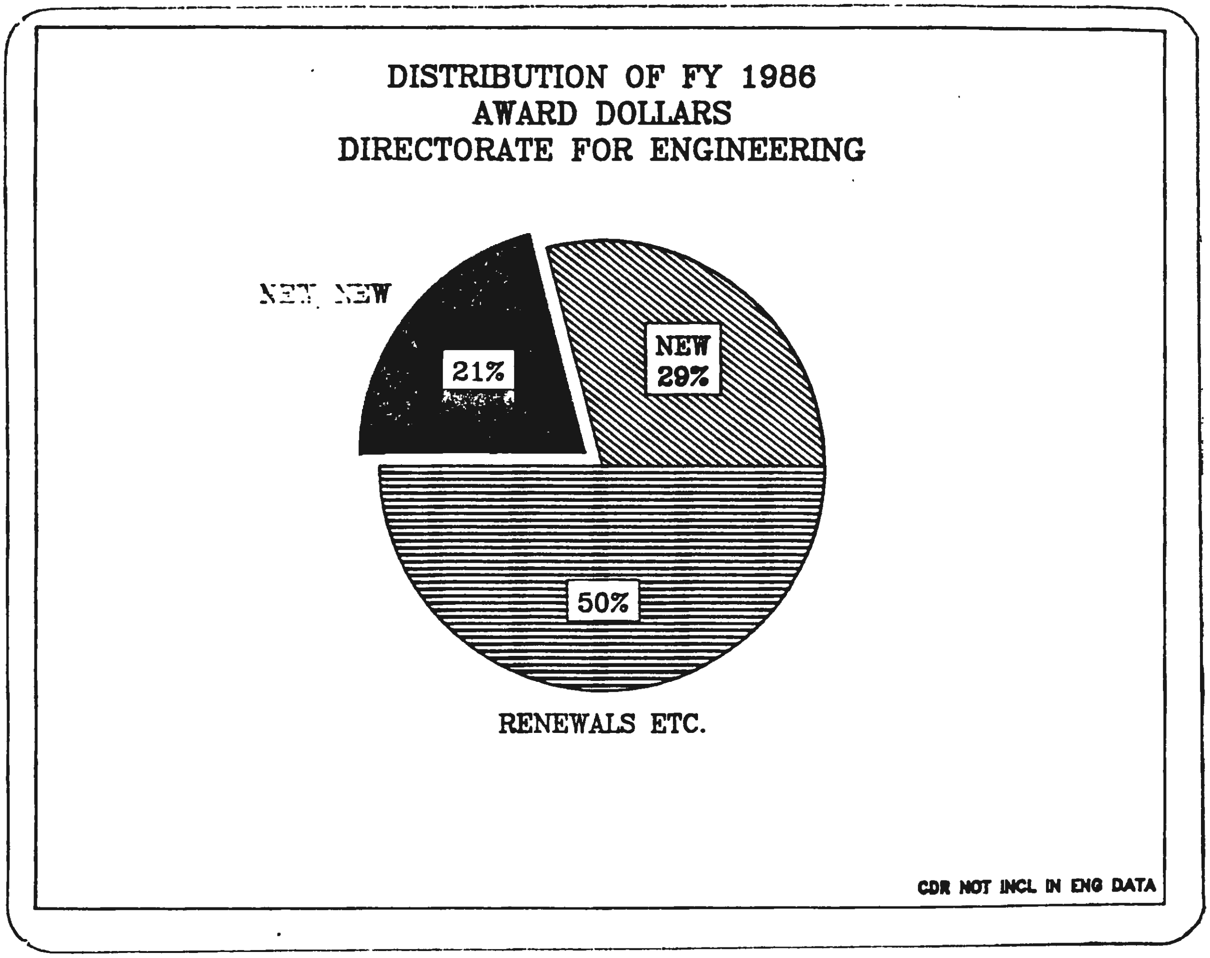
ENCOURAGING NEW PEOPLE INTO SYSTEM

- TEN PERCENT MINIMUM PERCENTAGE OF BUDGET FOR NEW INVESTIGATORS
- ENGINEERING INITIATION AWARDS PROGRAM (EIA); PYI PROGRAM
- EXPAND WOMEN AND MINORITIES SUPPORT
- INCREASE NUMBER OF IPA AND ROTATORS AT NSF
- INCREASE INTERNATIONAL COOPERATIVE ACTIVITIES
- FUND CREATIVE AND NOVEL APPROACHES (EXPEDITED AWARDS FOR NOVEL RESEARCH)
- ENSURE FUNDS ARE AVAILABLE FOR NEW INITIATIVES



FINANCIAL IMPACT PROJECTION

For Young Investigator Support



DISTRIBUTION OF FY 1986
AWARD DOLLARS
DIRECTORATE FOR ENGINEERING

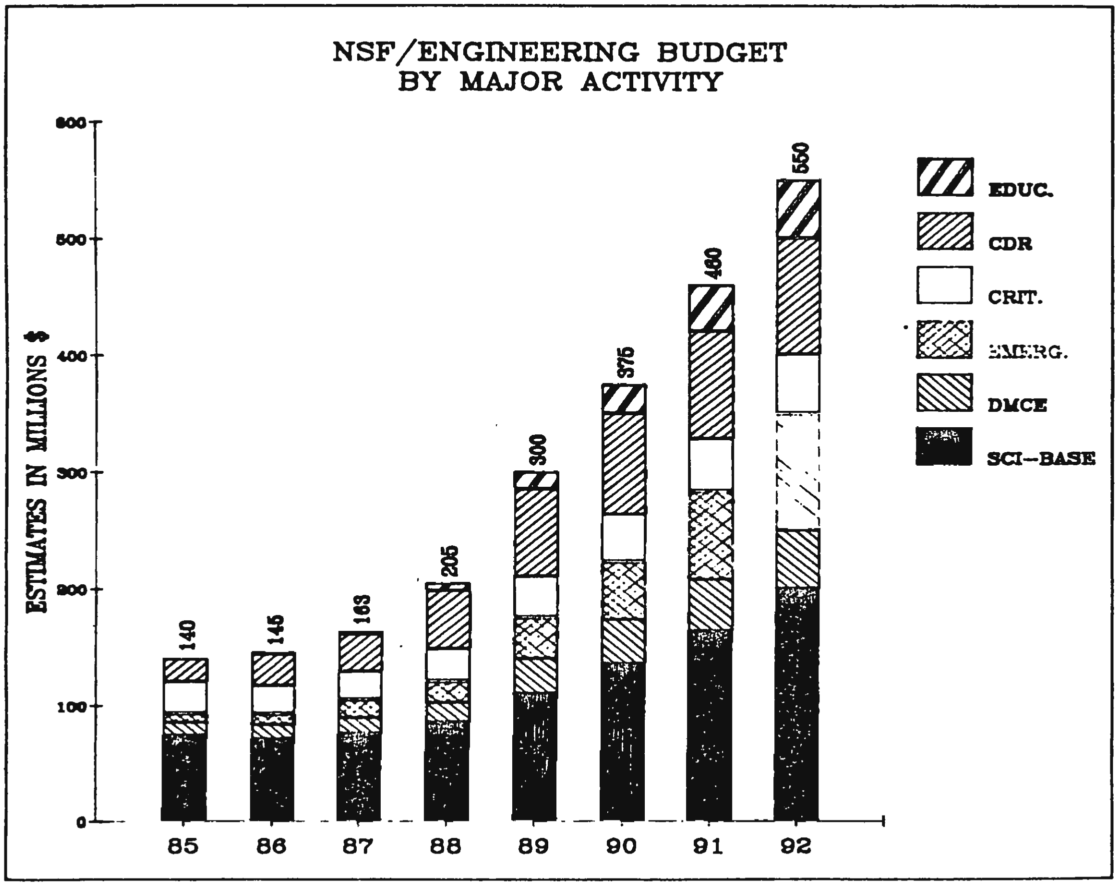
CDR NOT INCL IN ENG DATA

<u>SUMMARY</u>

- ENG MUST RESPOND TO THE LONG-TERM NEEDS OF THE NATION BY MAINTAINING THE EXISTING STRENGTHS OF THE ENGINEERING SCIENCE FIELDS AND BY CREATING FOCUSED EFFORTS IN SPECIAL AREAS OF UNIQUE OPPORTUNITY
- ENG MUST STRENGTHEN THE TECHNOLOGICAL CAPABILITY AND HUMAN RESOURCES FOR TECHNOLOGY-DRIVEN FIELDS SUCH AS DESIGN AND MANUFACTURING
- ENG MUST HELP CREATE ACADEMIC INFRASTRUCTURE IN EMERGING FIELDS
- ENG WILL STRIVE TO MEET ITS STATED GOALS FOR ERCS
- ENG WILL PLAY A MAJOR ROLE IN IMPROVING ENGINEERING EDUCATION

SUMMARY (CONT'D)

- THE RESOURCES REQUIRED TO IMPLEMENT THE ENG LONG-RANGE PLAN ARE ABOUT $550 MILLION
- ENG PLANS TO PROMOTE EFFECTIVE PROGRAMS/POLICIES FOR:
  - TECHNOLOGY TRANSFER; LONG-TERM COMPETITIVE POSITION
  - INTERNATIONAL COOPERATION
  - TECHNOLOGY INNOVATION
  - BE CATALYST FOR WORKING WITH VARIOUS AGENCIES/ORGANIZATIONS TO SUPPORT ENGINEERING EDUCATION AND RESEARCH



WIND ENGINEERING: THE FUTURE

A. G. Davenport

INTRODUCTION

Winston Churchill once said in referring to the future that "You should never look further than you can see". I will not therefore treat the future as the 'wide blue yonder' but rather a slight extension of some present problems that having been obvious for some time but which haven't yet received all the attention they deserve.

There are a number of topics one could touch on, triggered by the following thoughts:

> "Four fifths of the world is covered by waves and water" and "waves are generated by wind"
>
> "Most of the world's catastrophes are wind related"
>
> "The world is rapidly loosing its topsoil mainly through wind erosion"
>
> "The curse of complexity and the sweetness of simplicity".

I will attempt to enlarge on the first two of these, but before doing so comment on the last.

In looking to the future there is the need to examine new horizons but also to examine earlier work and try to simplify. One of the curses of a maturing field of research is the many headed hydra of complexity. It can be countered-productive and I have noticed this trend in recent years.

This is an important target area for improvement.

PART I: WIND ENGINEERING AND WINDSTORM CATASTROPHE

U.N. statistics indicate that roughly half of the major global natural catastrophes are now wind related and have been rising steadily over the pst decades. The appalling disasters in recent years due to the cyclones in the Bay of Bengal and typhoons in the South China Sea and the Pacific islands are tragic reminders.

The losses experienced during a major wind storm disaster depend on many factors. The life safety depends on the advanced warning given to the community and the emergency measures available for evacuation, the proximity to the water line and susceptibility to storm surge, the adequacy of the shelters during the storm, the availability of hospital care for the injured during and following the storm, the supply of food and water and the maintenance of essential services such as power, communications and roads. For the survivors, the ability to return to a normal life depends on the survival of their homes and shelter, the survival of the structures, facilities and services essential to the economy; and in the event of widespread destruction, the availability of the materials to rebuild and the funds to pay for them.

The recovery following a disaster is a responsibility shared by individuals, local communities, governments, international relief agencies and the insurance industry. Insurance plays a particularly vital role in cushioning the financial shock -- sometimes exceeding the GNP of a community -- on the individuals and the government bodies. There are now signs that now the insurance industry may face difficulties. Berz and Smolke have summarized the problem as follows:

> "In windstorm insurance ... their is not only a significant rise in the catastrophe frequency, but also in the catastrophe potential. The main reasons for this trend are:
>
> - the increase in the world's population and in insurance density,
> - the concentration of people and insured property in conurbations,
> - the improved standard of living,
> - the settlement in and industrialization of particularly exposed areas,
> - the introduction of less resistant building methods and more hazardous technologies.
>
> The growing number and size of large cities plays a very important role in this context. By the year 2000, the number of cities with more than one million inhabitants will have doubled from 200 to 400, and the number of cities with more than ten million inhabitants will have increased from 10 to 25. This trend is most pronounced in developing countries, the consequence being an increased susceptibility of these countries economies to natural hazards, as has been demonstrated many times during the last few decades.
>
> The coastal regions of tropical and subtropical latitudes have experienced an extraordinarily high degree of growth in population and industry in many countries which can be traced, among other things, to their high recreational value and the convenient transport routes. For the most part, the areas involved here are also areas with high windstorm and storm surge exposure so that the occurrence of greater windstorm disasters is inevitable. Unfortunately, this negative trend is often encouraged by the inexpensive insurability against windstorm and inundation losses. The trend can be reversed only if the responsible authorities undertake a consistent tightening up of the regulations for land use and construction, as has been done in a number of countries.
>
> When new technologies are introduced there is almost always an increased risk of loss at the outset owing to a lack of loss experience. The offshore platforms in the stormy North Sea or in the hurricane-exposed Gulf of Mexico can be used as examples to illustrate how enormous loss potential can develop within short periods of time and in small areas. In view of the unexpectedly strong fatigue and corrosion which can be observed here, this potential could increase out of proportion in the coming years."

These increasing concentrations of property at risk and the intermittency of the disasters themselves are both conditions unfavorable to the insurance industry, even after extensive reinsurance to spread the risk; these trends could lead to some areas becoming uninsurable -- a circumstance which could put an even greater burden on governments and international relief agencies.

There are measures that can mitigate these threatening catastrophes. In such an effort wind engineering research and practice has a significant role to play. Referring in particular to the insurance industry, Walker, in a thought provoking survey, has suggested that wind engineers "hold the key" to finding an alternative to the industry's total reliance on experience. He suggests that wind engineers an assist the insurance industry in the assessment of risk of a windstorm event occurring, in the assessment of the performance of buildings in wind, of ways to reduce risk, and in the identification of potential major individual risks.

These tasks are of course also of assistance to government in regulating construction and land use, in identifying where the hazard potential is highest and in defining special safety measures for structures of strategic importance. Throughout the value of the wind engineer is his ability to bridge between disciplines - meteorologist, aerodynamicist and structural engineer. In the following we will explore the opportunities where wind engineering can provide useful insights.

THE PREDICTION OF LOSS

To develop the arguments, it is useful to examine the question of loss prediction in more detail. Here we will assume for convenience that losses (in whatever units are appropriate, $'s or otherwise) are straightforwardly related to structural damage. Clearly however, the contingent losses on a communication tower or a hospital may be an order of magnitude greater than for non-strategic structures. These distinctions can be made at a later stage. The questions of importance to both government and insurance companies include:

- What are the magnitudes of the losses and their anticipated risk?
- How do the risks vary geographically?
- What are the potential losses for a region?
- How might these risks be reduced?

To clarify the thinking on the question of loss prediction, I would first like to carry out a "thought experiment" involving a hypothetical wind tunnel of enormous size in which entire full scale buildings and city blocks can be "tested". (In view of the fact that there already exist wind tunnels to test full size aircraft and shake tables for entire buildings this may not be so far fetched). The advantage of testing full scale structures in their real setting is that their failure mechanism and loading can be monitored exactly as it would happen without any speculation.

Figure I.1 shows a representative sample of buildings and other structures in this wind tunnel under test. The wind speed is gradually increased, and at a certain velocity (V_1), signs of distress and minor damage will be observed (see Figure I.1b). Further increase in wind speed to (V_2) will cause progressively more serious failures (Figure I.1c) until eventually, at a wind speed V_3 (Figure I.1d). The destruction is total. If each of these "damage states" is translated into its "loss equivalent" (in dollars or whatever), we can estimate the fraction of the total loss (or damage) quotient produced at each wind speed in the tunnel. This is depicted in Figure I.1e. Insofar as it is possible to construct identical structures, the experiment we will presume is accurately repeatable. This loss quotient Q(V) we will assume is an accurate means of relating losses to windspeed. In reality the ratio of windspeeds V_3/V_1 may be vary large - some structures being very much less wind sensitive than others.

Consider now Figure I.2 which shows the contours of maximum surface wind speeds estimated to have occurred during Hurricanes Frederic and Alicia. Maximum fastest mile wind speeds of over 125 miles/hr (200 km/hr) are noted for both storms and contours of 100 and 75 mph are also given. The path of the eye and its hourly position are given for each storm. The storms struck major cities in each case.

Knowing the geographic area affected by the various maximum wind speeds and the distribution or density of buildings, allows us to apply our knowledge of the damage quotient to estimate the losses in each of these storms. Denoting each storm by the subscript "i" we can write the total losses as

$$L_i = \int_A D(z)\, Q(V_{iz})\, dA_z \tag{1}$$

in which V_{iz} is the maximum windspeed at point z in hurricane i and D(z) is the total potential insured losses per unit area at point z.

If we possessed complete knowledge of the characteristics of all potential hurricanes or storms we could repeat the exercise for each and come up with a statistical distribution of the losses. Assuming we do have this knowledge, let us suppose that hurricanes precisely similar to "i" occur on average n_i times per century; then the total number of times that a loss L is exceeded is

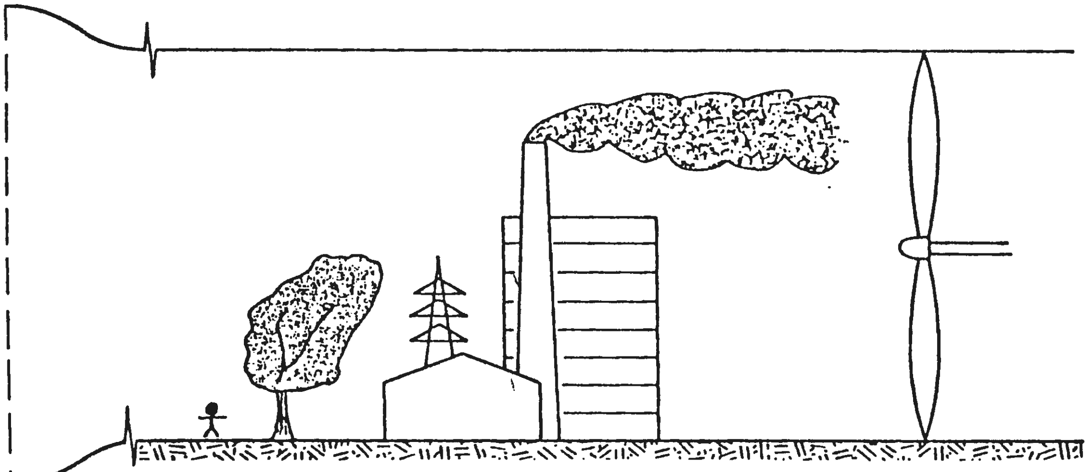
$$N_L(L) = \sum_i n_i \cdot L_i \cdot I(L - L_i) \tag{2}$$

where I is an indicator function and is equal to 1 if $L > L_i$ and 0 if $L < L_i$.

Assuming that these losses occur infrequently we may assume that the distribution of the largest losses in a period T follows a Poisson type, given by

$$F_L(L) = \exp - (N_L(L) \cdot T) \tag{3}$$

This relation goes a very long way in addressing the "insurance question". The approach can be used to answer questions concerning the geographical distribution of loss, and the cumulative total loss in a given time frame. Similar approaches can also be used in the study of storm surge.



