NIST Special Publication 1000-4

December 2003 Public Update on the Federal Building and Fire Safety Investigation of the World Trade Center Disaster

NIST National Institute of Standards and Technology • Technology Administration • U.S. Department of Commerce

NIST Special Publication 1000-4

December 2003 Public Update on the Federal Building and Fire Safety Investigation of the World Trade Center Disaster

December 2003

U.S. Department of Commerce
Donald L. Evans, Secretary

Technology Administration
Phillip J. Bond, Under Secretary for Technology

National Institute of Standards and Technology
Arden L. Bement, Jr., Director

Disclaimer

Certain commercial entities, equipment, products, or materials are identified in this document in order to describe a procedure or concept adequately or to trace the history of the procedures and practices used. Such identification is not intended to imply recommendation, endorsement, or implication that the entities, products, materials, or equipment are necessarily the best available for the purpose. Nor does such identification imply a finding of fault or negligence by the National Institute of Standards and Technology.

Disclaimer

The policy of NIST is to use the International System of Units (metric units) in all publications. In this document, however, units are presented in metric units or the inch-pound system, whichever is prevalent in the discipline.

Use in Legal Proceedings

No part of any report resulting from a NIST investigation into a structural failure or from an investigation under the National Construction Safety Team Act may be used in any suit or action for damages arising out of any matter mentioned in such report (15 USC 281a; as amended by P.L. 107-231).

National Institute of Standards and Technology Special Publication 1000-4
Natl. Inst. Stand. Technol. Spec. Publ. 1000-4, 40 pages (December 2003)
CODEN: NSPUE2

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 2003

For sale by the Superintendent of Documents, U.S. Government Printing Office
Internet: bookstore.gpo.gov — Phone: (202) 512-1800 — Fax: (202) 512-2250
Mail: Stop SSOP, Washington, DC 20402-0001

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

This page intentionally left blank.

LIST OF ACRONYMS AND ABBREVIATIONS

Acronyms

ASTM	American Society for Testing and Materials
DTAP	Dissemination and Technical Assistance Program
FDNY	Fire Department of New York
FDS	Fire Dynamics Simulator
LERA	Leslie E. Robertson Associates
NCST	National Construction Safety Team
NIBS	National Institute of Building Sciences
NIST	National Institute of Standards and Technology
NYC	New York City
NYPD	New York Police Department
PANYNJ	Port Authority of New York and New Jersey
PAPD	Port Authority Police Department
P.L.	Public Law
R&D	Research and Development
USC	United States Code
WTC	World Trade Center

Abbreviations

ft	foot
hr	hour
in.	inch
lb	pound
MW	megawatt
psi	pounds per square inch
min	minute

This page intentionally left blank.

PREFACE

The National Institute of Standards and Technology (NIST) initiated the federal building and fire safety investigation of the World Trade Center (WTC) disaster on August 21, 2002. This WTC Investigation, led by NIST, is being conducted under the authority of the National Construction Safety Team Act (Public Law [P.L.] 107-231).

Goals of the WTC Investigation

- To investigate the building construction, the materials used, and the technical conditions that contributed to the outcome of the WTC disaster.
- To serve as the basis for:
  - Improvements in the way buildings are designed, constructed, maintained, and used
  - Improved tools and guidance for industry and safety officials
  - Recommended revisions to current codes, standards, and practices
  - Improved public safety

Objectives of the WTC Investigation

The objectives of the NIST-led Investigation of the WTC disaster are to:

1. Determine why and how WTC 1 and WTC 2 collapsed following the initial impacts of the aircraft and why and how WTC 7 collapsed
2. Determine why the numbers of injuries and fatalities were so high or low depending on location, including technical aspects of fire protection, occupant behavior, evacuation, and emergency response
3. Determine what procedures and practices were used in the design, construction, operation, and maintenance of WTC 1, 2, and 7
4. Identify, as specifically as possible, areas in current national building and fire model codes, standards, and practices that warrant revision

Authorities and Use of Information in Legal Proceedings

NIST is a non-regulatory agency of the U.S. Department of Commerce. NIST investigations are focused on fact finding, not fault finding. No part of any report resulting from a NIST investigation into a structural failure or from an investigation under the National Construction Safety Team Act may be used in any suit or action for damages arising out of any matter mentioned in such report (15 USC 281a, as amended by P.L. 107-231).

Organization of the WTC Investigation

The Investigation includes eight interdependent projects that, in combination, meet the objectives. A detailed description of each of these eight projects is available at http://wtc.nist.gov. The purpose of each

project is summarized in Table P–1, and the key interdependencies among the projects are illustrated in Figure P–1.

Table P–1. Federal building and fire safety investigation of the WTC disaster.

