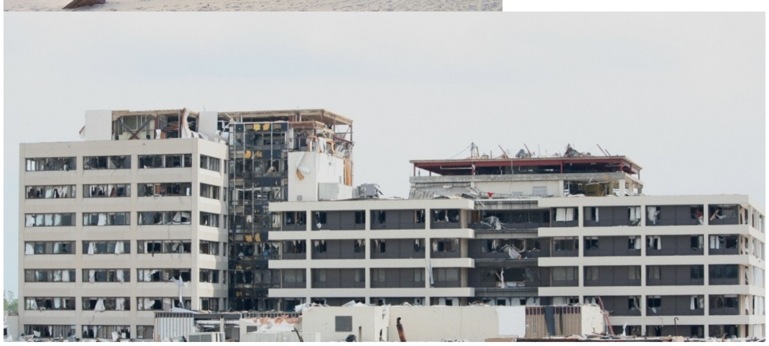
NIST GCR 14-973-13

Measurement Science R&D Roadmap for Windstorm and Coastal Inundation Impact Reduction



NEHRP Consultants Joint Venture
A partnership of the Applied Technology Council and the Consortium of Universities for Research in Earthquake Engineering

National Institute of Standards and Technology
U.S. Department of Commerce

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The Roadmap developmental effort was supported in part by the National Science Foundation (NSF) to obtain input on related long-term fundamental research challenges in windstorm and coastal inundation impact reduction.

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NIST policy is to use the International System of Units (metric units) in all its publications. In this report, however, information is presented in U.S. Customary Units (inch-pound), as this is the preferred system of units in the U.S. earthquake engineering industry.

Cover photos: top photo – condominium building destroyed by storm surge-induced scour during Hurricane Ivan in 2004, in Orange Beach, Alabama (FEMA); bottom photo – severe cladding damage to a hospital caused by wind and windborne debris during the May 22, 2011 tornado in Joplin, Missouri, resulting in the immediate and complete loss of functionality. The entire hospital and associated medical center were ultimately demolished (courtesy of ATC, 2011).

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Prepared for
U.S. Department of Commerce
National Institute of Standards and Technology
Engineering Laboratory
Gaithersburg, Maryland 20899

By
NEHRP Consultants Joint Venture
A partnership of the Applied Technology Council and the
Consortium of Universities for Research in Earthquake Engineering

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U.S. Department of Commerce
Penny Pritzker, Secretary of Commerce

National Institute of Standards and Technology
Patrick D. Gallagher, Under Secretary of Commerce for Standards and Technology and Director

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Participants

National Institute of Standards and Technology

Marc Levitan, Lead, National Windstorm Impact Reduction Program R&D, Engineering Laboratory
National Institute of Standards and Technology

NEHRP Consultants Joint Venture

Applied Technology Council
201 Redwood Shores Parkway, Suite 240
Redwood City, California 94065
www.ATCouncil.org

Consortium of Universities for
Research in Earthquake Engineering
1301 S. 46th Street, Building 420
Richmond, California 94804
www.CUREE.org

Joint Venture Management Committee

James R. Harris
Robert Reitherman
Christopher Rojahn
Andrew Whittaker

Joint Venture Program Committee

Jon A. Heintz (Program Manager)
Leighton Cochran
Kurtis Gurley
Spencer Rogers
Donald Scott
Joseph Shepard
Thomas L. Smith

Project Technical Committee

William L. Coulbourne (Project Technical Director)
Jon Galsworthy
Horia Hangan
Christopher Jones
Chris Letchford
Thomas L. Smith

Project Manager

William L. Coulbourne

Preface

In October 2011 the NEHRP Consultants Joint Venture, a partnership of the Applied Technology Council (ATC) and the Consortium of Universities for Research in Earthquake Engineering (CUREE), commenced a task order project under National Institute of Standards and Technology (NIST) Contract SB1341-07- CQ-0019 to develop a Measurement Science Research and Development (R&D) Roadmap to Reduce the Impacts of Windstorms and Coastal Inundation Hazards. The roadmap, to be developed by wind and coastal engineering practitioners and researchers from across the nation, was to incorporate a broad strategic approach and objectives for buildings, structures, and lifelines, including both new and existing construction.

The impetus for the project was the extensive property losses and casualties that have occurred over the last several decades as a result of damaging hurricanes, such as Hurricane Katrina, and severe tornadoes affecting the coastlines and interior portions of the nation. NIST's interest in the project stemmed from the agency's desire to expand its existing research and development capabilities in earthquake hazard reduction and fire engineering to include efforts to reduce the impacts of other hazards.

The roadmap development process included a review of the literature that identified research needs in the area of windstorm and coastal inundation hazards reduction, two workshops to obtain input from the nation's specialists in windstorm and coastal inundation hazard reduction, and an extensive roadmap preparation and review process.

The roadmap identifies a broad range of research and development activities for reducing the impacts of severe windstorms and coastal inundation hazards. The report includes:

- A vision for windstorm and coastal inundation resilient communities;
- A list of grand challenges in windstorm and coastal inundation impact reduction;
- Detailed descriptions of thirty priority research and development topics; and
- A proposed program of prioritized research and development activities, and their associated benefits.

The NEHRP Consultants Joint Venture is indebted to the leadership of William Coulbourne (ATC Director, Wind and Flood Hazard Mitigation), who served as

Project Technical Director and is the principal author of this report, and to the members of the Project Technical Committee, consisting of Jon Galsworthy, Horia Hangan, Christopher Jones, Chris Letchford, and Thomas L. Smith, for their contributions in developing this report and the resulting recommendations. Appreciation is also extended to the many individuals who participated in two workshops that were conducted as part of the roadmap development process, and to the National Science Foundation, who provided partial funding for the initial workshop and for the identification of grand challenges in windstorm and coastal inundation impact reduction. The names and affiliations of all who contributed to this report are provided in the list of Project Participants and in Appendices B and C.

The NEHRP Consultants Joint Venture also gratefully acknowledges Marc Levitan and Eric Letvin (of NIST) for their input and guidance in the preparation of the report, and Amber Houchen for ATC report production services.

Christopher Rojahn
ATC Executive Director

Table of Contents

List of Figures

List of Tables

List of R&D Topic Summaries

Executive Summary

Windstorms, storm surge, and other coastal inundation events caused 4,045 fatalities and property losses of $250 billion (in 2012 dollars) in the United States during the period of 1996-2012. More people are moving toward the nation's coastlines and thus more of the built environment is at risk from hurricanes and nor'easters and/or coastal inundation due to storm surge and tsunamis. In addition, a large part of the central United States is at risk from tornadoes, and all areas of the country can experience damage from other types of windstorms, such as thunderstorms, derechos, and straight line winds. Sometimes effects to a community are so great from the windstorm and coastal inundation events, the community never recovers, as the tax base moves away and businesses and schools stay permanently closed. The current state of practice for engineering design of the built environment to withstand extreme wind and coastal flood events must be improved in order to improve life safety, reduce property damage, and improve the resiliency and sustainability of communities.

This report describes results from a measurement science research and development (R&D) roadmap development process to identify and describe a much-needed problem-focused program to reduce the impacts of windstorms and coastal inundation hazards. This report is also intended to aid and provide focus for the broader wind, coastal, and structural engineering R&D community. The effort was conducted to assist the National Institute of Standards and Technology (NIST) in planning its research and development program related to these hazards over an approximately eight-year time frame. A Project Technical Committee comprised of practitioners and academics provided guidance for this project. As a starting point, research recommendations from past reports by the National Research Council, National Science Board, National Science and Technology Council, NIST, and other organizations were identified and reviewed. A two-day workshop of industry's leading practitioners, academics, and representatives from key government agencies was convened to identify the highest priority needs that form the basis of this roadmap. The workshop was co-funded by the National Science Foundation (NSF), with the aim to leverage this effort to also identify fundamental research challenges on a longer time frame than NIST usually operates within. A second half-day workshop was held to help refine and prioritize the specific topics identified in the first workshop. The 30 most relevant and needed research and development topics identified through these workshops are summarized in Table 1. The priorities are illustrated by color (legend is at the bottom of the table). The topics are grouped into four categories: (1) hazard identification; (2) hazard-specific loads and effects; (3) building-specific resistance; and (4) hazard-specific performance-based design.

The report also provides details on each recommended research and development topic, including (1) a description; (2) its estimated cost; (3) the estimated time to carry out needed R&D pertaining to the topic; (4) challenges in conducting the needed R&D; and (5) potential R&D solutions. For each topic, example stakeholders, and their respective roles, are also identified, as well as the significant impacts of the R&D to both engineering practice and community resilience, once the R&D is successfully completed and implemented. Also included in the report are explanations of how priorities for the R&D topics were assigned by workshop participants.

The proposed program description includes discussions on budgetary requirements, schedule and benefits. In cost terms, the program starts at a level of $4.0 million per year and quickly grows to $6.0 million per year over eight years. For the nation as a whole, implementation of the proposed R&D program will yield the following major benefits:

1. Reduced loss of life, injury, damage and economic impact following wind storm and coastal inundation events.
2. More resilient communities through faster recovery following wind storm and coastal inundation events.
3. Reduced costs through risk-consistent design and construction of the built environment subject to wind storm and coastal inundation events.

Table 1 Recommended Windstorm and Coastal Inundation Hazard Reduction R&D Topics

No.	Wind Topics	No.	Coastal Inundation Topics
	Hazard		
1	Hazard maps for high intensity non-synoptic events, including tornadoes	20	Quantification of flood-borne debris hazards
3	Quantification of wind-borne debris hazards	21	Effects of over-land flow on waves and other coastal inundation hazards
5	Joint description for hurricane wind, storm surge, and wave hazards	22	Characterization of the coastal inundation hazard for low probability events
2	Effects of climate change on extreme wind event characteristics	19	Effects of sea level rise and future shoreline changes on coastal inundation hazards
4	Hazard modification by terrain, topography, and nearby buildings		
	Loads and Effects		
6	Pressure coefficients for wind load determination	23	Field data collection of flood loads
7	Computational fluid dynamics (CFD) tools for practitioners	24	Load combinations for simultaneous flood hazards.
8	Rational approach for wind load analysis	25	Validation of flood forces on buildings
9	Modeling and simulation for determination of wind loads due to non-synoptic winds, including tornadoes		
	Resistance		
14	Guidelines for wind vulnerability assessment of existing buildings	26	Flood damage functions and fragility curves.
11	Field measurement techniques and test methods to evaluate condition of existing construction	27	Effects of erosion and scour on deep foundations
13	Methods or models to predict loss of strength due to aging and deterioration	28	Test methods for materials and systems subject to flooding
10	Test methods for resistance to cyclic loading		
12	Explicit factors of safety for materials and assemblies		
	Performance-Based Design		
15	Performance levels and acceptance criteria for wind hazards	29	Performance levels and acceptance criteria for buildings subject to coastal inundation
18	Measurement of windstorm resilience and benefits of performance-based design	30	Sound engineering basis for flood resistant design that is not based on flood insurance requirements
16	Analysis procedures for nonlinear system behavior used in performance-based design		
17	Cyber-based tools to support performance-based design		

Legend: Highest priority R&D topic; High priority R&D topic; Medium priority R&D topic

Chapter 1

Introduction

The National Institute of Standards and Technology (NIST) has a long history of research and development (R&D) in wind engineering and windstorm impact reduction, and has more recently expanded its R&D efforts to include coastal inundation, following Hurricane Katrina in 2005. With growth in these activities and with increasing national understanding of the significance of windstorm and coastal inundation disasters on the national ability to respond to and recover from these events, NIST has determined there is a need for a detailed *measurement science*[1] roadmap that identifies critical windstorm and coastal inundation impact reduction research and development priorities, to assist NIST with planning its research over the next decade. This roadmap will also aid and provide focus for the broader wind, coastal, and structural engineering R&D community.

1.1 Background

From 1996 to 2012, windstorms and coastal inundation events caused 4,045 fatalities in the United States and U. S. property losses of $250 billion (in 2012 dollars)[2]. More people are moving toward the nation's coastlines and now 40% of the U.S. population lives along the coasts (NOAA, 2013b). Thus, much of the built environment in coastal areas is at risk from hurricanes and nor'easters and/or coastal inundation due to storm surge and tsunamis. In addition, a large part of the central United States is at risk from tornadoes where wind speeds can significantly exceed those from hurricanes, and all areas of the country can experience damage from other types of windstorms, such as thunderstorms, derechos, and straight line winds. Impacts from these windstorm and coastal inundation events are not limited to fatalities, injuries, and property damage, but also include closed schools and businesses, people out of work, and damaged infrastructure, all making community recovery a long and expensive process. Sometimes, effects to a community are so

[1] As defined by NIST, the term *measurement science* includes "the development of performance metrics, measurement methods, predictive tools, and protocols as well as reference materials, data, and artifacts; the conduct of inter-comparison studies and calibrations; the evaluation and/or assessment of technologies, systems, and practices; and, the development and/or dissemination of technical guidelines and basis for standards, codes, and practices—in many instances via test beds, consortia, and/or other partnerships with the private sector."

[2] Fatality and property loss figures developed from data published by the National Oceanic and Atmospheric Administration (NOAA, 2013a)

great, the community never recovers as the tax base moves away and businesses and schools stay permanently closed. The current state of practice for engineering design of the built environment to withstand extreme wind and coastal flood events must be improved in order to improve life safety, reduce property damage, and improve the resiliency and sustainability of communities.

NIST research related to windstorm and coastal inundation impact reduction is part of the Engineering Laboratory's Structural Performance under Multi-Hazards Program, whose objective is "to develop and deploy advances in measurement science to enhance the resilience of buildings and infrastructure to natural and manmade hazards." As one of the agencies of the National Windstorm Impact Reduction Program (established by the National Windstorm Impact Reduction Act of 2004 (Public Law 108-360)), NIST also has specific responsibilities to "support research and development to improve building codes and standards and practices for design and construction of buildings, structures, and lifelines."

1.2 Roadmap Scope and Purpose

The scope of the roadmap addresses impact reduction from (1) damaging windstorms, such as hurricanes, tornadoes, thunderstorms, derechos, and straight line winds, and (2) coastal inundation, caused by storm surge and tsunamis. High priority needs for both industry practice and for standards and model codes are included in the roadmap.

The roadmap is intended to help guide NIST's investment in windstorm and coastal inundation impact reduction research. The rationale for public investment in these areas includes loss reduction potential (reduced fatalities, injuries, property loss, and business interruption; continuity of operations; community resilience) and enabling innovation in materials, design, construction, and retrofitting through performance-based engineering, standards, and model codes.

1.3 Roadmap Development Process

The starting point for the roadmap development process was an initial effort to identify recommendations from the research needs literature. A two-day workshop of invited specialists in windstorm and coastal inundation was then convened in June 2012 to identify the highest priority research and development needs, which were refined at a follow-up half-day workshop in October 2012. This report provides a synthesis of the information gathered through the review of the literature and both workshops. A Project Technical Committee consisting of several leading practitioners and academics in the areas of wind engineering and engineering for coastal hazards provided guidance throughout the roadmap development process.

Reports identified during the review of research needs literature of the past 20 years related to windstorm and coastal inundation impact reduction included publications by the National Research Council, National Science Board, National Science and Technology Council, NIST, and other organizations. A total of 20 publications were reviewed, including the traceable documents listed below.

- *Wind and the Built Environment, U.S. Needs in Wind Engineering and Hazard Mitigation*, National Research Council, 1993;
- *Windstorm Impact Reduction Implementation Plan*, National Science and Technology Council, April 2006;
- *Hurricane Warning: The Critical Need for a National Hurricane Research Initiative,* National Science Board of the National Science Foundation, January 2007;
- *Grand Challenges for Disaster Reduction*, National Science and Technology Council, Subcommittee on Disaster Reduction, 2008;
- *Disaster Resilience: A National Imperative*, National Academies Press, 2012; and
- ATC-57, *The Missing Piece: Improving Seismic Design & Construction Practices*, Applied Technology Council, 2003.

The ATC-57 report, which was formulated by the earthquake engineering community with funding in part from NIST, provides a research and development roadmap that was studied as a possible format for this measurement science roadmap on windstorm and coastal inundation. The list of documents reviewed at the outset of the roadmap development process (see Appendix A) is organized around two subject areas and five program elements that were patterned after those in the ATC-57 report and initially described in the work plan for the development of this roadmap to reduce the impacts of windstorm and coastal inundation hazards.

The literature provides an additional perspective on the research issues that is not possible from workshops or other data collected over a short period of time. The effort uncovered the fact that there have been more research needs assessments related to wind engineering than for coastal inundation. The documents on coastal inundation have mainly been produced in the last several years, in part as a consequence of the devastation wrought by storm surge during Hurricane Katrina in 2005.

The two-day workshop in June 2012, convened to identify the highest priority needs that form the basis of this roadmap, was attended by the industry’s leading practitioners, academics, and representatives from key government agencies. The workshop was co-funded by the National Science Foundation (NSF), with the aim to leverage this effort to also identify fundamental research challenges on a longer time frame than that in which NIST usually operates. The workshop was held at the headquarters of the American Society of Civil Engineers (ASCE) in Reston, Virginia (see Figure 1-1). Participants were provided with the information from the review of the research needs literature prior to the workshop.

Figure 1-1 Participants at the June 2012 workshop.

The design of the June 2012 workshop was such that all 61 participants were able to contribute by addressing the research needs in multiple ways. Initially, the participants were asked what their future vision of a resilient community was and describe how that resilient community could be defined. They were also asked to identify any gaps in current knowledge that need to be addressed to enable disaster-resilient communities. The participants were then grouped by technical disciplines and asked to identify research needs and gaps in the current state of the art and state of the practice for determination of windstorm and coastal inundation hazards, loads, resistances, and performance-based design.

During the June 2012 workshop, participants in each of the five breakout groups (one group per program element) were asked to identify the top ten research needs for each roadmap program element. The participants were then asked to rank the top three most important topics for each element. Results from the June 2012 workshop were reviewed, discussed, and refined at the October 2012 workshop. Participants in the latter event were also asked to identify the research and development topic they considered the most important and the topic they considered the best value. Based on the input received from both workshops, the research and development project topics were then revised or combined to eliminate duplication, overlap, and expand topics that were too narrowly focused, resulting in a finalized set of 30 priority topics.

1.4 Roadmap Framework

The framework adopted for the measurement science roadmap for wind and coastal inundation impact reduction consists of four key elements used to describe the range of research that needs to be pursued for both hazards. The recommended research and development efforts include work in hazard identification, hazard loads and effects, building-specific load resistance improvement, and developing performance-based design methodologies. Each area of research and development is briefly described below.

Hazard Identification: The need to improve methods for identifying and quantifying both the windstorm and coastal inundation hazard was described by workshop participants as one of the most important elements of the research program. It is extremely difficult to define accurately the loads created by the hazards if the hazard is not adequately identified. Improving hazard identification requires research into methods to better determine the extent and magnitude of the hazard, such as the probable inundation levels and wave heights for 500-year and larger coastal inundation events, and to identify elements of the hazard that are not currently described or mapped, such as non-synoptic winds or flood-borne debris. The effect of future conditions such as sea level rise must be included in the identification of the hazard, and it is also important to identify the hazards on the same risk-basis so designs for the hazards are risk-consistent.