(a) "SUPER TUNNEL"

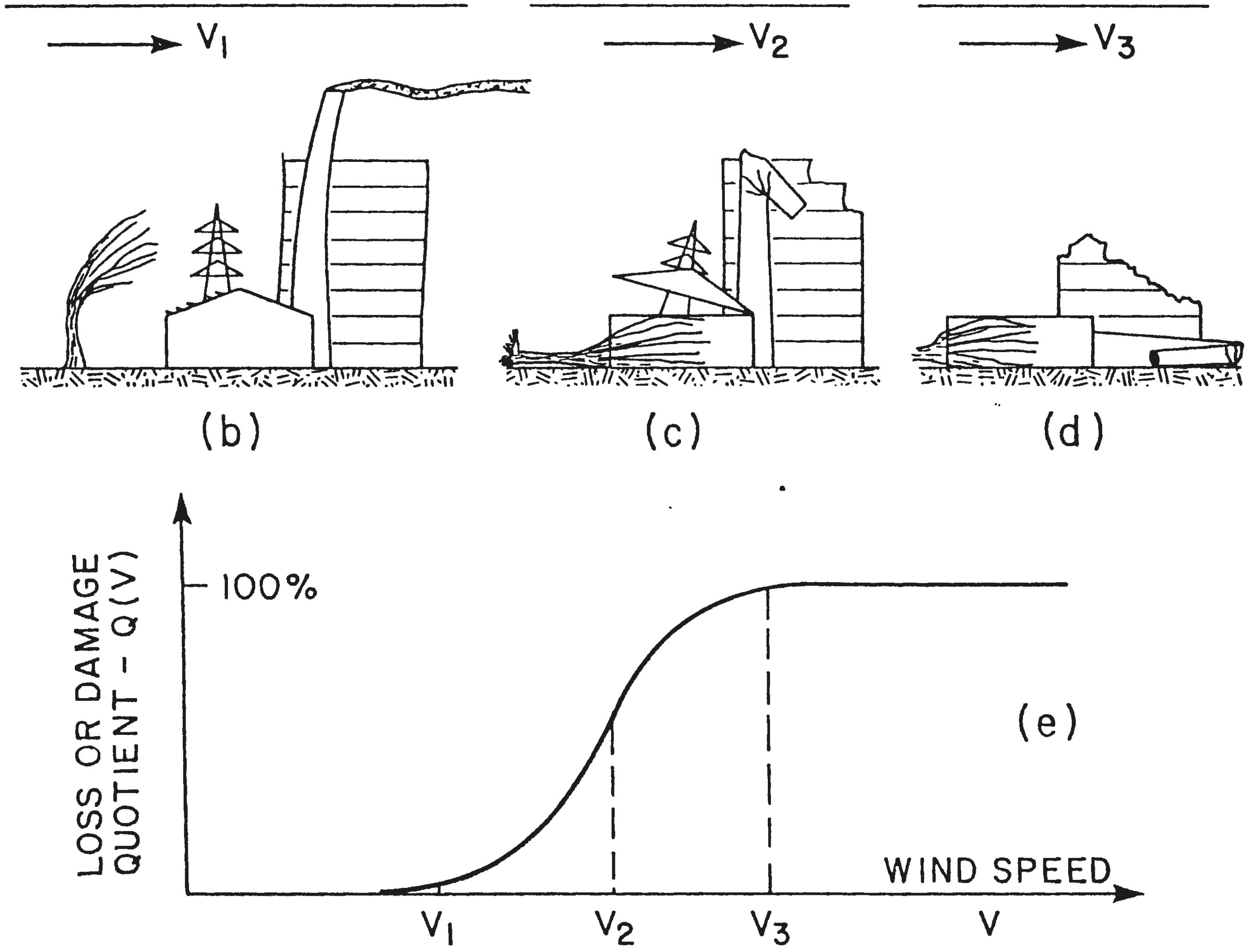


Figure I.1. The "Super Tunnel" and the Definition of the Damage Quotient

The prediction of loss in these terms relies on at least two quantities, the knowledge of the storm windfield in tropical cyclones as well as their statistical frequencies as well as the damage quotient. We will address both of these questions and indicate approaches to their description.

THE PREDICTION OF WINDS IN TROPICAL CYCLONES

The prediction of the windfields in severe tropical cyclones cannot be undertaken by normal instrumental methods and storm "footprints", such as those in Figure I.2, are the result of very detailed damage studies in the field backed up by extensive computer simulations. Even at a single point the collection of wind speed data is unreliable for a variety of reasons, due to the frequent destruction of instruments by debris, loss of power, etc. Furthermore, the relative infrequency of damaging storms at any one place (once a generation or so) requires that very long observation periods are necessary to obtain suitable samples. On the face of it these are formidable obstacles.

Fortunately, an alternative approach has been developed which relies on large scale information on storm history, generally available for a century or more. This is a simulation procedure which assumes that the windspeeds and directions in a tropical cyclone can be calculated with sufficient accuracy knowing only certain key characteristics parameters of the storm. Specifically these are the drop in barometric pressure relative to the surrounding region at the centre of the storm (Δp); the radius to the ring of maximum wind speeds (R_{max}) usually located just outside the storm eyewall; the speed at which the storm travels forward (the translation speed, V_t); the angle of its track (θ); and lately the distance of the point of interest from the track. The statistics of these parameters can be found for each geographic region from the historical records of past tropical cyclones. These records and the tracks of hurricanes over the past century or so have now been conveniently assembled, in the case of the North Atlantic, by the National Hurricane Centre in Coral Gables, Florida. The mathematical model from which the windfield within the storm is calculated is described in detail in reference 5.

The accuracy of the windfield model can be tested by comparing actual wind records obtained in tropical cyclones with those predicted knowing the values of the storm's central pressure difference, radius of maximum winds, translation velocity, and track. Figure I.2 shows a number of such comparisons for two North Atlantic hurricanes (Frederic, 1979; Alicia, 1983), two Northwest Pacific typhoons (Wanda, 1962; Ellen, 1983) and two Australian cyclones (Althea, 1971; Tracy, 1974). The conclusion from the study of a number of major storms, is that, although variations can be found from storm to storm, the errors from a statistical viewpoint are comparatively small.

An example of the historical data used to develop the statistical information is given in Figure I.3; this shows that 14 tropical cyclones passing within 50 km of Antigua in the period 1886-1983. In the actual simulation of Antigua's tropical cyclone wind history, as for all other locations in the Caribbean, all documented storms that passed within 250 kilometers of the island were used to determine the distribution of storm intensity, speed, direction, etc.

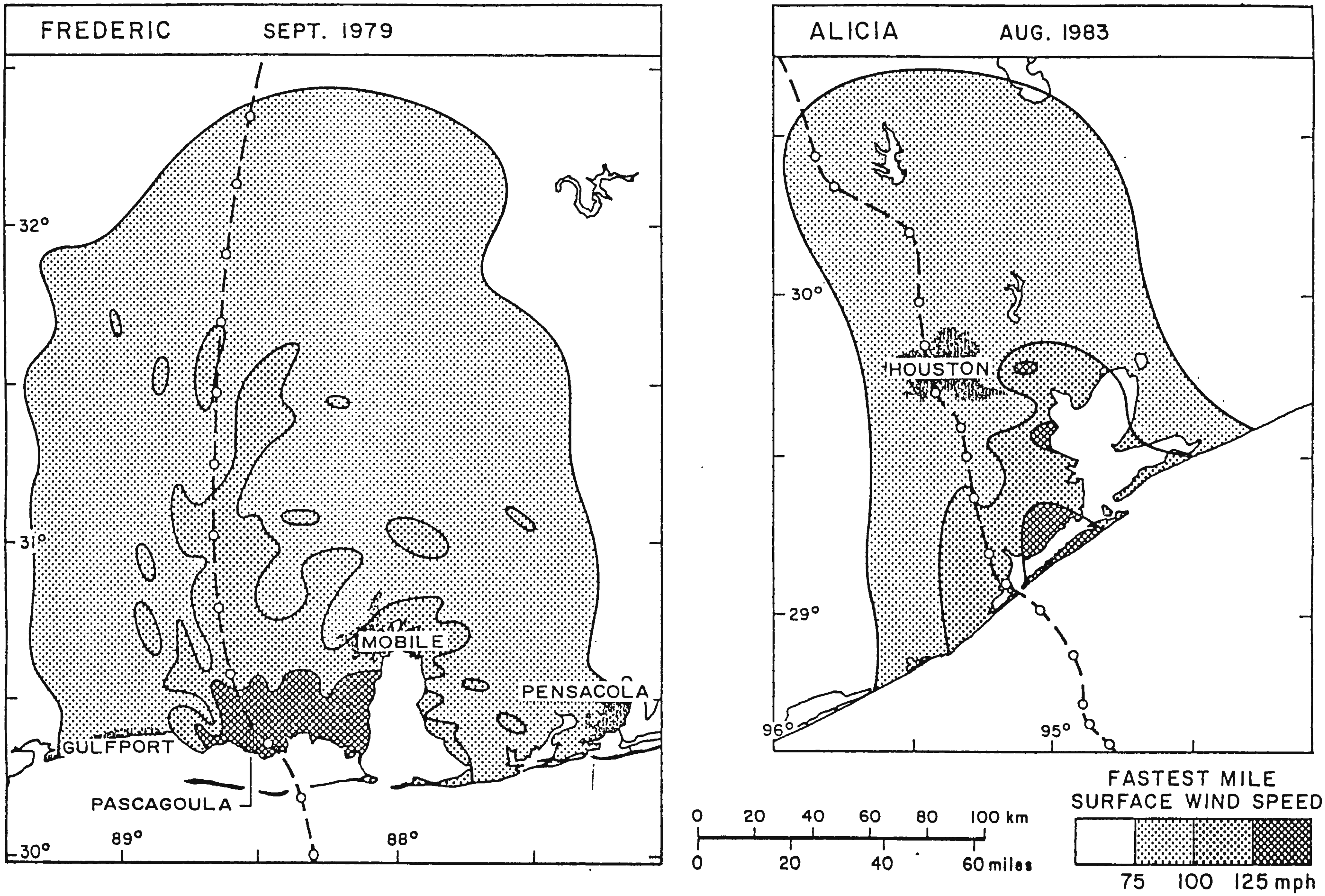


Figure I.2. "Footprint" of maximum wind speeds for Hurricane Frederic and Alicia.

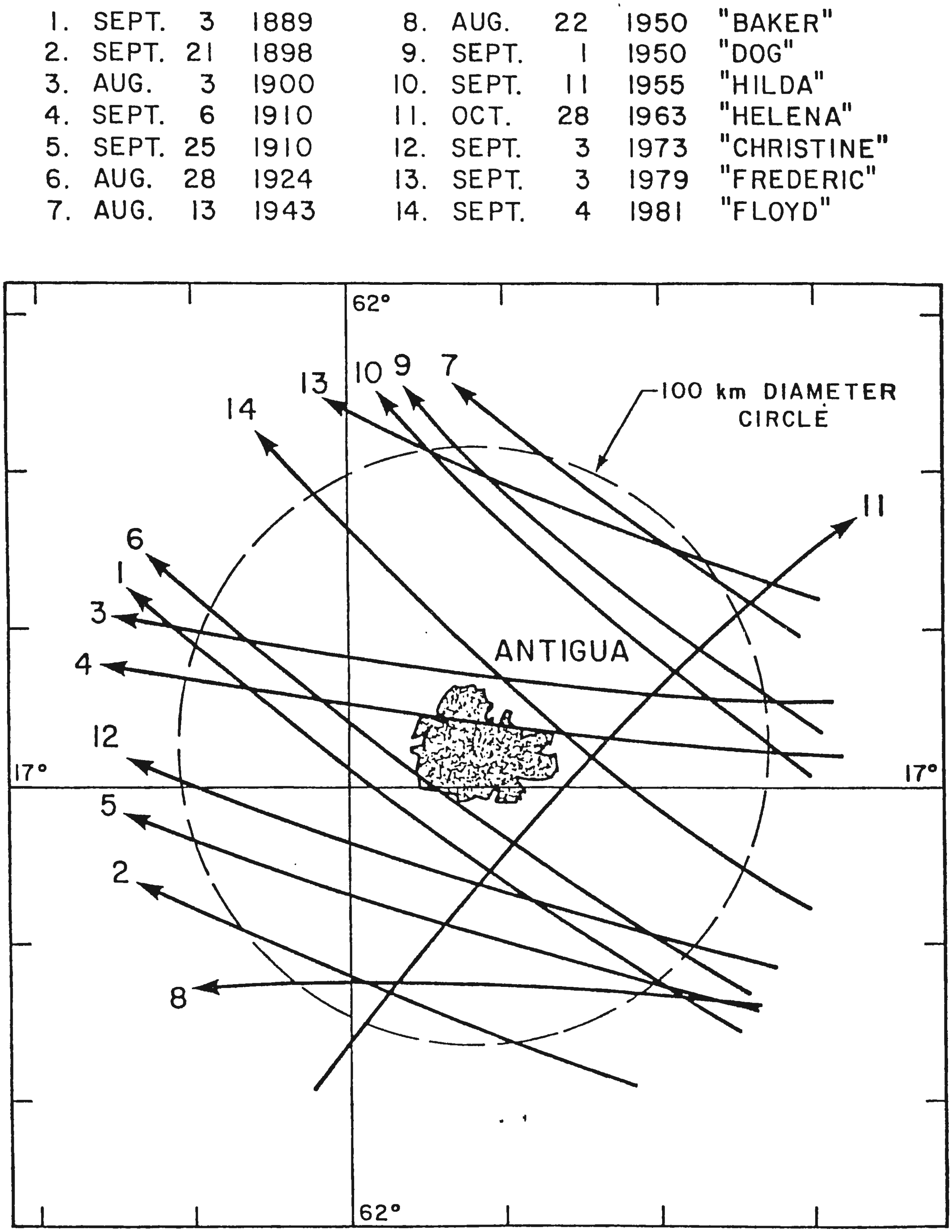


Figure I.3. Tropical Cyclones Reaching at Least Tropical Storm Intensity and Passing within 50 KM of Antiqua: 1886-1983

The simulation procedure follows the steps in the flow chart given in Figure I.4. **Step 1**: The historical records of hurricanes passing within 250 km radius of a point are analyzed to produce statistical distributions representing the tropical cyclone parameters (Δp, R_{max}, V_t and θ) required by the windfield model. **Step 2**: Sets of these characteristic parameters are sampled sequentially at random from these distributions. **Step 3**: From each set a new tropical cyclone is generated and the windfield computed. **Step 4**: The windfield is moved past the site of interest at some distance sampled at random and the wind speeds and directions at the site recorded. Both surface wind speed, (V_s) and "gradient" wind speed (V_g), at a height of 500 to 1000 meters and well above most surface features, are computed. **Step 5**: The simulation is run repeatedly until the results stabilize statistically. The resulting simulated windspeed records are then analyzed to yield predictions of extreme wind speeds etc. The storms created during the simulation correspond statistically to those that were determined at the site from the historical records, as well, it is assumed, to the future.

The results of the simulation for the island of Nevis, in the Caribbean, are shown in Figure I.5. The once in 100-year extreme-value estimates for the gradient and surface wind speed are 51.5 and 41.5 meters/sec respectively. The systematic application of this simulation procedure to the eastern Caribbean region yielded maps of the 10-year and 100-year extreme-value estimates of wind speeds (both surface and gradient). The diagram also shows the strong influence of the island topography on the wind speed.

Storms generated in this simulation can also be used to predict effects influenced by the entire windfield. One of these is the storm surge as the cyclone approaches the coastline; another is that discussed here, the "footprint" of the maximum winds shortly after landfall. In determining the latter allowance is made in the modelling of the cyclone for its decay as it moves inland. A complete family of such cyclone "footprints" generated for each milestone along a coastline is precisely the information needed in the loss calculation in equation (1). This illustrates the powerful potential of this type of simulation and its application to the Bay of Bengal and South China Sea could be no less effective than it has been in other tropical cyclone-prone regions.

PREDICTING DAMAGE

The other requirement in predicting losses is the fraction of structures damaged at each wind speed, the so-called "damage quotient". It was suggested in Figure I.1 that this could be obtained from tests in the "super tunnel". Such a curve in fact can be drawn for each structural type - tall buildings, chimneys, low buildings, masts, etc. In so doing the wind speed spread for each structural type will be reduced. The variability which remains will be due to the amalgamation of all the variable factors in the design and is in fact an expression of the reliability of the design. If we were in possession of a "super tunnel" and an adequate supply of full scale test samples we could establish the reliability directly and unambiguously. Unfortunately, we have neither and must use other ways; one way is to use reliability theory.

If we follow this approach we can contrast residential construction with engineered construction, as well as cyclone wind climates with extra tropical climates. Modern residential construction is often lightweight with relatively large variation of resistance and low safety index. Due to

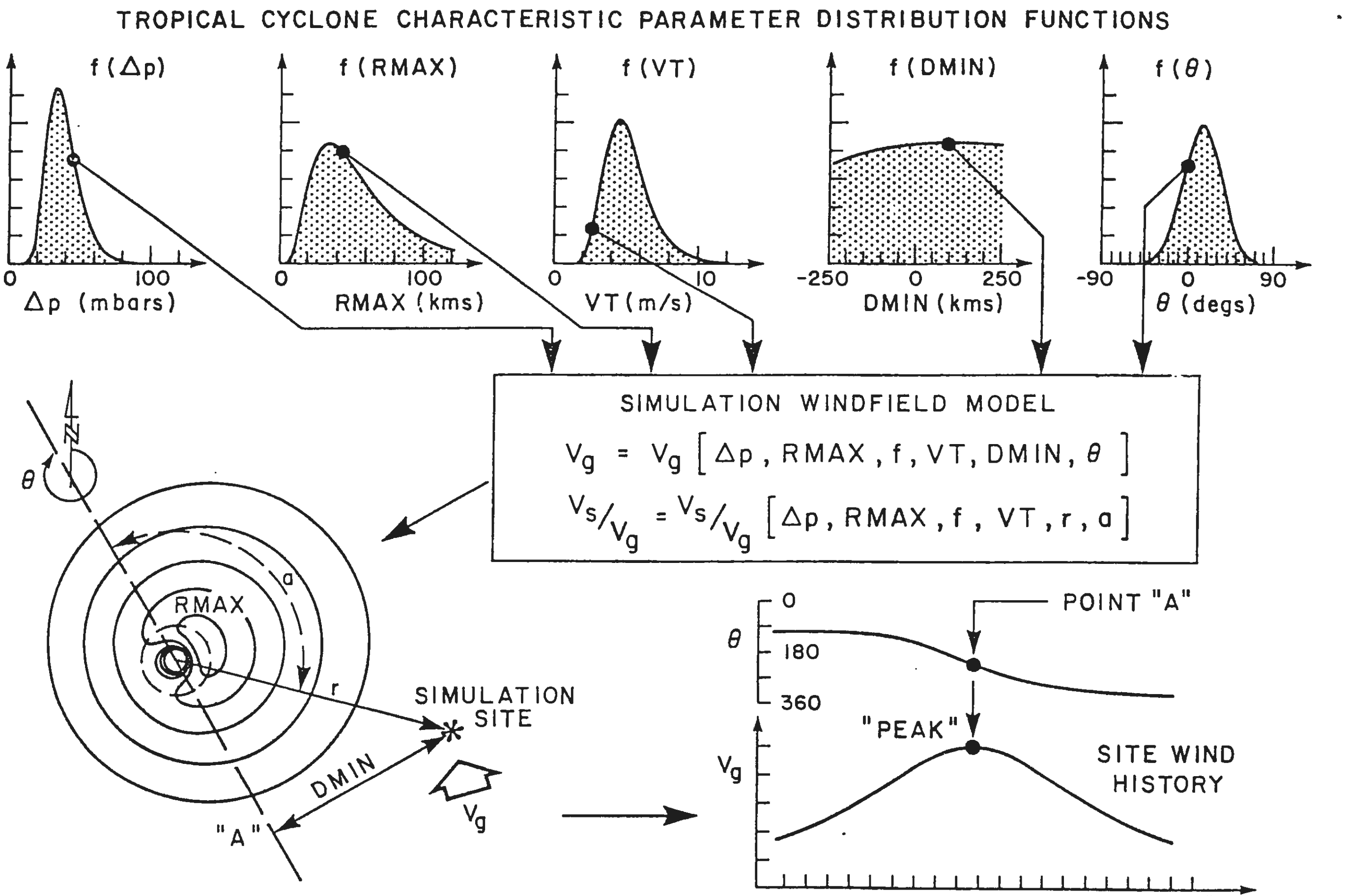


Figure I.4. The elements of the cyclone simulation.