Technical Area	Project No.	Project Purpose
Analysis of Building and Fire Codes and Practices	1	Document and analyze the code provisions, procedures, and practices used in the design, construction, operation, and maintenance of the structural, passive fire protection, and emergency access and evacuation systems of the WTC 1, 2, and 7.
Baseline Structural Performance and Aircraft Impact Damage Analysis	2	Analyze the baseline performance of WTC 1 and 2 under design, service, and abnormal loads, and aircraft impact damage on the structural, fire protection, and egress systems.
Mechanical and Metallurgical Analysis of Structural Steel	3	Determine and analyze the mechanical and metallurgical properties and quality of steel, weldments, and connections from steel recovered from WTC 1, 2, and 7.
Investigation of Active Fire-Protection Systems	4	Investigate the performance of the active fire protection systems in WTC 1, 2, and 7 and their role in fire control, emergency response, and fate of occupants and responders.
Reconstruction of Thermal and Tenability Environment	5	Reconstruct the time-evolving temperature, thermal environment, and smoke movement in WTC 1, 2, and 7 for use in evaluating the structural performance of the buildings and behavior and fate of occupants and responders.
Structural Fire Response and Collapse Analysis	6	Analyze the response of the WTC towers to fires with and without aircraft damage, the response of WTC 7 in fires, the performance of open-web steel joists, and determine the most probable structural collapse sequence for WTC 1, 2, and 7.
Occupant Behavior, Egress, and Emergency Communications	7	Analyze the behavior and fate of occupants and responders, both those who survived and those who did not, and the performance of the evacuation system.
Fire Service Technologies and Guidelines	8	Building on work done by the Fire Department of New York and McKinsey & Company, document what happened during the response by the fire services to the WTC attacks until the collapse of WTC 7; identify issues that need to be addressed in changes to practice, standards, and codes; identify alternative practices and/or technologies that may address these issues; and identify research and development needs that advance the safety of the fire service in responding to massive fires in tall buildings.

NIST's WTC Public-Private Response Plan

The goal of the WTC Public-Private Response Plan is to develop the technical basis for standards, technology, and practices needed for cost-effective improvements to the safety and security of buildings and building occupants, including evacuation, emergency response procedures, and threat mitigation.

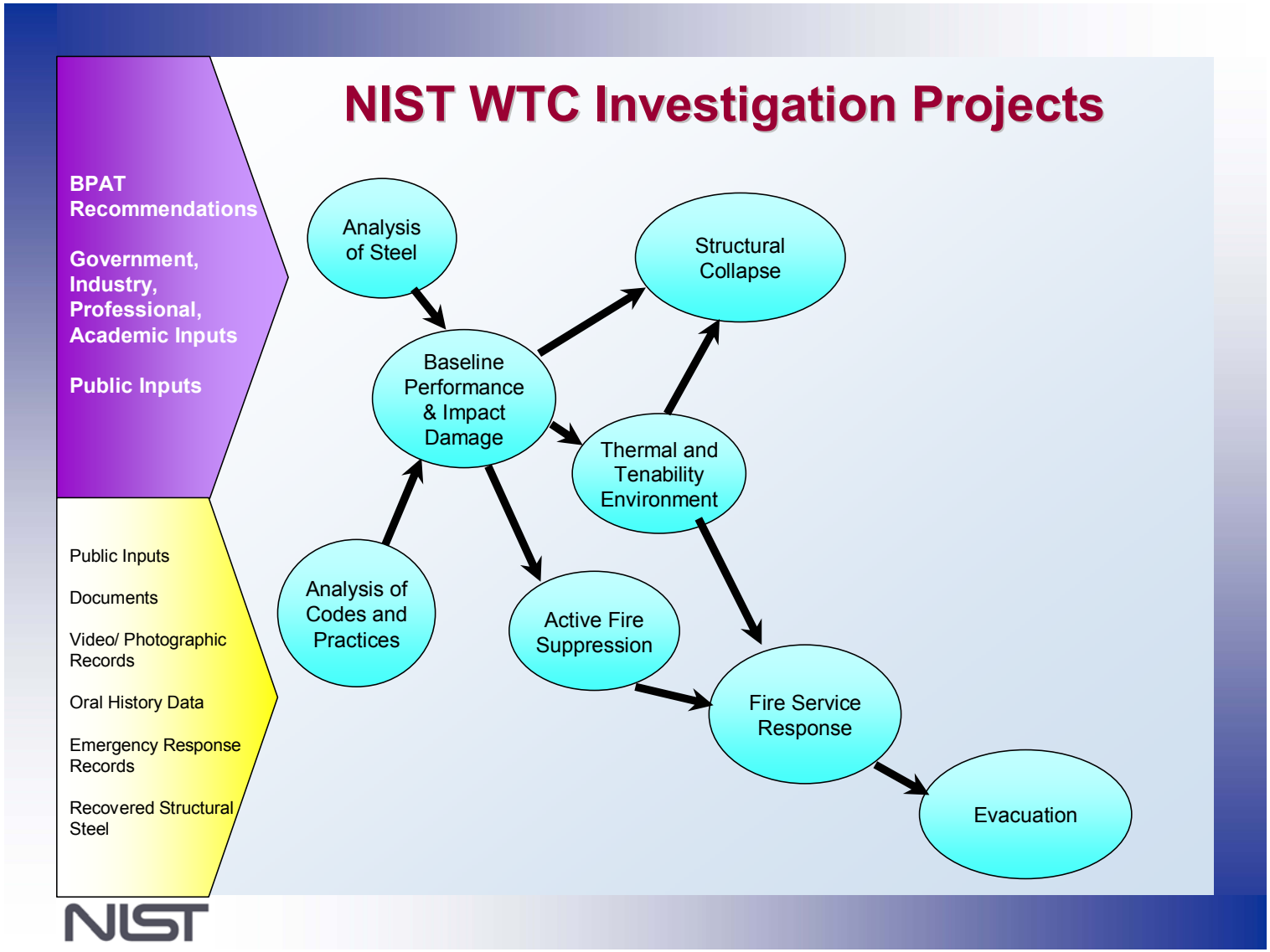


Figure P–1. The eight projects in the federal building and fire safety investigation of the WTC disaster.