Loads and Effects: The workshop participants identified gaps in the knowledge of loads and effects caused by the full spectrum of windstorm and coastal inundation hazards, ranging from the need for improved wind load external pressure shape factors and improved methods for determining wind loads, to needing reliable methods for determining coastal inundation loads caused by moving water and water-borne debris. Improving knowledge of loads and effects also includes the need for developing methods of load determination for non-synoptic winds and for developing computational methods and tools not sufficiently developed for use by the practice.

Improved Building-Specific Load Resistance: The knowledge about the actual resistance of buildings and the components to windstorms and coastal inundation is limited to that provided by testing products, from testing structural assemblies, and from post windstorm and coastal inundation-event analysis. There is a very large gap in knowledge about the resistance of existing buildings to these hazards and little information about the effects of aging on wind and coastal inundation resistance. Satisfactory building design for these hazards requires an adequate load determination methodology and an adequate approach to determine resistance to the loads.

Performance-based Design: There has been little research and development work in performance-based design for wind loading and almost no performance-based design

R&D work for coastal inundation. The suggested approach for this research and development element is to build on existing capabilities in performance-based seismic design, which is well developed, by developing performance targets and reliability criteria for the hazards considered by this roadmap, for both new and existing buildings. Building performance during windstorms and coastal inundation should be linked to community resiliency.

1.5 Roadmap Organization

This roadmap is organized as follows. Chapter 2 describes the vision for windstorm and coastal inundation resilient communities that is based on input received from the June 2012 workshop participants. Chapter 3 describes the "Grand Challenges" in windstorm and coastal inundation loss reduction, as identified by the June 2012 workshop participants. Details of the 30 priority research project topics that rose to the top of the many projects discussed and debated at both the June 2012 and October 2012 workshops are provided in Chapter 4. Chapter 5 provides a prioritization of the proposed research topics, along with a summary of the costs and duration of the associated projects. Four appendices are also included that provide details about the workshops and the review of the literature. Appendix A identifies research needs and recommendations from the review of the literature and mapped to the five roadmap program elements that had been identified in the original project work plan. Appendix B contains the June 2012 workshop agenda, participant list, description of technical presentations, and web site address for accessing the presentations from the workshop. A description of the October 2012 workshop and a list of individuals who attended are provided in Appendix C. The priority research and development needs, as identified by the June 2012 workshop participants and mapped to the initial set of five roadmap program elements, are provided in Appendix D. Following the appendices are acronym definitions and references.

Chapter 2

Vision for Windstorm and Coastal Inundation Resilient Communities

The term ‘resilience’ has a number of definitions. With regards to hazard events, and responding to hazard events, it has been defined as “the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events” (National Academies Press, 2012) or, similarly, “the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions” (Presidential Policy Directive PPD-21 (Obama, 2013)). Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.

Community resilience can address a range of topics that include physical security, business continuity, emergency planning, hazard mitigation, and how the built environment (e.g., facilities, transportation, utilities) resists and rapidly recovers from disruptive events. With regards to buildings and infrastructure systems in communities, resilience can be described as physical systems that resist damage through adequate strength and mitigation measures, and that can be readily repaired so that important community functions are maintained during and after a hazard event. To achieve such performance, goals and criteria for resistance and recovery from windstorm and coastal inundation events need to be developed at the facility, system, and community level.

2.1 Resilience

The characteristics of a resilient community include preparation for hazard events, continuity of operations during and after hazard events, and recovery plans that allow the population to resume work and activities within a reasonable period of time.

A resilient community has performance goals for primary hazard events that address community development, mitigation, operations, and recovery. The community performance goals provide a consistent framework for defining specific criteria for facilities and infrastructure systems. Government agencies and critical functions, such as police, fire, emergency response, and healthcare, should be able to provide service immediately after the event with no significant interruption or decrease in service levels. Both public and private sector organizations should have disaster response plans consistent with the community performance goals to increase the likelihood of less down time, continued employment, and lower recovery costs.

The issue of resilience in the built environment was addressed in several NIST-sponsored workshops in 2011 and are summarized in a NIST Technical Note entitled, *Developing Guidelines and Standards for Disaster Resilience of the Built Environment: A Research Needs Assessment* (NIST, 2013). The technical gaps and research needs for developing guidelines and standards supporting community resilience were characterized as short term (less than three years) and long term (greater than three years) and are listed below:

Short term activities:

- Identify technical gaps and research needs from reviews of past disaster events and existing model codes and standards;
- Define resilience terminology for the built environment; and
- Develop guidance for community resilience planning.

Long term activities:

- Develop significant hazard definitions and multiple hazard levels;
- Develop risk-consistent performance goals and metrics;
- Develop tools and metrics to support quantitative technical assessment, policy development, and decision making; and
- Develop codes and standards that address resiliency.

The short term activities address resilience planning at the community level, where the role of facilities or systems in a community's physical resilience is defined. The long term activities address identification and development of tools and metrics that determine the expected level of performance during and after a hazard event, and include recovery of functional performance.

2.2 Vision

The vision of a resilient community was discussed by the June 2012 workshop participants. The themes of that vision are:

1. The community understands hazard risks, has an effective risk management program, and plans for resilience across the community through mitigation actions, disaster procedures, and plans for recovery.
2. The community can sustain the effects of a windstorm or coastal inundation event, provide basic human needs immediately after the event, and return to normalcy within a short period of time after the event with little economic and social disruption;
3. The population, tax base, and business activity returns to normalcy within a short period of time after the event, indicating community functionality and stability.

The following gaps in current knowledge, information, and resources were also identified by the workshop participants:

- Degradation in facilities and infrastructure systems due to age and deterioration are not addressed by codes and standards. The range of capacity in physical systems across a community needs to be considered in resilience planning and performance goals.
- Climate change needs to be considered when setting resilience performance goals in areas where it may affect the magnitude and extent of windstorms and coastal inundation.
- Design hazard information with a probabilistic basis for tornadoes, tsunamis, and storm surge events needs to be developed to enable communities to develop risk-consistent buildings and infrastructure systems.
- Cost analysis tools are needed that can address long-term resilience strategies. Codes and standards for buildings primarily focus on life safety issues, and address minimum requirements. Codes and standards for utilities primarily focus on reliability of service. While codes and standards are necessary for a resilient community, they may not be sufficient to reach the desired level of resilience.
- The private sector needs to be engaged in creating a resilient community.
- The public needs to be better informed about the importance of resilience and the steps needed to improve a community's ability to respond to and recover from a windstorm or coastal inundation event.

The ability to communicate risk to the public is critical, yet has proven for the most part to be ineffective. For individuals, businesses and government agencies to work together towards a resilient community, the risks of building and living in coastal environments must be clearly conveyed. Based on these gaps, the following four areas were identified as the most significant gaps in available information and tools for communities that want to develop resilience goals and plans:

1. **Measurement Techniques Needed**. Metrics for assessing community resilience must support decision making about priorities and associated levels of resilience. Resilience metrics need to address individual buildings and neighborhoods, infrastructure facilities and systems, system interdependencies, recovery time. Metric development is expected to be a long-term effort and is key to developing resilient communities.
2. **Risk Communication Required**. Risk communication to the public, private, and business populations is required to shift the disaster recovery paradigm, where government is expected to address planning and recovery, to more proactive, community-wide disaster planning and loss reduction. A key element of risk

communication is clear statements about the hazards, associated risks, and community goals and plans.

3. **Community-Scale Solutions Needed**. Community-scale tools and examples that provide a framework for considering the many issues involved in planning resilience, including reducing losses from disasters and speeding up recovery, are needed.

4. **Changing the Development Paradigm**. Given the large uncertainty in predicting windstorm and coastal inundation intensity and damage, coastal communities might consider policies that identify areas that should not be developed or abandon their development, particularly for coastal inundation.

2.3 Connecting Resilience to Measurement Science Roadmap

The projects identified in this roadmap will help fill some of the gaps identified above. The projects that focus on hazard identification are key to developing metrics that could measure community resiliency, and they are vital in determining how to communicate hazard risk within communities. The projects that address long-term climate issues and those that improve building performance over a long time frame are at the heart of resiliency and are crucial to improving a community's chance at more rapid recovery.

The roadmap topics do not address all of the gaps, however. While thorough hazard identification is fundamental to reducing risk uncertainty and important to risk communication, acting on the information, determining how, when and where to communicate risk, and how to mobilize communities to work toward improving their own long-term resiliency is a matter of public policy and is beyond the issues addressed in this roadmap. Any community decision to abandon development, or even severely restrict it, would be a matter of public policy and would require lengthy public debate, even though the fundamental hazard identification and quantification would hopefully be the basis for those policy discussions.

Chapter 3

Grand Challenges in Windstorm and Coastal Inundation Impact Reduction

The workshop participants identified "Grand Challenges" for both windstorms and coastal inundation research needs. These topics are anticipated to require a longer time frame (on the order of a decade or more to fully address) than the issues articulated in the remainder of this roadmap, but help shape a comprehensive research agenda for which new or additional knowledge is sought. However, the roadmap includes many topics on which significant progress could be made towards meeting these challenges.

Workshop participants also identified one means for efficiently making progress on research objectives for both windstorm and coastal inundation issues—development of a laboratory network for wind and coastal inundation-focused research similar to the Network for Earthquake Engineering Simulation (NEES)[1]. Such a network could provide shared-use laboratory facilities and allow research institutions to improve collaboration, with an objective to maximize effectiveness and efficiency of research across both the windstorm and coastal inundation hazards.

The Grand Challenges identified are focused in four main areas of study. They are:

- Developing new computer-aided tools and techniques to better simulate and predict hazard effects
- Developing techniques to measure the response of buildings to hazards and using the information as predictive tools
- Incorporating future conditions into hazard identification
- Improving community-wide resiliency and resistance to the effects of the hazards

Following are the identified Grand Challenges for both windstorm and coastal inundation hazard reduction. The Grand Challenges are not listed in priority order.

[1] NEEShub, the NEES platform for research, collaboration, and education, is located at http://nees.org/

3.1 Windstorm Grand Challenges

3.1.1 Develop Simulation Techniques for Non-synoptic Windstorms

Physics-based simulation methods that accurately represent the near-surface wind field during non-synoptic windstorms (e.g., thunderstorms, tornadoes) are needed. Applications of these simulation methods include improved hazard quantification and mapping, enhanced computational fluid dynamics modeling of wind loads and wind structure interaction, and more accurate estimation of windstorm disaster losses.

3.1.2 Define Hazard Characteristics of Wind Interacting With Other Environmental Effects

Windstorms most often are accompanied by other environmental effects, such as storm surge, rain, and wind-borne debris. The influence on building designs and event losses caused by the simultaneous impact of wind and one or more of these other environmental effects is not well understood and has been inadequately considered in current design practices. Studies have been initiated on the effect of high winds and wind-driven rain, yet much is to be learned about this means of water intrusion, as the combined effects of high winds with storm surge at a building site have not been studied in any substantive way. Results from research studies of the combined effects of these hazards could significantly improve designs, suggest changes in materials being specified, and reduce losses.

3.1.3 Develop Computer-Based Simulation Tools for Use in Design

Computer simulation tools such as computational fluid dynamics are needed to better understand wind pressures on buildings and other structures. Computational fluid dynamics, coupled with models of the structural response of the building, can be used to predict building performance from a high-wind event. Development of these simulation capabilities could ultimately enable a wind tunnel simulated on a computer desktop with computational fluid dynamics as a core function. Integrating such a simulation capability with Building Information Modeling (BIM) of a particular building would enable design of that building based on wind loads specific to each building and surrounding terrain. Variations in the extreme wind climate could be simulated, executing computational fluid dynamics simulations of the building and surroundings for multiple storms and directions, and then evaluating loads and load effects for design, including incorporating the effects of aging and deterioration.

3.1.4 Develop 'Smart' Buildings

'Smart' buildings would have wind performance monitoring systems built into the structural system that could provide information on building health or damage, and assist in predicting possible collapse, warning any building occupants of impending dangers, predicting excessive drift caused by wind, or alerting an owner about infiltration of excessive amounts of water or air. These buildings could lower storm shutters or secure photovoltaic solar panels prior to a storm impacting the building.

3.1.5 Improve Infrastructure Performance During High Wind Events

Power transmission and distribution systems are often crippled by high wind events. Methods to transmit power other than by electric lines draped between poles where both wind speeds and fallen trees disable the power grid are needed. Possible options might be to transmit power using electronic transmitters, moving the power lines underground or using the network of roads and streets to transmit the power within inlaid electrical conductors. Improved performance of electric lifelines would have a significant positive impact on reducing losses from windstorms. Similar performance of telephone and IT distribution systems has been observed during high wind events and solutions to these problems could be similar to those pursued for electric distribution systems.

3.1.6 Develop Community-Wide Wind-Resistant Design Techniques

Techniques are needed for determining wind vulnerabilities across a range of contiguous communities to make it more feasible to develop strategies to reduce those vulnerabilities. These techniques would include methods for creating redundancies between community systems such as infrastructure, critical facilities, and housing and employment facilities, so that communities could address their most urgent needs. These techniques would go well beyond the need for adoption and enforcement of stronger building codes.

3.2 Coastal Inundation Grand Challenges

3.2.1 Develop Observation and Measurement Technologies for Coastal Flood Hazard, Load, and Building Response Data Collection

Coastal inundation hazard data include time histories of water elevation, wave height and velocity, amount and type of sediment, and amount and characterization of flood-borne debris. Technologies or measurement systems are needed where buildings are located so information can be captured on water velocity, wave, and sediment supply to inform design approaches. Technologies might include load sensors attached to buildings to collect this information or buildings instrumented when built to continuously provide relevant coastal hazard information. The hazard data collected is extremely important in improving the understanding of overland flow of storm surge, the magnitude of flood loads on buildings, and the response of the buildings to those loads.

3.2.2 Create Modeling Tools to Predict the Effects of Overland Hydrodynamic Transport

During an extreme flooding event, loads on buildings and other structures are affected by a variety of phenomena, such as significant near-shore flood effects, including waves and storm surge; flow through the built and natural environments, considering time dependency and building interaction; sediment transport, including the effects of scour and erosion; and generation and transport of debris. Understanding the overland flow and the propagation of waves inland is important to determining loads on buildings and would help define the flood hazard for communities. This knowledge could be used to create powerful predictive tools to estimate potential losses due to overland hydrodynamic transport.

3.2.3 Develop Coastal Inundation Hazard Models Capable of Resolution at Parcel-Level Scales

A physics-based flood mapping methodology is needed that will provide both inundation limits and elevations at any building site. The methodology should include all coastal influences, as well as rainfall runoff, and be available to users electronically at the parcel level. Hazard information at the parcel-level would provide valuable flood design information for any particular site. .

3.2.4 Develop Probabilistic Storm Surge And Tsunami Models That Incorporate Changing and Future Conditions

Methodologies are needed to determine probabilistic flood risks for short- and long-return periods for both hurricanes and tsunamis, considering changing and future conditions. These conditions include sea level rise and shoreline changes, including long term erosion and any other effects of climate change on water surface elevations and land forms. The changing conditions should also include those that could generate a tsunami, such as underwater landslides or shifting tectonic plates under the ocean floor, or changes in bathymetry that would affect tsunami surge.

3.2.5 Develop Innovative Flood Resistance Techniques for Buildings

Current coastal inundation hazard mitigation techniques are limited to elevating structures above some predicted event or relocating them away from such an event. Techniques must be developed that improve building performance from coastal inundation hazards that are more comprehensive than those represented by simply elevating or relocating a structure. Pursuit of this challenge requires extensive knowledge about the magnitude of the coastal inundation hazard elements (e.g., changes in water elevation, wave height and velocity, amount and type of sediment, and amount and characterization of flood-borne debris) and about overland hydrodynamic transport, as well as accurate mapping of the hazard for various return periods, including inundation limits and elevations at specified building sites and considering changing conditions with time. Innovative materials and/or building systems to better withstand flood forces and allow faster recovery would significantly impact a reduction in coastal inundation losses.

3.2.6 Develop Community-Wide Flood-Resistant Design Techniques

Techniques are needed for determining flood risks and vulnerabilities across communities to make it possible to develop strategies to reduce those vulnerabilities, based on the risks. These techniques would include methods for creating redundancies between community systems, such as infrastructure, critical facilities, housing and employment, so that communities could address their most urgent needs. These techniques would go well beyond the need for adoption and enforcement of stronger building codes or floodplain ordinances.

Chapter 4

Recommended Research and Development Topics

4.1 Introduction

The research and development (R&D) project topics recommended by participants in the June 2012 and October 2012 workshops, and the subsequent effort to eliminate overlap and duplication and refine their focus, resulted in the identification of 30 priority research and development topics. The topics were then analyzed, categorized, and further elucidated for inclusion in the overall framework for this measurement science R&D roadmap for windstorm and coastal inundation impact reduction.

The priority R&D topics were grouped into two primary categories (wind hazard reduction and coastal inundation hazard reduction), with the following sub categories: (1) hazard identification; (2) hazard-specific loads and effects; (3) building-specific resistance; and (4) hazard-specific performance-based design (see Table 4-1). Workshop participants also examined possible research topics by the five program areas identified in the original project work plan from several different directions, including looking for grand challenges, exploring resiliency issues, and

Table 4-1 Priority Research and Development Topics, as Identified by Workshop Participants

No.	Research and Development Topic
	Wind Hazard
1	Hazard maps for high intensity non-synoptic events, including tornadoes
2	Effects of climate change on extreme wind event characteristics
3	Quantification of wind-borne debris hazards
4	Hazard modification by terrain, topography, and nearby buildings
5	Joint description for hurricane wind, storm surge, and wave hazards
	Wind Loads and Effects
6	Pressure coefficients for wind load determination
7	Computational fluid dynamics tools for practitioners
8	Rational approach for wind load analysis
9	Modeling and simulation for determination of wind loads due to non-synoptic winds, including tornadoes

Table 4-1 Priority Research and Development Topics, as Identified by Workshop Participants (continued)

No.	Research and Development Topic
	Wind Resistance
10	Test methods for resistance to cyclic loading
11	Field measurement techniques and test methods to evaluate condition of existing construction
12	Explicit factors of safety for materials and assemblies
13	Methods or models to predict loss of strength due to aging and deterioration
14	Guidelines to wind vulnerability assessment of existing buildings.
	Performance-based Design-Wind
15	Performance levels and acceptance criteria for wind hazards
16	Analysis procedures for nonlinear system behavior used in performance-based design
17	Cyber-based tools to support performance-based design
18	Measurement of windstorm resilience and benefits of performance-based design
	Coastal Inundation Hazard
19	Effects of sea level rise and future shoreline changes on coastal inundation hazards
20	Quantification of flood-borne debris hazards
21	Effects of over-land flow on waves and other coastal inundation hazards
22	Characterization of the coastal inundation hazard for low probability events
	Coastal Inundation Load and Effects
23	Field data collection of flood loads
24	Load combinations for simultaneous flood hazards
25	Validation of flood forces on buildings
	Coastal Inundation Load and Effects
26	Flood damage functions and fragility curves
27	Effects of erosion and scour on deep foundations
28	Test methods for materials and systems subject to flooding
	Performance-based Design-Coastal Inundation
29	Performance levels and acceptance criteria for buildings subject to coastal inundation
30	Sound engineering basis for flood resistant design that is not based on flood insurance requirements

suggesting projects with high impacts and rapid delivery times across disciplines (see Appendix D).