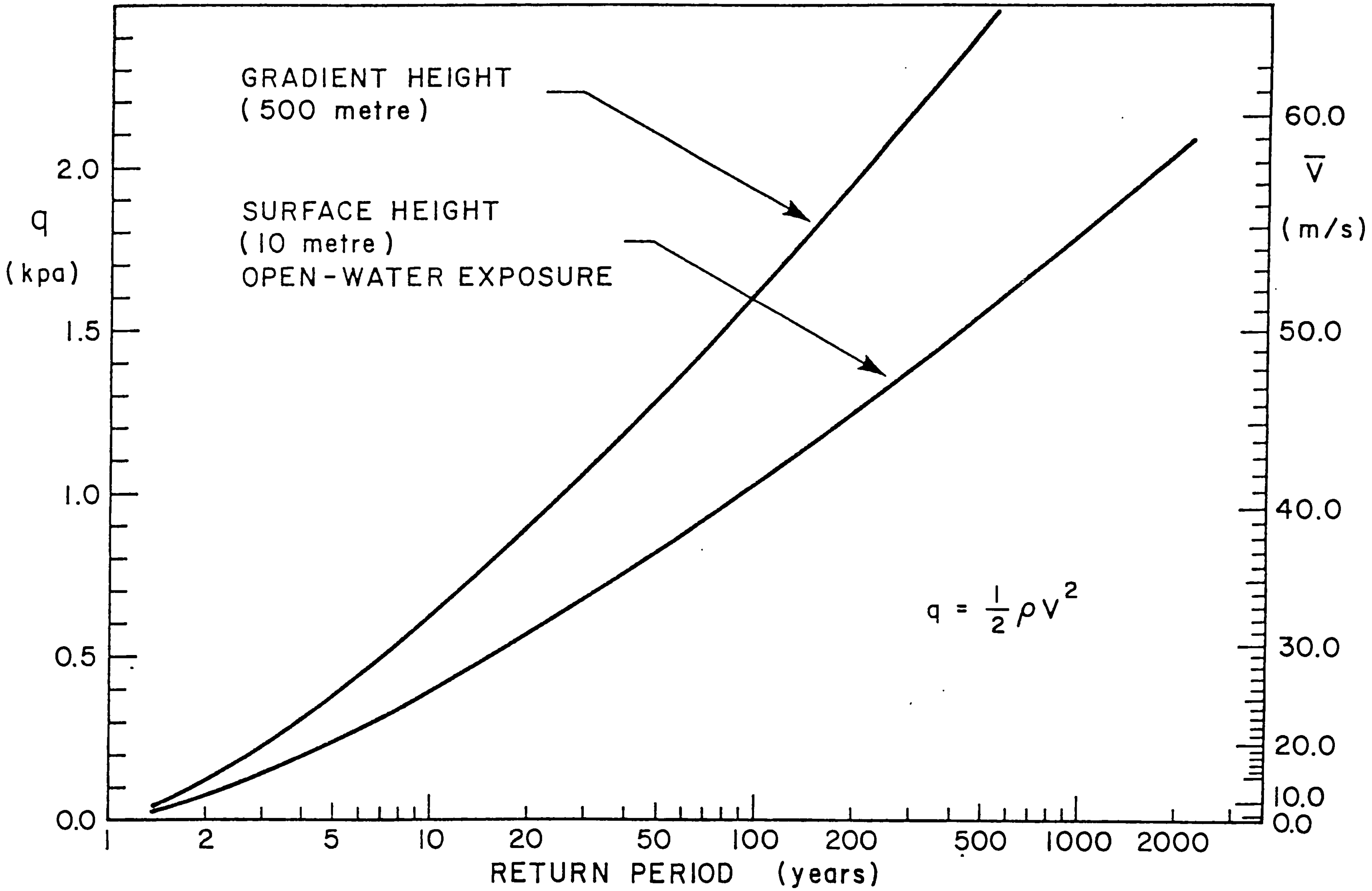


Figure I.5. The hurricane simulation.

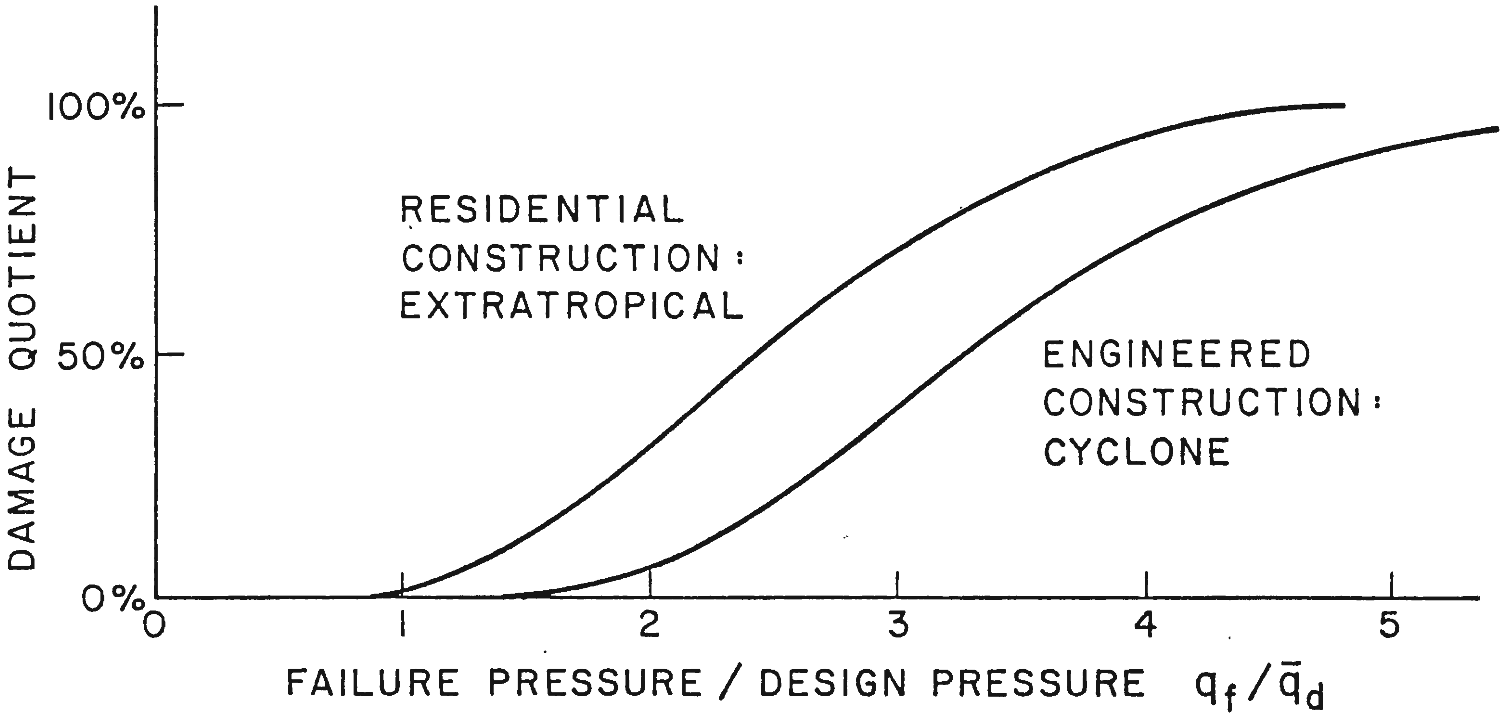


Figure I.6. Estimated damage quotient.

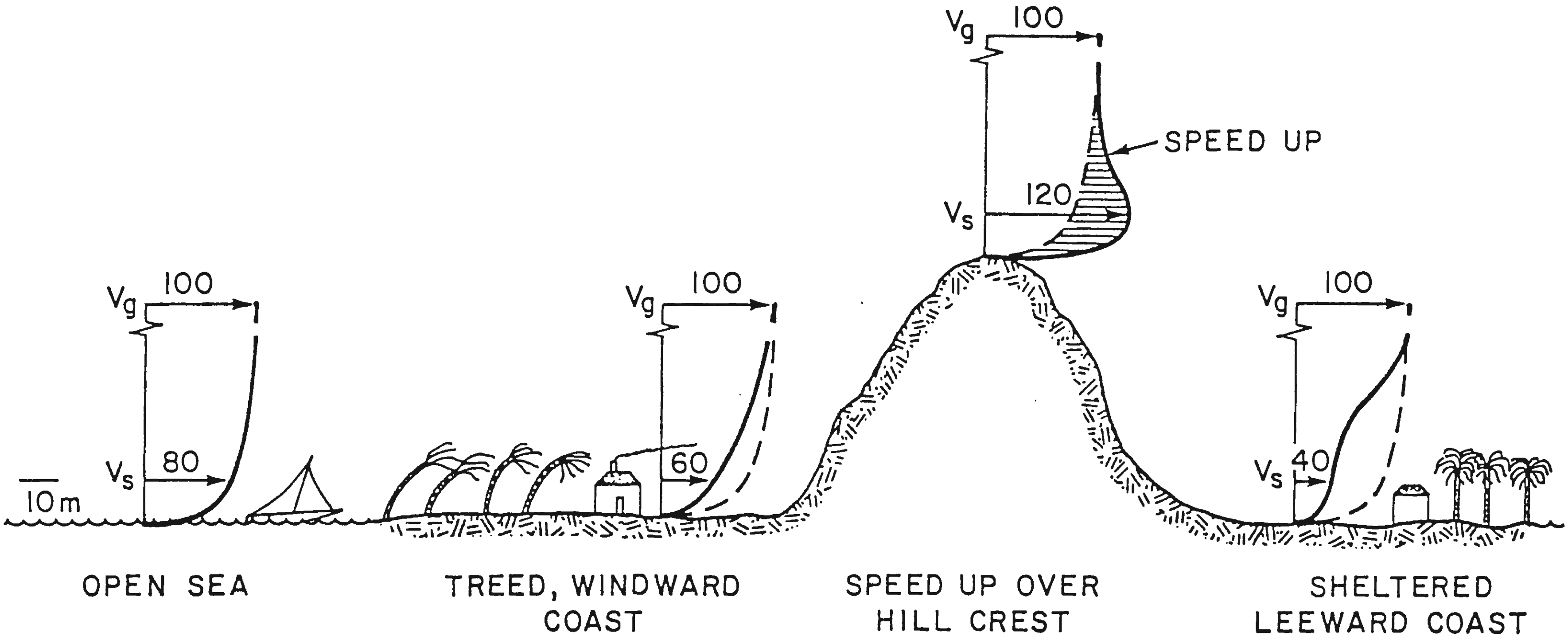


Figure I.7. Influence of terrain and topography.

the proximity to the ground the pressure coefficients and exposure factor are strongly variable. Engineered construction is likely to have a higher safety index and lower variability in the resistance and pressure coefficients. Many engineered structures such as towers and chimneys are dynamically sensitive adding to the variability.

PART II: WIND ENGINEERING AND WAVES

Although four fifths of the earth's wind boundary layer lies over the oceans, wind engineering has been primarily concerned with the remaining one fifth, over the land. Since the development of offshore activities there is a prospect for wind engineering to become amphibious.

There are a variety of important problems in which wind and wave act together -- sometimes interactively -- and where wind engineering expertise may prove useful. We attempt to provide a preview of the experimental and/or mathematical challenges which may await.

The following is a selection of these problems:

- The wind loading of offshore structures; it is now apparent that wind loading can, in certain instances, dominate the action of waves;
- The manoeuvering of vessels including the towing of barges;
- The hydro-aero-dynamics of sailing and other wind powered vessels;
- Problems of air-sea rescue;
- The drift of icebergs; and
- The drift of oil-slicks.

Other important problems of a more fundamental character where understanding is till not complete includes:

- wave generation and dissipation;
- storm surge;
- littoral drift and currents.

The groundwork for understanding the underlying physical processes has been prepared on the one hand by oceanographers and meteorologists interested in the air sea interface and on the other, by the extensive and sophisticated studies of wave action in wave tanks. What we will focus on is the niche between these areas in which the wind imposes a new and important dimension to the problem.

We begin by tracing some of the developments of wind loading on offshore structures over the past two decades.

WIND LOADING ON OFFSHORE STRUCTURES TO THE PRESENT

Currently the design advice on wind loading of offshore structures, such as defined by the American Bureau of Shipping (1980) and the American

Petroleum Institute (1982) is generally based on calculations for a static distribution of pressure on the frontal area of the structure. Some allowance for gusts is made in the selection of the design wind speed incorporated into the static design pressure. In contrast, the design approach for waves recognizes this self-evident dynamic nature of the loading, and recommends dynamic approaches involving appropriate design wave height or sea surface spectra and frequency dependent hydrodynamic drag coefficients.

These approaches grew up at a time when most of the structures built were jacket type or gravity based and anchored relatively rigidly to the sea bed (Ellers, 1982). For these the wave forces dominated the wind. Any deficiencies in the wind loading, particularly dynamic, would be masked by the wave action.

With these static conventions for wind loading the most influential factors for design were the static aerodynamic coefficients -- primarily drag (or surge) but including also the lift (or heave), and side force, and the pitching, rolling and yawing moments (the latter usually measured about the waterline). Wind tunnel tests using standard static wind tunnel balances could be used straightforwardly.

The development of the floating semisubmersible rig has latterly had a considerable impact on wind tunnel testing techniques. In use since the mid-1960's, they were generally designed for wind using empirical classification society rules until the late 1970's. Bjerregaard and Velshou (1978) found that wind tunnel based static wind loads indicated smaller overturning moments than the rules when the rig was heeled over and similar values when on an even keel. This suggested to owners and operators that design rules led to conservative estimates of the stability limits and deckloads. As a result, an increasing number of wind tunnel tests have been carried out on semisubmersibles and the sophistication in testing has increased. Apart from a complete range of rig attitudes in heave and heel, consideration has also been given to the presence of waves. In the latter, tests are conducted with various rigid waves which can be progressively moved past the test model. To represent the mobility of the water surface itself, Macha has immersed the hull and support structure of the model in "green slime", this flows in response to the air pressure without interfering with the static force measurement. Unfortunately it cannot be used to reflect a wave contour.

Full-scale measurements of the surface forces on a semisubmersible were undertaken by Boonstra et al. (1979, 1982). These results are shown in Figure II.1 and compared to the design rules, static model tests with the static mooring forces. On the face of it the wind tunnel tests show lower forces than the rules. These however are only the static forces.

A systematic study of the static coefficients has recently been undertaken by Freathy (1985) who found a similar result and made useful suggestions for the modification of design rules to account for the additional effects of lift on the overturning moment.

In February 1982 the capsizing of the semisubmersible "Ocean Ranger" off the coast of Newfoundland resulted in a very intensive investigation of wave and wind action. (Although inappropriate operation of trim control was found to be the cause, the tests were needed to confirm the failure sequence.) Studies carried out in wave tanks in Norway and Ottawa included

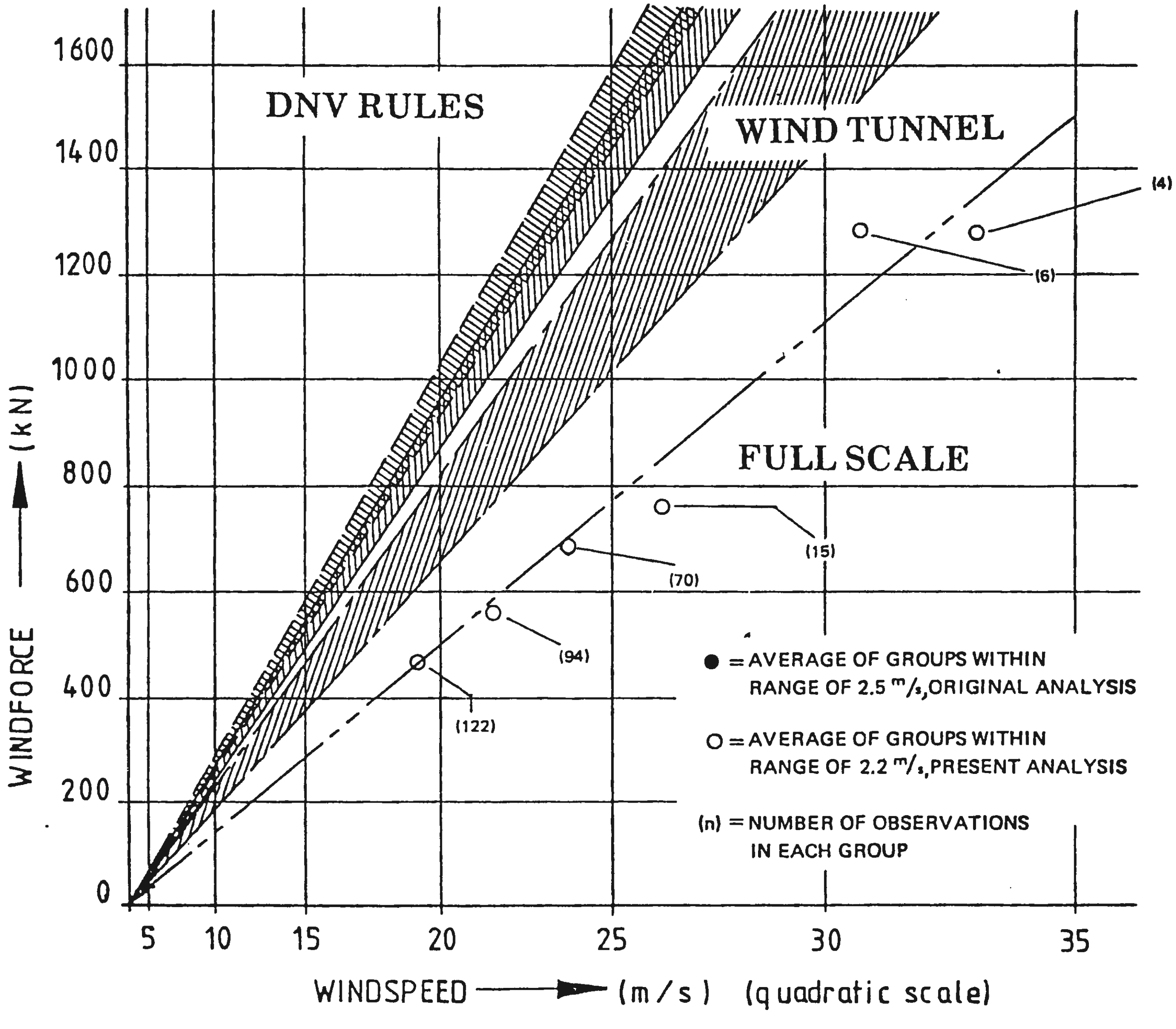


Figure II.1. Surge Forces on Semisubmersible (After Boonstra) the influence of the wind through two quite different techniques. The Norwegian approach used fans suspended over the wave tank; the Ottawa test used a system of computer controlled force actuators referenced to the instantaneous attitude of the rig. The aerodynamic coefficients for all attitudes were derived through wind tunnel tests in a representative turbulent boundary layer flow (Tryggvason, 1983). The balance used in this study however has a high resolution force balance (developed initially at the BLWT Laboratory (Davenport and Tschanz, 1981)). This allowed direct measurement of the dynamic forces due to turbulence and to estimates of the dynamic pitch and roll which turned out to be significant.