The strategy to meet this goal is a three-part NIST-led public-private response program that includes:

- A federal building and fire safety investigation to study the most probable factors that contributed to post-aircraft impact collapse of the WTC towers and the 47-story WTC 7, and the associated evacuation and emergency response experience.
- A research and development (R&D) program to provide a technical foundation that supports improvements to building and fire codes, standards, and practices that reduce the impact of extreme threats to the safety of buildings, their occupants and emergency responders.
- A dissemination and technical assistance program (DTAP) to engage leaders of the construction and building community in implementing proposed changes to practices, standards, and codes. This effort also will provide practical guidance and tools to better prepare facility owners, contractors, architects, engineers, emergency responders, and regulatory authorities to respond to future disasters.

The desired outcomes are to make all buildings safer for occupants and first responders and to ensure better evacuation systems and emergency response capabilities for future disasters.

EXECUTIVE SUMMARY

The National Institute of Standards and Technology (NIST) initiated a formal federal building and fire safety investigation of the World Trade Center (WTC) disaster on August 21, 2002. At the same time, NIST also released the final plan for its investigation. In addition, NIST provided an update on investigation activities on December 9, 2002, and issued a detailed technical progress report on May 8, 2003. The investigation plan, which reflects comments received in writing and at a June 24, 2002, public meeting held in New York City, and prior updates and progress reports, may be found at the Web site http://wtc.nist.gov.

This public update summarizes investigation activities since the May 2003 progress report. NIST expects to release the next detailed technical progress report early in 2004. This update documents the good progress made on the investigation and covers the following highlights:

- Access obtained to all of the essential information needed for the investigation from a variety of organizations and agencies.
- Completion of the selection process for all major contractors and experts to augment NIST in-house capabilities.
- Progress toward building comprehensive models for analyzing the most probable structural collapse sequences, from aircraft impact to collapse initiation, and simplified models to supplement results from detailed models.
- Progress in experimental/field work to (1) analyze the recovered WTC structural steel, (2) support fire dynamics modeling, and (3) conduct fire endurance testing of typical WTC floor systems using ASTM E 119.
- Progress in the collection and analysis of photographic and video images to document the evolution of fire and smoke conditions and damage to the WTC buildings.
- Status of the first-person data collection effort involving WTC occupants, families of victims, and first responders, and summary status of overall evacuation and emergency response effort.
- Status of work on analysis of building and fire codes and practices, including a detailed review of the extraordinarily large volume of documents on the design, construction, operation, maintenance, and modifications to the WTC towers and WTC 7.
- Status of work on the investigation of installed active fire protection systems, specifically the sprinkler systems, the fire alarm systems, and the smoke management systems.
- Progress on research and development related to the WTC investigation on (1) fire safety design and retrofit of structures, and (2) emergency use of elevators.

Under the National Construction Safety Team (NCST) Act, signed into law in October 2002, NIST is authorized to investigate major building failures. The NIST investigations will establish the likely technical causes of the building failure and evaluate the technical aspects of emergency response and evacuation procedures in the wake of such failures.

A comprehensive Web site on the WTC Investigation and related work to improve the safety of buildings, their occupants, and first responders is at http://wtc.nist.gov.

This page intentionally left blank.

PUBLIC UPDATE

STATUS OF DATA COLLECTION EFFORTS

NIST is basing its review, analysis, modeling, and testing work for the WTC Investigation on a solid foundation of technical evidence. This requires access to critical data such as building documents, video and photographic records, emergency response records, and oral histories, in addition to the samples of steel that have been recovered.

NIST has received considerable cooperation and large volumes of information from a variety of organizations and agencies representing the building designers, owners, leaseholders, suppliers, contractors, and insurers. The documents and other information relate to the design, construction, operation, inspection, maintenance, repair, alterations, emergency response, and evacuation of the WTC complex.

Local authorities providing information include the Port Authority of New York and New Jersey (PANYNJ or Port Authority) and its consultants and contractors; the Fire Department of New York (FDNY); the New York Police Department (NYPD); the New York City (NYC) Department of Design and Construction; the NYC Department of Buildings; and the NYC Office of Emergency Management. In addition, the Occupational Safety and Health Administration provided correspondence sent to it regarding the evacuation experience of WTC occupants on September 11, 2001.

NIST also has received information from Silverstein Properties and its consultants and contractors; the group of companies that insured the WTC towers and its technical experts; Nippon Steel; Laclede Steel; Isolatek International, formerly known as U.S. Mineral Products; Roger Morse Associates; WR Grace; United Airlines; American Airlines; and Boeing. NIST also received a lot of information on floor plans, furnishings, and contents from tenants of all three buildings.