Analysis and further elucidation of the priority R&D topics identified in Table 4-1 resulted in the expansion of each topic to include (1) a more in-depth description; (2) an indication of the roadmap program element in which it falls; (3) its estimated cost; (4) the estimated time to carry out needed R&D pertaining to the topic; (5) challenges in conducting the needed R&D; and (6) potential R&D solutions. One-page summaries for each priority research topic containing the above-cited information are provided throughout the remainder of this chapter. For each topic, example stakeholders, and their respective roles, are also identified, as well as the significant impacts of the R&D to both engineering practice and community resilience, once the R&D is successfully completed and implemented.

The costs are based on estimates provided by the workshop participants, based on their knowledge of costs for similar R&D efforts. Estimated costs for each research and development topic are provided using one of the following ranges: $100,000 to $500,000 (a low cost); $500,000 to $1,000,000 (a moderate cost); $1,000,000 to $3,000,000 (a high cost); and exceeding $3,000,000.

Similarly, the time requirements to properly address each R&D topic was estimated by the workshop participants, based on their personal experience with comparable R&D efforts. Estimates are provided using the following time period ranges: 1-to-2 years (a short time period); 2-to-5years (a moderate time period); 5-to-8years (a long time period), and exceeding 8 years.

4.2 Priority Windstorm R&D Topics

The priority windstorm R&D topics are elucidated in the following four subsections: identification and characterization of wind hazards (Section 4.2.1); wind loads and effects (Section 4.2.2); wind resistance (Section 4.2.3); and performance-based engineering methodology (Section 4.2.4). Each subsection begins with a brief description of the overall scope of research and development topics for that topic category, along with examples of over-arching issues that need resolution, available resources and information for use in conducting the needed R&D, and examples and details of needed R&D outcomes. The one-page priority R&D topic summaries follow; 3-to-5 topics are provided for each topic category (subsection).

4.2.1 Identification and Characterization of Wind Hazards

All types of wind events are included under this category, and each type of wind hazard must be defined and delineated so that both present and future conditions can be considered. Users should be provided with the ability to determine needed parameters for wind resistant design, considering related phenomena and attributes, such as windborne debris, wind-driven rain, non-synoptic versus synoptic wind events and event probabilities. The magnitude of the hazard should be determined with variations in exposure, topography, urban interface (intersection of exposure variations), and land-sea interface (at the water line where both wind and storm surge transition). The risk of various magnitude wind events should be delineated clearly. Methods to modify the risk basis should also be available so that designs for less or greater risk events can easily be developed. The design risk basis should correspond to the design risk basis of other hazards.

Following is a summary of the current availability of sources and types of wind hazard information:

1. The wind speeds used for design are currently available in two formats: (1) in printed format in the ASCE/SEI 7-10 engineering standard, *Minimum Design Loads For Buildings and Other Structures* (ASCE/SEI, 2010); and (2) on the internet in digital form at the Applied Technology Council Windspeed Determination website (www.atcouncil.org/windspeed) , which provides location-specific wind speed to the nearest 1 mph, computed from digital information based on the printed ASCE/SEI 7-10 maps. Wind speeds, which are "illustrated" by lines on the ASCE/SEI 7-10 maps along the hurricane-prone coastline, have been developed using computer simulations of hurricane wind fields making landfall, with wind speeds decreasing as the hurricane decays inland. Codification of the wind speeds has led to a simplified compartmentalization of wind speeds into three regions: the western United States (California, Oregon, and Washington), the central United States, and the hurricane coast (both the Gulf of Mexico coast and the Atlantic Ocean coast).
2. There are 1004 Automated Surface Observing System (ASOS) sites across the country operated by the National Weather Service. These stations collect and record wind speeds 24 hours per day, every day of the year. These data are archived and can be accessed for wind speed histories. No attempt to date has been made to use these data for building designs, except on a case-by-case basis. The data have not been mapped. NIST is currently working on mapping this wind speed data so that it could possibly be used in ASCE/SEI 7 and be available to practitioners.
3. There have been minimal attempts to determine a joint probability of a hurricane wind and associated storm surge; these events are mapped independently and the design event is defined by two very different mean recurrence intervals.
4. There have been minimal attempts to characterize non-synoptic wind systems or their probability.
5. There has been no attempt to define the joint probability between non-synoptic and hurricane wind systems.

The required types and levels of information needed about the wind hazard that were described by workshop participants and interpreted from the literature search are:

1. With greater spatial information available, simplified regionalization should be replaced with information about the wind hazard defined by isotachs of wind

speeds or location-specific wind speed points, such that interpolation could be used everywhere in the country.

2. Given the difficulty with resolution on existing printed wind speed maps that are used for design (e.g., the ASCE/SEI 7 maps), wind speed data, as it is improved, needs to continue to be made available in digital form through the internet (as is currently done by the Applied Technology Council through the internet site, www.ATCouncil.org/windspeed).

3. A method is needed for delineating the wind-borne debris on a regional basis. Such wind-borne debris regions should further be defined by describing the type of debris and the level of damage that might occur from this debris, including the wind speed required to get the debris airborne.

4. Either through mapping or some other designation, the wind hazard most likely to be the design event, whether it be synoptic or non-synoptic, must be described with sufficient detail for the designer to know which design approach and criteria for wind speeds and resultant forces should be followed for a given building site.

5. For hurricane coastlines, designers should have an event defined by one mean recurrence interval that incorporates impacts from the joint high wind and storm surge hazard.

Following are the five priority research and development topics that fall under this wind hazard identification and characterization category.

R&D Priority: Wind Hazards

Topic No. 1: Hazard maps for high intensity non-synoptic events, including tornadoes

Description: Current wind hazard maps used for design of buildings do not consider all extreme wind hazards, and the unique characteristics associated with different windstorm types, such as tornadoes and downbursts. Maps and databases that provide design level information for all types of damaging windstorms are needed.

Estimated Cost: $1,000,000 to $3,000,000

Estimated Time: 5-8 years

Measurement Science Challenges and Potential Solutions

Challenges

- Tornado event history not generally captured by weather stations
- Tornado wind speeds inferred from observed damage and Enhanced Fujita (EF) scale ratings
- Identification of event type from wind climate data

Potential Solutions

✓ Algorithms to automatically identify and extract specific storm types from wind climate records

Stakeholders and Roles

Government	Provide support/funding; conduct research; collect and archive data
Industry	Develop and critique maps; provide feedback on usefulness
Standards Organizations	Adopt maps into standards; provide feedback on quality
Building Code Organizations	Adopt maps into codes

Impacts

- Improved safety through inclusion of all significant wind hazards in the design process

R&D Priority: Wind Hazards

Topic No. 2: Effects of climate change on extreme wind event characteristics

Description: Climate change is not currently considered in the estimation of wind hazards, and the effects of climate change on the probabilities and characteristics of extreme wind events are uncertain. Research is required to determine how and if climate change affects the wind climate; subsequently, methods should be developed to account for this uncertainty for use in development of wind hazard maps for design.

Estimated Cost: $1,000,000 to $3,000,000

Estimated Time: 2-5 years

Measurement Science Challenges and Potential Solutions

Challenges

- Lack of consensus regarding climate change impacts on characteristics of severe storms
- Validation of climate models
- Must determine if climate change could affect all types of wind events (i.e. hurricanes, tornadoes, straightline)
- Some areas of the country have very limited historical data requiring more modeling of events

Potential Solutions

✓ Investigate the range of modeling results to quantify uncertainty, and how to incorporate in wind hazard estimation

Stakeholders and Roles

Government	Provide support/funding; conduct research on future conditions.
Universities	Conduct research on the effect of climate change on wind climate
Industry	Critique maps; provide feedback on usefulness
Standards Organizations	Adopt maps into practice; provide feedback on quality

Impacts

- Improved safety margins against future changes in extreme wind climate, and increased protection against current wind hazards

R&D Priority: Wind Hazards

Topic No. 3: Quantification of wind-borne debris hazards

Description: There is a limited technical basis for the wind-borne debris hazard provisions in current building codes and standards, which rely on simple deterministic assumptions of a typical missile triggered by a single wind speed. Probabilistic methods are needed to enable site-specific and storm-type specific characterization of likely debris types, weights, and speeds.

Estimated Cost: $500,000 to $1,000,000

Estimated Time: 2-5 years

Measurement Science Challenges and Potential Solutions

Challenges

- Wind-borne debris type, size and volume dependent on many variables, including wind characteristics, sources, and accumulated damage to buildings
- Unknown vertical wind characteristics in tornadoes

Potential Solutions

- ✓ Numerous studies of numerical and wind tunnel experiments on debris flight characteristics
- ✓ Post-storm investigations to validate debris models
- ✓ New wind tunnel facilities in industry and academia to provide opportunities for large/full scale testing of debris flight/impact/generation

Stakeholders and Roles

Government	Provide support/funding; conduct research on wind-borne debris
Industry	Critique maps; provide feedback on usefulness
Standards Organizations	Adopt maps into practice; provide feedback on quality
Trade Organizations (wood, plywood, new materials, shutter and shelter industries)	Provide information about materials and material behavior that is important in causing debris

Impacts

- Realistic characterization of wind-borne debris hazards can lead to development of improved test methods, wind-borne debris resistant products, and a better-defined field of expected wind-borne missile impacts

R&D Priority: Wind Hazards

Topic No. 4: Hazard modification by terrain, topography, and nearby buildings

Description: Current methods for determination of the effects of terrain on local wind characteristics are cumbersome and prone to error, particularly at building sites with nonuniform surrounding terrain. Tools are needed to automate the process by taking advantage of widely available digital aerial photographic and elevation data.

Estimated Cost: $500,000 to $1,000,000

Estimated Time: 2-5 years

Measurement Science Challenges and Potential Solutions

Challenges

- Automated evaluation of surface roughness
- Estimation of topographic effects in complex terrain

Potential Solutions

- ✓ Algorithms to use web GIS-based aerial photographs and digital elevation models (e.g., Google Earth)
- ✓ Inclusion of terrain determination on windspeed web site so more wind design information is in one location

Stakeholders and Roles

Government	Provide support/funding; conduct research
Universities/Research Organizations	Conduct research; develop mapping or mapping modification techniques for terrain
Industry	Develop methodologies; critique maps or methods; provide feedback on usefulness
Standards Organizations	Adopt maps or methods into practice; provide feedback on quality

Impacts

- Improved accuracy of site-specific wind characteristics
- Improved designs of structures located on steep terrain, especially towers, signs, and buildings on bluffs, resulting in reducing losses to these structures

R&D Priority: Wind Hazards

Topic No. 5: Joint description for hurricane wind, storm surge, and wave hazards

Description: Coastal buildings and infrastructure are exposed to potentially simultaneous actions from extreme wind, storm surge, and wave hazards during hurricanes and other coastal storms, yet this loading condition is not directly addressed in codes, standards, and practice. Methods are needed to produce joint descriptions of these hazards, along with data/maps for site-specific design guidance.

Estimated Cost: $1,000,000 to $3,000,000

Estimated Time: 2-5 years (Topic 22 [Characterization of the coastal inundation hazard for low probability events] must be completed before this topic can be completed)

Measurement Science Challenges and Potential Solutions

Challenges

- Data requirements , including needed extensive libraries of high resolution hurricane wind/surge/wave simulations
- Efficient tools for data processing
- Changing conditions, including coastlines and bathymetry, sea level rise, and effects of climate change on storms

Potential Solutions

- ✓ Proof of concept for method developed by NIST
- ✓ Newly available high resolution coastal storm modeling and storm model results database systems (e.g., CSTORM-MS)

Stakeholders and Roles

Government	Provide support/funding; conduct research
Universities/Research Organizations	Conduct research; develop mapping techniques
Industry (including the Insurance Industry)	Critique maps
Standards Organizations	Adopt maps/mean recurrence intervals into practice; provide feedback on quality

Impacts

- Risk-consistent design across the range of coastal hazards
- Improved community resilience to multiple hazards

4.2.2 Wind Loads and Effects

Wind loads on buildings and other structures are currently determined by either calculating loads using formulas and methodologies available in ASCE/SEI 7-10 (ASCE/SEI, 2010) or by using the results from wind tunnel studies. There is evidence that the current methodologies in ASCE/SEI 7-10 are so complex (or confusing) that for any particular wind load determination, no two practitioners are likely to get the same calculated result. There are many uncertainties in wind load determination, given the variability of the wind speed and changing direction, and the influence of topography, terrain and building shape. However, it seems clear that how these uncertainties are dealt with has not adequately been explained in either ASCE/SEI 7 or other documentation.

Following is a summary of the current availability of sources and types of information on wind loads and effects:

1. Wind loading methodologies have grown increasingly cumbersome to the average practitioner. There are two formula-based methods and two tabular methods for finding wind loads on buildings. The building type and structural frame restrictions placed on each of the methods are not well understood.
2. Wind loads are determined irrespective of the type of windstorm event except there is no defined method for determining loads from tornadoes (although this will likely be addressed for the first time in the 2016 version of ASCE/SEI 7 commentary).
3. Most information on pressure coefficients related to building shape is more than 30 years old and needs to be updated in a consistent manner.

The required level of information needed about wind loading and its effects that was described by workshop participants and interpreted from the literature search is:

1. Wind loading simulation tools (e.g., computational fluid dynamics) need to be developed for use in the practice of wind engineering, and must be validated by other wind pressure testing or calculation methods.
2. Wind loading methods need to be researched for non-synoptic wind events and differences in the loads created by these events described in current engineering standards.
3. Wind loading created by internal pressurization of a "breached building envelope" caused by wind-borne debris should be modified, perhaps by requiring designs for internal pressurization unless debris impact protection is provided.

4. A more seamless transition in pressure coefficients between components and cladding (C&C) loading and main wind force resisting system (MWFRS) loading is needed.

Following are the four priority research and development topics that fall under this wind loads and effects category.

R&D Priority: Wind Loads and Effects

Topic No. 6: Pressure coefficients for wind load determination

Description: Much of the pressure coefficient data in current wind loading standards and codes is based on wind tunnel test data for rectangular cubic shapes. Pressure coefficients and wind loading procedures based on appropriate test data that address the range of actual building geometries are needed.

Program Element: 1: Provide technical support for windstorm and coastal inundation engineering practice and code development process.

Estimated Cost: > $3,000,000

Estimated Time: > 8 years

Measurement Science Challenges and Potential Solutions

Challenges

- Comparison of wind tunnel data from different labs using a consistent basis
- Pressure coefficients for use with non-synoptic winds are not well defined
- Narrowing the range of shapes and sizes to be tested

Potential Solutions

- ✓ Development of extensive wind tunnel databases in industry and academia for a wide range of building shapes, and methods for their effective use

Stakeholders and Roles

Government	Provide support/funding; conduct research
Universities/Research Organizations	Conduct research; develop revised pressure coefficients and methods for their effective use
Industry	Critique revised coefficients; provide feedback on the effect revised coefficients have on design; use wind tunnels to confirm revised coefficients
Standards Organizations	Adopt changes to coefficients into practice; provide feedback on quality

Impacts

- Improved safety or efficiency of design
- Reduction of possible errors when developing pressures for building shapes not currently covered by the existing standard

R&D Priority: Wind Loads and Effects

Topic No. 7: Computational fluid dynamics tools for practitioners

Description: While computational fluid dynamics tools are commonly used in many areas of engineering practice, no such validated tools exist for wind engineering applications. Computational fluid dynamics software systems and means for verification of model results are needed.

Estimated Cost: > $3,000,000

Estimated Time: > 8 years

Measurement Science Challenges and Potential Solutions

Challenges

- Techniques to reduce computational resources needed
- Simulation of peak pressures
- Validation process and criteria

Potential Solutions

- ✓ Adaptation of existing open source computational fluid dynamics software for wind engineering applications
- ✓ Simplification of turbulence modeling to remove low frequency components

Stakeholders and Roles

Government	Conduct research, provide funding
Universities/Research Organizations	Conduct research; develop an improved method
Industry	Validate the calculation methods with real problems and wind tunnel testing
Standards Organizations	Adopt changes in methods into practice; provide feedback on quality of results

Impacts

- Much faster, easier, less expensive, and more flexible analysis of wind loads compared to existing wind tunnel test procedures
- If coupled with building information modeling (BIM), improved efficiency in building design because loads defined by wind effects could be used to determine member sizes in one step

R&D Priority: Wind Loads and Effects

Topic No. 8: Rational approach for wind load analysis

Description: The numerous procedures for determining wind loads in current codes and standards, which are based on different datasets, methods, and assumptions, are very confusing to the engineering profession, and can provide significantly different results for a single building. A new approach is needed that provides consistent and accurate results for all building geometries.

Estimated Cost: $500,000 to $1,000,000

Estimated Time: 2-5 years (Completion of Topic 6 [Pressure coefficients for wind loads] first would improve the results of the effort spent on this topic)

Measurement Science Challenges and Potential Solutions

Challenges

- Limitations of existing pressure coefficient datasets (see Topic 6)
- Covering buildings with static and dynamic response in a single method

Potential Solutions

✓ Use of database-assisted design tools to validate potential methods

Stakeholders and Roles

Universities/Research Organizations	Conduct research; develop an improved singular method
Industry	Work with universities/research organizations to develop singular method; test the calculation methods with real problems
Standards Organizations	Adopt changes in method into practice; provide feedback on quality of method

Impacts

- Increased consistency in repeatable results and reduced errors associated with computation of wind loads

R&D Priority: Wind Loads and Effects

Topic No. 9: Modeling and simulation for determination of wind loads due to non-synoptic winds, including tornadoes

Description: There is limited information about the loading effects on buildings from non-synoptic winds, and building occupants are in danger of death or injury from these types of events, in addition to significant property damage occurring annually. Additional modeling or simulation of the wind effects from these events needs to be conducted so wind load standards can be developed to be used by practitioners.

Estimated Cost: > $3,000,000

Estimated Time: > 8 years

Measurement Science Challenges and Potential Solutions

Challenges

- Lack of data on non-synoptic wind hazard and load characteristics

Potential Solutions

- ✓ new tornado simulators at several institutions

Stakeholders and Roles

Government	Provide support/funding; conduct research
Universities/Research Organizations	Conduct research; develop revised pressure coefficients
Industry	Critique revised coefficients; provide feedback on the effect revised coefficients have on design; use wind tunnels to confirm revised coefficients
Standards Organizations	Adopt changes to coefficients into practice; provide feedback on quality

Impacts

- Performance improvements for buildings subject to non-synoptic winds that would save lives, reduce injuries, and reduce damage
- Improved community resiliency to recover faster from severe non-synoptic wind events

4.2.3 Wind Resistance

Resistance is determined either by calculation of the strength of materials and connections or by test methods developed by independent test organizations and employed by a product manufacturer or product trade organization. Buildings have many components and connections, such that the cause of failure of a building due to high winds is often difficult to determine. The failure could be initiated by either component/connection failure or structural frame movement during the event and eventual failure from cyclic loading or from a breach of the building envelope, leading to a change in the aerodynamic characteristics. Knowledge of the actual level of safety built into any wind design remains uncertain except for the testing performed by product manufacturers and trade organizations, which is component-based rather than system-based. However, most testing is done statically, and not dynamically, so the testing that is done does not closely represent an actual wind event. There are an extremely large number of buildings already built along hurricane-prone coastlines, and in tornado-prone areas, that might need to be retrofitted to yield better wind performance, yet currently there is little known about what level of resistance to a high-wind event actually exists for those buildings. Thus, it is not possible to determine how much retrofitting would be appropriate for such buildings. To further complicate the problem of determining wind resistance, there has been little work done on identifying the reduction in resistance as buildings get older and deterioration in both materials and connections occurs.