In a dynamic numerical study of a semisubmersible, Rowe, Brendling and Davies (1984), reached a similar conclusion; that "response to wind gusts is an important source of pitch and roll motion which might considerably reduce the weave-deck clearance, and consequently lead to major wave impact and structural damage".

A major contributing factor to this dynamic response is the low stiffness of the semisubmersible, particularly in roll and pitch, and the very long natural period of vibration -- of the order of 1 to 2 minutes.

Long periods of vibration both in surge and pitch are also characteristic of other fixed base compliant structures, in particular the tension leg platform and the guyed tower. The dynamic response of the TLP has been investigated theoretically by several researchers (Kareem and Dalton, 1982; Armstrong and Barnes, 1983; Simiu and Leigh, 1983) with estimates of the dynamic surge due to wind being of similar order to the waves and somewhat less than the mean wind.

The guyed tower has been reported on by Vickery and Pike (Pike and Vickery, 1982; Vickery and Pike, 1985). Dynamic force measurements were carried out on a high resolution dynamic force balance and indicated that the dynamic background drag forces of the same order as the mean; with the resonant response included, the peak dynamic component of the response could exceed the mean. The measurement of the important aerodynamic admittance is shown in Figure II.2.

The low natural frequencies of the compliant structures are thus well below those of the maximum wave, filtering out any dynamic wave action, however, energy prevailing in the wind gustiness increases at the lower frequencies and the response to wind is enhanced (see Figure II.3). Vickery has discussed this trend and shown that the relative response of wind to wave increases progressively at lower frequencies (Vickery, 1983).

Another type of structure for which the wind response may be particularly important is the jack-up rig. In a study by Davenport and Hambly (1984) it was shown that jack-up platforms are sensitive to variations in wind load because:

1. The turbulence wind pressures can subject the platform with its large bluff structures at each end to loads the fluctuate in direction as well as torsional loads (about a vertical axis).

2. Jack-up structure are very sensitive to torsional forces, so that the distribution of forces between the legs can be altered by a torsional force working in conjunction with the lateral forces.

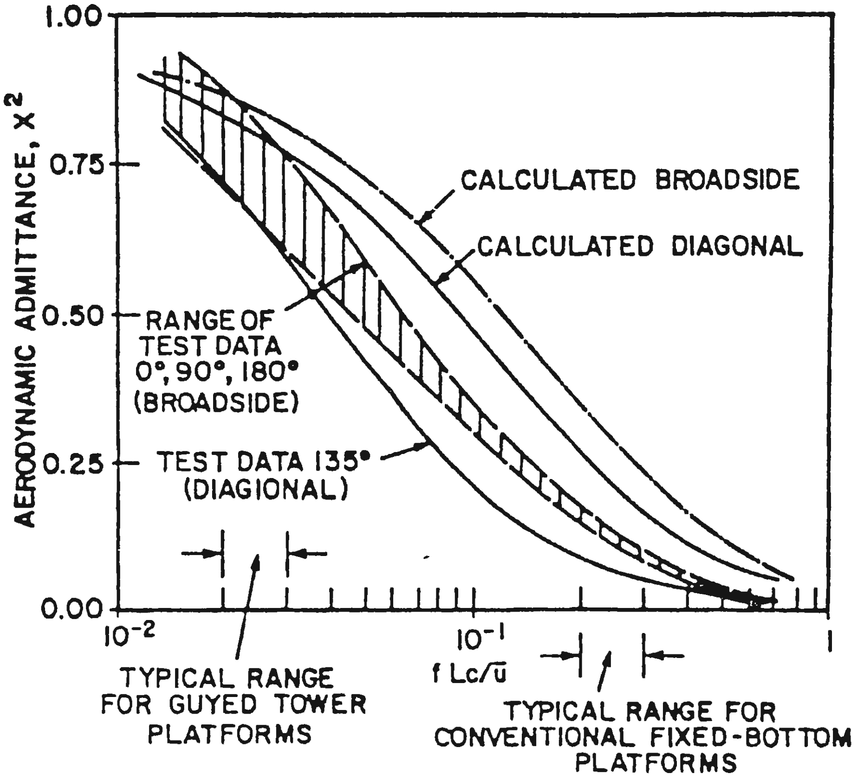


Figure II.2. Aerodynamic Admittance: Guyed Tower (Vickery)

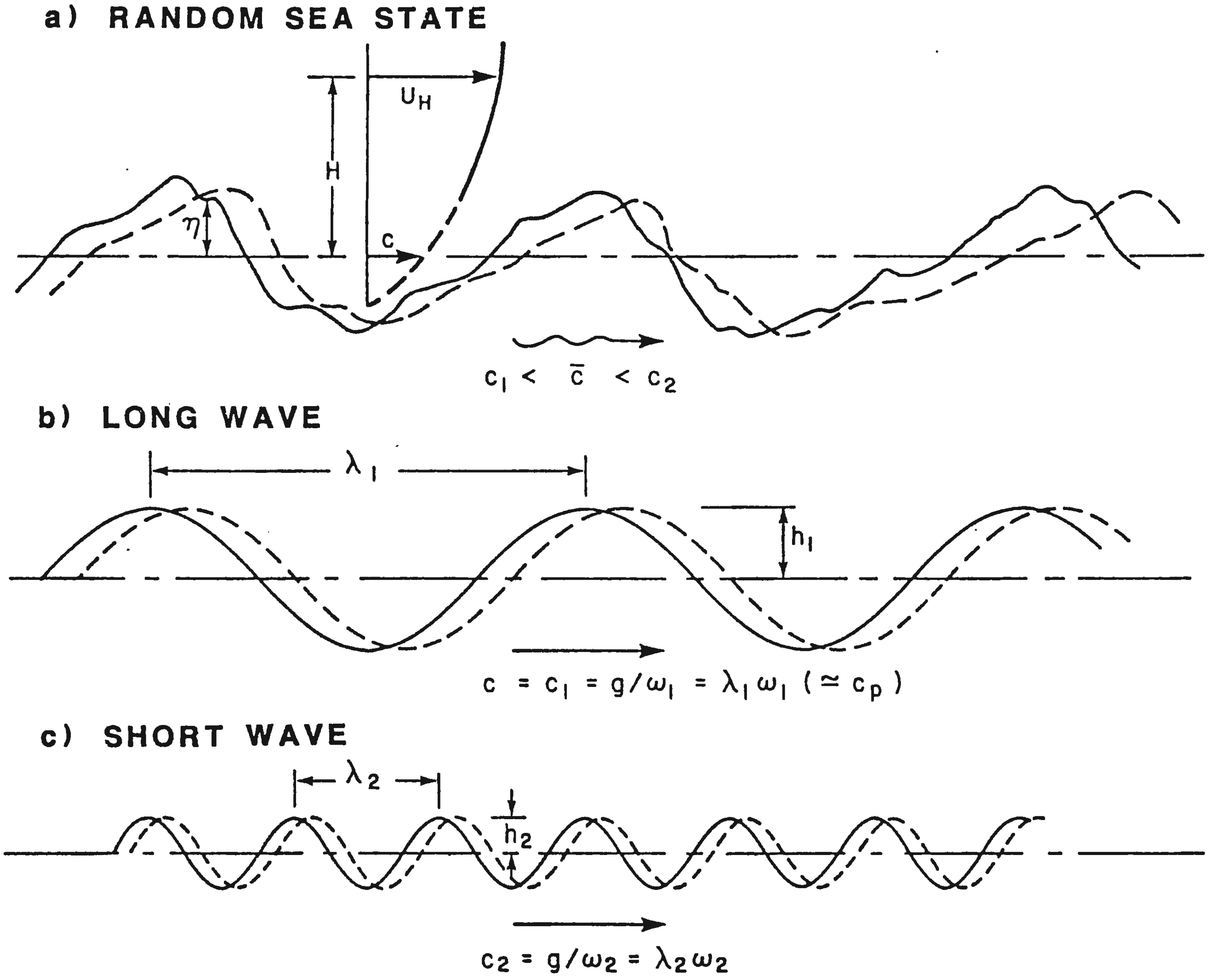


Figure II.3. Components of Waves at Sea

3. Jack-up structures frequently have natural periods of 3-seconds and longer and can response dynamically to the fluctuations in load from the turbulence wind. This can arise both from a resonant response at the natural period as well as at lower frequencies.

The severe dynamic resonant loads led to a high sensitivity to fatigue -- much greater than that due to waves.

The above remarks have suggested that the action of wind on compliant structures may be as significant as the action of waves -- or more so. Due to needs in the petroleum industry for deep water drilling and production, the use of these types of structures is likely to increase.

Unfortunately, the procedures that have been used to identify the dynamic action of wind in the presence of waves present a number of unanswered questions. Since high wind and high waves accompany one another the potential for interaction is real. These effects are difficult to determine without a realistic representation of wave and wind together.

We now discuss the wind/wave interface and its modelling.

THE WIND/WAVE BOUNDARY LAYER

In many respects the wind boundary layer over the ocean resembles that over land. Expressions describing the turbulence and the increase of mean wind speed with height are representative of those over a very smooth terrain. The principle difference lies in the instability of the surface of the sea and the variability of its roughness.

It is common for waves as a point on the sea to be broken down into component frequencies (see Figure II.3). The sea surface can then be described by sea surface displacement (h) spectra such as the well known Person-Moskowitz spectrum shown in Figure II.4. The dimensionless form of this spectrum, $S_h(\omega)$, is

$$\frac{\omega S_h(\omega)}{\sigma_h^2} = 4\beta(\omega_o/\omega)^4 \exp[-\beta(\omega_o/\omega)^4] \tag{1}$$

ω = $2\pi f$ is the circular frequency;

ω_o = $g/U_{19.5}$ is a characteristic frequency related to the windspeed $U_{19.5}$ at 19.5 meters above MSL; and g is gravitational acceleration;

σ_h = the rms sea surface displacement; and

β = 0.74, an empirical constant.

The rms sea surface displacement is

$$\sigma_h^2 = [U^2/(2g)]0.105 \tag{2}$$

The peak of the spectrum is at a frequency $\omega p = (4\beta/5)^{1/4}\ \omega_o = 0.88\ \omega_o$. Waves on the ocean (see Figure II.3) are travelling waves and have a speed (or celerity) c,

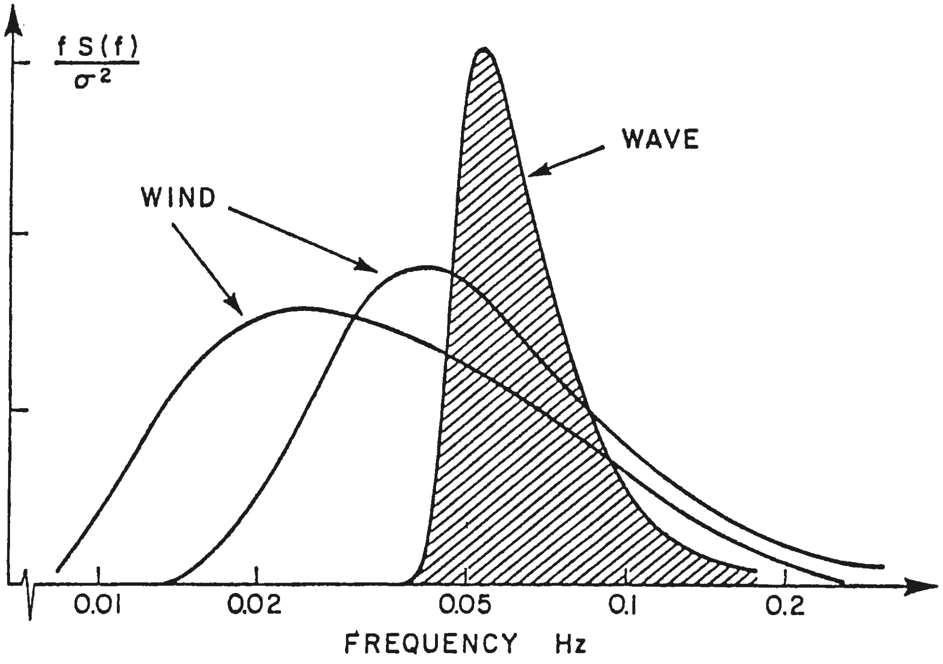
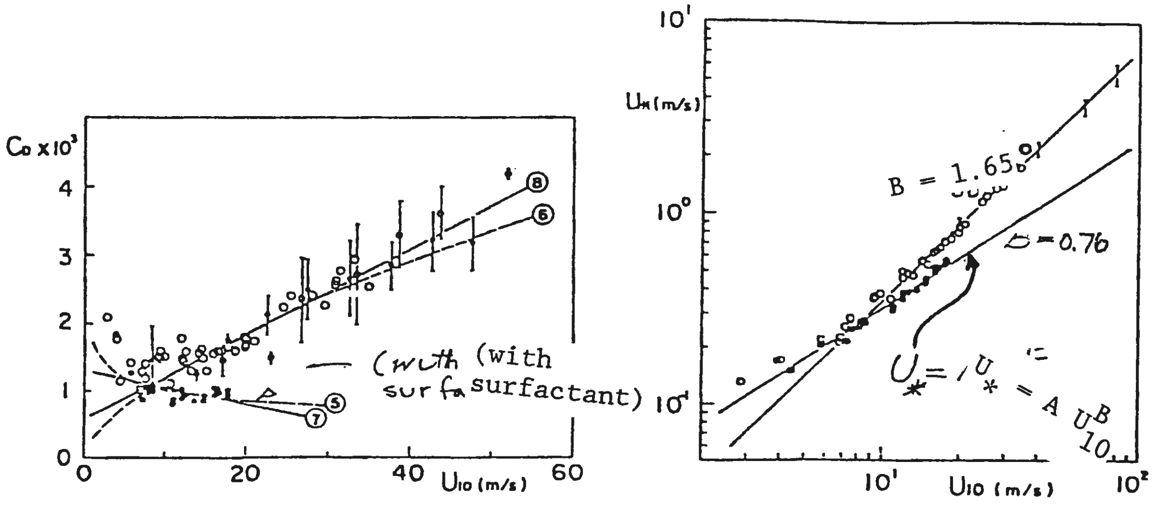


Figure II.4. Spectra of Wind and Waves (30 m/s)



B = 0.76

Figure II.5. Drag Coefficient over Water Surface Under the Action of Strong Wind

$$c = g/\omega \qquad (3)$$

Thus we find the important result that the wave with frequency ω_o travels with a speed equal to the wind speed $U_{19.5}$; this windspeed is then only 88 percent of the speed of the wave at the peak of the spectrum with frequency ω_p. The windspeed is slower than the dominant wave. This feature is clearly not represented by rigid waves in a wind tunnel. Waves whose frequencies are higher than ω_o however move more slowly than the wind.

The P-M spectrum holds for "fully developed sea states" in which the wind has been blowing steadily for some hours and an equilibrium is reached. If the fetch or the curation of the wind is not long enough, the spectrum will be lacking in low frequency components as indicated in the Jonsrap spectrum. The process of wave generation by wind and its dissipation are still not totally understood although it is the subject of an extensive literature. One point is certain and that is that the phase of the pressure at the wave surface must be shifted relative to the surface elevation (and to the "potential flow" pressure).

The first theory for wave generation, by Jeffreys (1924, 1925), suggested that the down wind slope of the wave is sheltered and the pressure there is reduced and increased on the upwind face. This produces a form drag on the wave and the fractional wave energy increase per wave cycle per unit area of the sea surface is

$$2\pi\zeta = 2\pi\ C_s|U/c - 1|\ (U/c - 1) \qquad (4)$$

where C_s is a "sheltered coefficient". The absolute value sign allows for the possibility that waves are moving both with and against the wind. In the latter case the waves are dissipated. Experiments in a wave/wind tunnel by Donelan (1983), as well as results by Hsiao and Sheridin (1983), suggest that the value of C_s is roughly 0.11 for "swell" with a predominant frequency for both production and attenuation.

Equation (4) helps explain why waves near the characteristic frequency ω_o, when $(U/c - 1) = 0$, take a long time to be generated, while much smaller waves grow more rapidly. The theory does not clearly explain the growth of waves near the peak frequency. (It is speculated here that low frequency turbulence may contribute to this process).

Because the largest waves are moving as fast as the wind they contribute much less to the drag than the smaller, slower moving waves, which also break. This movement of the larger waves presents a moving floor boundary to the wind and explains the low surface resistance of the ocean relative to the size of the roughness elements.

Larger waves will only follow changes of wind direction after a considerable time lag. Thus shifts in wind direction can be accompanied by dramatic changes in surface drag (particularly in a hurricane, for example, when the shift may be 180° and the wind then moves against the waves generated earlier). This has been discussed by Donelan (1982).

The consistency of wind/wave drag coefficients in the ocean and in the wind/wave flume has been shown by Mitsuyasu and Kusaba (1984) (see Figure II.5). In the lower curves the water has a surface film of surfactant inhibiting the development of waves. The upper points are from hurricane data.

WIND/WAVE MODELLING

The modelling of structures to wind waves was discussed in a valuable paper by Plate and Nath (1969). Wind wave modelling depends primarily on Froude number scaling in which the velocity is the square root of the length sealing. Given a long enough fetch the wave spectrum will conform to the fully developed spectrum in equation (1). If the fetch is not long enough the longer wavelengths will not reach their fully developed state. The additional input of a wave paddle can then be used to supplement the low frequency end of the spectrum. Given these conditions the study of wind and wave action should be represented with improved similarity.

The full description of the wind and wave facility at the Boundary Layer Wind Tunnel Laboratory is described in Davenport et al. (1985).

SPECTRA OVER THE SEA

The low natural frequencies of compliant structures has emphasized the importance of defining the spectrum of the wind over the sea in this frequency range (Vickery, Vickery, Davenport, 1985). An opportunity for such a study arose using data obtained from a rig 10 km due east of Sable Island. Readings from the anemometer on the oil rig required significant corrections for position (as much as 50 percent on the turbulence intensity) and ±10 percent on the mean. Spectra from moderately strong winds are compared in Figure II.6. The extended low frequency range for the west wind spectra contrast with the much higher frequency energy peak for the easterly winds. This suggests a range of spectral intensities may be needed for design at this end of the frequency range.

OTHER WIND/WAVE STUDIES

Icebergs

Since the days of the Titanic the threat of icebergs off the Newfoundland Coast has been real, no less to offshore structures. The prediction of their movement is difficult as the erratic movements in Figure II.7 indicate. The contributing factors to their motion include the wind induced current, the wind drag, the underwater drag, the wave drift and the coriolis force (Figure II.8). Attempts (Sodhi and El Tahan, 1980) to identify the variability of these components are being made currently.

Oil Spills

The tracking of soil spills is an important environmental exercise. Its effective cleanup is equally important. The prediction of the movement of the center of mass of the spill relies mainly on meteorological and tide information in which it is assumed that the water surface moves at 3 percent of the windspeed (Lawrence and Trites, 1983). The dispersion by wave action is a more local phenomenon and the effective means for cleanup can be tested in the wind/wave test environment.