The information from Silverstein and the insurance companies includes the large body of technical work completed by both parties as part of the insurance litigation involving the WTC towers, such as reports on the structural collapse, fire spread and severity, and wind tunnel test results for the WTC towers. In addition, technical experts for both parties independently provided extensive briefings to the WTC Investigation team and discussed the tenability environment and the evacuation procedures in the buildings.

NIST has received all of the essential information it needs for the WTC Investigation. That information includes NYC 9-1-1 tapes, the transcripts of approximately 500 interviews of employees of the FDNY who were involved in WTC emergency response activities, and supporting documents for McKinsey & Company's FDNY study. NIST will gain access to the former two sets of information at NYC offices no later than December 31, 2003.

The following is the list of documentary information received or inspected by NIST since May 2003 (the complete list is available at http://wtc.nist.gov/media/status_collection.htm).

As of August 2003

- Design and structural calculations from Leslie E. Robertson Associates (LERA) for the WTC towers, including TV antenna, beams, and beam girders, as well as wind analysis and calculations

- Correspondence from LERA during the time of construction
- Laclede floor truss shop drawings (1,364) and other documents on steel and joints
- Information on steel from Nippon Steel
- List of WTC drawings in possession of Yamasaki and Associates
- Information on the flammable contents of the American Airlines B-767 aircraft
- Information regarding building contents and floor layouts from some tower tenants and one WTC 7 tenant (more tenant packages are expected)
- Mechanical and electrical system specifications/books for WTC 7
- Asbestos litigation documents from PANYNJ
- Underwriters' Laboratories test reports on spray-on fireproofing from supplier (Isolatek)
- Correspondence on the selection of WR Grace fireproofing products, test data, and Underwriters' Laboratories design listings (WR Grace)
- Data on the WTC internal radio system and FDNY radio repeater from PANYNJ
- Some FDNY training practices for operations in high-rise buildings
- Global positioning system coordinates where human remains and equipment were located and map from FDNY
- FDNY personnel killed on 9/11/01 and map of fire and EMS Command Post locations
- NYPD internal communications (43 cassette tapes) concerning the terrorist attacks on WTC
- Disaster Response Plan, Patrol Guide Procedures, and other guides and manuals from NYPD, including the Unusual Occurrence Report on the 1993 WTC bombing
- Reviewed a large portion of NYPD and FDNY extensive photographic and video collection and gained access to images needed for the Investigation
- Updated badge list of WTC occupants maintained by PANYNJ
- WTC Fire Safety and PA/FDNY WTC Training Videos and Pre-9/11 WTC photographs

As of November 2003

- Information on the flammable contents of the United Airlines B-767 aircraft
- Documents from PANYNJ on accessibility for disabled persons, active fire protection systems, and adoption of revisions to NYC Building Code
- Elevator and escalator contract information from PANYNJ
- Status of changes to WTC towers (March 1973) from PANYNJ
- Transcripts from 9/11/01 Port Authority Police Department (PAPD) audiotapes, police reports, and 9/11/01 PAPD special awards ceremony documents
- Additional documents from PANYNJ on asbestos litigation
- Supporting documents for McKinsey & Company's FDNY study

- Review of Underwriters' Laboratories test reports on spray-on fireproofing from supplier (WR Grace)
- Information from Boeing on flammable contents of aircraft that contributed to fires
- Port Authority white paper titled "Salient points with regard to the structural design of The World Trade Center towers"
- More than 6,100 photographs representing more than 185 photographers and many organizations (FDNY, NYPD, Associated Press, Corbis, New York Daily News, Reuters, New York Times, Star Ledger)
- About 5,726 video clips from 150 hours of videotapes and more than 20 individuals, news organizations, documentaries (FDNY, NYPD, ABC News, CBS News, NBC News, WABC, WCBS, WNBC New York, New York 1 News, WPIX)

In addition, NYC has agreed that no later than December 31, 2003, it will provide NIST access to NYC 9-1-1 tapes and logs as well as the transcripts of about 500 interviews of FDNY employees who were involved in the WTC emergency response activities. The review of materials will take place at NYC offices.

The few NIST requests for materials currently pending or not yet located include:

- Original contract specifications for WTC towers (lost in the collapse of the buildings)
- Construction and maintenance logs for WTC 1, 2, and 7 (lost in the collapse of the buildings)
- Calculations and analyses that supported the original aircraft impact studies (lost in the collapse of the buildings)
- Descriptions of partitions and furnishings in most of the tenant spaces of WTC 2 and 7 in the fire and impact zones
- Shop drawings showing connection details of WTC 7

NIST is making efforts to re-create this information from various sources because much of it was lost when the buildings collapsed. NIST will pursue other materials as needed for the Investigation.

SELECTION OF EXTERNAL EXPERTS AND CONTRACTORS TO SUPPORT THE WTC INVESTIGATION

NIST has assembled a seasoned group of in-house experts at the agency to carry out the Investigation. This group has the needed technical expertise as well as experience from significant prior investigations. More than two dozen NIST experts will be involved over the course of the Investigation.