Following is a summary of the current availability of sources and types of information on wind resistance:

1. Resistance of materials is determined by materials testing of some limited number of products. Most test methods provide static resistance.
2. Capacities of mechanical connectors are given in allowable loads; therefore, some unknown factor of safety has been used to reduce ultimate loads determined by tests to the allowable load.
3. Capacities of members may be provided in either allowable or ultimate stresses, depending on the material type. Allowable stresses account for some unknown factor of safety used to reduce ultimate failure test results to allowable stresses.
4. There is no current methodology available to reduce expected resistance of either materials or connections based on age, weathering, deterioration (from weathering or from material-destroying organisms) or other age-related strength reductions.

The required level of information needed that was described by workshop participants and interpreted from the literature search is:

1. Test methods need to be developed to realistically determine the wind resistance of components and cladding materials in installed conditions for materials, aging, wind-driven rain, water infiltration, material deterioration, and other conditions, such as those caused by heat, thermal expansion and contraction, and corrosion.
2. Guidance on wind retrofitting of residential buildings is newly available (FEMA, 2013) ; however, this guidance assumes effectiveness of the entire structure once the retrofit is complete as though the rest of the structure was new, which is not the case. Important differences in performance of the retrofit measures are expected, since the structures being retrofitted are existing. These differences need to be studied and understood so adjustments in the retrofit techniques can be made as needed to achieve optimum performance.
3. Test methods for materials should be developed using a dynamic analysis technique to better replicate the cyclic nature of the wind loading (dynamic load testing for glass does exist and some test methods have been developed in other parts of the world).
4. Practitioners need better information about the expected levels of safety factors used for the products and materials they are specifying and using for design.
5. Practitioners need information about system-level safety factors that require analytical tools to assess.

Following are the five priority research and development topics that fall under this wind resistance category.

R&D Priority: Wind Resistance

Topic No. 10: Test methods for resistance to cyclic loading

Description: Existing test methods for wind pressure resistance to cyclic loading do not reflect realistic loading conditions. New methods are needed that are verified to produce effects comparable to those experienced in service.

Estimated Cost: $1,000,000 to $3,000,000

Estimated Time: > 8 years

Measurement Science Challenges and Potential Solutions

Challenges

- The wide range of building components and materials and thus the need to select some strategic number of components and materials for testing improvements
- Connection of tested component to building must also be accounted for

Potential Solutions

✓ New wind tunnel/wind load experimental facilities in industry and academia to provide opportunities for large/full scale testing to validate effectiveness of proposed test methods

Stakeholders and Roles

Government	Provide sport/funding; conduct research
Universities/Research Organizations	Conduct research; develop test equipment and test protocols
Industry	Test and use new testing apparatus; provide results to user groups and practitioners; compare results to calculated requirements
Standards Organizations	Adopt changes to test methods into standards of practice; provide feedback on quality of developed test methods

Impacts

- Improved component and cladding products and their attachment schemes to the building frame
- Reduced wind-borne debris fields

R&D Priority: Wind Resistance

Topic No. 11: Field measurement techniques and test methods to evaluate condition of existing construction

Description: There is a lack of methods and tools for field evaluation of the condition of installed wall and roof cladding elements. New measurement techniques and methods are needed that provide information on the strength, condition, remaining service life, and ability to resist penetration of water and wind-driven rain.

Estimated Cost: > $3,000,000

Estimated Time: > 8 years

Measurement Science Challenges and Potential Solutions

Challenges

- Likely require new test and measurement equipment
- Wide range of building cladding types and materials
- Attachment of cladding to building is often not exposed or easily accessible

Potential Solutions

✓ Adaptation of nondestructive evaluation testing methods for structural materials

Stakeholders and Roles

Government	Provide support/funding; conduct research
Universities/Research Organizations	Conduct research; develop test equipment and test protocols
Industry	Test and use new testing apparatus; provide results to user groups and practitioners; compare results to calculated requirements
Standards Organizations	Adopt changes to test methods into standards of practice, provide feedback on quality of developed test methods

Impacts

- More robust windstorm vulnerability assessments and early warning of problems before evidenced through failures
- Improved assessment of community resiliency and potential decreased service downtime in affected buildings

R&D Priority: Wind Resistance

Topic No. 12: Explicit factors of safety for materials and assemblies

Description: As wind and flood design progresses to ultimate strength and becomes performance-based, knowledge about the stress limit states of both building frame and component materials and assemblies becomes more critical. While material development work is conducted by trade groups, there is no limit-state development work being conducted on assemblies or systems. Knowledge about the levels of safety in design is crucial to preventing failures in the future.

Estimated Cost: $500,000 to $1,000,000

Estimated Time: 2-5 years

Measurement Science Challenges and Potential Solutions

Challenges

- Large body of materials and systems

Potential Solutions

✓ Modeling or simulation of material behavior grouped into a system or assembly with predictive stresses at failure

Stakeholders and Roles

Government	Provide support/funding; conduct research
Universities/Research Organizations	Conduct research; develop test equipment and test protocols
Industry	Test materials-components-systems; provide results to user groups and practitioners; compare results to results obtained with use of ultimate wind speeds
Standards Organizations	Adopt changes to load factors into standards of practice; provide feedback on quality of developed test methods

Impacts

- Improved building system reliability and improved information for performance-based design

R&D Priority: Wind Resistance

Topic No. 13: Methods or models to predict loss of strength due to aging and deterioration

Description: Field investigations after high wind and coastal inundation events often indicate failures in materials and in structural and component connections due to aging or deterioration, yet there is no existing method to measure the extent of reduced resistance from these factors. A method for estimating the possible loss of strength of original construction due to these factors is needed. In addition, retrofit techniques need to be developed to counteract the lack of or loss of this resistance in existing buildings.

Estimated Cost: $500,000 to $1,000,000

Estimated Time: 2-5 years

Measurement Science Challenges and Potential Solutions

Challenges

- No current method or standard of practice to account for aging.
- Numerous building materials and building systems to consider.

Potential Solutions

✓ Develop proxy method for loss of resistance based on existing material properties (e.g., moisture content, reduced section of steel from corrosion)

Stakeholders and Roles

Government	Provide support/funding; conduct research
Universities/Research Organizations	Conduct research
Industry	Develop retrofit techniques using materials not currently used for retrofitting; conduct outreach and training on retrofit techniques; provide results to user groups and practitioners, compare results to current methods

Impacts

- Significantly reduced damage from windstorm events
- Improved performance for components and cladding (where most wind losses occur)

R&D Priority: Wind Resistance

Topic No. 14: Guidelines for wind vulnerability assessment of existing buildings

Description: There is a lack of guidance available for assessment of the vulnerability of existing buildings to windstorms. The limited existing guidance is primarily related to critical facilities and is qualitative in nature. Quantitative methods of assessment are needed that are more generally applicable.

Estimated Cost: $500,000 to $1,000,000

Estimated Time: 2-5 years

Measurement Science Challenges and Potential Solutions

Challenges

- Data to support quantifiable assessments
- Limited methods for evaluation of condition of installed cladding (see Topic 11)

Potential Solutions

✓ Adaptation of existing methods, guidelines and standards for seismic capacity and vulnerability evaluation

Stakeholders and Roles

Government	Provide support/funding
Universities/Research Organizations	Research; develop test equipment and test protocols
Industry	Develop guidance based on available research and data, including new testing apparatus and protocols; provide results and training to practitioners and other user groups; compare evaluation results to observed high wind effects
Standards Organizations	Convert guidelines into standards of practice

Impacts

- Improved measurement of building and community resiliency through a uniform basis to evaluate vulnerability
- Improved understanding of needed mitigation actions to address identified vulnerabilities

4.2.4 Performance-based Engineering Methodology

Performance-based design for wind engineering should cover wind hazards for hurricanes, extra-tropical storms, and non-synoptic winds such as thunderstorms and tornadoes. The use of performance-based design analysis methods are intended to provide a more direct connection between the design of the building and the owner-expected and required performance of that building. Specifying a specific level of performance for a defined hazard level, and quantifying the consequences to the owner for such a hazard could improve understanding of building design and operation and aid in developing more optimum designs to achieve the desired performance. The current static analysis methods provide conservative results and do not consider post-elastic behavior and stresses beyond the yield strength. The method used for performance-based design of wood, steel, and concrete structures will vary somewhat, depending on material properties.

Following is a summary of the current availability of sources and types of information on performance-based engineering for wind design:

1. There is little written information about performance-based wind engineering that has made its way into practitioner use.
2. There are examples of limited uses of the concept on a project-by-project basis. The examples show promise in taking advantage of reserve structural capacity in order to design more cost-effective structures.
3. Performance-based design procedures have been developed for the seismic hazard; the application of performance-based design methods for wind is expected to generally be based on the approaches used in seismic design.

The required level of information needed that was described by workshop participants and interpreted from the literature search is:

1. Performance targets and acceptability criteria need to be developed for use in wind engineering
2. A wind engineering performance-based design approach should be developed that is analogous to the ASCE 41 standard, *Seismic Rehabilitation of Existing Buildings*, which is based on extensive FEMA-funded guidance development efforts (an important step preceding the adoption of standards).
3. Tools are needed to define the hazard and to conduct assessments of both new and existing buildings.
4. Performance-based designs performed across the spectrum of a community should be linked to resiliency and sustainability.

Following are the four priority research and development topics that fall under this wind engineering performance-based design category.

R&D Priority: Wind Performance-Based Design

Topic No. 15: Performance levels and acceptance criteria for wind hazards

Description: There is a lack of tools and guidance available to design and evaluate buildings to withstand windstorms on a performance basis. A critical first step towards enabling performance-based design is to define expected levels of performance and acceptance criteria for different hazard levels.

Estimated Cost: $1,000,000 to $3,000,000

Estimated Time: > 8 years

Measurement Science Challenges and Potential Solutions

Challenges

- Requires integration of technical and societal/policy-level input

Potential Solutions

✓ Adaptation of performance-based seismic design and evaluation guidance

Stakeholders and Roles

Government	Provide support/funding
Universities/Research Organizations	Develop and refine performance-based design methodologies
Industry	Develop guidelines for practitioners; conduct outreach and training for practitioners
Standards Organizations	Convert guidelines into standards of practice

Impacts

- Cost-effective performance-based design procedures that, when implemented, result in substantial improvement in building performance during extreme wind events
- The adoption of performance-based seismic design procedures in codes and standards provide the potential for understanding possible reduction in wind hazard losses

R&D Priority: Wind Performance-Based Design

Topic No. 16: Analysis procedures for nonlinear system behavior used in performance-based design

Description: Current design procedures for resisting wind loads assume linear elastic material behavior. There is a lack of procedures for applying nonlinear analysis methods for wind loads. Such methods are needed to provide the ability to predict building performance to failure.

Estimated Cost: $500,000 to $1,000,000

Estimated Time: 5-8 years

Measurement Science Challenges and Potential Solutions

Challenges

- Procedures are needed for both strength and serviceability limit states
- Many types of building envelope materials and building systems

Potential Solutions

✓ Adaptation of non-linear analysis methods used in seismic design and in design to avoid progressive collapse

Stakeholders and Roles

Government	Provide support/funding
Universities/Research Organizations	Develop analysis procedures
Industry	Develop guidelines for practitioners that incorporate the analysis procedures; conduct outreach and training for practitioners
Standards Organizations	Convert guidelines into standards of practice

Impacts

- Improved methods for analysis of building performance for rare, extreme events
- Material and cost savings in buildings designed using these analysis procedures

R&D Priority: Wind Performance-Based Design

Topic No. 17: Cyber-based tools to support performance-based design

Description: Engineering, modeling and simulation tools used in performance-based design should be broadly available to the profession electronically so the various tools can be tested and used. Broadly available tools and information will speed up the rate at which performance-based design is accepted as part of normal practice. These tools might include those used for structural analysis, modeling wind behavior on a building, determining serviceability limits and effects, modeling terrain effects on buildings and similar methods for studying wind effects on buildings.

Estimated Cost: $1,000,000 to $3,000,000

Estimated Time: 5-8 years

Measurement Science Challenges and Potential Solutions

Challenges

- Some proprietary issues may slow down offering tools to the public
- Accumulation of information and task of determining how to make it available are not inconsequential

Potential Solutions

- ✓ Tools and information that flow from NIST so that most tools will be in the public domain

Stakeholders and Roles

Government	Provide support/funding; conduct research and develop cyber tools
Universities/Research Organizations	Conduct research; develop cyber tools and metrics
Industry	Test cyber tools; develop guidance for their use; provide results to user groups and practitioners; compare evaluation results
Standards Organizations	Convert guidance into standards of practice, if necessary

Impacts

- More rapid delivery of information to the practice on performance-based design

R&D Priority: Wind Performance-Based Design

Topic No. 18: Measurement of windstorm resilience and benefits of performance-based design

Description: Measures of community resilience specific to windstorm hazards, and documentation on associated benefits, are lacking and are in need of development.

Estimated Cost: $500,000 to $1,000,000

Estimated Time: 5-8 years

Measurement Science Challenges and Potential Solutions

Challenges

- Measurement of resilience in general is still ill-defined
- Link between performance-based design and resiliency has not previously been attempted

Potential Solutions

✓ Leveraging NIST's ongoing efforts to develop methods for measurement of resilience

Stakeholders and Roles

Government	Provide support/funding, develop resiliency initiatives
Universities/Research Organizations	Conduct research; develop performance-based design metrics specific to community resiliency
Industry	Evaluate performance-based design metrics; develop guidance to apply metrics
Standards Organizations	Convert guidelines into standards of practice, as necessary

Impacts

- More rapid delineation of the positive benefits of performance-based design, leading to more rapid adoption of performance-based design by the design profession

4.3 Coastal Inundation Priorities

The priority coastal inundation R&D topics are elucidated in the following four subsections: identification and characterization of coastal inundation hazards (Section 4.3.1); coastal inundation loads and effects (Section 4.3.2); resistance to coastal inundation (Section 4.3.3); and performance-based engineering design for coastal inundation (Section 4.3.4). As in the case for wind, each subsection begins with a brief description of the overall scope of research and development topics for that topic category, along with examples of over-arching issues that need resolution, available resources and information for use in conducting the needed R&D, and examples and details of needed R&D outcomes. The one-page priority R&D topic summaries follow; 2-to-4 topics are provided for each topic category (subsection).

4.3.1 Identification and Characterization of Coastal Inundation Hazards

The coastal inundation hazard must include the effects of future conditions (e.g., climate change and future development), must consider inland effects in bays and tributaries that are sometimes great distances from tidal-influenced coastlines, should be characterized by volume and type of flood-borne debris, must be correlated with the wind influence on the extent of inundation, and must consider the influence of the slope and roughness of the coastal floor and the channeling effects of the onshore built environment.

Following is a summary of the current availability of sources and types of information on coastal inundation hazards:

1. Current hazard identification is provided by two primary sources: (1) community specific flood maps that delineate the hazard by the limit of inundation for various mean recurrence interval storms; and (2) storm surge inundation limits from a maximum of maximum flood events illustrated on maps used for evacuation purposes.
2. Flood maps published by FEMA are intended for insurance rating purposes primarily; they are used for design because they are the only design tool with inundation extent indicated, and water surface elevation expectations noted, that are based on the probability of a specific flood elevation occurring.
3. Flood-borne debris is not characterized at all for any coastal site.
4. There is no inundation depth information on flood maps although new mapping graphical interfaces are beginning to provide site-specific depths in some limited number of communities across the nation.

5. Some coastal communities have very recent flood hazard information and some are very outdated. The revisions and updating only occur when the community, the state, or FEMA provide funding to update the flood maps.
6. Tsunami hazard maps are mainly produced for evacuation and do not contain information needed for engineering design (until a new tsunami loads section is added to ASCE/SEI 7 in 2016).

The required level of information needed about the coastal inundation hazard that was described by workshop participants and interpreted from the literature search is:

1. Hazard identification information must include ways to consider future conditions such as sea-level rise, long-term erosion, subsidence, and future development.
2. There should be a flood-borne debris data layer for flood mapping that would help determine the possible magnitude and extent of this hazard.
3. Tsunamis should be included in the coastal inundation hazard mapping.
4. Methods to determine the hazard for lower-probability but more extreme events (lower than 1% and 0.2% annual probability) should be developed.
5. Wave heights need to be provided for lower-probability events.
6. Hazard information should be provided in a data repository easily accessed by those who need this information.
7. Ways to define and describe the hazard other than just water depth and water inundation limits should be explored. These definitions and descriptions should separate engineering information needs from insurance information needs, given that the flood maps were, and still are, used primarily for flood insurance rating for individual properties located in floodplains.

Following are the four priority research and development topics that fall under this coastal inundation hazard category.

R&D Priority: Coastal Inundation Hazards

Topic No. 19: Effects of sea level rise and future shoreline changes on coastal inundation hazards

Description: Current methods for defining the coastal flood hazard ignore future conditions such as sea level rise and shoreline changes. Methods must be developed to characterize the coastal inundation hazard for future conditions such as sea-level rise, subsidence, long-term erosion, and future development, perhaps by specifying scenarios, including the number of years in the future that are being considered. This must be done at a community scale since broader implications of sea level rise are beyond the scope of this roadmap. This flood hazard characterization should be consistent with wind speed hazard characterizations.

Estimated Cost: $500,000 to $1,000,000

Estimated Time: 5-8 years

Measurement Science Challenges and Potential Solutions

Challenges

- Creating future conditions as a data layer
- Estimating sea level rise for site-specific locations

Potential Solutions

✓ Adapt information from Intergovernmental Panel on Climate Change to create scenarios based on a rate of rise times a specified number of years into the future

Stakeholders and Roles:

Government	Conduct research on possible future conditions; identify historical references to use as a basis to predict future conditions
Universities/Research Organizations	Conduct research; provide historical references to use as a basis to predict future conditions
Industry	Create scenario visualization tools for use by regulators and design practitioners

Impacts

- Scenario development for future conditions that would improve decision making about foundation types, depth of embedment of pile foundations, and siting approaches
- Visualization tools demonstrating scenarios that would illustrate the impact of future conditions to communities

R&D Priority: Coastal Inundation Hazards

Topic No. 20: Quantification of flood-borne debris hazards

Description: Probabilistic methods are needed that can estimate debris generation and debris characteristics based on flood variables (depth, waves, velocity) and then a methodology needs to be developed for determining how flood-borne debris 'layers' could be used with flood mapping technology to describe the possible magnitude (quantity, size, weight and speed) and extent (area of flooded surface) of debris, so flood loads from debris could be determined from this information.

Estimated Cost: $1,000,000 to $3,000,000

Estimated Time: 5-8 years (Topics 21 [Effects of over-land flow] and 26 [Flood damage functions] must be completed before this topic can be completed)

Measurement Science Challenges and Potential Solutions

Challenges

- Using satellite tools to predict magnitude of debris
- Mapping inland extent of debris and combining with other flood hazard data

Potential Solutions

✓ Create an overlay tool that works with a geospatial image that would estimate debris within some range of distances from a site and that could be used to define flood debris characteristics

Stakeholders and Roles:

Government	Provide technical support and possible access to other geospatial tools that could accelerate research and development on this topic
Universities/Research Organizations	Conduct research; develop methods for aggregating data meaningfully for flood-borne debris
Industry	Test and refine graphics tools

Impacts

- Specific data about both the extent and magnitude of flood-borne debris that would improve decision making about siting approaches and the magnitude of the debris load at any particular building location
- Visualization tools demonstrating flood-borne debris scenarios that would illustrate to communities the impact on various design decisions

R&D Priority: Coastal Inundation Hazards

Topic No. 21: Effects of over-land flow on waves and other coastal inundation hazards

Description: The effects of over-land flow, including waves, debris, flood velocity, wind-driven influences, erosion effects at buildings and channeling effects of the built environment need to be determined. Ways to characterize these effects into a comprehensive hazard identification system are also needed.