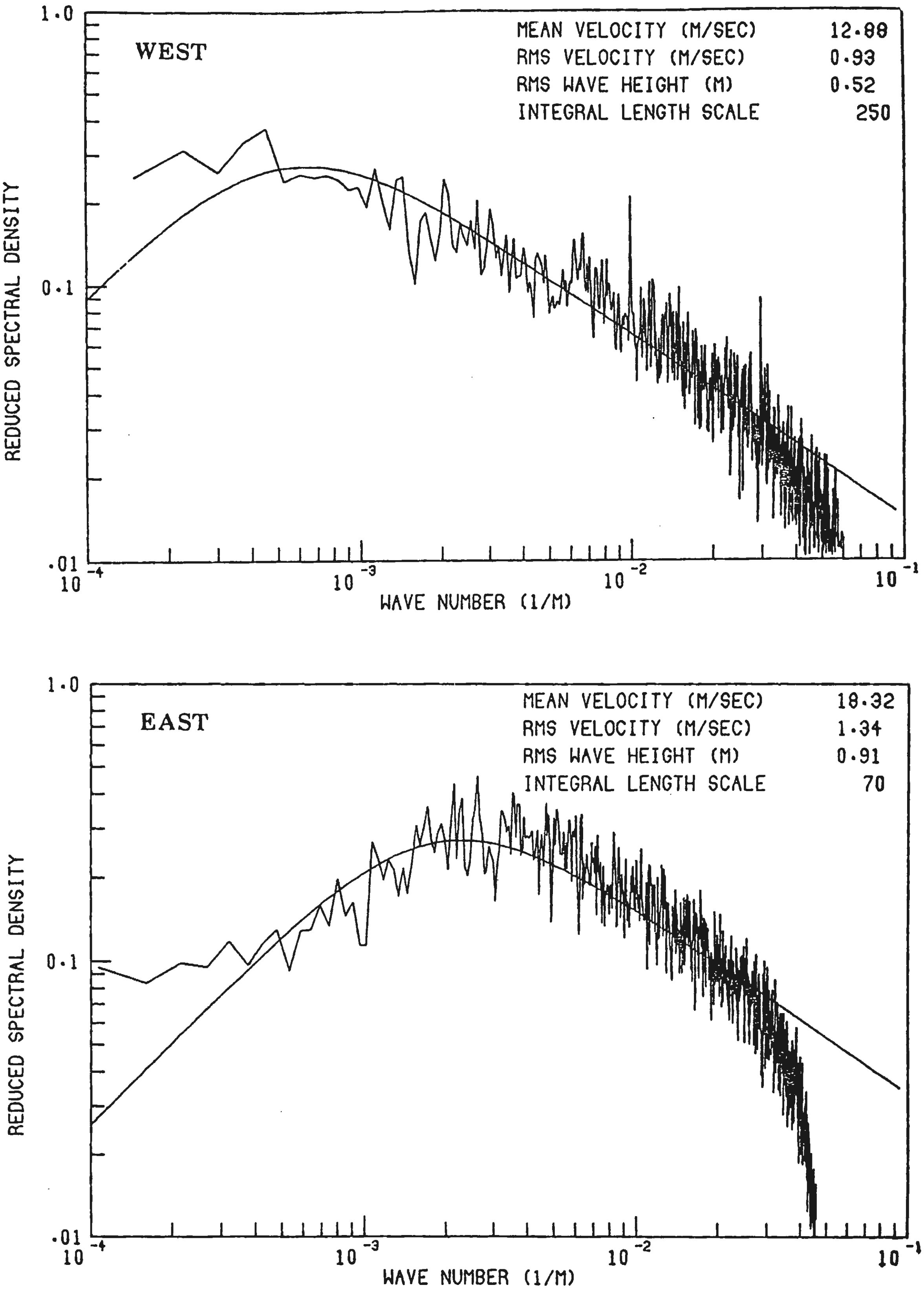


Figure II.6. Wind Speed Spectra Off Sable Island

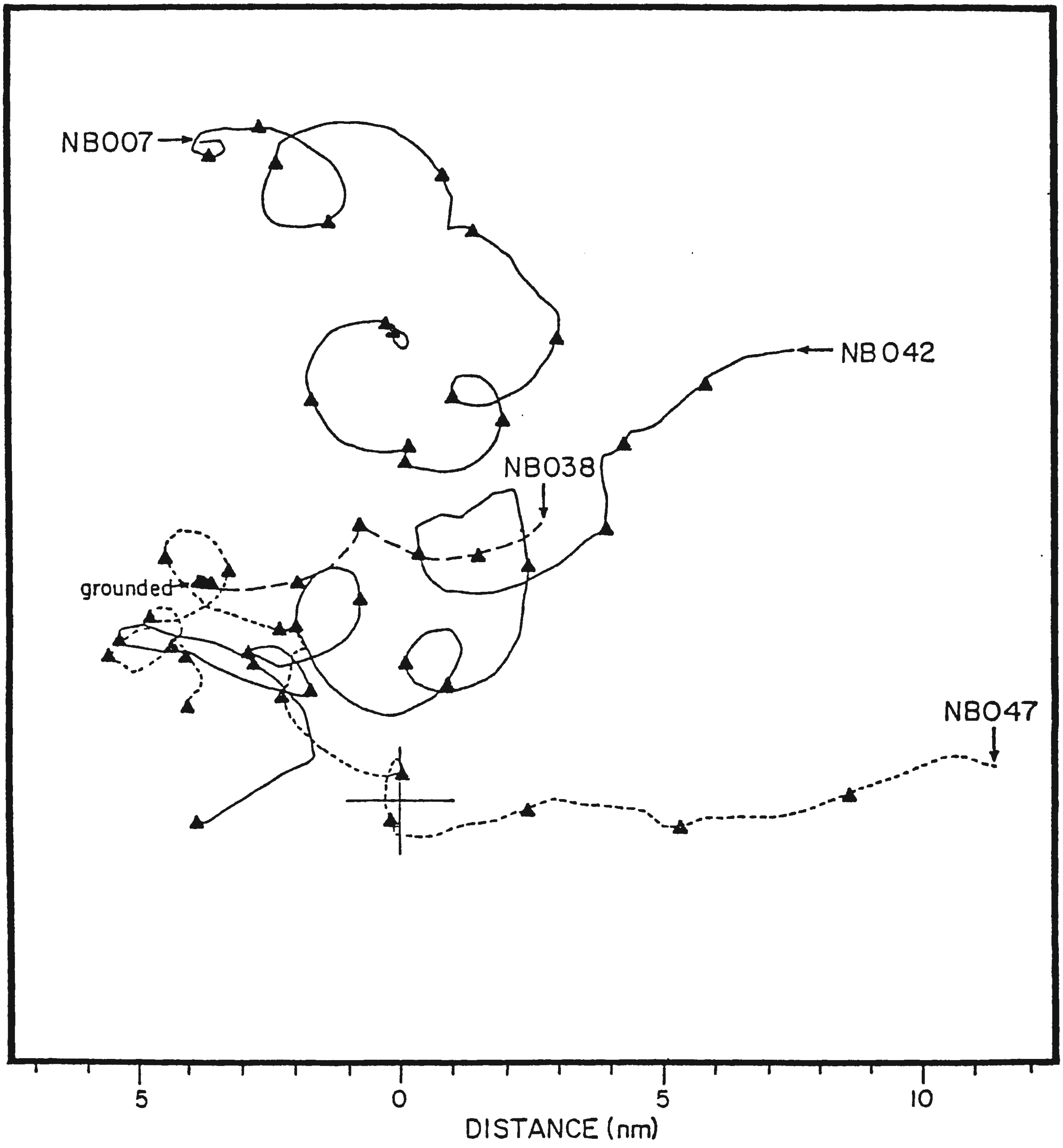


Figure II.7. Iceberg Drift

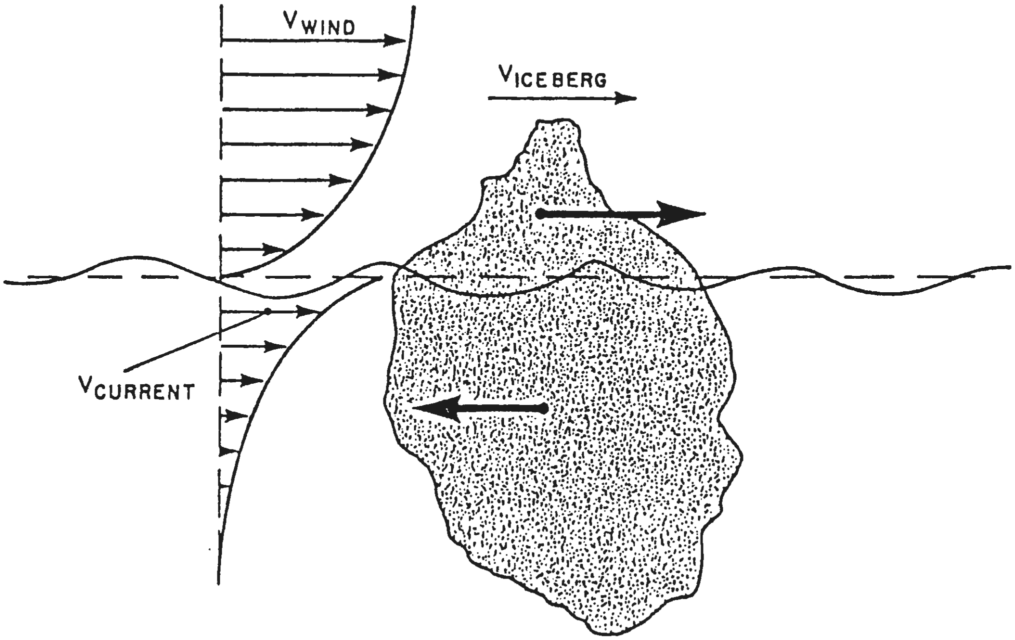


Figure II.8. The Components of Iceberg Drift

Figure II.9.

Sailboats

The art of sailing has been somewhat resistant to research partly due to the lack of appropriate facilities. Dynamic testing of sail boat models can now be considered (Figure II.9) (Killing, 1972; Jackson, 1982).

CONCLUSIONS

The above remarks have been intended to introduce wind engineers to the extensive boundary layers over the ocean, the complex interaction with the waves and a few important problems deserving study.

REFERENCES

1. Aiston, S. T., and Nath, J. H., "Wind Drag Coefficients for Bluff Offshore Ocean Platforms," Proc. OTC, Paper 1068, Vol. 1, Houston, 1969.

2. American Bureau of Shipping, "Rules for Building and Classing Mobile Offshore Drilling Units," 1983.

3. American Petroleum Institute, "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms," 1984.

4. Anon, "Report One: The Loss of the Ocean Range and Its Crew," Royal Commission on the Ocean Ranger Marine Disaster, Canadian Govt. Supply & Services, 1984.

5. Bjerregaard, E. T. C., and Sorenson, E. G., "Wind Overturning Effect on a Semisubmersible," 13th Offshore Technology Conference, OTC 4124, 1981.

6. Bjerregaard, E. T. C., and Velshou, S., "Wind Overturning Effect on a Semisubmersible," 10th Offshore Technology Conference, OTC 3063, 1978.

7. Boonstra, H., and Leynse, C., "Wind Tunnel Tests on a Model of a Semi-submersible Platform and Comparison of the Results with Full Scale Data," 14th Offshore Technology Conference, OTC 4245, 1982.

8. Boonstra, H., "Analysis of Full Scale Wind Forces on a Semi-submersible Platform Using Operator's Data," 11th Offshore Technology Conference, OTC 3623, 1979.

9. Davenport, A. G. and Hambly, E. C., "Turbulent Wind Loading and Dynamic Response of Jack-Up Platform," 16th Offshore Technology Conference, OTC 4824, 1984.

10. DeSouza, P., and Miller, N. S., "The Intact and Damaged Stability Behavior of Two Semi-submersible Models Under Wind and Wave Loading," 10th Offshore Technology Conference, OTC 3298, 1978.

11. Det Norske Veritas, "Rules for the Design, Construction and Inspection of Mobile Offshore Structures," 1984.

12. Donelan, M., "Attenuation of Laboratory Swell in an Adverse Wind," Scripps Inst. of Oceanography Advanced Study Program, Dec. 1983. To be published in Interactions of the Atmospheric and the Upper Ocean by Springer Verlag.

13. Donelan, M. A., "The Dependence of the Aerodynamic Drag Coefficient on Wave Parameters," ICMA/SICZ, Hague, Netherlands, American Met. Soc., 1982.

14. Ellers, F. S., "advanced Offshore Oil Platforms," Scientific American, Vol. 246, 1982, p. 39.

15. Freathy, P., "Wind Loads on Floating Offshore Structures," M.E.Sc. Thesis, Faculty of Engineering Science, University of Western Ontario, 1985.

16. Jackson, P. S., "The Science of Sail Design," Proc. of Conf. at the Boundary Layer Wind Tunnel Laboratory, University of Western Ontario, 1982.

17. Jacobsson, P., and Dyne, G., "Reynolds Number Effects in Model Tests with a Four Column Semi-submersible," 2nd Int. Symposium on Ocean Eng. and Ship Handling, Swedish Maritime Research Institute, 1983.

18. Jeffreys, H., "On the Formation of Waves by Wind," Proc. Roy. Soc. A 107, 1924, pp. 189-206.

19. Jeffreys, H., "On the Formation of Waves by Wind II," Proc. Roy. Soc. A 110, 1925, pp. 341-347.

20. Kareem, A., and Dalton, C., "Dynamic Effects of Wind on Tension Leg Platforms," 14th Offshore Technology Conference, OTC 4229, 1982.

21. Killing, S., "A Study of Sail Performance," Bachelors Degree Thesis, Faculty of Engineering Science, The University of Western Ontario, 1972.

22. Kueo, C., et al., "Semi-submersible Intact Stability - Static and Dynamic and Steady Tilt in Waves," 9th Offshore Technology Conference, OTC 2976, 1977.

23. Lawrence, D. J., and Trites, R. W., "Surface Oil Spill Trajectory Modelling for Georges and Browns Banks," Bedford Inst. of Oceanography, Canadian Tech. Report of Hydrography and Ocean Sciences, No. 19, 1983.

24. Macha, J. M., "An Analysis of Wind Tunnel Data and Calculations Based on Classification Society Methods," Technical Report, Texas Engineering Experiment Station, Produced for MS-3 Panel of Society of Naval Architects and Marine Engineers, 1983.

25. Macha, J. M., and Reid, D. F., "Semi-submersible Wind Loads and Wind Effects," Ann. Mtg., Society of Naval Architects and Marine Engineers," Nov. 7-10, 1984.

26. Miller, N. S., "Notes on Wind Heeling Moments on Semi-submersibles," Technical Report NAOE-HL-76-04, University of Glasgow. This note was prepared for Panel 8 of the Offshore Structures Fluid Loading Advisory Group in the U.K. - OSFLAG, 1976.

27. Mitsuyasu, H., and Kusaba, T., "Drag Coefficient of Water Surface under Action of Strong Wind," Natural Disaster Science, Vol. 6, 1984, pp. 43-50.

28. Nath, J. H., "An Experimental Study of Wind Forces on Offshore Structures," N.S.F., PB 198037, Aug. 1970.

29. Numata, E., Michel, W. H., and McClure, A. C., "Assessment of Stability Requirement for Semi-submersible Units," Presented to the Society of Naval Architects and Marine Engineers in the United States, 1976.

30. Pike, P. J. and Vickery, B. J., "A Wind Tunnel Investigation of Loads and Pressures on a typical Guyed Tower Offshore Platform," 14th Offshore Technology Conference, OTC 4288, 1982.

31. Plate, E. and Nath, J. H., "Modeling of Structures Subjected to Waster Waves," Jnl. of Waterways and Harbors Division, ASCE, Vol. 95, Nov. 1969, p. 491.

32. Ponsford, P. J., "Wind Tunnel Measurement of Aerodynamic Forces and Moments on a Model of a Semi-submersible Offshore Drilling Rig," Technical Report R34, National Maritime Institute, 1982.

33. Ponsford, P. J., "Wind Tunnel Measurement of a Lift, Drag and Overturning Moment on a Semi-submersible Offshore Drilling Rig," Technical Report R152, National Maritime Institute, 1982.

34. Rolfsman, H., and Bjerregaard, E. T. D., "Wind Forces on a Semi-submersible," 15th Offshore Technology Conference, OTC 4531, 1983.

35. Rowe, S. J., Brendling, W. J., and Davies, M. E., "Dynamic Wind Loading of Semisubmersibles," RINA Offshore Eng. Group Int. Symp. on "Developments in Floating Production Systems" London, 21-22 March 1984.

36. Sekigawa, T., et al., "Seakeeping Qualities of Semi-submersible Drilling Rig 'Bingo 4000'," Technical Report Overseas 38, Nippon Kokan, 1983.

37. Simiu, E., and Leigh, S. D., "Turbulent Wind Effects on Tension Leg Platform Surge," Nat. Bur. Stds. (U.S.) Building Science Series 151, March 1983.

38. Sodhi, D. S., and El Tahan, M., "Prediction of Iceberg Drift Trajectory During a Storm," Zeet Gletscherk Eiszeit Forsc. Gesh, Klimas, Vol. 1, 1980, pp. 77-82.

39. Troesch, A. W., VanGunst, R. W., and Lee, S., "Wind Loads on a 1:15 Model of a Semi-submersible," Marine Technology, Vol. 20, No. 3, 1983.

40. Tschanz, T., and Davenport, A. G., "The Base Balance Technique for the Determination of Dynamic Wind Loads," Proc. 6th Int. Conf. Wind Engineering, Gold Coast, Australia, 1983.

41. Vickery, B. J., "Wind Loads on Compliant Structures," Proc. Symp. on Ocean Str. Dynamics, Dept. of Civil Engineering, Oregon State University, Corvallis, 1982.

42. Vickery, B. J., and Pike, P. J., "An Investigation of Dynamic Loads on Offshore Platforms," 17th Offshore Technology Conference, OTC 4955, 1985.

43. Vickery, P. J., Vickery, B. J., and Davenport, A. G., "Gust Factors and Turbulence Measured at 50 m over the Sea Off Sable Island," Int. Workshop on Offshore Winds and Icing, Halifax, Nova Scotia, Atmospheric Env. Service of Canada, October 1985.

WIND ENGINEERING PROBLEMS RELATED TO BUILDINGS

Emil Simiu, P.E.
National Engineering Laboratory
National Bureau of Standards, Gaithersburg, MD
and
The Johns Hopkins University, Baltimore, MD

The design of buildings for wind loads has been significantly influenced in the last twenty years by (1) the use of wind tunnels intended to simulate the action of turbulent wind on structures, and (2) the use of probabilistic and statistical tools for the development of loading criteria. Uncertainties related to wind tunnel simulations and to probabilistic modeling have stimulated a considerable amount of research. Nevertheless, a number of important questions remain only partially answered and are the object of disagreement among practitioners. These include:

1. The magnitude of errors due to the imperfect knowledge of the characteristics of atmospheric flows. This problem may be particularly acute for hurricane winds, whose structure appears to differ significantly in the region of highest winds from the structure of extratropical storms.

2. The magnitude of errors due to the imperfect simulation in wind tunnels of various features of atmospheric flows, e.g., integral scales of turbulence, or ordinates of turbulence spectra at and near the fundamental frequencies of vibration of tall buildings.

3. The correct use of directional aerodynamic and climatological data to estimate wind loads corresponding to various mean recurrence intervals.