In addition, NIST has augmented its in-house technical staff with experts outside of NIST who can contribute significantly to the goals and objectives of the WTC Investigation. In most cases, this is accomplished through contracts to provide specific deliverables required for successful completion of the Investigation. Awarding contracts on technical tasks allows NIST access to capabilities and expertise available in the private sector and makes efficient use of in-house staff resources on the WTC Investigation. These contractors complement the team approach that is the essence of the NCST Act.

NIST has completed the selection process for all major contractors and experts to augment in-house capabilities for the WTC Investigation. The total value of the awards is about $5.5 million.

This includes the administrative services contract awarded to Science Applications International Corporation in August 2002 to support the two-year investigation. A complete list of the awards and information related to the awards is available at http://wtc.nist.gov/solicitations/. A summary list of awards is provided in Table 1.

NIST used a rigorous source selection process that considers both technical and cost reviews and review of potential conflicts of interest. The process is managed by the NIST Acquisition and Logistics Division (Contracts Office). Details of the process are available at the WTC Web site address http://wtc.nist.gov/solicitations/solicitation_selection_process.htm.

NIST is also able to directly hire experts or consultants for intermittent work (up to 130 days per year) and has used this approach to hire a media expert to work in New York to collect photographic and video evidence relevant to the WTC Investigation. NIST has hired three individuals with knowledge and experience gained as former FDNY employees as it relates to firefighting in NYC high-rise buildings.

The role of the contractors and experts in the WTC Investigation is discussed throughout this public update. However, NIST, not the contractors and experts, is responsible for determining investigation findings, conclusions, and recommendations.

ANALYZING THE MOST PROBABLE STRUCTURAL COLLAPSE SEQUENCE

There are several leading hypotheses—postulated publicly by experts—for the structural collapse sequence from the time of aircraft impact to the collapse of each WTC tower. Similarly, hypotheses have been postulated for the collapse of the 47-story WTC 7 building. NIST is analyzing these and other possible structural collapse sequences as part of its investigation. Further work is needed to ensure that the results of any analysis can adequately explain the observations contained in photographs, videos, and first-person accounts of the events.

NIST has developed and adopted a comprehensive approach to identify the most probable of technically possible collapse sequences, from aircraft impact to collapse initiation. The approach accounts for variability in modeling, input parameters, analysis, and observed events within and between each analysis. The approach—which combines mathematical modeling and statistical and probabilistic methods—integrates multiple disciplines and can be used to discern which parameters significantly influence the results and determine the most probable sequence of events leading to the initiation of structural collapse.

The objectives of the failure analysis are to answer the following questions:

- What is the most probable collapse sequence?
- What confidence levels are associated with the most probable collapse sequence?
- What is the probability of other possible collapse sequences?
- What parameters have the strongest influence on the most probable collapse sequence?

The extent to which (or whether) confidence levels can be estimated will not be evident until the later stages of the Investigation.

This integrated approach enables the evaluation and comparison of plausible collapse hypotheses, which are based on probable damage states, fire paths, and structural response, to determine the most probable sequence of events.

Table 1. WTC Investigation contract solicitations and awards

WTC No.	Project No.	Title	Recipient	Status
1	7	Outside Experts for Occupant Behavior and Evacuation	Dr. Dennis Mileti, Dr. Norman Groner, and Dr. Guylene Proulx (NRCC)	Awarded 9/30/02 and 10/16/02
2	5, 6, 7	Fire Safety Engineering Expertise	Mr. Harold Nelson	Awarded 12/23/02
3	5	Media, Visual and Database Expert with Experience in Obtaining WTC Visual Materials	Hired NIST expert consultant Mr. Val Junker	Canceled Solicitation
4	3	Document and Evaluate the Steel Recovered from the WTC Towers	Wiss, Janney, Elstner Associates, Inc.	Awarded 6/9/03
5	7,8	WTC Investigation Survey Administration and Report Delivery: Questionnaires, Interviews and Focus Group Synopsis	NuStats (Subs: DataSouce, GeoStats, and MBC Research Center also Dr. Jon Krosnick and Ms. Jamie Abelson)	Awarded 6/9/03
6	2	Development of Structural Databases and Baseline Models for the WTC Towers	Leslie E. Robertson Associates	Awarded 2/23/03
7	1	Analysis of Building and Fire Codes and Practices	Rolf Jensen & Associates, Inc. (Subs: S.K. Ghosh Associates, Inc. and Rosenwasser/Grossman Consulting Engineers)	Awarded 7/25/03
8	7	World Trade Center Investigation First-Person Accounts of Egress	National Fire Protection Association	Awarded 4/15/03
9	6	Fire Endurance Testing of the WTC Floor System	Underwriters' Laboratory	Awarded 7/10/03 Modified 8/22/03
10	2, 5, 6	Outside Experts for Baseline Structural Performance, Impact Analysis, Structural Response to Fire, Collapse Initiation and Probabilistic Assessment of the WTC Investigation	Area 1: Skidmore, Owings & Merrill Area 2: Dr. David Parks Area 3: Dr. Kaspar Willam Area 4: Teng & Associates, Inc. Area 5: Dr. Daniele Veneziano and Dr. Jozef Van Dyck	Awarded 6/16/03, 6/23-25/03, and 7/3/03
11	2	Analysis of Aircraft Impacts into the WTC Towers	Applied Research Associates, Inc. (Subs: Dr. P. V. Banavalkar and Dr. Matthew H. Koebbe)	Awarded 9/22/03
12	4	Analysis of Active Fire Protection Systems—Sprinklers, Standpipe, and Pre-Connected Hoses in WTC 1, 2, and 7	Hughes Associates, Inc.	Awarded 9/22/03
13	6	Development of WTC 7 Structural Models and Collapse Hypotheses	Gilsanz Murray Steficek LLP (Subs: Dr. John Fisher and Computer Aided Engineering Associates Inc.)	Awarded 10/27/03
14	6	Structural Response of WTC Towers to Fire With/Without Impact Damage	Simpson, Gumpertz, Heger (Sub: Computer Aided Engineering Associates Inc.)	Awarded 10/30/03
15	4	Analysis of Active Fire Alarm Systems, WTC 1, 2, and 7	Rolf Jensen & Associates, Inc.	Awarded 10/21/03
16	4	Analysis of Smoke Management Systems, WTC 1, 2, and 7	Hughes Associates, Inc.	Awarded 10/30/03