Estimated Cost: $1,000,000 to $3,000,000

Estimated Time: 5-8 years

Measurement Science Challenges and Potential Solutions

Challenges

- Methods to determine the extent of erosion at buildings from either inflow or outflow are not well developed or tested.
- No methodology exists for determining the effects of channeling of flow between buildings or other obstructions in the built environment

Potential Solutions

- ✓ Creating a web-based tool that determines erosion from historical data at a specific site
- ✓ Using satellite imagery, develop a method for determining channeling effects between obstructions

Stakeholders and Roles:

Government	Provide support/funding
Universities/Research Organizations	Conduct research; develop metrics for over-land flow
Industry	Evaluate metrics for over-land flow; develop guidelines for implementation of a comprehensive hazard identification system that incorporates methods to determine the effects of overland flow
Standards Organizations	Convert guidelines into standards of practice, if necessary

Impacts

- Improved community resilience through consideration of overland flow effects
- Improved community zoning, floodplain ordinances, flood insurance rates, and building codes

R&D Priority: Coastal Inundation Hazards

Topic No. 22: Characterization of the coastal inundation hazard for low probability events

Description: Methods for estimating the full range of storm surge and tsunami coastal inundation hazards (including depth/elevation, velocity, and wave heights and periods) for low-probability events are lacking and need to be developed. Tools must then be created to map these hazard characteristics.

Estimated Cost: $1,000,000 to $3,000,000

Estimated Time: 5-8 years

Measurement Science Challenges and Potential Solutions

Challenges

- Each varying segment of the coastline may need to be studied for extremely long return period events
- Creating an ultimate-strength building design for a low-probability coastal inundation event that is compatible with an ultimate strength design for a corresponding wind event

Potential Solutions

✓ Creating a web-based tool that would determine return periods at a specific site using shoreline topography

Stakeholders and Roles:

Government	Provide support/funding; conduct research
Universities/Research Organizations	Conduct research; develop methods for revising the mean recurrence interval of a design event
Industry	Develop guidelines to revise mean recurrence intervals for design events, based on new research
Standards Organizations	Adopt guidelines into standards of practice, as necessary

Impacts

- Improved knowledge about community vulnerabilities to low probability coastal inundation events could improve storm surge warning systems and improve the criteria for identifying evacuation areas
- Consistency in probability-based design for windstorm and coastal inundation

4.3.2 Coastal Inundation Loads and Effects

Loads for coastal inundation conditions are calculated from formulas that are in ASCE/SEI 7 (Chapter 5), the USACE *Coastal Engineering Manual*, the FEMAP-55 *Coastal Construction Manual*, and the FEMA P-646 *Guidelines for Design of Structures for Vertical Evacuation from Tsunamis*. There are formulas for loads on buildings from hydrostatic, hydrodynamic, breaking wave, and flood-borne debris conditions. The formulas in all of the above references are essentially the same. The determination of the loads requires information about flood velocity and flood depth at the site-specific location of interest. Given the lack of knowledge about flood velocity and the impact that storm forward speed, wind speed or coastal bathymetry may have on flood velocity, the current method for determining velocity is derived primarily from flood depth. There are significant uncertainties in determining flood loads, and there is not wide spread use yet of the current flood load knowledge by practitioners.

Following is a summary of the current availability of sources and types of information on coastal inundation loads and their effects:

1. Flood velocity is currently derived from flood depth at the near shore or inland locations, depending on the building site.
2. Hydrodynamic flow is a function of flood velocity.
3. Breaking wave loads are determined from wave heights, which are derived from flood depths at the building site.
4. Flood-borne debris loads are derived from flood velocity and requires an assumption about debris type and weight. All debris is assumed to float at the still water level and at the same velocity as the water.
5. There is little guidance on how individual flood loads should be combined with each other to account for the simultaneous influence of various flood aspects (e.g., the combined influence of breaking wave loads occurring at the same time as hydrodynamic loads)

The required level of information needed about coastal inundation loads and their effects described by workshop participants and interpreted from the literature search is:

1. Laboratory testing in wave tanks should be conducted to validate flood loads on buildings for waves, velocity, debris and the effects of scour.
2. Flood load combinations should be developed to account for the simultaneous influence of various flood loads that include probability and uncertainty of simultaneous occurrence.

3. Load formulas should be studied for waves breaking onto buildings above the lowest floor.

Following are the three priority research and development topics that fall under this coastal inundation loads and effects category.

R&D Priority: Coastal Inundation Loads

Topic No. 23: Field data collection of flood loads

Description: Methods of determining flood loads on buildings caused by waves, velocity, and debris, including the effects of scour, need to be validated and tested. The data required for this validation requires instrumentation that can be field deployed to capture wave heights, water velocity, water depths and wave direction. Building response to flood loads must also be determined, which requires buildings be instrumented to determine load effects.

Estimated Cost: > $3,000,000

Estimated Time: 5-8 years

Measurement Science Challenges and Potential Solutions

Challenges

- Measurement devices do not currently exist.
- Instrumenting existing buildings is expensive and landfalling storm locations uncertain and infrequent
- Determining storm surge information across the flood field and not just at fixed surge measurement devices

Potential Solutions

- ✓ Leveraging existing university and government storm surge data collection efforts
- ✓ Using existing tsunami test basins for storm surge load validation
- ✓ Pre-instrument locations to collect flood data

Stakeholders and Roles:

Government	Provide support/funding, develop field measurement techniques
Universities/Research Organizations	Conduct research; develop and test load validation methods, develop field measurement techniques
Industry	Develop guidance for use of validated flood loads by design practitioners
Standards Organizations	Adopt new guidance into standards of practice

Impacts

- Improved flood load accuracy for design of buildings and other structures in coastal inundation areas
- Improved information about building response to flood loads, allowing designers to develop building framing systems more capable of resisting the loads and thus reducing damage

R&D Priority: Coastal Inundation Loads

Topic No. 24: Load combinations for simultaneous flood hazards

Description: Flood load combinations need to be developed to account for the simultaneous impacts of various flood forces, such as those generated by breaking waves, moving water and flood-borne debris.

Estimated Cost: $500,000 to $1,000,000

Estimated Time: 2-5 years (Topic 22 [Characterization of the coastal inundation hazard for low probability events] and Topic 23 [Field data collection of flood loads] must be completed before this topic can be completed)

Measurement Science Challenges and Potential Solutions

Challenges

- Load combinations might depend on time sequence of greatest magnitudes of the flood components
- Flood load return periods for design must be determined before load combinations can be created

Potential Solutions

✓ Verifying numerical models with field data would provide confidence in developing designs more resistant to floods

Stakeholders and Roles:

Government	Provide support/funding
Universities/Research Organizations	Conduct research; develop appropriate load combinations
Industry	Develop guidelines for applying the new flood load combinations in design
Standards Organizations	Convert guidelines into standards of practice

Impacts

- Improved design and performance of buildings and other structures during floods in coastal inundation areas, resulting in reduced losses

R&D Priority: Coastal Inundation Loads

Topic No. 25: Validation of flood forces on buildings

Description: Flood load estimation procedures must be validated for coastal inundation forces impacting a building. The load information could come from field collected information, current formulas and calculation techniques, numerical models, or laboratory testing.

Estimated Cost: $1,000,000 to $3,000,000

Estimated Time: 5-8 years (Topic 23 [Field data collection of flood loads] must be completed before this topic can be completed)

Measurement Science Challenges and Potential Solutions

Challenges

- Verifying wave loads on buildings through testing and numerical modeling
- Establishing realistic boundary conditions for use in numerical models

Potential Solutions

- ✓ Using computational fluid dynamics to model interface and impact between water loads and buildings

Stakeholders and Roles:

Government	Provide support/funding
Universities/Research Organizations	Conduct research; develop appropriate equations
Industry	Develop guidelines for applying flood (wave) load calculations in the design of new and the retrofit of existing buildings
Standards Organizations	Convert guidelines into standards of practice

Impacts

- Reduced coastal flood damage in new and retrofitted buildings that can resist or deflect wave forces
- Would potentially provide a computer-based approach to study flood effects on existing buildings prior to a storm surge event.

4.3.3 Resistance to Coastal Inundation

The resistance to the effects of coastal inundation is typically accomplished by reducing the possibility of being inundated. The most effective way to resist the effects of inundation is to not be located in a coastal inundation area (i.e., stay outside of the coastal floodplain). The next most effective way to resist inundation is to be above the inundation height, whatever that height is for any storm event. Building survival is frequently accomplished if the foundation survives, and if load path continuity is maintained throughout the structural systems. There is very little engineering design of the building to resist flooding, given what is currently known about flood forces, so the solutions that are known to work are removal of the building from the floodplain or elevation of the building above the expected flood elevation.

Following is a summary of the current availability of sources and types of information on resistance to coastal inundation:

1. Elevate the building above the flood (top of the waves) to eliminate the possibility of waves striking the building structure at or above the floor system. The expected wave impact assumes that service connections will be severed and will need to be replaced.
2. Foundations, such as piles or columns, must be specifically designed to withstand flood forces and to resist other lateral and vertical loads; as a result, the foundations can survive a “design flood event”.
3. Little is known about how to design the building above the top of the foundation to resist flood forces.
4. Erosion and scour effects are known to affect foundation performance because of the loss of supporting soil around the foundation, but the critical amount of soil loss is not known.
5. There is little variation in foundation materials used; thus, the benefits of new materials are never discovered, and there are few known techniques to strengthen an existing pile foundation.

The required level of information needed about the resistance to coastal inundation that was described by workshop participants and interpreted from the literature search is:

1. Flood damage functions should be studied to give designers a better idea of the extent of loss likely at various levels of damage that occur at various levels of flood depth.

2. Fragility curves should be developed for various building components, systems and infrastructure elements that reflect damage by flood forces.
3. Foundation type and depth should be studied to provide better design guidance on foundations that are required to resist the effects of flood forces, erosion and scour.
4. Building materials and systems located below the lowest floor, and thus in the path of flood forces, should be studied to develop increased resistance to damage from flooding.
5. Test methods need to be developed to test the materials and systems used in the various flood scenarios.

Following are the three priority research and development topics that fall under this resistance to coastal inundation category.

R&D Priority: Resistance to Coastal Inundation

Topic No. 26: Flood damage functions and fragility curves

Description: Flood damage functions and fragility curves should be developed to give designers better guidance on the magnitude of likely damage from various magnitude flood events. This information would also aid in determining when additional freeboard would significantly improve building performance.

Estimated Cost: $500,000 to $1,000,000

Estimated Time: 2-5 years

Measurement Science Challenges and Potential Solutions

Challenges

- Fragility curves need to be developed for a significant number of components and systems
- Levels of flood damage have not been defined

Potential Solutions

✓ Laboratory testing of materials and some systems could provide significant information for fragility curve development

Stakeholders and Roles:

Government	Provide support/funding and flood damage information
Universities/Research Organizations	Conduct research; develop damage functions and fragility curves
Industry	Develop guidelines for considering flood-damage functions and fragility curves in the design process
Standards Organizations	Convert guidelines into standards of practice

Impacts

- Reduced flood damage and improved community resiliency through use of flood-damage functions (fragility curves) in the design of systems and components that undergo flooding
- Improved vulnerability and risk assessments conducted for new and existing structures, and possibly improved HAZUS loss estimates.

R&D Priority: Resistance to Coastal Inundation

Topic No. 27: Effects of erosion and scour on deep foundations

Description: Foundation design needs to be improved with a focus on pile material and spacing, embedment depths, and the load effects caused by erosion and scour at the foundation. Materials and system improvements could lead to less expensive and/or easier to install foundations that would result in reduced damage from coastal inundation events. Testing of foundation aging and the soil consolidation that occurs over time would provide very useful input into new foundation design.

Estimated Cost: $500,000 to $1,000,000

Estimated Time: 2-5 years (Topic 23 [Field data collection of flood loads] must be completed before research and development on this topic can begin)

Measurement Science Challenges and Potential Solutions

Challenges

- Soil properties vary greatly along the storm surge-prone coastlines
- Limited research on the effects of scour and erosion at building foundations

Potential Solutions

- ✓ Soil modification techniques might reduce loss of soil
- ✓ New pile material could improve resistance to flood loads, minimizing impact from loss of soil

Stakeholders and Roles:

Government	Provide support/funding; conduct research
Universities/Research Organizations	Conduct research; develop improved foundation and pile design methods, including improved material specifications
Industry	Develop guidelines for improved foundation design to resist the effects of scour and erosion.
Standards Organizations	Convert guidelines into standards of practice

Impacts

- Reduced foundation damage, resulting in more rapid post-storm recovery and reduced coastal inundation impacts on communities.

R&D Priority: Resistance to Coastal Inundation

Topic No. 28: Test methods for materials and systems subject to flooding

Description: Test methods do not currently exist and must be developed for materials and systems installed to improve the performance of building components located below the Base Flood Elevation (BFE) that obstruct the flow of flood waters (e.g., breakaway walls). When such components break loose, they become flood-borne debris. New materials and systems for such components also need to be developed.

Estimated Cost: $1,000,000 to $3,000,000

Estimated Time: 5-8 years

Measurement Science Challenges and Potential Solutions

Challenges

- Federal regulations regarding floodplain development may impede acceptance of new materials or systems
- Performance testing under full flood loads

Potential Solutions

- ✓ Materials or systems with flow through capability
- ✓ Materials that might disintegrate when flooded but remain stable when dry

Stakeholders and Roles:

Government	Provide support/funding; incorporate acceptable materials/systems in current standards
Universities/Research Organizations	Conduct research; test materials and systems in flow tanks
Industry	Evaluate proposed materials and/or systems

Impacts

- Reduced flood-borne debris
- Materials and systems that comply with current flood regulations.

4.3.4 Performance-Based Design for Coastal Inundation

The National Flood Insurance Program (NFIP) language in the Code of Federal Regulations (CFR) 44, Section 60.3, is performance-based in its approach. The NFIP language says:

- "Buildings must be sited reasonably safe from flooding.
- Buildings must be designed to prevent flotation, collapse and permanent lateral movement during flooding.
- Buildings must be designed using flood-resistant materials below the Base Flood Elevation (BFE).
- Buildings must be constructed to minimize flood damage.
- The HVAC (heating, ventilation, air conditioning) and plumbing equipment must be designed to prevent water entry into those systems."

The use of performance-based design analysis methods are intended to provide a more direct connection between the design of the building and the owner-expected and required performance of that building. Specifying a specific level of performance for a defined hazard level, and quantifying the consequences to the owner for such a hazard could improve understanding of building design and operation and aid in developing more optimum designs to achieve the desired performance. However, there are no performance-based design metrics for the performance of either communities or individual buildings during a coastal inundation event. The premise behind minimizing losses during flooding has always been to "run from flood" to minimize the loss of life. Reduced building damage is expected to occur when it is elevated above the defined flood elevation (Base Flood Elevation) for the 1% annual probability event. Freeboard (additional elevation above the Base Flood Elevation) is either mandated by community flood ordinances or included as a best practice to provide a margin of safety.

Following is a summary of the current availability of sources and types of information about performance-based design, as it relates to coastal inundation:

1. Other than the performance statements in the National Flood Insurance Program language (see above), there are no performance-based design standards used in flood-resistant design.
2. The current information about magnitude of flood damages resides in the insurance claims information of the National Flood Insurance Program and lags several years behind actual events.

3. The current damage information caps losses at 50% of the building value, so any loss greater than 50% is largely undetermined from the current insurance claims data.
4. Most losses occur to residential buildings; thus, there is minimal information about non-residential building losses caused by coastal inundation.

The required level of needed information about performance-based design for coastal inundation that was described by workshop participants and interpreted from the literature search is:

5. Performance-based design information is needed for storm surge, waves, and tsunamis.
6. The engineering requirements for buildings in the flood plain need to be separated from the insurance requirements (i.e., engineering requirements should not be based on insurance requirements).

Following are the two priority research and development topics that fall under this performance-based design for coastal inundation category.

R&D Priority: Performance-based Design for Coastal Inundation

Topic No. 29: Performance levels and acceptance criteria for buildings subject to coastal inundation

Description: There is a lack of tools and guidance available to design and evaluate buildings to withstand coastal inundation on a performance basis beyond what is provided in the NFIP language. A critical first step towards enabling performance-based design is to define expected levels of performance and acceptance criteria for different hazard levels.

Estimated Cost: $500,000 to $1,000,000

Estimated Time: 2-5 years

Measurement Science Challenges and Potential Solutions

Challenges

- Slow pace of change to traditional design methods
- Need cost/benefit tools to provide federal funding support for performance-based design for flood damage reduction

Potential Solutions

- ✓ Explore solutions used by the Netherlands, Germany and other European countries

Stakeholders and Roles:

Government	Provide technical support and flood insurance data; modify grant programs to support performance-based design solutions
Universities/Research Organizations	Conduct research; develop performance-based design metrics that link to loss reduction
Industry	Develop guidelines that define performance levels and metrics and their application
Standards Organizations	Convert guidelines into standards of practice

Impacts

- Cost-effective performance-based design procedures that, when implemented, result in substantial improvement in building performance during coastal inundation events
- The adoption of performance-based seismic design procedures in codes and standards would provide the potential for reducing coastal inundation hazard losses

R&D Priority: Performance-based Design for Coastal Inundation

Topic No. 30: Sound engineering basis for flood resistant design that is not based on flood insurance requirements

Description: Unlike any other hazard, existing flood guidance and engineering standards are closely tied to NFIP regulations, insurance policy, and flood insurance rate maps. The entire spectrum of flood hazard determination, flood loads, effects and resistance and performance specifications need to be revised from the ground up using engineering principles.

Estimated Cost: > $500,000 to $1,000,000

Estimated Time: > 8 years (Topics 21-29, which encompass flood load determination through building response to flooding, should be completed before this topic can be completed; however, the effort spent in the other areas reduces the cost of accomplishing this topic)

Measurement Science Challenges and Potential Solutions

Challenges

- Must start with a clean slate and no preconceived notions
- Getting flood engineering community to accept a different approach

Potential Solutions

✓ Develop flood design approaches for building codes that are based on engineering methods and get them slowly accepted into the codes or engineering standards

Stakeholders and Roles:

Government	Provide technical support and modeled flood hazard data
Universities/Research Organizations	Conduct research; develop engineering methods that lead to loss reduction
Industry	Develop guidelines for engineering methods, based on new research, that are not related to flood insurance requirements
Standards Organizations	Convert guidelines into standards of practice

Impacts

- Engineering basis for coastal inundation would be more-risk-consistent with the other hazards
- Achievement of performance-based metrics for coastal inundation could be more closely tied to engineering than happenstance

Chapter 5

Prioritization and Benefits of Recommended R&D Activities

This chapter provides information on the priorities assigned to each research and development topic by workshop participants, as well as a summary overview of the costs and time required to conduct work under each R&D topic. The chapter concludes with a discussion of the benefits in implementing the recommended R&D activities.