4. The choice of safe and economical mean recurrence intervals for the design wind loads determined by taking into account aerodynamic and climatological directionality. To insure levels of safety comparable to those inherent in conventional building code approaches, such intervals should in general differ from the standard 50-year interval.

5. The justification for, and the possible modification of, current provisions on allowable stress increases for combinations of dead, live, and wind loads.

The talk is devoted to a brief discussion of these problems.

INDUSTRY VIEWPOINT
4. POWER PLANT DISPERSION

R. L. Claussen, P.E.
United Engineers & Constructors, Inc.
Stearns-Roger Division

This presentation will discuss some of the practical considerations involved in the development of designs for power plant and other industrial facilities. Specifically, several problems are encountered for which current methods of solution are either overly conservative or inadequate. The suggestion is offered that many of these problems might lend themselves to solutions which are more accurate and less costly to determine through the utilization of research and wind tunnel modeling capabilities. Better understanding of the forms for these solutions might then lead to better and less expensive programs for computer simulations which can be placed in the hands of regulators and designers.

Some of the considerations which fall into the category above are:

1. Dispersion problems involving two and three phase changes such as; the condensation of water vapor from cooling tower plumes and subsequent freezing at switchyard and transmission line structures, conditions and patterns for ground level precipitation and fog/snow within cooling tower plumes, and condensation and local deposition of acids from chimney plumes.

2. Problems involving the dispersion of entrained solids such as; patterns for deposition of salts from saltwater cooling tower plumes and other impurities which are concentrated in cooling towers, and patterns for dispersion of radioactive particulates from advanced reactor plant designs employing passive decay heat removal systems.

3. Problems involving the dispersion of radioactive gases which decay to radioactive particulates and are dispersed further.

4. Problems involving the dispersion of dusts resulting from coal pile operations employing varying coals, handling equipment, and dust control measures.

5. Problems involving the dispersion of noise from power and industrial plant operations and the masking effects of wind generated background noise.

6. Structural and dispersion problems involving the wind induced interactions of multiple structures, such as chimneys and hyperbolic cooling towers.

7. Equipment design problems involving wind induced effects on hyperbolic cooling tower performance characteristics.

8. Equipment design problems involving fluid flow characteristics in kiln and furnace ducts and oil shale retort internals.

9. Equipment design problems involving the dispersion of exhaust emission from rocket and jet engine test stands.
10. "Macro" considerations like the model of the North American acid rain phenomena to gain better understanding of the problem in support of appropriate legislation and regulatory control.

WIND ENGINEERING RESEARCH ISSUES IN THE SIMULATION OF THE DISPERSION OF HAZARDOUS VAPORS

Steve J. Wiersma
Gas Research Institute

Wind tunnel simulation of the dispersion of heavier-than-air vapors from potential accidental spills of hazardous liquids is being used to determine safe exclusion zones around industrial facilities. It is desired to determine the confidence limits for wind tunnel simulations so that hazard zones can be determined and excess conservatism in specifying safe exclusion zones can be eliminated. A goal might be to demonstrate a 90-95 percent probability that predicted exclusion distances would be conservative.

PAST RESEARCH

The Gas Research Institute (GRI) has sponsored research since 1979 on the development and use of wind tunnel simulation to determine the dispersion of vapor from accidental spills of liquefied natural gas (LNG). The dispersion of vapors from an LNG spill by an operational accident or construction fault has been identified as the most serious hazard associated with LNG facilities. This is due to the potential for cold LNG vapor, which is a heavier-than-air gas, to carry long distances before diffusing to noncombustible concentrations. A 1977 assessment showed that different dispersion modeling techniques in use at that time, all applied to the same spill, produced dispersion distances to the lower flammability limit that ranged over almost two orders of magnitude. It has been an objective of GRI-sponsored research to evaluate the applicability and accuracy of dispersion modeling techniques, both numerical and physical, to define hazard zones and to evaluate potential mitigation techniques.

Wind tunnel simulations of the 40 m^3 LNG spill tests conducted for the U.S. Department of Energy (DOE) at China Lake Naval Weapons Center in California in 1980 and of the heavy gas dispersion trials conducted for the British Health and Safety Executive at Thorney Island, Great Britain have shown shown support for the validity of relatively small scale modeling (1,2). Experiments which included a large range of conditions for source gas specific gravity, gas flow rate, gas time duration and wind speed were used to examine the deviations in plume similarity resulting from different modeling approximations (3). Wind tunnels were used to examine the interaction of LNG plumes with surface obstructions such as would be found in an industrial facility and with fences and other turbulence generating structures that could be built to enhance the plume dispersion (4,5). Large-scale LNG tests planned for the summer of 1987 at the DOE liquefied gaseous fuels spill test facility have been simulated in pre-trial wind tunnel tests to assist in planning and execution of the field tests, particularly in instrumentation placement (6). And, a guideline for fluid modeling of LNG cloud dispersion has been developed to provide a basis for specification of standardized practices for wind tunnel modeling in future regulations (7). The attached Figure 1 from Meroney (1986) illustrates a performance envelope that was developed for the guideline to show ranges over which scaling parameters must be maintained to produce credible physical modeling. Prototype wind velocity is plotted as a function of the length scale ratio of the prototype to the model. Three regions are shown, where no sealing errors occur, where minor scaling errors occur, and where major scaling errors occur. Operational limitations are shown as follows:

1. Line 1 is the limit of spatial resolution of 2 mm that is considered realistic in the laboratory.

2. Line 2 is a limitation from lateral interference with a spreading dense plume by the wind tunnel walls. This limitation is a function of the wind tunnel dimensions and the vapor generation rate.

3. Line 3 is the limit of wind speeds (0.1 m/s) below which wind tunnels become sensitive to small disturbances, both external and internal, which lead to unrealistic perturbation of the mean flow.

4. Mixing rates associated with molecular diffusion exaggerate dilution at low wind speeds. Molecular dispersion becomes significant at low Peclet/Richardson number ratios; e.g. less than 1500 for unobstructed flows. Line 4 shows this limitation.

5. When the characteristic obstacle Reynolds number falls below 3300, wake turbulence no longer remains similar to field conditions. And when wall roughness Reynolds number falls below 2.5, then the near-wall region may not behave in a fully turbulent manner. The Reynolds number limitation is shown by line 5.

It appears to be possible to meet molecular diffusion and fully turbulent flow constraints only for very modest scale ratios and high prototype velocities. However, many laboratory tests have given satisfactory results while somewhat relaxing the Peclet/Richardson number ratio and Reynolds number criterion.

RESEARCH ISSUES

Based primarily on the past research on simulation of the dispersion of LNG vapors, the following issues need further attention for wind tunnel simulation to be most useful to industry and regulatory agencies in addressing storage and transportation of combustible and toxic fluids. As will be seen, the identified issues are not independent.

1. Confidence limits for wind tunnel simulations need to be better defined.

2. Limitations associated with molecular diffusion need to be better understood. Experimentally, good correlations have been obtained well below threshold valves of the Pe/Ri parameter that have been suggested.

3. The limitations in simulating sharp-edged mixing elements needs to be further researched. There is evidence that the lower validity threshold Reynolds number can be relaxed.

4. Wind tunnel simulation methodology needs to be verified in large-scale tests.

5. The combined complementary use of numerical and physical modeling needs further development. The uncertainties in mathematical

modeling of complex dispersion processes are greatest in the near field where mechanically induced vortex turbulence is present. Conversely, the far field simulation of such complex processes in wind tunnels is limited because of scaling considerations. Consequently, the combination of wind tunnel simulation of near field processes with mathematical modeling of dispersion processes further downfield need to be developed.

REFERENCES

1. Neff, D. E., and Meroney, R. N., "The Behavior of LNG Vapor Clouds: Wind-Tunnel Simulation of 40 m^3 LNG Spill Tests at China Lake, Naval Weapons Center, California," Gas Research Institute Report No. GRI 80/0094, NTIS No. PB82-199027, July 1981.

2. Davies, M. E., and Inman, P. N., "Wind Tunnel Modeling of Thorney Island Heavy Gas Dispersion Trials," Gas Research Institute Report No. GRI 86/0264, September 1986.

3. Neff, D. E., and Meroney, R. N., "The Behavior of LNG Vapor Clouds: Wind-Tunnel Tests on Modeling of Heavy Plume Dispersion," Gas Research Institute Report No. GRI 80/0145, NTIS No. PB83-109868, September 1981.

4. Kothari, K. M., Meroney, R. N., and Neff, D. E., "LNG Plume Interaction with Surface Obstacles," Gas Research Institute Report No. GRI 80/0095, NTIS No. PB82-198995, September 1981.

5. Kothari, K. M., and Meroney, R. N., "Accelerated Dilution of LNG Plumes with Fences and Vortex Generators," Gas Research Institute Report No. GRI 81/0074, NTIS No. PB83-161083, May 1982.

6. Neff, D. E., and Meroney, R. N., "LNG Vapor Barrier and Obstacle Evaluation: Wind-Tunnel Pre-Field Test Results," Colorado State University Report to Lawrence Livermore National Laboratory, September 1986.

7. Meroney, R. N., "Guideline for Fluid Modeling of Liquefied National Gas Cloud Dispersion, Volume I: Instruction Guide, and Volume II: Technical Support Document," Gas Research Report No. GRI 86/0102, May 1986.

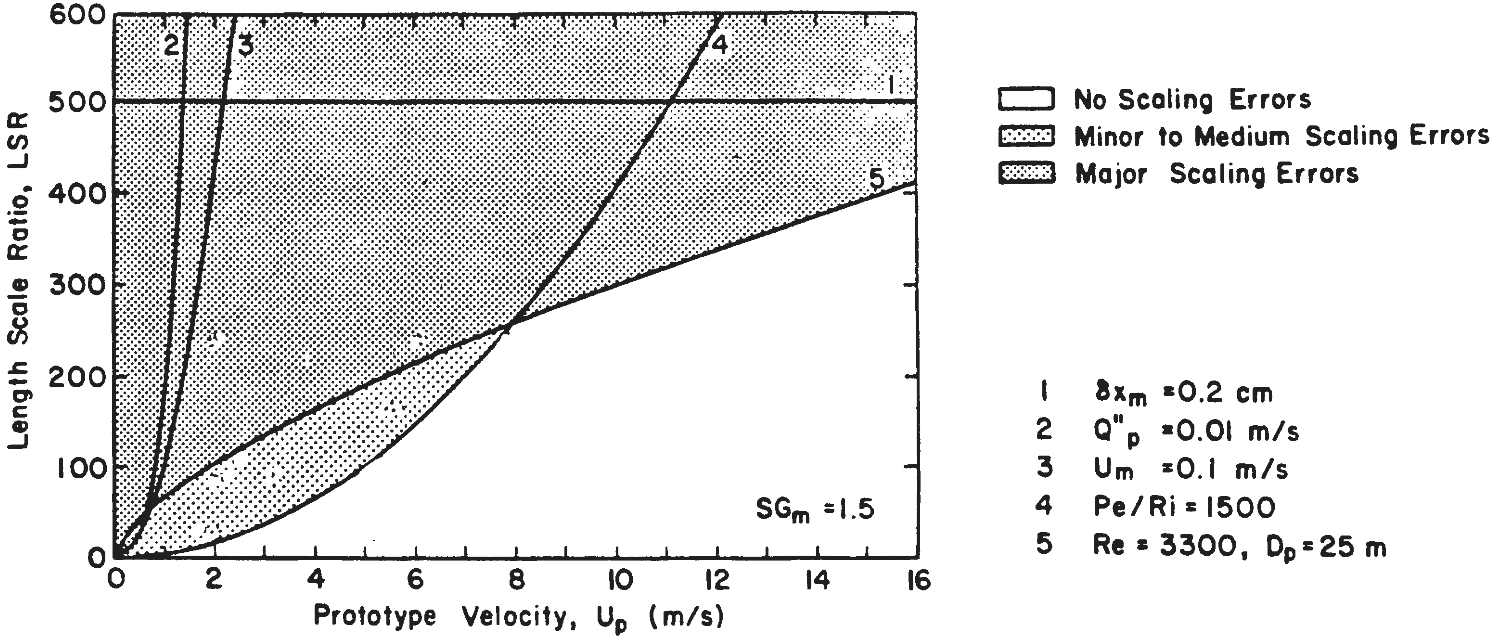


Figure 1. Performance envelope to simulate LNG spills -- constant boiloff conditions, SG = 1.5, tunnel width = 4 m. Length scale ratio vs. prototype wind speed.

Section IV:

WORKSHOP SUMMARIES

Problem Definition

Research Program

WORKSHOP SESSION ON PROBLEM DEFINITION

WIND LOADS

Session Co-Chairmen: Dr. M. Gaus, National Science Foundation
Dr. N. Isyumov, University Western Ontario
Dr. J. A. Peterka, Colorado State University

This Workshop considered various aspects of the action of wind on structures, buildings, components and appendages. To cover a wide range of topics, the Workshop was structured to allow the identification of problem areas and their discussion in eight general topics or themes. These were furnished to the participants at the beginning of the Workshop in order to structure the discussion. There were approximately 35 participants in this Workshop.

The main themes, the identified research needs and a summary of the discussions by participants are provided below. The research needs are believed to represent a general concensus by the Workshop. Their listing is not prioritized. It is not possible to reproduce the discussions in full and the summary; therefore, only attempts to capture the most significant contributions were made.

1.0 WIND STRUCTURE AND CLIMATOLOGY

Identified Research Needs

- Improved understanding and information on the nature and structure of wind in extreme storms including thunderstorm outflows and downbursts, hurricane winds, tornadoes, downslope winds, etc.
- The prediction of the severity and the directionality of extreme winds.
- The selection of an effective equivalent mean wind speed to supplement or replace the fastest mile wind speed as the standard measure of wind speed.
- Improved definitions of the wind structure in complex terrains, including areas with unusual terrain roughness and/or topography.
- The action of wind in combination with other meteorological effects, including temperature, precipitation, snow accumulation, icing, etc.
- The need to define the wind information required for engineering applications and the communication of wind engineering needs to the National Weather Service.

Discussion

- Wind is not a stationary phenomenon and the effects of downbursts and other short duration disturbances are not fully understood nor adequately reflected in current wind data.

- Despite the significant data-base available for extratropical winds there is still a shortage of information on many aspects of the atmospheric boundary layer, including information on the mean wind speed above the surface layer and the structure of turbulence particularly in nonhomogeneous and unusual terrains. Relatively little is known about the structure of wind well above the earth surface. This becomes an important uncertainty for very tall structures, i.e. the "supertall" building.

- There is a need for an international engineering standard for wind data. This would improve data exchange.

- Wind records are often influenced by the local setting and there is a need to examine and improve anemometer sitings. Clearly there would also be advantages in developing more economic and effective instrumentation.

- Micro-zonation of wind has been found effect in complex terrain. This and wind tunnel topographic model studies are useful means to improve the prediction of extreme winds in complex settings.

- The choice of the most suitable measure of the wind speed requires further consideration. The relationships between the average wind speed, the fastest mile and the peak gusts vary with the type of storm system. The use of Durst's curve for relating wind data, obtained with different averaging times, needs further examination.

- There are advantages to phasing out the fastest mile wind speed as the basic wind speed measurement and replacing it with an equivalent mean wind speed. While this has advantages, it is also important to ensure a long-term continuity of wind records. Improved extreme wind speed predictions require long records of wind data with consistent statistical properties. This has implications for wind loading codes.

- More work is needed in determining the duration of wind storms and the resulting exposure of buildings and structures to wind action. Good information on the effective length of wind storms is important for estimates of fatigue damage and the response of buildings and structures in general. There is clearly a need for studying the effects of winds in combination with other meteorological variables. Combined snow and wind or ice and wind loads can be important for some structures. Other important areas involve dust and particle transport as well as the comfort of pedestrians.

- In addition to possible structural effects, the combined action of various weather phenomena has other implications. For example wind affects the performance of rain and snow gauges and can "contaminate" data base.

- We should encourage the self-help collection of local wind and other meteorological data.

- In improving our climatic models of wind speed it is important to look for other sources of data including the National Hurricane Center, the Strong Storms Laboratory and other centers.

2.0 STRUCTURAL LOADS AND RESPONSES

Identified Research Needs

- More work is needed in the area of bluff body aerodynamics. This includes studies of generic shapes and the development of theoretical, empirical and/or numerical models of various wind loading mechanisms like vortex shedding, motion-induced forces or aeroelastic effects and various aerodynamic instabilities.

- Improved understanding of the action of wind on actual buildings and structures with an emphasis on carefully defining the requirements of wind loading information on different structures and developing procedures which would help to limit wind tunnel testing of specific structures to unusual situations.

- Development of improved wind tunnel testing procedures which would allow standardization and which would lead to more consistent and comparable data, generated by various testing facilities.

- The development of wind tunnel facilities which would allow studies of the effects of nonboundary layer and nonstationary winds such as experienced during tornadoes, in the eyewalls of hurricanes, during thunderstorms, etc.

- There is a need to examine action of wind on non-engineered structures, such as residential houses, which to-date have received less attention from wind tunnel researchers.

- Deliberate efforts are needed to develop procedures which adequately take into account the influence of terrain and neighboring structures and how these may change over the life of a structure.

- Attention is needed to wind related serviceability considerations including, inter-storey drift and its effect on cladding; damage to interior walls and finishes; possible fatigue; and the effects of wind-induced motions on building occupants. The latter is particularly important for tall buildings and more consistent and widely accepted criteria are needed for limiting wind-induced accelerations.

- A great deal of data are available from wind tunnel studies of specific buildings and structures. It is highly desirable to "distill" such data into generic structures and aerodynamic shapes and to use such data-bases for improving codes and for providing information in situations, where a specific wind tunnel study cannot be justified.

Discussion

- Extreme wind loads used for design are predicted from the tails of extreme value distributions of wind speed where indeed there are few data. There is a need to examine these procedures and develop new approaches to the prediction of extreme winds, loads and responses.

- In the dynamic analysis of civil engineering structures it is common to assume that the degree of freedom are uncoupled and that the motions of the structure along particular directions are independent. In reality, there can be significant coupling between the degrees of freedom and a three-dimensional dynamic analysis is needed to properly define structural behavior. It was pointed out that it is important for designers to realize that both the forces and the dynamic responses of all structures tend to be three-dimensional.

- There was considerable discussion regarding the use of the high-frequency base balance for evaluating the dynamic wind-induced loads and responses of tall buildings. It was pointed out that procedures are available for allowing for the effects of departures of the mode shape from a linear variation with height and the three-dimensional character of the dynamic response in which particular modes of vibration comprise movements in both sway directions, as well as a rotation about the vertical axis. Additional research is needed in this area.

- More consideration should be given to the proper risk assessment in the design against wind action. The selection of design loads should be based on an acceptable risk for given situations. For example, based on consistent risk design, it may be appropriate to use different wind loads in evaluating structures during their construction. In developing proper risk-based design procedures, it is important to calibrate against current practice.

- It was pointed out that predictions of the response of non-engineered buildings, which are typically designed by code procedures are not well established nor do they necessarily lead to economic design. There is clearly need to examine the action of wind on such structures including their components and connections. It is paramount that there is proper information transfer to designers and builders.

- Developments in wind engineering, in particular the action of wind on buildings and structures, should be of considerable interest to the insurance industry.

- There appears to be a definite need for more information on the dynamic nature of the wind in a form which designers could use. Similarly, more attention should be given to the evaluation of structural behavior including nonstationarities in the loading and nonlinearities both in the structure and in the aerodynamics.