NIST has made significant progress in defining the requirements for these complex series of analyses, formulating detailed modeling approaches to capture the complexities with sufficient accuracy, augmenting in-house expertise with contractors and outside experts, and commencing technical work in all of these areas. Specifically, the approach integrates the following components:

- The ***reference structural models*** are needed to establish the baseline performance of the WTC towers under normal design loading conditions. These reference models, with a level of detail never before attempted for these buildings, provide a consistent basis for the development of subsequent, significantly more detailed models for aircraft impact, fire dynamics, thermal-structural response, and collapse initiation analyses. In addition, NIST is analyzing the baseline performance of the WTC tower structures under the wind loads used in design based on wind tunnel tests conducted in the 1960s and wind loads that reflect current knowledge based on wind tunnel tests conducted in 2002 for the insurance litigation. The engineers who were involved in the design, construction, maintenance, inspection, and modifications to the WTC tower structures, *LERA RLLP* (http://wtc.nist.gov/solicitations/LERA_Award.htm) are working with NIST experts on the effort to develop the reference structural models and analyze the baseline performance under normal design loads. NIST has retained the firm of *Skidmore Owings & Merrill (SOM) LLP* (http://wtc.nist.gov/solicitations/awards0322.htm) to conduct an independent, third-party review to augment its rigorous in-house review of the LERA work.
- The ***impact damage analysis*** will determine the probable damage state(s) of the structure in the region of aircraft impact, with identification of damaged structural components and collateral damage caused by fragments to the mechanical, architectural, and fire protection systems. Probable damage state(s) provide initial building conditions for subsequent fire dynamics and thermal-structural response analyses. A group of engineers led by *Applied Research Associates, Inc.* (http://wtc.nist.gov/solicitations/wtc_awardQ0334.htm) is working with NIST experts on this analysis effort.
- The ***fire dynamics analysis*** will determine the probable paths of fire spread from the impact region up until the time of collapse initiation and the time-history of the heat imparted to the structure. The compartment-to-compartment spread of the fires is constrained by the observed timeline of fire and smoke movement through the structure. The transfer of energy from the fires through insulation materials to structural materials is also included here. This work is conducted in-house by a group of NIST scientists and engineers.
- The ***thermal-structural analysis*** determines the probable structural response time-histories of the impact-damaged structural system to the identified fire paths, accounting for cumulative heat-induced effects on structural components, such as thermal expansion, reduced structural stiffness and strength, and redistribution of loads. This analysis identifies the probable sequences of component damage or failure and provides the initial conditions for analyzing the stability of the structural system. A group of engineers led by *Simpson Gumpertz and Heger, Inc.* (http://wtc.nist.gov/solicitations/wtc_awardR0044.htm) is working with NIST experts on structural analysis of the WTC towers and an engineering group led by *Gilsanz Murray Steficek LLP* (http://wtc.nist.gov/solicitations/wtc_awardR0028.htm) is working with NIST experts on structural analysis of the 47-story WTC 7.
- The ***collapse initiation analysis*** determines the most probable collapse sequence from each of the identified thermal-structural response time-histories through a stability analysis of the

structural system. This analysis ranks the probable collapse sequences and times to failure, from which the most probable collapse sequence is identified. The group led by *Simpson Gumpertz and Heger, Inc.* (http://wtc.nist.gov/solicitations/wtc_awardR0044.htm) is working with NIST experts on the collapse analysis of the WTC towers and the group led by *Gilsanz Murray Steficek LLP* (http://wtc.nist.gov/solicitations/wtc_awardR0028.htm) is working with NIST experts on collapse analysis of the 47-story WTC 7.

To complement the analyses described above, **NIST is developing a rigorous technical approach to evaluate the role of thermal insulation (i.e., fireproofing) in the collapse of the WTC towers.** This includes (1) documenting and modeling the as-built condition of the fireproofing prior to September 11, 2001, accounting for variations in thickness and missing insulation, including statistical effects; (2) testing to determine the cohesive and adhesive properties of the fireproofing material; and (3) estimating the extent to which the fireproofing was dislodged from columns and floor systems due to aircraft impact via analysis of the direct impact of fragments on structural components and local deformation/acceleration of components.