5.1 Prioritization of R&D Topics by Workshop Participants

Table 5-1 summarizes the research and development topics recommended by the June 2012 workshop participants and indicates the priorities assigned to those topics. A combination of methods was used to assign priorities. As topics were developed by breakout groups during the June workshop, each topic was initially assigned a relative importance of high (H), medium (M), or low (L). At the closing plenary session, each workshop participant was asked to identify his/her "top 3" topics out of the 30 recommended R&D topics. None of these 30 had an initial importance rating of low. Participants at the October workshop were briefed on each of these topics, including relative estimated cost and time to complete. They were then asked to vote on which topics they considered to be the most important, irrespective of cost and time required, or the best value, including consideration of importance, cost, and time. The final priorities of highest, high, and medium were assigned using information from both workshops. In addition to the initial ratings of high or medium, topics receiving two or more of the priority designations "top 3", most important (I), or best value (V), were assigned the highest priority. The highest priority topics were generally found to be topics that have been identified frequently in the research needs literature (see Appendix A). Final priorities for each of the 30 topics are shown in the far right-hand column of Table 5-1.

5.2 Summary Overview of Recommended R&D Topic/Activity Costs and Time Requirements

Table 5-2 provides a summary of costs of the recommended activities for each R&D topic, in priority order, along with the estimated costs and time requirements for each topic. The total cost to complete all 30 research and development activities is estimated to be on the order of $35-to-60 million. Assuming annual budgets on the

Table 5-1 Prioritization of Recommended R&D Topics

No.	R&D Topic	Subject Area and Program Element*	June Workshop Priorities: Initial Importance Category	June Workshop Priorities: Top 3	October Workshop Priorities: Most Important	October Workshop Priorities: Best Value	Final Priority
			Wind Hazard				
1	Hazard maps for high intensity non-synoptic events, including tornadoes	1-2	H	T	I	V	Highest
2	Effects of climate change on extreme wind event characteristics	1-1	M				Medium
3	Quantification of wind-borne debris hazards	1-2	H	T			High
4	Hazard modification by terrain, topography, and nearby buildings	1-1	M				Medium
5	Joint description for hurricane wind, storm surge, and wave hazards	2-5	H				High
			Wind Loads and Effects				
6	Pressure coefficients for wind load determination	2-1	H			V	High
7	Computational fluid dynamics tools for practitioners	2-3	H				High
8	Rational approach for wind load analysis	1-1	H	T			High
9	Modeling and simulation for determination of wind loads due to non-synoptic winds, including tornadoes	1-1	H		I		High

*Values in cells are provided in x-x format, with the first number indicating either subject area 1 or 2 and the second number indicating program elements 1 through 5, as described in Figure A-1 (Appendix A).

H, M: High and medium importance, respectively, as assigned by June 2012 workshop participants

I: Most important topic in topic category, irrespective of cost and time required

T: One of ten topics receiving the highest number of “Top 3” votes by workshop participants.

V: Best value in topic category, considering importance, cost, and time

Table 5-1 Prioritization of Recommended R&D Topics (continued)

			June Workshop Priorities		October Workshop Priorities		
No.	R&D Topic	Subject Area and Program Element*	Initial Importance Category	Top 3	Most Important	Best Value	Final Priority
			Wind Resistance				
10	Test methods for resistance to cyclic loading	2-3	M				Medium
11	Field measurement techniques and test methods to evaluate condition of existing construction	2-3	H	T			High
12	Explicit factors of safety for materials and assemblies	1-2	M				Medium
13	Methods or models to predict loss of strength due to aging and deterioration	2-3	H			V	High
14	Guidelines for wind vulnerability assessment of existing buildings.	2-4	H	T	I		Highest
			Performance-based Design-Wind				
15	Performance levels and acceptance criteria for wind hazards	1-2	M	T	I		Highest
16	Analysis procedures for nonlinear system behavior used in performance-based design	1-2	H				High
17	Cyber-based tools to support performance-based design	2-3	H	T			High
18	Measurement of windstorm resilience and benefits of performance-based design	2-5	H	T		V	Highest

*Values in cells are provided in x-x format, with the first number indicating either subject area 1 or 2 and the second number indicating program elements 1 through 5, as described in Figure A-1 (Appendix A).

H, M: High and medium importance, respectively, as assigned by June 2012 workshop participants

I: Most important topic in topic category, irrespective of cost and time required

T: One of ten topics receiving the highest number of “Top 3” votes by workshop participants.

V: Best value in topic category, considering importance, cost, and time

Table 5-1 Prioritization of Recommended R&D Topics (continued)

No.	R&D Topic	Subject Area and Program Element*	June Workshop Priorities: Initial Importance Category	June Workshop Priorities: Top 3	October Workshop Priorities: Most Important	October Workshop Priorities: Best Value	Final Priority
			Coastal Inundation Hazard				
19	Effects of sea level rise and future shoreline changes on coastal inundation hazards	1-1	M				Medium
20	Quantification of flood-borne debris hazards	1-2	H	T			High
21	Effects of over-land flow on waves and other coastal inundation hazards	2-3	H		I		High
22	Characterization of the coastal inundation hazard for low probability events	2-5	H			V	High
			Coastal Inundation Load and Effects				
23	Field data collection of flood loads	2-3	H	T	I	V	Highest
24	Load combinations for simultaneous flood hazards	2-3	H				High
25	Validation of flood forces on buildings	2-3	M				Medium
			Resistance to Coastal Inundation				
26	Flood damage functions and fragility curves	2-3	H		I		High
27	Effects of erosion and scour on deep foundations	1-2	H			V**	High
28	Test methods for materials and systems subject to flooding	2-4	M			V**	Medium

*Values in cells are provided in x-x format, with the first number indicating either subject area 1 or 2 and the second number indicating program elements 1 through 5, as described in Figure A-1 (Appendix A).

H, M: High and medium importance, respectively, as assigned by June 2012 workshop participants

I: Most important topic in topic category, irrespective of cost and time required

T: One of ten topics receiving the highest number of “Top 3” votes by workshop participants.

V: Best value in topic category, considering importance, cost, and time

**tie vote for best value topic in Resistance to Coastal Inundation

Table 5-1 Prioritization of Recommended R&D Topics (continued)

No.	R&D Topic	Subject Area and Program Element*	June Workshop Priorities: Initial Importance Category	June Workshop Priorities: Top 3	October Workshop Priorities: Most Important	October Workshop Priorities: Best Value	Final Priority
	Performance-based Design-Coastal Inundation						
29	Performance levels and acceptance criteria for buildings subject to coastal inundation	1-2	H		I	V	Highest
30	Sound engineering basis for flood resistant design that is not based on flood insurance requirements	2-3	H				High

*Values in cells are provided in x-x format, with the first number indicating either subject area 1 or 2 and the second number indicating program elements 1 through 5, as described in Figure A-1 (Appendix A).

H, M: High and medium importance, respectively, as assigned by June 2012 workshop participants

I: Most important topic in topic category, irrespective of cost and time required

T: One of ten topics receiving the highest number of “Top 3” votes by workshop participants.

V: Best value in topic category, considering importance, cost, and time

order of $6 million, the complete list of activities would take 6-to-10 years to complete.

5.3 Proposed Program Budget and Schedule for the First Eight Years

The proposed budget (in constant dollars) and schedule for the R&D program for the first eight years of its operation are summarized in Table 5-3. The total budget for each of the 30 R&D activities is based on the “estimated cost” for each topic/activity shown in Table 5-2. In most instances, the proposed budget is taken as the mid-range cost in Table 5-2; in other instances, judgments were made to keep the annual cost for all R&D efforts constant at $6.0 million per year. The costs are spread out over the estimated time the R&D activity is expected to require. The costs are summed for both the wind R&D topics/activities and the coastal inundation R&D topics/activities; total costs are also shown for the overall R&D program (all topics/activities).

The overall R&D program starts at a level of $4.0 million per year and grows to $6.0 million per year over the eight year projected time frame. The spending plan through the first eight years illustrates a rapid increase in spending over the first few years.

Table 5-2 Cost and Time Requirements for Recommended R&D Activities

No.	R&D Topic	Priority	Estimated Cost	Estimated Project Duration
	Wind Hazard			
1	Hazard maps for high intensity non-synoptic events, including tornadoes	Highest	$1,000K-3,000K	5-8 years
3	Quantification of wind-borne debris hazards	High	$500K-1,000K	2-5 years
5	Joint description for hurricane wind, storm surge, and wave hazards	High	$1,000K-3,000K	2-5 years
4	Hazard modification by terrain, topography, and nearby buildings	Medium	$500K-1,000K	2-5 years
2	Effects of climate change on extreme wind event characteristics	Medium	$1,000K-3,000K	2-5 years
	Wind Loads and Effects			
6	Pressure coefficients for wind load determination	High	>$3,000K	> 8 years
7	Computational fluid dynamics (CFD) tools for practitioners	High	>$3,000K	> 8 years
8	Rational approach for wind load analysis	High	$500K-1,000K	2-5 years
9	Modeling and simulation for determination of wind loads due to non-synoptic winds, including tornadoes	High	>$3,000K	> 8 years
	Wind Resistance			
14	Guidelines for wind vulnerability assessment of existing buildings.	Highest	$500K-1,000K	2-5 years
11	Field measurement techniques and test methods to evaluate condition of existing construction	High	>$3,000K	> 8 years
13	Methods or models to predict loss of strength due to aging and deterioration	High	$500K-1,000K	2-5 years
12	Explicit factors of safety for materials and assemblies	Medium	$500K-1,000K	2-5 years
10	Test methods for resistance to cyclic loading	Medium	$1,000K-3,000K	> 8 years
	Performance-based Design-Wind			
15	Performance levels and acceptance criteria for wind hazards	Highest	$1,000K-3,000K	> 8 years
18	Measurement of windstorm resilience and benefits of performance-based design	Highest	$500K-1,000K	5-8 years
16	Analysis procedures for nonlinear system behavior used in performance-based design	High	$500K-1,000K	5-8 years
17	Cyber-based tools to support performance-based design	High	$1,000K-3,000K	5-8 years

Table 5-2 Cost and Time Requirements for Recommended R&D Activities (Continued)

No.	R&D Topic	Priority	Estimated Cost	Estimated Project Duration
	Coastal Inundation Hazard			
20	Quantification of flood-borne debris hazards	High	$1,000K-3,000K	5-8 years
21	Effects of over-land flow on waves and other coastal inundation hazards	High	$1,000K-3,000K	5-8 years
22	Characterization of the coastal inundation hazard for low probability events	High	$1,000K-3,000K	5-8 years
19	Effects of sea level rise and future shoreline changes on coastal inundation hazards	Medium	$500K-1,000K	5-8 years
	Coastal Inundation Load and Effects			
23	Field data collection of flood loads	Highest	>$3,000K	5-8 years
24	Load combinations for simultaneous flood hazards	High	$500K-1,000K	2-5 years
25	Validation of flood forces on buildings	Medium	$1,000K-3,000K	5-8 years
	Resistance to Coastal Inundation			
26	Flood damage functions and fragility curves	High	$500K-1,000K	2-5 years
27	Effects of erosion and scour on deep foundations	High	$500K-1,000K	2-5 years
28	Test methods for materials and systems subject to flooding	Medium	$1,000K-3,000K	5-8 years
	Performance-based Design-Coastal Inundation			
29	Performance levels and acceptance criteria for buildings subject to coastal inundation	Highest	$500K-1,000K	2-5 years
30	Sound engineering basis for flood resistant design that is not based on flood insurance requirements	High	$500K-1,000K	> 8 years

Legend: Highest priority R&D topic; Medium priority R&D topic; High priority R&D topic

While there can be large variations in budgets from year to year, based on agency priorities and authorized funding levels, the proposed spending plan provides a possible framework for enacting a Windstorm and Coastal Inundation Impacts Reduction R&D Program.

The scheduling plan (Table 5-3) reflects the proposed priorities for the overall R&D program. Since some of the 30 research and development activities must be done before others, this approximate sequencing also provides a framework identifying which R&D activities should be done or completed first and which should or must follow. The highest priority R&D topics/activities are scheduled to be conducted

Table 5-3 Proposed Windstorm and Coastal Inundation Impacts Reduction R&D Program Schedule and Costs (In thousands of dollars)

	Wind R&D Topics/Activities	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Total
1	Hazard maps for high intensity non-synoptic events, including tornadoes	500	500	500	100	100	100	100	100	2000
2	Effects of climate change on extreme wind event characteristics		550	550	400	300	200			2000
3	Quantification of wind-borne debris hazards				150	150	150	150	150	750
4	Hazard modification by terrain, topography, and nearby buildings				150	150	300	200	100	900
5	Joint description for hurricane wind, storm surge, and wave hazards				400	400	400	400	600	2200
6	Pressure coefficients for wind load determination	500	500	500	500	500	500			3000
7	Computational fluid dynamics tools for practitioners	300	300	300	300	300	300	500	700	3000
8	Rational approach for wind load analysis							200	550	750
9	Modeling and simulation for determination of wind loads due to non-synoptic winds, including tornadoes	500	500	500	300	300	300	300	300	3000
10	Test methods for resistance to cyclic loading			200	250	250	350	500	450	2000
11	Field measurement techniques and test methods to evaluate condition of existing construction		300	300	300	300	300	400	500	2400
12	Explicit factors of safety for materials and assemblies					200	200	200	150	750
13	Methods or models to predict loss of strength due to aging and deterioration	150	150	150	150	150				750
14	Guidelines wind vulnerability assessment of existing buildings.	250	250	250						750
15	Define performance levels and acceptance criteria for wind hazards	250	250	250	250	250	250	250	250	2000
16	Analysis procedures for nonlinear system behavior used in performance-based design		100	100	100	100	100	100	150	750
17	Cyber-based tools to support performance-based design		200	200	300	300	300	300	400	2000
18	Measurement of windstorm resilience and benefits of performance-based design	100	100	100	150	150	150			750
Wind R&D Activities Total		**2550**	**3700**	**3900**	**3800**	**3900**	**3900**	**3600**	**4400**	**29750**

From Topic 22 (Characterization of the coastal inundation hazard for low probability events)

Legend: Highest priority R&D topic; High priority R&D topic; Medium priority R&D topic;
Activity link pointing to sequential activity

Table 5-3 Proposed Windstorm and Coastal Inundation Impacts Reduction R&D Program Schedule and Costs (In thousands of dollars) **(Continued)**

	Coastal Inundation R&D Topics/Activities	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Total
19	Effects of sea level rise and future shoreline changes on coastal inundation hazards				100	100	100	100	350	750
20	Quantification of flood-borne debris hazards					500	500	750	750	2500
21	Effects of over-land flow on waves and other coastal inundation hazards	400	400	400	500	300				2000
22	Characterization of the coastal inundation hazard for low probability events	400	400	450	400	350				2000
23	Field data collection of flood loads	700	750	750	750	50				3000
24	Load combinations for simultaneous flood hazards						250	250		500
25	Validation of flood forces on buildings					500	500	500		1500
26	Flood damage functions and fragility curves						250	250		500
27	Effects of erosion and scour on deep foundations						200	350		550
28	Test methods for materials and systems subject to flooding		300	300	350	300	300			1550
29	Define performance levels and acceptance criteria for buildings subject to coastal inundation	200	200	200	100					700
30	Develop sound engineering basis for flood resistant design separate from flood insurance requirements							200	500	700
	Coastal Inundation R&D Activities Total	**1700**	**2050**	**2100**	**2200**	**2100**	**2100**	**2400**	**1600**	**16250**
	Wind R&D Activities Total (prior page)	**2550**	**3700**	**3900**	**3800**	**3900**	**3900**	**3600**	**4400**	**29750**
	R&D Program Total (All Activities)	**4250**	**5750**	**6000**	**6000**	**6000**	**6000**	**6000**	**6000**	**46000**

To Topic 5 (Joint description for hurricane wind, storm surge, and wave hazards)

Legend: Highest priority R&D topic; High priority R&D topic; Medium priority R&D topic;
Activity link pointing to sequential activity

first, unless their completion is dependent upon the completion of other tasks. Linked tasks are connected with arrows. Only the first eight years are mapped.

It is recommended that the Windstorm and Coastal Inundation Impacts Reduction R&D Program be implemented at the earliest possible moment. Start-up should be rapid, since there has already been a significant amount of effort (in this Roadmap development effort) in defining what is to be done and how it can be accomplished.

5.4 Benefits of Implementing R&D Activities for Windstorm and Coastal Inundation Loss Reduction

The benefits of the recommended R&D program include:

- Better, more technically sound wind- and coastal inundation-resistant engineering design practices;
- More reliable structures that perform better in high winds and flooding;
- Fewer lives lost in a destructive windstorm (especially tornadoes) or coastal inundation event;
- Lower initial and retrofit costs related to wind- and/or coastal inundation-resistant construction;
- Mitigation of the consequences of windstorms and coastal events; and
- Better written, more easily understood codes and standards.

For the nation as a whole, implementation of the proposed R&D program will yield the following major benefits:

1. Reduction in the traumatic life loss, injury, damage, and economic impacts when windstorms and coastal inundation events occur.
2. More rapid recovery and restoration of the physical community and economic activity following a significant windstorm and/or coastal inundation event.
3. Reduced investment required to achieve risk-consistent design and construction of buildings subject to wind and coastal inundation events

The accrual of benefits to the design practice will begin almost immediately once the program has begun. Researchers and practitioners in both the wind and coastal engineering communities have requested research help for numerous important technical issues for many years. Implementation of the proposed R&D program will immediately signal an important positive change to the technical community that should spark new enthusiasm for pursuing worthy research and developmental efforts that will improve current knowledge about both the windstorm and coastal inundation hazards and ways to reduce significantly the impacts of these hazards.

Appendix A

Research Needs Literature

A.1 Literature Review of Existing Resources and Past Workshops on Identifying Research Needs

The review of the research needs literature included identification of the key documents from the past 20 years and extracting research recommendations relevant to the measurement science roadmap. Following is a list of documents reviewed. The full citation for each document is provided in the list of References.