- An important area of uncertainty is the prediction of the likely damping of the structure. There are no reliable procedures for estimating the damping of the structures at the design stage. In contrast, estimates of both the stiffness and the mass can usually be made with confidence. A significant data-base of damping values of actual structures is emerging. A positive step to ensure some minimum effective structural damping, is to deliberately add damping to the structural system. Both tuned-mass dampers and viscoelastic dampers have been successfully used for major buildings. A reliance on added damping is expected to increase as we move towards taller and eventually "super-tall" buildings. Also, there are advantages in examining the effectiveness of various active control systems and aerodynamic appendages.

- There were suggestions for improving the mathematical and numerical modeling of both the wind and structural behavior starting with the structural frame and continuing on with the cladding, its components and connections. At the same time, there appears to be a need for further basic studies of bluff body aerodynamics using generic shapes and different types of turbulent boundary layer flows.

- It was suggested that codes should include requirements for wind tunnel tests for certain types of structures. This requires the development of standard wind tunnel testing procedures. Some of the participants were opposed to strict regulatory measures and favored the inclusion of precautions which should alert designers to the possible need of wind tunnel tests.

- In some situations difficulties arise when wind tunnel tests indicate unusually low loads. Minimum loads should be maintained in such situations in spite of the wind tunnel data.

3.0 CLADDING LOADS AND LOCAL EFFECTS

Identified Research Needs

- Improved specifications of wind loads acting on components of the exterior envelope are needed. Such loads should recognize the sensitivity of different types of cladding to static versus dynamic effects, load duration, differences in material properties and possible local resonances.

- Wind-induced internal pressures can significantly contribute to the loads on the exterior envelope and interior walls and partitions for structures which are partially open or which have aerodynamically dominant openings. It is important to develop analytical and wind tunnel testing procedures for evaluating internal wind pressures in such situations. Also needed are improvements of code treatments of internal pressures.

- Further developments of wind tunnel testing procedures are needed to provide wind loading information required for the design of cladding and glazing components. These should include considerations of the effects of internal pressures. It is also important to ensure that the data generated by wind tunnel studies are properly explained and hence understood by designers.

- Methods for predicting likely loads due to wind-borne missiles and debris.

- Wind loads on appendages, for example microwave dishes, solar panels, billboards, etc. are complicated by the aerodynamic presence of the building or structure and can be more severe. Improved methods for estimating these loads and assisting designers are needed.

- More information is needed on the effects of wind on roofs and roofing systems. This includes information on the stability of roof ballasts and the evaluation of the resistance of roof systems to uplift.
- More information is needed on the behavior of glass under wind loading. Questions of its static fatigue characteristics, its propensity for load capacity reduction from surface scratches during service and its statistical variability all require further investigation.

<u>Discussion</u>

- The majority of the building envelope is currently not designed by professionals. More engineers should take an interest in cladding loads and cladding design rather than leaving this to a few select consultants and the cladding manufacturers.
- The one-minute loading concept, currently used in glass charges, dates back to Thom's work at the U.S. Weather Bureau. The whole question of how glass performs under time varying load warrants more basic research.
- There was extensive support for the need for improved loading specifications and the recognition that these may depend on material properties.
- The duration of storms and hence the persistence of loads should also be considered in attempts to improve load specifications and the performance of cladding systems. Some storms could result in loading durations approaching many hours.
- Some building elements serve as both cladding components, as well as structural elements. Designers should be provided with guidance regarding the applicability of "framing" and "local" loads in such situations.
- Mock-up tests of cladding systems are currently limited to the application of static loads and tests for water infiltration in the presence of a fluctuating load which does not simulate likely full-scale time-varying pressures. There is a need to develop procedures for the dynamic testing of curtainwall mock-ups. Such dynamic loads should reflect estimates of the actual prototype loads to which a curtainwall may be exposed during a period of several years. Also, research programs are needed to examine the behavior and response of in-situ curtainwall systems.
- There is a need for limiting the drift of the building frame in order to limit motion-induced loads on cladding systems. It is not clear that cladding systems are currently properly designed for movements of the structure. The drift of many buildings may be controlled by the floor-to-floor deflection limitations imposed by cladding systems. The requirements of current curtainwall

systems need to be firmly established and communicated to designers. It is also important to develop new cladding systems with relaxed drift requirements.

- There is a need for greater attention on the action of wind on interior surfaces of buildings. These can be significant for structures with aerodynamically dominant openings. Basic research in this area, as well as improved coverage in codes are needed.

4.0 PEDESTRIAN WINDS

Identified Research Needs

- Development of improved criteria for assessing the acceptability of wind conditions in pedestrian areas including considerations of human comfort an safety. Comfort related criteria should include such other parameters as air temperature, relative humidity, etc.

- Preparation of a manual or guide for architects and city planners to indicate aerodynamically desirable trends and to flag potential problem areas at conceptual design. Such a manual should also include a catalogue of mitigating measures from which to draw corrective measures for windy situations.

- Reconciliation of air quality and pedestrian comfort in considerations of the micro-climate of urban areas.

- Development of improved wind tunnel procedures which would allow wind conditions in areas of interest to be studied cost effectively and which would permit greater interaction with designers and city planners. Attention should also be given to improved procedures for combining wind tunnel model findings with local climatic information in order to predict the anticipated wind environment in full scale.

Discussion

- Different test procedure and acceptability criteria now used by different laboratories can lead to different conclusions about the suitability of pedestrian wind conditions. Research is needed to improve acceptability criteria and wind tunnel testing methods.

- It is important that attempts be made to expand acceptability criteria to consider other climatic factors including air temperature, radiation, precipitation, relative humidity, the presence of dust and airborne debris, etc.

- An improved comfort index should consider the desirability of somewhat higher winds in a hot climate and concerns for wind chill in a cold climate. There were questions whether the "comfey" meter, used in ASHRAE criteria for internal spaces, could be extended to apply in outdoor pedestrian areas. Comfort related criteria should not disregard the beneficial effects of wind in diluting the "flushing" out automobile exhausts and other pollutants in built-up city areas.

- Criteria for pedestrian safety also require further consideration as these also tend to depend on weather conditions.

- There is a need for a greater involvement by architects and city planners in studies of pedestrian level winds and the translation of their findings to design. Such involvement should be interactive and are most effective at the conceptual design stage where changes are still possible.

- Systematic research is needed to identify aerodynamically desirable trends and to arrive at effective measures to mitigate specific windy situations. A "catalogue" of mitigating measures, providing information on the effectiveness of various canopies, screens, windbreaks and landscaping elements would be highly valuable.

- Other areas which require information on wind conditions at ground level include local snow drifting and its control, soil erosion, the control of dust and debris, damage and stability of furniture and breakage and long-term growth damage to trees and vegetation.

5.0 CODES AND STANDARDS

Identified Research Needs

- There are several model codes which deal with wind effects now in use in the U.S. Efforts to achieve greater similarity of approach and unification of these codes should be a long range objective.

- It is important to maintain a balance between simplicity and fidelity of building codes.

- Improvements are needed in the definition of wind loads acting on buildings and structures. Particular attention must be given to the development of a vortex excitation loading model for slender dynamically-sensitive structures; the recognition of the eccentricity present in actual wind loads and hence the presence of torsional moments; requirements should be included for the simultaneous application of sway loads and torsion with appropriate joint action or combination factors; and allowances for directional preferences of severe wind speeds. It is also important to expand the aerodynamic data base of codes, including information on wind loads acting on partially clad structures, shielding factors for downstream members in frameworks and latticed and trussed structures and guidance for determining construction wind loads.

- There is a need to develop reliability or risk based wind loading codes.

- It is important to include serviceability criteria dealing with the total and inter-storey drift and occupant perception and tolerance of wind-induced building motions.

- Wind-induced internal pressures can be important for partially open structures and buildings with aerodynamically dominant openings. Improved procedures for including the effects of internal pressures in design are needed. Also included should be guidance for estimating the infiltration through the exterior building envelope and pressure which may develop within cavities or air spaces between cladding elements and interior walls. It is also important to specify some minimum wind-induced loads which may act on internal walls and partitions.

- Some building codes currently allow the use of wind tunnel tests to provide design information. It is important that minimum standards for such tests be established and situations where wind tunnel tests are needed be more clearly defined. It would also be desirable to specify minimum loads below which reductions would not be allowed even on the basis of wind tunnel model tests.

- A considerable body of both wind tunnel and full scale experience is emerging. It is important to accelerate the transfer of new information to codes and performance criteria.

- There is a clear need for a greater education of code users, such as structural engineers and architects, and code officials.

- There are clear advantages in improved numerical methods and shifting towards code formats and approaches which make greater use of computers.

Discussion

- It appears that the ANSI code format is too complex for many uses. The question was raised if the use of computers might simplify the complexity of computations without detracting from the fidelity of the code. Furthermore, commentaries, which better explain the philosophy, the technical data bases and the assumptions, may help designers in understanding and utilizing codes.

- If the ANSI Standard is too complex, would user-friendly software made available for personal and other computers enhance the use of improved wind code provisions.

- Should codes provide more than two levels of complexity; namely, loads acting on essentially rigid structures and those where there is a significant resonant magnification.

- The use of wind tunnel tests as alternative design procedures was extensively discussed. Should tests be mandated for most structures or reserved for special situations. Furthermore, if wind tunnel tests are mandated by code then should the code also mandate the specifications of such tests and require that wind tunnels be properly calibrated.

- The need for more unification or commonality in wind codes was clearly recognized. Attention should also be given to the development of international wind standards.

- The use of allowable stress design tends to obscure the risk and possible consequences of extreme events. Attempts should be made to move towards load resistance-based design. Many of the current procedures are difficult to explain and warrant review in the future. For example, the origin of the 33 percent increase in allowable stresses in situations where wind loads act in combination with dead loads is unclear. Possibly its origin is historic and comes from the increased load resistance of certain materials, for example wood, to loads with short duration.

- It appears that code enforcement is lax and improvements are highly desirable. This may be achieved through education of building officials, architects, inspectors, etc.
- There appear to be difficulties with the effects of missiles, particularly in relation to the performance of the building envelope. It is not clear how the effects of missiles should be handled in codes and further research is needed in this area.
- Building codes have tended to concentrate on the completed structure. Often structures are most vulnerable to wind action during their erection. Codes should provide guidance to designers on wind loads during construction stages.
- Improvements are needed in the specification of design winds in codes. In addition to specifying the severity of extreme wind speeds, it may also be desirable to provide information on the directional preferences of wind storms. Some codes include an allowance for directional effects and provide "effective" aerodynamic coefficients which reflect the unlikelihood of experiencing winds of the same severity from all compass directions. Furthermore, it would be desirable to include provisions for speed-up over hills.
- In addition to dealing with buildings, codes should give attention to the action of wind on other structures including masts, bridges, large roofs, etc.

6.0 FULL-SCALE MEASUREMENTS AND EXPERIENCE

Identified Research Needs

- Full-scale measurements provide valuable validations of codes and wind tunnel methods. There is a need for more benchmark full-scale experiments including measurements of the approach field; overall structural loads and responses; subjective assessments of occupants to building motion; local panel and point loads; interior pressures; pedestrian wind conditions; and various possible effects of new buildings or structures on their surroundings.
- It is important to develop a data base bank which would act as a repository of results from full-scale experiments. Such a bank would provide valuable opportunities for theoreticians, wind tunnel experimenters and code bodies to test and evaluate new ideas and procedures.
- In addition to information on the behavior of buildings and structures during particular storms, information is needed on their long-term performance. An initiative is needed to develop

and fund well designed and well maintained long-term monitoring programs.

- Consideration should be given to some level of mandatory monitoring of the behavior of significant structures and buildings above a certain height. This would make valuable contributions to the full-scale data base. Recent improvements in electronics, instrumentation and micro-processors would allow such monitoring to be carried out at relatively modest cost.

Discussion

- Internal pressures in buildings are difficult to simulate in wind tunnel test and there is a definite need for full-scale observations. In particular, it would be valuable to measure internal pressures in a variety of building and cladding types.

- While the overall behavior of full-scale structures can be measured relatively readily, there are difficulties with measuring ambient pressures and hence pressure coefficients. Full-scale pressure measurements are more effective when dealing with the difference in pressure between locations or differential pressures across exterior surfaces.

- There is a need for an easily accessible data and information base for wind engineering similar to NISEE (National Information Service for Earthquake Engineering) which is operated by the University of California at Berkeley and the California Institute of Technology. Such a service can supply bibliographic and reference material, abstract significant papers and journals and supply computer programs developed under public support or from willing depositors.

- It was felt that the question of mandatory instrumentation for significant buildings and structures should be given serious consideration. Requirements for monitoring the earthquake response of buildings have produced valuable data. It may be feasible to develop a data-chip which would be able to gather response measurements above a preset threshold level. There are low cost "smart" data acquisition systems currently available and marked improvements in technology are expected to be just around the corner.

- Concerns were raised that full-scale data tend to be limited by data quality and format. Clearly, there are definite needs for standardization.

- There is a need to measure meteorological variables together with the wind-induced response. Estimate of the actual wind speed and wind direction would greatly improve the value of the full-scale response data and would permit more meaningful comparisons with wind tunnel and code data.

- There is a need for full-scale measurements of wind loads on generic bluff aerodynamic bodies together with meaningful measurements of the characteristics of natural wind including various properties of atmospheric turbulence with emphasis on measurements of the scales of turbulence.

7.0 INFORMATION TRANSFER

Identified Research Needs

- In addition to establishing data banks, as suggested in connection with other areas discussed at the Workshop, efforts should be made to vigorously disseminate such information to potential users and interested parties.
- Improvements in information transfer would be achieved through greater communication with other disciplines and improved education of city and code officials, and other users such as insurance underwriters, and the public.
- Efforts should be made to take advantage of the rapidly expanding system of computer networks and high density information storage techniques for making wind engineering information available to users.

Discussion

- An opinion was expressed that professional journals, conventional publications and even videos are ineffective means of information transfer to users. Much more effective would be information transfer at the "grass roots" level and on-the-job training.
- Wind engineers should do more "missionary" work and more actively bring their activities to the attention of users and the community at large. It would be particularly important to penetrate professional organizations and to present courses and sponsor sessions on wind engineering for the consumption of other professionals. For example few architects are following current developments in the area of pedestrian level winds and their mitigation. Wind engineers should take this information to architects by participating in their conferences, meetings, etc.
- The enforcement of code provisions by local building officials is important to ensure their correct implementation. Information transfer would be enhanced by requiring more strict code enforcement.
- Users of wind engineering information are often out of date and practice with obsolete technology. It was suggested that researchers have to go to the users -- they will not come to the researchers as easily.

8.0 INTERNATIONAL DECADE OF NATURAL HAZARD REDUCTION (IDNHR)

The IDNHR has been designated as the decade from 1990 to the year 2000. during that decade an international effort will be made to reduce the impact of natural hazards of all types with emphasis on the effects of wind, flood, earthquake, landslide, volcanic activity, wild fires, and tsunami. The U.S.A. is currently in the process of forming a national committee with the intent to participate in the IDNHR. The Committee will seek support from agencies of the U.S. Government and Congress as appropriate. This national Committee may operate under the auspices of the national Research Council. International coordination may be implemented through agencies of the United Nations. Development of research efforts in the U.S.A., related to the mitigation of the effects of wind, should take account of possible international efforts in order to maximize the impact of research funding expended in the U.S.A.

It was felt that the IDNHR provides a unique opportunity to make advances which could not be accomplished with normal uncoordinated efforts. The humanitarian benefits in reducing loss of life and property and human suffering are enormous. There are great opportunities for cooperative research and wide-scale definitive experiments. Such efforts are expected to encourage exchanges of professionals, improve the state of the art of risk assessment and mitigation of hazards around the world, lead t a better exchange of technical information worldwide, and result in the development of information bases which will be of great future value.

WORKSHOP SESSION ON PROBLEM DEFINITION

SCALAR TRANSPORT

Session Chairmen: Dr. R. P. Hosker, ATDL, NOAA, Oak Ridge
Dr. R. L. Petersen, CPP, Inc., Fort Collins
Dr. R. N. Meroney, Colorado State University

The purpose of this session was to identify and prioritize wind-engineering research problems in the area of wind transport of pollutants, particles and particulates. For purposes of discussion, the general topic was divided into four separate areas -- air pollution, hazardous/toxic releases, wind blown particle, and odors. The session chairmen also provided introductory comments to promote discussion. Topic outlines were provided to the workshop participants to provide organization to the deliberation of the session. The topic outlines were expanded or modified by participant discussion. Topics for strategic research which will make a significant contribution during the next twenty-five years were sought.

1. Air Pollution:

Identification of Research Needs

Stationary sources	Small sources	Small industrial Incinerators Wood burning
	Stack design	Flow management Stack exit design
	Near-building and wake dispersion	Reingestion Impact on neighbors Building clusters HVAC placement
	Peak/mean concentration ratios	
	Field study design	Coordination with numerical and fluid modeling Tracer source design Quantification of errors
	Fluid model design	Quantification of errors related to relaxing criteria Simulation of non-stationary phenomena
Transportation sources		Urban highways Tunnels Parking garages

Chemically active sources	Entrainment mechanism Evolving buoyancy Visibility Fluid modeling of phenomena
Indoor air pollution	Natural ventilation Reingestion Mitigation schemes
Complex terrain effects	Source/terrain interaction Effects of local heat sources or uneven heating Stability effects on plume dispersion Effects of vegetation

Discussion

- Recirculation of air pollutants over complex terrain is a major contributor to air pollution incidents, yet current regulatory models do not consider these effects.

- Plume bifurcation downwind of stacks can lead to dispersion significantly different than predicted by regulatory models.

- More research needed on the relationship between dispersion coefficients used in many models and the averaging times used to specify coefficients.

- There is a need to couple the contributions of numerical, physical modeling and field data whenever possible to obtain maximum value from costly field experiments and to take advantage of the talents of each approach.

- Uneven surface heating and wind shear should be incorporated into fluid and numerical modeling approaches.

- Research should begin on more exotic areas such as nonstationary simulation of atmospheric flows, uneven surface heating, convective boundary layers with crossflows, etc.

2. Hazardous/Toxic:

Identification of Research Needs

Source configurations	Existing Optimization
Chemical/phase changes	Entrainment effects Buoyant evolution Dense gas control

Pressurized containers	Release rate effects Pipeline, tankfarm, transportation configurations Optimum facility design
Mitigation schemes	Scenario comparisons Optimum designs
Extreme events	Worst case evaluation Peak/mean ratios

Discussion

- The effect of larger surface roughness elements on heavier-than-air dispersion should be examined. All works to date has been in more-or-less idealized homogeneous terrain. Consider character of petroleum refinery or a chemical complex.

- Better numerical models need to be developed to describe the initial phase of cloud development (jet or spill type releases).

- Methods need to be developed to handle the dispersion/evaporation of droplets formed by pressurized releases.

- Field and laboratory studies are needed to determine the internal character of gas clouds, the correlation of concentration with eddy size and the connectivity of regions exceeding lower flammability limit (LFL) or lethal dosage (LD) levels with gas clouds.

- Studies are needed of the physics of the mixing process across stratified shear layers, which can produce improved numerical turbulence and entrainment models.

- Studies of near-source dilution mechanisms, supersonic decompression, water and steam spray curtains and building aerodynamic interaction with instantaneous plume behavior are desired.

- An evaluation of how two-phase or reactive gas activity influence dilution mechanisms should be completed.

- Terrain effects on heavier-than-air gas cloud transport and dilution should be examined.