NIST is also developing a number of simplified modeling approaches to (1) implement and evaluate the integrated approach to combining impact damage, fire dynamics, thermal-structural response, and collapse initiation analyses; (2) performance and failure of connections, components, and subsystems, including thermal effects; and (3) the effect of the failure of key components and subsystems on the stability of the WTC towers. **These simplified analyses are beginning to provide useful insights and a basis to evaluate results from the detailed models.**

A number of outside experts are working with NIST to support the above efforts. They include Harold Nelson (http://wtc.nist.gov/solicitations/wtc_awardQ0084.htm), Teng & Associates, Dr. Kaspar Willam, Drs. Daniele Venziano and Jozef Van Dyck, and Dr. David Parks (http://wtc.nist.gov/solicitations/awards0322.htm).

Finally, NIST is developing the complex computational interfaces needed to communicate extraordinarily large information files seamlessly between different software systems used in the series of analyses. These include the commercial software SAP 2000 for the reference models, the commercial software LS-DYNA for impact analysis, the NIST in-house software Fire Dynamics Simulator (FDS) for fire dynamics, the commercial software ANSYS for thermal analysis, and the same software ANSYS for structural response and collapse initiation analyses.

NIST has identified a need for a powerful and flexible approach to automate these large software conversions. This approach is based on translating output files into a neutral IGES file format and using TrueGrid to import and export IGES at any revision level. The latter is important since commercial software, for example, SAP and ANSYS, often support different levels of IGES that are incompatible with each other. In addition, the translators must convert not only geometry information but also finite element meshing, materials, and loads information.

NIST has worked intensely in partnership with commercial software developers to make changes to their programs by developing and verifying translators and interfaces that automate two key software conversions: SAP-IGES-TrueGrid-ANSYS and SAP-IGES-TrueGrid-LSDYNA. **These developments to automate software conversions will greatly enhance the capabilities needed not only for this Investigation, but for future failure analyses of complex structural systems subjected to fire and impact damage.**

EXPERIMENTAL/FIELD WORK TO SUPPORT THE INVESTIGATION

Analysis of Recovered WTC Structural Steel

NIST has in its possession about 236 pieces of WTC steel, representing roughly 1/4 to 1/2 percent of the 200,000 tons of steel used in the WTC towers. Most of the pieces are of large size and include perimeter prefabricated column-spandrel panels, rectangular box beams, wide flange sections, bar joist floor sections, and channels. NIST also has in its possession several smaller pieces, such as bolts. **NIST believes that this collection of steel from the WTC towers is adequate for purposes of the Investigation.**

Regions of impact and fire damage were emphasized in the selection of steel for the Investigation. These pieces represent a small fraction of the enormous amount of steel examined at the various salvage yards where the steel was sent as the WTC site was cleared. In addition, NIST has examined additional steel stored by the Port Authority at JFK airport and has transported 12 of those specimens to NIST.

NIST has samples of all 14 grades of steel used in the exterior column-spandrel panels. It also has samples of two grades of steel used for the core columns (wide flange and built-up box columns) that represent steel used to fabricate 99 percent of the core columns. Further, it has samples of both strengths of steel that were specified for the floor joists; two strengths each for the rods and the angles that comprised the bar joists.

The NIST analysis of recovered WTC steel includes the following:

- Collection and cataloging of the structural steel
- Documenting failure mechanisms and damage based on visual observations
- Determining the metallurgical and mechanical properties of steel, weldments, and connections for use in analyzing baseline structural performance, aircraft impact damage, and thermal-structural response to the fires until collapse initiation
- Estimating the maximum temperature reached by available steel
- Comparing measured steel properties with applicable material specifications