[1] *Hurricane Warning: The Critical Need for a National Hurricane Research Initiative*, National Science Board of the National Science Foundation, January 2007;

[2] *Windstorm Impact Reduction Implementation Plan*, National Science and Technology Council, April 2006;

[3] *Wind Engineering Research and Outreach Plan*, American Association for Wind Engineering and the American Society of Civil Engineers (ASCE), May 2004;

[4] *New Opportunities to Reduce Wind Hazard Losses and Improve Quality of Life in the USA*, American Association for Wind Engineering, August 1997;

[5] *Proceedings of International Workshop on Wind Engineering Research and Practice: Current State of the Art and Future Needs/Plans*, Chapel Hill, NC, May 2010;

[6] *NOAA's Storm Surge Roadmap: Transition Research to NWS Operations*, J. Feyen, July 2010;

[7] *Coastal Storm Modeling – System Integration*, US Army Corps of Engineers, T. Massey, T. Wamsley, M. Cialone, 2011;

[8] *Wood Engineering Challenges in the New Millennium – Critical Research Needs*, Proceedings of the Workshop Offered in Conjunction with the Structural Engineering Institute (SEI) of ASCE Structures Congress 2008, V. K. A. Gopu, April 2008;

[9] *Performance Based Design Extreme Wind Loads on a Tall Building, The Structural Design of Tall Buildings*, A. Jain, M. Srinivasan, G. C. Hart, August 2000;

[10] *Toward the Probabilistic Simulation of Storm Surge and Inundation in a Limited-Resource Environment*, Davis et al, American Meteorological Society, 2010;

[11] *Grand Challenges for Disaster Reduction*, National Science and Technology Council, Subcommittee on Disaster Reduction, 2005;

[12] *Proceedings, Workshop on Research Needs in Wind Engineering*, NISTIR 5597, National Institute of Standards and Technology, 1995;

[13] *Windstorm Mitigation Initiative, Retrofit Workshop Report*, Texas Tech University, December 1999;

[14] *Grand Challenges for Disaster Reduction*, National Science and Technology Council, Subcommittee on Disaster Reduction, 2008;

[15] *Coastal Hazards Colloquium*, Department of Homeland Security, Science and Technology Directorate, University of North Carolina, December 2008;

[16] *Wind Engineering Research Needs*, P. Irwin, ASCE Technical Council on Wind Engineering, 2011;

[17] *Disaster Resilience: A National Imperative*, National Academies Press, 2012;

[18] *Developing Guidelines and Standards for Disaster Resilience of the Built Environment: A Research Needs Assessment*, NIST Technical Note 1795, March 2013;

[19] *Wind and the Built Environment, U.S. Needs in Wind Engineering and Hazard Mitigation*, National Research Council, 1993; and

[20] *ATC-57, The Missing Piece: Improving Seismic Design & Construction Practices*, Applied Technology Council, 2003.

A.2 Categorization of Reviewed Documents by Initial Set of Program Subject Areas and Elements

The recommendations from the literature were organized under the initially identified two subjects areas and five program elements (as adapted from the ATC-57 Report) that were included in the work plan for this roadmap development effort (Figure A-1). Under each program element, a brief summary is provided, followed by a list of specific recommendations, where the number in [ ] before each entry in the list refers to the number assigned to each reference in Section A.1.

- ***Systematic Support of the Windstorm and Coastal Inundation Code Development Process***

  Program Element 1: Provide technical support for windstorm and coastal inundation engineering practice and code development process.

  Program Element 2: Develop the technical basis for performance-based windstorm and coastal inundation engineering by supporting problem-focused, user-directed research and development.

- ***Improve Windstorm and Coastal Inundation Design and Community Resilience***

  Program Element 3: Support the development of technical resources (e.g., guidelines, manuals, software tools) to improve windstorm and coastal inundation engineering practice.

  Program Element 4: Make evaluated technology available to practicing professionals in the windstorm and coastal inundation design and construction communities.

  Program Element 5: Develop the technical basis for windstorm and coastal inundation engineering to support community resilience within an all-hazards framework.

Figure A-1 Program subject areas and elements as defined in the work plan for this Roadmap development effort.

A.2.1 Subject Area 1: Systematic Support of the Windstorm and Coastal Inundation Code Development Process

Program Element 1: Provide technical support for windstorm and coastal inundation engineering practice and code development process.

The literature focused on modeling of hazards for the purposes of determining loading requirements and the simulated effects of the hazards on the structures. Given the variety of building shapes, and the lack of more precise knowledge about the specific impacts of wind loading on various structural and non-structural elements, the literature also suggests that simulation and modeling techniques for wind must be created in order for practitioners to develop cost-effective wind designs. These techniques should include numerical modeling, visualization, database-assisted design, and wind simulations.

The literature that focused on codes and standards suggested that improvements were needed in the number of building shapes for which wind pressure coefficients exist and that risk and vulnerability tools were needed for assessing the probable performance of critical facilities and infrastructure.

[3] Develop simulation techniques for wind modeling;

[3] Develop database and knowledge-based models for wind loading on structures;

[3] Develop simulation techniques for modeling of wind loading on structures;

[3] Develop techniques for modeling effects of wind hazards;

[3] Improve characterization of properties of severe winds;

[3] Develop instrumentation and data transfer/processing infrastructure for wind data acquisition;

[3] Develop computational methods for simulating wind loading;

[3] Develop databases and visualization tools for simulation of wind effects;

[4] Modeling of wind-structure interaction, including effects of integral wind loads on structural systems, components and cladding, effectiveness of retrofitting schemes, effects of structural fatigue and impact by wind-generated missiles, design of cost effective tornado shelters and shelters for hurricane zones to minimize evacuation;

[4] Application of effective numerical schemes using computational fluid dynamics to determine the wind environment and wind loading on and response of buildings, structures, transportation systems and other critical components of civil engineering infrastructure, and to mitigate these effects;

[5] Study the possibilities of using wind database-assisted design techniques;

[5] Study the possibilities of using wind database-assisted design techniques;

[5] Need new gust loading factors, including 3-D gust loading factors;

[5] Need wind design methodology for photovoltaic systems;

[5] Investigate shape coefficients for more roof shapes than currently exist in ASCE 7, *Minimum Design Loads for Buildings and Other Structures*;

[13] Develop tools to simulate aging of components including corrosion;

[13] Develop methods for assessing load path continuity;

[14] Provide the technical basis for revised codes and standards for critical infrastructure and essential facilities by using risk and vulnerability assessment tools;

[16] Increase the number of building shapes available in the codes and standards;

[19] Develop or improve analytical, numerical and experimental methods for determining wind loading; and

[19] Develop comprehensive wind speed database.

Program Element 2: Develop the technical basis for performance-based windstorm and coastal inundation engineering by supporting problem-focused, user-directed research and development.

The literature focused on defining performance measures for structural frames and the building envelope for the wind hazard. Performance levels should be defined for varying levels of hazard intensity. The design criteria should reflect system reliability issues, not component reliability.

Several specific problem-focused studies were mentioned in the literature, including the need to better understand both wind- and flood-borne debris, serviceability thresholds, and the changes that occur in both wind fields and coastal inundation levels at the land-sea interface.

[1] Study the interaction of hurricanes with engineered structures;

[2] Evaluate the response of the built environment and critical infrastructure to wind events by investigating aerodynamic response, load path, ultimate capacity and the performance of the building envelope;

[2] Assess the impact of wind and windborne debris or wind and water/ice/snow;

[3] Improve understanding of wind-borne debris;

[3] Define performance measures;

[4] Conduct research on debris impact potential in windstorm and develop impact resistant building components;

[5] Research the transition in turbulence from Exposure D to Exposure B at landfall;

[5] Determine serviceability thresholds for wind motion in tall buildings;

[5] Conduct research on wind-borne debris;

[8] Develop and implement performance-based approaches for the design of wood structures;

[11] Develop reliable methods to design structures to meet specific performance levels under increasing levels of hazard intensity;

[12] Establish design criteria that reflects system reliability as opposed to component reliability; and

[13] Determine characteristics of wind-borne missiles, including better definition of the geographical boundaries where missile impacts should be taken into account in design, and determination of the correlation between missile size, weight and impact speed with wind speed.

A.2.2 Subject Area 2: Improve Windstorm and Coastal Inundation Design and Community Resiliency

Program Element 3: Support the development of technical resources (e.g., guidelines, manuals, software tools) to improve windstorm and coastal inundation engineering practice.

The literature focused on the development of guidance for wind and coastal inundation issues that could be modeled after the guidance already developed for other hazards, such as earthquakes. Specifically, the literature mentioned loss assessment methodologies, damage and fragility models, response of structural systems and probabilistic methods as examples of issues that have been studied and written about for earthquake practitioners that could be carried forward and studied for wind and flood practitioners.

The literature also suggested that some tools specific to coastal inundation should be made available to practitioners, such as a storm surge model that could be used to develop surge scenarios or could be used specifically for design and an improved method for determining water levels or depths at any point in the flooded area.

[2] Explore the near-ground and channeling/shielding effects of winds on buildings through testing and instrumentation

[2] Measure the response of bridges and other highway structures to wind events, including stability, serviceability and functionality leading up to and through extreme events

[3] Improve knowledge on behavior of structural and non-structural components;

[3] Improve understanding of response of structural systems;

[3] Improve damage and fragility models for structures;

[3] Improve indirect loss estimation models for wind hazards;

[3] Develop real-time loss estimation tools;

[4] Study internal load paths and the performance of structural systems, and effectiveness of connections between structural components;

[6] Develop the Advanced Circulation (ADCIRC) model for operational use;

[6] Improve determination of storm water levels;

[6] Develop techniques to show flood depth above ground;

[11] Improve loss assessment methodologies and decision support tools to include multiple hazards, based on existing tools developed for earthquake engineering;

[13] Improve probabilistic treatment of the variability in loads and resistance;

[14] Develop probabilistic inundation hazards prediction and methods to effectively quantify and communicate risk; and

[19] Develop effective technology transfer techniques to apply research results to design of wind-resistant structures and components.

Program Element 4: Make evaluated technology available to practicing professionals in the windstorm and coastal inundation design and construction communities.

The literature focused primarily on developing technologies since there have been few resources available for pursuing technology to the point where it could be made available and useful to practitioners. Some of the topics would appear to need some significant study before tools can be developed for use by practitioners. However, once available, the information could be of significant use to the practice with the potential to reduce design and construction costs of buildings built in wind and coastal inundation areas and to reduce losses caused by these events.

The topics discussed in the literature include hazard identification issues, such as improved mapping of the wind hazard; loading issues, such as the effects of various types of windstorms on structural loading; and the very dynamic transition that occurs in both wind and water loads at the interface between the water and the land. Also included were topics dealing with how to better determine the appropriate retrofitting requirements for existing buildings.

[1] Develop improved techniques for in situ observations;

[1] Develop a better understanding of air-sea interaction;

[2] Develop new technologies and ground, airborne and satellite based storm observation systems to improve knowledge and understanding of windstorms and the wind variability within those storms;

[2] Examine the interaction between wind and storm surge to determine the impact on building foundations and critical infrastructure;

[3] Improve mapping of wind hazard;

[3] Develop tools for real-time monitoring of wind hazards;

[3] Continue to develop remote-sensing technologies for damage assessment;

[3] Develop retrofit techniques for new and existing materials, components systems and subsystems;

[3] Demonstrate application of new tools in post-event setting;

[4] Collect wind speed data using robust instrumentation and state-of-the-art technology to map the detailed structure of the wind, topographic effects, and long-term climate effects;

[4] Develop effective techniques for collection, rapid archiving, and dissemination of data acquired during post-disaster investigations;

[4] Develop cost-effective retrofit techniques to enhance wind resistance of existing structures;

[4] Map wind climate in urban areas;

[4] Simulate hurricanes and their wind fields, and other extreme wind effects for statistical analysis of wind, wind loads, and wind-induced response of structures and their components;

[5] Study the variations of results of wind tunnel studies;

[5] Develop/improve damping technology for tall buildings;

[5] Study the effects of exposure and terrain on wind pressures at buildings;

[5] Study the effects of building size and shape on attenuating wind pressure;

[5] Study the flow around buildings from tornado vortex to determine pressure requirements for design;

[7] Improve storm surge modeling by coupling five other coastal models to the U.S. Army Corps of Engineers' Engineering Research and Development Center's Coastal Storm Modeling System (CSTORM-MS);

[13] Develop an understanding of long-term performance of glues, adhesives and coatings;

[14] Examine the interaction between wind, storm surge and shallow water waves to determine the impact on building foundations, critical infrastructure, and vegetation;

[14] Evaluate capabilities of radar for swell/wave and deformation measurements;

[14] Develop coastal wind/wave climate maps and shoreline coastal process models to better understand and predict aspects of coastal erosion and inundation;

[14] Determine climate scale factors that relate to sea level variability and rise;

[15] Improve quantitative predictions of coastal erosion;

[15] Improve understanding of the physics of tropical cyclones or coastal ocean conditions at the land-water interface;

[16] Study the effects on structures of wind loading caused by various wind event types;

[16] Study the effects of building surroundings on structural reliability and risk of damage caused by wind loading;

[16] Establish a program of real-time wind monitoring of buildings;

[19] Better define wind loads in codified form for use with small buildings;

[19] Research windflow around buildings to improve empirical prediction of cladding pressures;

[19] Improve knowledge of dynamic loading effects on flexible structures; and

[19] Research cyclic loading to improve understanding of fatigue problems.

Program Element 5: Develop the technical basis for windstorm and coastal inundation engineering to support community resilience within an all-hazards framework.

The literature had a significant number of references to improvements that are needed in assessing community resiliency including determining the benefits to the community for community-wide loss reduction measures. There are several references to the need for technologies to aid in the rapid repair and restoration of critical infrastructure and for material development to improve long-term building performance and reduce construction cost.

The literature also articulated the need to develop hazard identification tools for multiple hazards across the broad spectrum of what could constitute a hazard for any particular community.

[1] Develop better capabilities to predict hurricane intensification and size, and thereby reduce the uncertainty associated with where and when hurricanes will make landfall;

[1] Study the economic and social impacts of hurricanes and develop new mitigation measures;

[1] Assess and improve the resilience of the built environment;

[2] Develop and implement technologies for rapid repair and restoration of critical infrastructure and critical services;

[2] Assess individual and community capability to respond to wind events, including vulnerability analyses, risk perception, risk communication, risk management, communication of wind warnings and public response, evacuation capability, and public knowledge of appropriate protective actions for wind events, especially among vulnerable populations;

[3] Develop methodologies and assess effectiveness in enhancing community resilience to the wind hazard;

[4] Develop and apply reliable techniques for cost-benefit analysis of wind hazard mitigation measures and other means for socio-economic evaluations;

[5] Study the interface between wind engineering and green building design;

[8] Develop next generation wood systems, including materials, connections, assemblies and products;

[8] Develop advanced design and construction methodologies using combined materials (hybrid construction);

[11] Identify mitigation strategies and technologies that can provide simultaneous protection against more than one hazard for a single cost; and

[11] Develop technologies to prevent cascading failures of complex lifeline systems.

A.3 Research Priorities Identified from the Literature

The literature search covered approximately 20 years of reports and studies on the need for wind and coastal inundation research and each of these studies in some way identified specific research topics. The literature used for this analysis is only that which represented the views of many reviewers, workshop participants, or authors of the document. The number of times the various research and development recommendations identified above were cited in the literature is summarized in Table A-1 as a measure of their importance and/or longevity of need. The topics are organized by hazard type (wind or coastal inundation) and then by hazard subject area (hazard identification, loads, resistance, and performance-based design.

Table A-1 Research Priorities from Literature Search

Research Topic	Number of Times Mentioned	Program Element Mapping*
Wind Hazard		
Develop modeling or simulation techniques for wind hazard	7	1-1
Develop better understanding of wind-borne debris	4	1-2
Improve wind mapping	3	2-4
Wind Loads		
Develop computational models or use databases for wind loading	12	1-1
Develop wind pressure coefficients for an increased number of building shapes and systems	2	1-1
Study terrain, exposure factors in developing wind pressures	1	2-4
Collect real-time wind pressure measurements to calibrate models	7	2-4
Wind Resistance		
Develop capability to assess load path continuity	4	1-1 2-3
Develop tools to simulate aging	1	1-1
Improve loss estimation tools, including fragility models	5	2-3
Develop retrofit techniques	2	2-4
Performance-based Design–Wind		
Define performance levels and acceptance criteria for the wind hazard	4	1-2
Coastal Inundation Hazard		
Improve techniques for finding flood depths, storm surge inundation extent, and probabilistic flood depths	5	2-3
Coastal Inundation Loads		
Improve knowledge of erosion, climate changes, and wave impacts	5	2-4
Coastal Inundation Resistance Performance-based Design & Coastal Inundation Resiliency and Sustainability		
Improve performance of infrastructure	3	2-5
Research new materials and assemblies	4	2-5
Develop cost-effectiveness and reliability assessment methods	5	2-5

*Values in cells are provided in x-x format, with the first number indicating either subject area 1 or 2 and the second number indicating program elements 1 through 5 (See Figure A-1 for program subject area and element definitions).

Appendix B

June 2012 Reston, Virginia Workshop

B.1 Workshop Agenda

Wednesday, June 13, 2012

8:00 - 8:30 am	Registration, Continental Breakfast
8:30 - 8:40 am	Welcome, Housekeeping, Plan for the 2 Days – Bill Coulbourne (ATC)
8:40 - 9:30 am	Overview of NIST and Engineering Laboratory – and Charge to Workshop Participants - Shyam Sunder (NIST)
9:30 - 9:45 am	NSF's Role in Research - Kishor Mehta (NSF)
9:45 - 10:00 am	Introduction of the Research Focus Areas – Marc Levitan (NIST)
10:00 - 10:15 am	Break
10:15 - 10:45 am	1st Technical Plenary – Disaster Resilience of Building, Infrastructure, and Communities– Steve Cauffman (NIST)
10:45 - 10:50 am	Instructions for Morning Breakout Sessions – Bill Coulbourne (ATC)
10:50 - 11:50 am	Break-Out Sessions - Future Vision of Resilient Communities and How We Get There

For the first breakout sessions, each pre-assigned group will define what they think constitutes a disaster resilient community, how this community would be identified or defined, and the gaps in current knowledge that need to be addressed to enable disaster-resilient communities.

11:50 - 12:20 pm	Resilience Groups Report Out (*Plenary Meeting Room)*
12:20 - 1:00 pm	Lunch
1:00 - 1:45 pm	2nd Technical Plenary – Moving Toward Performance-Based Design for Wind: Larry Griffis (Walter P. Moore) *Chris Letchford to introduce Larry Griffis*
1:45 - 2:15 pm	3rd Technical Plenary – R&D Challenges for Coastal Inundation Impact Reduction: Gary Chock (Chock and Martin) *Chris Jones to introduce Gary Chock*

2:15 - 2:20 pm Instructions for Afternoon Breakout Sessions – Bill Coulbourne (ATC)

2:20 - 5:05 pm Break-Out Sessions – by Discipline Groups

Breakouts into the five pre-assigned discipline areas listed below for identification of gaps in current knowledge and research needs. Use literature search document as background for gaps in knowledge and research needs identified by other groups over the last 10-15 years. Groups also discuss possible Grand Challenge needs.