3. Wind Blown Particles:

Identification of Research Needs

Physics of sand, soil and snow movement
Fugitive dusts from mining and manufacturing
Mitigation schemes, optimum facility designs
Validation of numerical models

Discussion

- Field data bases for snow and particle accumulations on structures needs to be prepared for comparison with wind tunnel results and codes.
- There need to be an assessment of errors associated with relaxing scaling requirements during fluid modeling.
- General guidelines need to be established for credible simulation of blowing or falling particles.

4. Odors:

Identification of Research Needs

Modes of dispersion	Ventilation transport paths Odor superposition
Mitigation methods	
Verification program	Numerical, physical model and field comparisons

Discussion

- Since odors and hazardous or toxic gases both act over short time periods they require similar research activities.
- The statistic of extreme events need to be further developed for the behavior of gas clouds since most past EPA work ha emphasized long-time (greater than ten minute) averages.
- Plume intermittency needs to be integrated into plume models for odor transport, Gaussian type models are not adequate to define plume boundaries.

Summary Remarks: A repeated theme throughout the discussion was a need for more interaction between the scientists working on field programs, numerical modelers, and physical modelers. Field data is absolutely necessary in order to verify models and identify basic physical phenomena of interest, but greater coordination will lead to more efficient field experiments, better pre-field test planning, more economical experiments, and field data of greater specific value for model verification.

WORKSHOP SESSION ON RESEARCH PROGRAMS

ENERGY

Session Chairmen: N. Kelley, SERI, Golden, CO
A. Lewandowski, SERI, Golden, CO
V. A. Sandborn, Colorado State University
W. Z. Sadeh, Colorado State University

This session was devoted to reviewing issues associated with wind and solar energy of interest to wind engineering. The major issues of importance to wind power are wind prospecting, that includes wind conditions and optimum siting, wind loading on wind turbines, and mechanical-structural optimization of wind turbines. Wind prospecting and wind loading are directly related to wind engineering. Major issues of interest to solar energy are wind loading on collectors and concentrators, wind effects on convection heat transfer, and siting for optimum wind conditions.

1. Review of Wind Turbine Related Problems

Wind Turbines	Contenders	Three blade upwind. Two blade down- and upwind.
Wind Turbine Installation	U.S. Involvement	Foreign designs and manufactures appear to be the major suppliers in the last two years. Number of U.S. manufactures are less than half of the peak year of 1983.
Wind Turbine Design	Machine Size	Large systems all have experienced physical failures, which has led to nearly complete backoff of any current considerations of the large machines for near term use. Smaller (50 kw) machines are only units currently being used.
	Energy loss	Mechanical Downtime 3 to 10% Soiled Blades 1 to 13% Wire Losses 1 to 3% Array Losses 2 to 15% Other 2 to 5%

2. Review of Collector and Concentrator Related Problems

Major Problems	Wind Loads	Protection of fragile collectors and concentrators from high winds
	Contamination	Degradation of reflecting surfaces by contamination

3. Review of Site Locations

Wind Prospecting	Wind Quality	Consistent steady winds with minimum shear and turbulence
	Micro Siting	Local terrain effects on winds
Array Location	Interference	Location of wind turbines so that each unit extracts the maximum energy from the wind

Summary Remarks: Due to the availability of less expensive energy sources wind and solar energy interest has greatly decreased in the past few years. Only limited government and private funding are currently available. The initial experience with large turbine machines and similar large solar collector systems has pointed out the major problems.

WORKSHOP SESSION ON RESEARCH PROGRAMS

SCALAR TRANSPORT

Session Chairmen: Dr. R. P. Hosker, ATDL, NOAA, Oak Ridge
Dr. R. L. Petersen, CPP, Inc., Fort Collins
Dr. R. N. Meroney, Colorado State University

The purpose of this session is to propose appropriate methods to address the problems identified in the previous afternoon session on Scalar Transport, e.g. research management methods, opportunities for cooperative research programs, joint industry/government/university research teams, possible research centers, etc. Only through such cooperation are we likely to address the necessary laboratory-field-numerical model comparisons required for wind engineering credibility.

During the time allocated for this session the workshop leaders would like to obtain participant consensus concerning research strategies that wold expedite the development of new information, engender cooperation and stimulation between members of the research community and industry, disseminate research results and assure maximum benefits for dollars invested. Discussion will focus on the possible advantages and disadvantages of different research strategies. Particular attention will be given to any unique management aspects related to scalar transport problems.

Cooperative research -
- Industry/university/government boards
- Scientific screening committees
- Research working groups
- Seed money for research
- Fund matching programs
- Combined laboratory/super-computer/micro-computer research

Technology utilization -
- Data centers
- Software centers
- Computer-aided instruction
- Co-op training programs
- Industry/university internship programs
- Common report series

Independent research -
- Separate roles of government, university and industry laboratories
- Funding of nontraditional research concepts
- Funding of research projects outside the "master plan"

WORKSHOP SESSION ON RESEARCH PROGRAMS

Session Chairmen: Dr. R. P. Hosker, ATDL, NOAA, Oak Ridge
Dr. R. L. Petersen, CPP, Inc., Fort Collins
Dr. R. N. Meroney, Colorado State University

The purpose of this session was to propose appropriate methods to address the problems identified in the sessions on wind loading, scalar transport and energy e.g., research management methods, opportunities for cooperative research programs, joint industry/government/university research teams, possible research centers, etc.

During this session the workshop leaders sought participant consensus concerning research strategies that would expedite the development of new information, engender cooperation and stimulation between members of the research community and industry, disseminate research results and assure maximum benefits for dollars invested. Discussion focused on the possible advantages and disadvantages of different research strategies.

Topic outlines were provided to the workshop participants to provide organization to the deliberations of the session. The topic outlines were expanded or modified by participant discussion.

1. Cooperative Research

Industry/university/government boards
Scientific screening committees
Research working groups
Seed money for research
Fund matching programs
Combined laboratory/super-computer/
  micro-computer research

Discussion

- Cooperative style research between industry, university and government laboratories should be encouraged. The approach brings a cross-section of abilities, facilities, techniques and instrumentation to bear on a stated problem.

- Money often limits the effective participation of industries both in the wind loading and dispersion areas. Neither the construction industries nor the environmental analysis firms appear to be fiscally or operationally prepared to support basic research from their own resources.

- Cooperative research efforts such as the DOE ASCOT program on complex terrain flows, the EPA dispersion in complex terrain program, or the GRI dense gas dispersion program have effectively integrated researchers working on field data, numerical modeling and fluid modeling.

- Cooperative programs involving many different groups require very strong management to be effective; otherwise frustrating delays can occur related to program deadlines, reports, etc.

- To be effective all research groups should be involved early during development of research plans. It is often difficult to modify research plans for a project already underway.

- Sometimes cooperative efforts try to accomplish too much. Programs should have realistic goals and strong follow-up activities.

- Research programs should be oriented toward long-term goals. Often industry has difficulty focusing attention beyond immediate concerns.

- The concept of a Wind Engineering Research Center was strongly supported, but several participants felt that it was unlikely in the current construction marketplace that industry would ever pick up a significant level of support. Since research often goes to improving or modifying codes and regulatory conditions most commercial businesses do not feel committed to support research which may improve a product but does not make them money.

- Concern was expressed over the tendency for government to funnel research dollars for Universities through national laboratories or centers. It was felt that during times of financial exigency money stayed in the national laboratories and did not reach the university researcher.

2. <u>Technology Utilization</u>

Data centers
Software centers
Computer-aided instruction
Co-op training programs
Industry/university internship programs
Common report series

<u>Discussion</u>

- A software center or central clearing house for wind engineering programs would be a good idea, but it should eventually be self supporting by charging fees.

- Internships have worked very effectively in National Laboratories to transfer ideas between universities and government. DOE, NOAA, EPA, and DOD all have internship programs for university faculty.

- Internships have worked in some cases in Canada, but problem was often Industry awareness of a suitable role of exchange.

3. <u>Independent Research</u>

Separate roles of government, university and industry laboratories
Funding of nontraditional research concepts
Funding of research projects outside the "master plan"

Discussion

- Centers may cause loss of research independence, and the structure may be inhibiting to good research.
- New laboratories are vital because of new people and new ideas. A successful program needs a constant flux of new people and new ideas.
- When national research program plans are tightly defined many researchers find it is difficult to obtain funding for nontraditional research concepts outside the "master plan".

Summary Remarks: In general the participants were comfortable with the concept of combined program, center, or multi-university research activities. Much emphasis was placed on the need for careful and early planning by all participants. Most participants conceded that for most areas of wind engineering that industry is not likely to bear a substantial part of the support cost for research. Substantial contributions made in countries like Japan (i.e., 3% of gross sales by construction industry set aside for research) are legislated by national laws; whereas most contributions in the USA are voluntary (e.g., 0.01% of gross sales by construction industry, see ENR/July 31, 1986).

WORKSHOP SESSION ON RESEARCH PROGRAMS

ENERGY

Session Chairmen: N. Kelley, SERI, Golden, CO
A. Lewandowski, SERI, Golden, CO
V. A. Sandborn, Colorado State University
W. Z. Sadeh, Colorado State University

This session was devoted to identifying and discussion of the advantages and disadvantages of research strategies in the area of wind and solar energy. The use of laboratory wind tunnels to model wind sites and identify local terrain effects has proven feasible. Development of techniques to test the large wind turbine blades under dynamic conditions appears to be of major interest if the large machines are ever to be developed.

1. Siting

Wind Quality	Properties	Identification of scaling parameters Need to match shear and turbulence
Micro Siting	Local	Modeling of local terrain
	Array	Wake interference effects

2. Turbine Modeling

Blade Testing	Scaling	Major requirements of matching actual Reynolds numbers, tip speed, aeroelastic and vortex motions as well as generator interactions

Summary Remarks: Once an area is identified as a feasible wind power site, detailed modeling in the laboratory can inhance the ability to locate the regions of high wind power production. The micro-siting using the wind tunnel could prevent costly mislocations of the wind turbines. The major problems encountered by the large scale wind turbines -- mechanical failure due to loads associated with the wind shear and turbulence as well as rotational effects -- are not easily evaluated in the present laboratory facilities.

Section V:

AFTERWORD

AFTERWORD

The primary objective in formulating the Seminar/Workshop on WIND ENGINEERING: THE PAST TO THE FUTURE was to provide a forum in which the wealth of wind engineering experience on the North American continent could be brought to consider profitable directions for future wind engineering research. Additionally, given the identified research needs, the organizing committee wanted to stress the desirability of planned and cooperative research among universities, industry and government. Finally, we viewed the seminar as an opportunity to celebrate 35 years of service in the fields of Fluid Mechanics and Wind Engineering at Colorado State University.

The degree to which the objectives of the Seminar/Workshop were realized must be viewed in the perspective of the overall goal of WIND ENGINEERING: to provide the engineering community with information about the effects of the wind which will allow the engineer to design for the protection and comfort of the general public. It is clear that, while the formal part of the Seminar/Workshop program is now completed and the attendees have returned home, many problems and research initiatives have been identified, which should keep the Wind Engineering Community busy during the next decade. The Seminar/Workshop was a "beginning, not an end in itself".

Robert N. Meroney, Chairmen and Editor
Seminar/Workshop on WIND ENGINEERING:
THE PAST TO THE FUTURE

APPENDIX

List of Participants

SEMINAR/WORKSHOP ON WIND ENGINEERING: THE PAST TO THE FUTURE

June 4-6, 1987

PARTICIPANT LIST

(as of June 29, 1987)

1. S.P.S. Arya
Dept. of Geosciences
N. Carolina State University
Raleigh, NC 27607
919-737-7002

2. Pres. Philip Austin
Colorado State University
Administration Building
Fort Collins, CO 80523
303-491-6211

3. B. Bienkiewicz
Colorado State University
Civil Engr. B207 ERC
Fort Collins, CO 80523
303-491-8232

4. J.E. Cermak
Colorado State University
Civil Engr. A127 ERC
Fort Collins, CO 80523
303-491-8204

5. Riley Chung
Div. of Geotech Engr/Hazard MIT
2101 Constitution Ave., NW
Washington, DC 20418
202-334-3312

6. Ron Claussen
United Engr. & Constr., Inc.
700 S. Ash St., P.O. Box 5888
Denver, CO 80217
303-692-2604

7. We Clements
Los Alamos National Lab
Group ESS-7 MS-D466
Los Alamos, NM 87545
505-667-2637

8. M.E. Criswell
Colorado State University
B205 Civil Engineering
Fort Collins, CO 80523
303-491-5605

9. Allen Davenport
Boundary Layer Wind Tunnel Lab
University of Western Ontario
London, Ontario, Canada N6A 5B9
519-661-3338

10. J. De Krasinski
The University of Calgary
2500 University Drive NW
Calgary, Alta T2W 2N5, Canada
403-220-7283

11. Russell Derickson
205 E. Plum
Fort Collins, CO 80524
303-482-4389

12. R. Dickeson
University of Northern Colo. &
Governor's Office, State of CO
Denver, CO
303-866-2471

13. Ron Ewald
829 Tyler St.
Fort Collins, CO 80521
303-484-7848

14. Morteza Fartash
Univ. of Missouri-Columbia
Civil Engineering Dept.
Columbia, MO 65211
314-882-6269

15. Paul Filliger
Colorado State University
B321 Engineering Res. Center
Fort Collins, CO 80523
303-491-8659

16. Doug Fox
USDA Forest Service
240 W. Prospect
Fort Collins, CO 80526
303-224-1231

17. H.A. Franklin
Bechtel National, Inc.
50 Beale St., P.O. Box 3965
San Francisco, CA 94119
415-768-8778

18. Mike Gaus
Critical Engineering Systems
1800 G Street, NW
Washington, DC 20550
202-357-9500

19. C.W. Hall
National Science Foundation
1800 G St., NW
Washington, DC 20550
202-357-7717

20. Craig Hansen
Mechanical Engineering Dept.
University of Utah
Salt Lake City, UT 84112
801-581-4145

21. Rayford Hosker
Air Resources, ATDL
Oak Ridge, TN 37830
615-576-1233

22. N. Isyumov
University of Western Ontario
Boundary Layer Wind Tunnel Lab
London, Ontario, Canada, N6A 5B9
519-661-3338

23. Nicholas Jones
The Johns Hopkins University
34th N Charles Street
Baltimore, MD 21218
301-338-7874

24. Rakesh Kapania
Virginia Tech
213E Randolph Hall
Blacksburg, VA 24061
703-961-4881

25. Ahsan Kareem
Dept. of Civil Engineering
University of Houston
Houston, TX 77004
713-749-1559

26. Neil Kelley
SERI
1617 Cole Blvd.
Golden, CO 80401
303-866-7140

27. Richard Klein
University of Illinois
1206 W. Green St.
Urbana, IL 61801
217-333-3299

28. F.A. Kulacki
Colorado State University
Civil Engr. B111 ERC
Fort Collins, CO 80523
303-491-6603

29. Richard Kutz
1200 East Stuart Street #56
Fort Collins, CO 80525
303-493-8590

30. J.T. Lee
Los Alamos National Lab
Group ESS-7 MS-D466
Los Alamos, NM 87545
505-667-2701

31. Vincent Lee
Univ. of Southern California
DRB382, U.S.C. m/c 1114
Los Angeles, CA 90089
213-257-5392

32. Yingcheng Liao
Colorado State University
905 Whedbee St.
Fort Collins, CO 80524
303-484-7116

33. Henry Liu
Dept. of Civil Engineering
Univ. of Missouri - Columbia
Columbia, MO 65211
314-882-2779

34. Paul Lyons
TLMRC
P.O. Box 220
Haslet, TX 76052
817-439-5900

35. Robert McKinley
McKinley Management
P.O. Box 305
Hancock, NH 03449

36. Kevin McNamara
Colorado State University
500 West Prospect Apt. 28K
Fort Collins, CO 80526

37. Bob McNamara
KKBNA Consulting Engineers
100 Broadway
St. Louis, MO 63102
314-421-5073

38. Kishor Mehta
Institute for Disaster Res.
Texas Tech University
Lubbock, TX 79490
806-742-3475

39. R.N. Meroney
Colorado State University
Civil Engr. B219 ERC
Fort Collins, CO 80523
303-491-8574

40. Janet Montera
Colorado State University
Dept. of Civil Engineering
Fort Collins, CO 80523

41. Lawrence Murphy
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401
303-231-1050

42. Fariborz Nateghi
Univ. of Missouri-Columbia
Civil Engineering Dept.
Columbia, MO 65211
314-882-6269

43. Ben Nelson
University of Colorado
6828 Marshall Street
Arvada, CO 80003
303-425-9391

44. John Nelson
Colorado State University
Civil Engr. B204 ERC
Fort Collins, CO 80523
303-491-5048

45. Dale Perry
MBMA
1230 Keith Building
Cleveland, OH 44115
216-468-0328

46. J.A. Peterka
Colorado State University
Civil Engr. A127 ERC
Fort Collins, CO 80523
303-491-8344

47. Ron Petersen
Cermak, Peterka, Petersen, Inc.
1415 Blue Spruce
Fort Collins, CO 80525

48. Roger Pielke
Atmospheric Science Dept.
Colorado State University
Fort Collins, CO 80523
303-491-8293

49. Michael Ratcliff
Cermak, Peterka, Petersen, Inc.
1415 Blue Spruce
Fort Collins, CO 80524

50. Timothy Reinhold
Applied Research Engr. Services
6404 Falls of Neuse Road
Raleigh, NC 27615
919-876-0018

51. K.H. Rhee
Univ. of Missouri-Columbia
Civil Engineering Dept.
Columbia, MO 65211
314-882-6269

52. J.E. Sabadell
National Silver Foundation
Washington, DC 20550

53. W.Z. Sadeh
Colorado State University
Civil Engr. B223 ERC
Fort Collins, CO 80523
303-491-8573

54. V.A. Sandborn
Colorado State University
Civil Engr. B229 ERC
Fort Collins, CO 80523
303-491-8551

55. Robert Scanlan
The Johns Hopkins University
34th North Charles Street
Baltimore, MD 21218

56. E. Simiu
U.S. Dept. of Commerce
National Bureau of Standards
Washington, DC 20234

57. F.W. Smith
Colorado State University
205 ERC, A219 Engineering
Fort Collins, CO 80523
303-491-8657

58. Ben Song
Colorado State University
999 W. Laurel #3
Fort Collins, CO 80521

59. Roger Thompson
U.S. Envir. Protection Agency
MO-81
Research Triangle Park, NC 27711
919-541-1895

60. Charles Thornton
Lev Zetlin & Associates
641 Avenue of the Americas
New York, NY 10011
212-741-1300

61. Sigurdur Thoroddsen
606 Sheldon Dr.
Fort Collins, CO 80521
303-491-8204

62. William Wall
Intnat'l Conf. Bldg. Officials
6738 NW Tower Drive
Kansas City, MO 64151
816-741-2241

63. Wen-Whai Li
Colorado State University
B213 Engrg. Res. Center
Fort Collins, CO 80523
303-491-8580

64. Steve Wiersma
Gas Research Institute
8600 W. Bryn Mawr Ave.
Chicago, IL 60631
312-399-8126

65. John Wiggins
1600 S. Pacific Coast Hwy. ST206
Redondo Beach, CA 90277
213-316-2257

66. Ted Yamada
Los Alamos Nat'l Laboratory
P.O. Box 1663
Los Alamos, NM 87545
505-667-8353

67. Karl Zeller
CSU-CE
3717 NCR 2SE
Bellvue, CO 80512
303-224-1238