(Moderators for each group shown in italics)

Room A – Wind hazard group *(Chris Letchford)*
Room B – Wind loading group *(Jon Galsworthy)*
Room C – Wind resistance group *(Tom Smith)*
Room D – Flood hazard group *(Chris Jones)*
Room E – Flood loading and resistance group *(Bill Coulbourne)*

3:15 - 3:30 pm Break (take at leisure)

5:05 - 5:15 pm Organization for Tomorrow – Bill Coulbourne (ATC)
Plenary Meeting Room

5:15 pm Adjourn
Shuttle buses will take participants back to the Sheraton Hotel

Thursday, June 14, 2012

8:00 - 8:30 am Continental Breakfast

8:30 - 9:40 am Discipline Groups Report Out Including Grand Challenge Ideas
Plenary Meeting Room

9:40 - 9:45 am Instructions for Morning Breakout Sessions – Bill Coulbourne (ATC)

9:45 - 11:45 am Break-Out Sessions – Crosscutting by Program Element

Groups will change for Day 2 as the focus will shift. Participants are pre-assigned to one of the five areas listed below; corresponding to the program elements adapted from ATC-57 approach and will be provided summaries of the Resilience and Disciplinary breakout group research needs lists. Each group must identify the Top 10 research needs for their assigned program element.
(Moderator for each breakout group shown in italics)

Room A – Provide technical support for windstorm and coastal inundation engineering practice and code development process. What specific technical support is needed by the committees that develop model codes and the standards upon which the model codes depend? (*Chris Letchford)*

Room B – Develop the technical basis for performance-based windstorm and coastal inundation engineering by supporting problem-focused, user-directed research and development. What research is required to develop the technical basis for performance-based design for windstorms and coastal inundation? (*Jon Galsworthy)*

Room C – Support the development of technical resources (e.g., guidelines and manuals) to improve windstorm and coastal inundation engineering practice. What new technical resources are needed by practitioners? What research and development must be done in order to provide these resources? (*Chris Jones)*

Room D – Make evaluated technology available to practicing professionals in the windstorm and coastal inundation design and construction communities. In what ways should evaluated technology be made available to practicing professionals in the windstorm and coastal inundation design and construction communities? On what current topics is significant research reported in the literature but needs to be evaluated and coalesced into a single document designed for use by practitioners. (*Tom Smith)*

Room E – Develop the technical basis for windstorm and coastal inundation engineering to support community resilience within an all-hazards framework. Building on the discussion in Day 1 on community resilience, what research is needed to define, measure, and provide the basis for improvements to the resilience of buildings, infrastructure, and communities for windstorms and coastal inundation? (*Horia Hangan)*

10:00 - 10:15 am	Break (take at leisure)
11:45 - 12:15 pm	Lunch
12:15 - 2:00 pm	Report Out and Discuss Top 10 Research Projects per Program Element *Plenary Meeting Room*
2:00 - 2:30 pm	Breakout Session - Fine-Tuning Research Priorities *Return to morning breakout rooms*
2:30 - 2:45 pm	Break
3:00 - 3:55 pm	Discuss and Prioritize Overall Top 15 Research Projects *Plenary Meeting Room*
3:55 - 4:00 pm	Workshop Closing Remarks – Marc Levitan (NIST)
4:00 pm	Adjourn *Shuttle buses will take participants back to the Sheraton Hotel*

B.2 Workshop Presentations

The following is a synopsis of each of the three technical presentations delivered in the June workshop.

- *Disaster Resilience of Building, Infrastructure, and Communities* by Stephen Cauffman (NIST)

This presentation focused on defining resilience especially at the community level. Resilience was described as the capability of a system to maintain acceptable levels of functionality during and after a disruptive event and to recover fully within some specified time period. Issues were identified to help achieve resilient communities. An example was given of what the City of San Francisco has done to develop performance goals for their inventory of buildings and infrastructure. New design codes and standards are needed that deal with performance objectives.

- *Moving Toward Performance-Based Design for Wind* by Larry Griffis (Walter P Moore)

This presentation covered the state of current structural engineering practice for wind and compared it to potential benefits if the practice were modified using performance-based design concepts. The current state of the practice is to design to yield strength instead of extending the load into the elastic response range. The current practice thus uses a static elastic analysis procedure instead of considering the dynamic effects of wind and using a non-linear dynamic analysis procedure using performance objectives to establish the limits of allowable motion. ASCE 41-06 *Seismic Rehabilitation of Existing Buildings* was used as guide for the comparative analysis.

- *R&D Challenges for Coastal Inundation Impact Reduction* by Gary Chock (Martin & Chock)

This presentation began with the general effects of flood inundation and used earthquakes and the effects of tsunamis as the basis for the R&D challenges since storm surge impacts are similar to tsunamis. The R&D needs were defined as: coastal storm flood depths and velocity maps with mean recurrence interval consistent with wind standards; tsunamis inundation design maps; a better understanding of tsunami drawdown flow, which can be very significant; research on scour effects of water flow around buildings; a better understanding of combined structural loadings on building and non-building structures; research on post-elastic structural response of extreme hydrodynamic forces; and structural response metrics for performance-based tsunami design.

B.3 Workshop Participants

Table B-1 June 2012 Workshop Participants

Last Name	First Name	Organization
Adams	Stuart	Louisiana State University
Annane	Bachir	University of Miami
Baskaran	Bas	National Research Council
Bienkiewicz	Bogusz	Colorado State University
Bitsuamlak	Girma	Western University
Bosch	Harold	Federal Highway Administration (HRDI-50)
Bres	Dana	U.S. Dept. of Housing and Urban Development
Caracoglia	Luca	Northeastern University
Cauffman	Stephen	NIST-Engineering Laboratory
Chock	Gary	Martin & Chock, Inc.
Chowdhury	Arindam	Florida International University
Cocke	Elizabeth	U.S. Dept. of Housing and Urban Development
Coulbourne	William	Applied Technology Council
Cox	Daniel	Oregon State University
Dickinson	Tamara	Office of Science and Technology Policy
Dregger	Philip	Technical Roof Services, Inc.
Ehrlich	Gary	National Association of Home Builders
Feyen	Jesse	National Oceanic and Atmospheric Administration
Francis	Mathew	URS Corp.
Friedland	Carol	Louisiana State University
Friis	Donna	CDM Smith
Galsworthy	Jon	Rowan Williams Davies & Irwin, Inc.
Goupil	Jennifer	Structural Engineering Institute of ASCE
Griffis	Lawrence	Walter P Moore
Grosshandler	William	NIST-Engineering Laboratory
Hajj	Muhammad	Virginia Tech
Hall	Tom	Natural Hazards Zurich North American
Hangan	Horia	Western University
Harvey	Doug	Building Officials Association of Florida
Jones	Christopher	Christopher P. Jones & Associates
Kareem	Ahsan	University of Notre Dame
Kennedy	Andrew	University of Notre Dame
Laatsch	Edward	Department of Homeland Security Federal Emergency Management Agency

Table B-1 June 2012 Workshop Participants (continued)

Last Name	First Name	Organization
Letchford	Chris	Rensselaer Polytechnic Institute
Letvin	Eric	NIST-Engineering Laboratory
Levitan	Marc	NIST-Engineering Laboratory
Lin	Ning	Massachusetts Institute of Technology
Lombardo	Franklin	NIST-Engineering Laboratory
Lynett	Patrick	University of Southern California
Mehta	Kishor	National Science Foundation
Ockerman	Darwin	U.S. Geological Survey
Pauschke	Joy	National Science Foundation
Phan	Long	NIST-Engineering Laboratory
Prevatt	David	University of Florida
Reed	Dorothy	University of Washington
Reinhold	Timothy	Insurance Institute for Business & Home Safety
Resio	Don	University of North Florida
Rojahn	Christopher	Applied Technology Council
Sadek	Fahim	NIST-Engineering Laboratory
Sarkar	Partha	Iowa State University
Schroeder	John	Texas Tech University
Scott	Donald	PCS Structural Solutions
Shackelford	Randall	Simpson Strong-Tie Co.
Shyam-Sunder	Sivaraj	NIST-Engineering Laboratory
Simiu	Emil	NIST-Engineering Laboratory
Smith	Douglas	Texas Tech University
Smith	Thomas	TLSmith Consulting, Inc.
Vickery	Peter	Applied Research Associates
Yeo	DongHun	NIST-Engineering Laboratory

Appendix C

October 2012 Miami, Florida Workshop

C.1 Workshop Description

A second workshop was held in Miami on October 26, 2012, following the conclusion of the ATC/SEI *Advances in Hurricane Engineering Conference*, where many practitioners and academics were already gathered discussing the latest research on hurricanes, storm surge, and broader aspects of wind and coastal engineering. The objective of the October Wind and Coastal Inundation Research Needs Workshop was to refine the results of the workshop held in June 2012. The October workshop was held in two sessions (each 90 minutes in length), with 36 participants in the windstorm session and 15 in the coastal inundation session. Participants were briefed on the roadmap project and the results of the June workshop. Each research topic in the areas of hazard, loads, resistance, and performance-based design was discussed by the participants. The participants had the opportunity to provide comments on the research topics, input from which is reflected in Chapter 4.

At the conclusion of each workshop session, participants were provided a "ballot" and asked to select in each of the four topic areas (hazard identification, loads, resistance, and performance-based design) the research item that they considered to be the most important (irrespective of time and cost) and also the topic that they considered to be the best value (including consideration of importance, time and cost). These rankings are indicated in Table 5-1.

C.2 Workshop Participants

Table C-1 October 2012 Wind Workshop Participants

Last Name	First Name	Affiliation
Adams	Stuart	Louisiana State University
Aponte	Luis	University of Puerto Rico at Mayaguez
Baradaranshoraka	Mohammad	Louisiana State University
Boggs	Daryl	CPP, Inc.
Cai	Steve	Louisiana State University
Carter	Russell	Texas Tech University
Charney	Finley	Virginia Tech
Chock	Gary	Martin & Chock, Inc.
Cochran	Leighton	Leighton Cochran Consulting
English	Elizabeth	University of Waterloo
Friedland	Carol	Louisiana State University
Galsworthy	Jon	RWDI
Griffis	Larry	Walter P Moore
Jain	Anurag	Weidlinger Associates, Inc.
Karns	Jesse	MiTek Ind.
Lavelle	Francis	Applied Research Associates
Liu	Fanggian	Clemson University
Mason	Matthew	Risk Frontiers - Macquarie University
Masters	Forrest	University of Florida
Matthews	Elizabeth	Louisiana State University
Mehta	Kishor	National Science Foundation
Miltiades	Ted	Georgia Department of Community Affairs
Nelson	Rawn	MiTek Ind.
Pan	Fang	Louisiana State University
Pei	Bin	Clemson University
Peterka	Jon	CPP, Inc.
Prevatt	David	University of Florida
Rojahn	Christopher	Applied Technology Council
Roueche	David	University of Florida
Ruark	Dean	PGT Industries
Scott	Donald	PCS Structural Solutions
Shafieezadeh	Abdollah	Ohio State University
Smith	Douglas	Texas Tech University
Smith	Mario	None provided
Smith	Tom	TLSmith Consulting
Towson	Bill	Georgia Department of Community Affairs

Table C-2 October 2012 Flood Workshop Participants

Last Name	First Name	Affiliation
Adams	Stuart	Louisiana State University
Aponte	Luis	University of Puerto Rico at Mayaguez
Chock	Gary	Martin & Chock, Inc.
Cochran	Leighton	LCC Ltd.
English	Elizabeth	University of Waterloo
Friedland	Carol	Louisiana State University
Hayden	Jesse	URS Corporation
Matthews	Elizabeth	Louisiana State University
Mehta	Kishor	National Science Foundation
Miltiades	Ted	Georgia Department of Community Affairs
Ogea	Shandy	Louisiana State University
Rojahn	Christopher	Applied Technology Council
Shahieezadeh	Abdollah	Ohio State University
Smith	Douglas	Texas Tech University
Towson	Bill	Georgia Department of Community Affairs

Appendix D

Workshop Research Needs Mapped to Program Elements

Breakout groups at the June 2012 workshop identified a number of research and development needs for each of the initial program elements, as defined in the work plan for this Roadmap development effort. These research and development needs are identified in the subsections that follow. Within each program element, the groups were also asked to identify the three most important topics, which are indicated in italics at the beginning of each list and factored into the selection of the priorities provided in Chapter 5. The designation of “maps to” indicates how the item corresponds to the numbered R&D topics in Chapters 4 and 5, for those topics that were ultimately included.

D.1 Subject Area 1: Systematic Support of the Windstorm and Coastal Inundation Code Development Process

Program Element 1: Provide technical support for windstorm and coastal inundation engineering practice and code development process.

- *Tornado loads (maps to R&D topic 9)*
- *Develop & validate test methods for assemblies (wind, rain, debris, wave) (maps to R&D topic 11)*
- *Update and validate wind/wave/debris loading (maps to R&D topic 20)*
- Characterize wind/coastal flooding hazards (probability distribution) and joint probability distribution (maps to R&D topic 1)
- Impact of climate change on wind/wave hazard (maps to R&D topic 2)
- Hazard modification by terrain/topography/buildings (maps to R&D topic 4)
- Uncertainty analysis of systems (maps to R&D topic 5)
- Aging and repeated loading (inter & intra hazard events), (maps to R&D topic 11)

Program Element 2: Develop the technical basis for performance-based windstorm and coastal inundation engineering by supporting problem-focused, user-directed research and development.

- *Develop the hazard maps for wind and hydrodynamic loading (maps to R&D topic 1)*
- *Define performance levels by hazard (e.g., wind, hydrodynamic loads) (maps to R&D topic 15)*
- *Develop loading & structural analysis procedures and validation (maps to R&D topics 8 and 23)*
- Develop debris hazard maps (wind & water) (maps to R&D topics 3 and 19)
- Define acceptability criteria by performance level (maps to R&D topic 15)
- Study non-linear/post-elastic behavior of structural systems (maps to R&D topic 16)
- Cyber-based tools for improved sharing of information and resources (maps to R&D topic 17)
- Performance-based design for multiple hazards (e.g., wind & wave) (maps to R&D topics 18 and 30)
- Component testing to establish acceptability criteria (maps to R&D topic 26)
- Apply performance-based design framework to evaluate existing codes & standards

D.2 Subject Area 2: Improve Windstorm and Coastal Inundation Design and Community Resiliency

Program Element 3: Support the development of technical resources (e.g., guidelines and manuals) to improve windstorm and coastal inundation engineering practice.

- *Evaluation of resistance of existing buildings (maps to R&D topic 14)*
- *Single wind procedure, including building shapes, attachments, emerging (green) technologies (e.g., solar panels) (maps to R&D topic 8)*
- *Better flood load calculation procedure (maps to R&D topic 23)*
- Low probability of exceedance hazard maps (maps to R&D topics 1 and 22)
- Design for single family houses against tornado (maps to R&D topic 9)
- Setting performance goals for expected wind events (maps to R&D topic 15)
- System-based standards for multi hazard community resilience (maps to R&D topic 18)
- Flood data damage set, damage functions/fragility (maps to R&D topic 26)

- Improved means for risk communication including replacement of deterministic lines on flood maps
- Effective attachment of cladding – includes roof edges

Program Element 4: Make evaluated technology available to practicing professionals in the windstorm and coastal inundation design and construction communities.

- *Wind characteristics & loads for non-conventional boundary layer wind (maps to R&D topic 3)*
- *Integrated portal – GIS risk-based lookup for all-hazards engineering data (maps to R&D topic 17)*
- *Centralized website portal of publications and data (maps to R&D topic 17)*
- Computational Fluid Dynamics – move into practice (maps to R&D topic 7)
- Advanced hybrid wind resistance testing for building components (maps to R&D topic 11)
- Vulnerability assessment – repair or replace, each type of building envelop component (maps to R&D topic 14)
- Benchmark proven models with new techniques (e.g., computational fluid dynamics) to increase the number of tools for practitioners to use
- Cost-benefit improvements for mitigation & code+ construction so more benefits can be considered
- Education/training/certification of design & building professionals

Program Element 5: Develop the technical basis for windstorm and coastal inundation engineering to support community resilience within an all-hazards framework.

- *Coupled modeling (maps to R&D topics 18 and 23)*
- *Resiliency linked to sustainability (maps to R&D topic 18)*
- *Database improvements (maps to R&D topic 17)*
- Laboratory tests (maps to R&D topics 6, 11, and 23)
- Linkage with other professional models – social and economic (maps to R&D topic 18)
- Probabilistic Risk Analysis – need statistics of local storm and surge systems incidence (maps to R&D topic 22)
- Guidance for practitioners and consumers

- Stress tests: HAZUS as a possible point of departure
- Field measurements for model validation (maps to R&D topic 23)

Acronyms

AIA:	American Institute of Architects
ASCE:	American Society of Civil Engineers
ASTM:	American Society for Testing and Materials
ATC:	Applied Technology Council
BIM:	Building Information Modeling
BSE:	Base Flood Elevation
C&C:	Components and cladding
CFD:	Computational fluid dynamics
CFR:	Code of Federal Regulations
CSTORM-MS:	The U. S. Army Corp of Engineers Research and Development Center's Coastal Storm Modeling System
FEMA:	Federal Emergency Management Agency
HVAC:	Heating, ventilation, air conditioning
MWFRS:	Main wind force resisting system
NFIP:	National Flood Insurance Program
NOAA:	National Oceanic & Atmospheric Administration
NSF:	National Science Foundation
NSSA:	National Storm Shelter Association
NWIRP:	National Windstorm Impact Reduction Program
NWS:	National Weather Service
USACE:	U. S. Army Corps of Engineers
USGS:	U. S. Geological Survey

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Project Participants

National Institute of Standards and Technology

Eric Letvin
National Institute of Standards and Technology
Engineering Laboratory (MS8611)
100 Bureau Drive
Gaithersburg, Maryland 20899

Marc Levitan
National Institute of Standards and Technology
Engineering Laboratory (MS8611)
100 Bureau Drive
Gaithersburg, Maryland 20899

NEHRP Consultants Joint Venture

APPLIED TECHNOLOGY COUNCIL
201 Redwood Shores Parkway, Suite 240
Redwood City, California 94065

CONSORTIUM OF UNIVERSITIES FOR RESEARCH IN EARTHQUAKE ENGINEERING
1301 S. 46th Street, Building 420
Richmond, California 94804

Joint Venture Management Committee

James R. Harris
J.R. Harris & Company
1775 Sherman Street, Suite 1525
Denver, Colorado 80203

Christopher Rojahn
Applied Technology Council
201 Redwood Shores Parkway, Suite 240
Redwood City, California 94065

Robert Reitherman
Consortium of Universities for Research in Earthquake Engineering
1301 S. 46th Street, Building 420
Richmond, California 94804

Andrew Whittaker
University at Buffalo
Dept. of Civil, Structural, and Environmental Engineering, 230 Ketter Hall
Buffalo, New York 14260

Windstorm and Coastal Inundation Program Committee

Jon A. Heintz (Program Manager)
Applied Technology Council
201 Redwood Shores Parkway, Suite 240
Redwood City, California 94065

Leighton Cochran
Leighton Cochran Consulting
35 Astor Terrace, Suite 504
Spring Hill, 4000, Queensland Australia

Kurtis R. Gurley
University of Florida
Dept. of Civil and Coastal Engineering
P.O. Box 116580, 365 Weil Hall
Gainesville, Florida 32611-6580

Spencer Rogers
North Carolina Sea Grant
5600 Marvin Moss Lane
Wilmington, North Carolina 28409

Donald R. Scott
PCS Structural Solutions
1250 Pacific Avenue, Suite 710
Tacoma, Washington 98402

Joseph B. Shepard
Haskell
111 Riverside Avenue
Jacksonville, Florida 32202

Thomas Lee Smith
TLSmith Consulting Inc.
16681 Boswell Road
Rockton, Illinois 61072

Project Technical Committee

William L. Coulbourne (Project Tech. Director)
Applied Technology Council
19266 Coastal Highway, Unit 4, #19
Rehoboth Beach, Delaware 19971

Jon Galsworthy
RWDI
650 Woodlawn Road West
Guelph, Ontario, Canada N1K 1B8

Horia Hangan
University of Western Ontario
Western Engineering
Spencer Engineering Building
London, Ontario, Canada N6A 5B8

Christopher Jones, P.E.,
Christopher P. Jones Consulting
5525 Jomali Drive
Durham, North Carolina 27705

Chris Letchford
Renessalear Polytechnic Institute
Department of Civil and Environmental Engineering
110 Eighth Street
Troy, New York 12180

Thomas Lee Smith
TLSmith Consulting Inc.
16681 Boswell Road
Rockton, Illinois 61072

Publication Services

Amber Houchen
Applied Technology Council
201 Redwood Shores Parkway, Suite 240
Redwood City, California 94065