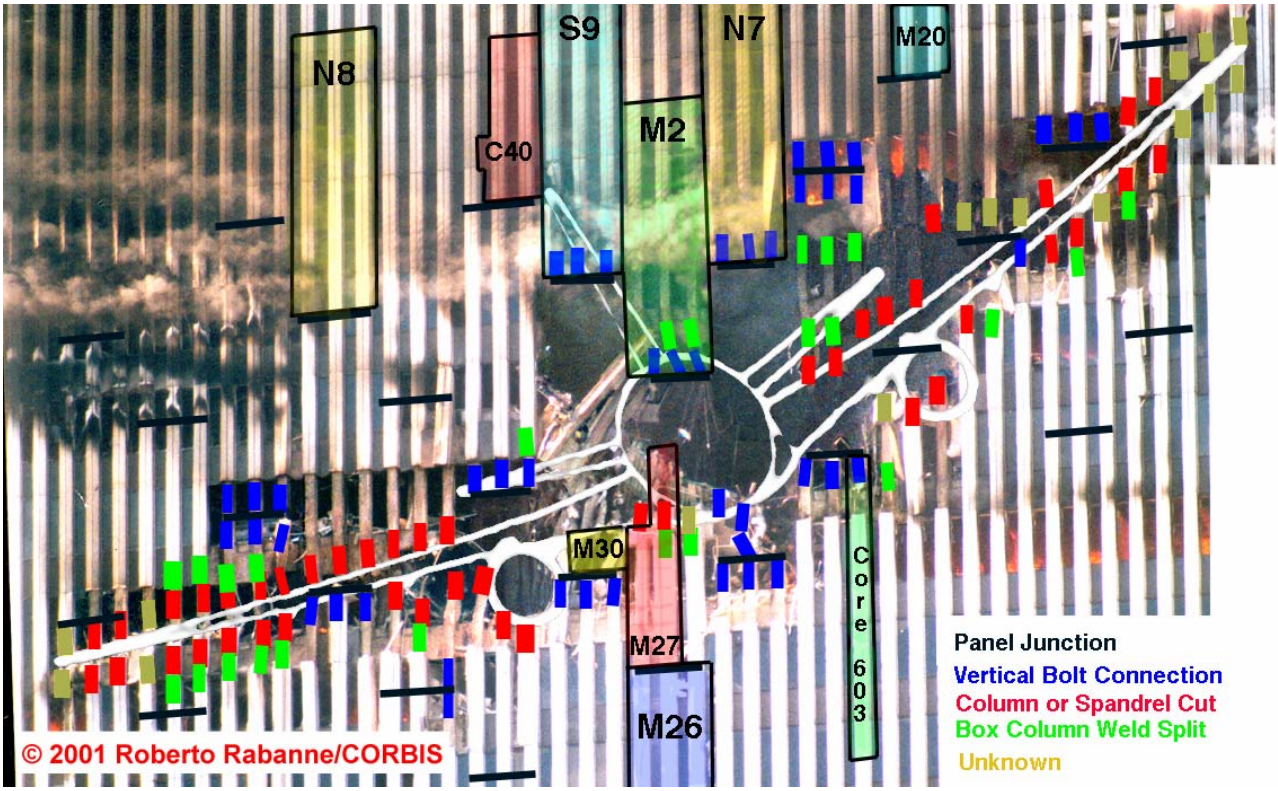
NIST has completed 127 room temperature tensile tests (per ASTM A 370 and ASTM E 8) on specimens taken from 36 distinct steel pieces and representing nearly all grades of steel. About 5 percent of the tests remain to be conducted and will be completed in December 2003. The room temperature properties, used in conventional structural design, are needed to analyze the baseline structural performance of the WTC towers under normal design loads.

Preliminary results show that the measured room temperature steel strengths met the relevant ASTM specifications; in many instances exceeding the specifications by 5,000 to 15,000 psi. Work is ongoing to evaluate the design of the steel building components and system and their performance under design, impact, and fire conditions until collapse initiation.

NIST is testing steel at high strain rates in support of the aircraft impact damage analysis task and at elevated temperatures for use in analysis of thermal-structural response under fires. These tests are expected to be completed early in 2004.

In addition, NIST has documented contemporaneous structural steel and construction specifications, developing an inventory of the recovered steel, identifying the location of the pieces within the buildings,

and documenting failure mechanisms and damage via an extensive visual analysis of the WTC steel and enhanced image analysis of photographs of the damaged buildings. One example of such an analysis is in Fig. 1, which shows the north face of WTC 1 with the outline of the impacting aircraft and observed failure and damage patterns in the steel from photographic evidence and examination of recovered steel. The photograph also identifies the exterior panels and the core column in NIST's possession. NIST experts are working with engineers from *Wiss, Janney, Elstner Associates, Inc. (WJE)* (http://wtc.nist.gov/solicitations/Elstner_Award.htm) to document failure mechanisms and damage observed in the recovered WTC steel.



Enhancements added by NIST.

Figure 1. North face of WTC 1 with outline of aircraft showing observed failure and damage patterns in the steel from photographic evidence and examination of recovered steel. Exterior panels and the core column in NIST's possession are labeled.

Fire Model Validation Experiments

In its reconstruction of the thermal and tenability environment, NIST is taking the following into account:

- The fire load provided by the building contents, jet fuel and combustible aircraft contents (WTC 1 and 2), and fuel storage tanks (WTC 7)
- The ventilation available for combustion
- The intercompartment fire growth through partitions, ceiling/floor systems, and air passages within the buildings

NIST is conducting experiments to provide input to its analytical and numerical work, including the validation of those results. These studies include the following:

- Fire tests in large compartments to measure the heat release and transfer rate to compartment gases and steel specimens (steel bar joists and columns, with and without fireproofing) for validating fire dynamics and thermal-structural analyses, including the coupling between the two analyses. NIST reported on these tests in May 2003.
- Shake table experiments to determine the magnitude of impulses that could result in damage of the ceiling tile systems, increasing the accessibility of the fire energy to the ceiling/floor membranes.
- Office workstation fire tests, based on descriptions of furnishings used in WTC 1 office space, to generate a database on the thermo-physical properties of the materials for input to the fire dynamics simulation tool.
- Fire tests to validate the model predictions of the sensitivity of fire intensity, duration, and spread to the distribution and nature of the combustibles.

The extent, intensity, and duration of the fires in each of the three WTC buildings played a pivotal role in their eventual collapse. Because of the dearth of information from inside the WTC buildings on the progression of the fires, the fires must be reconstructed using available information on the buildings' interiors and the photographs of the exteriors. Much of the combustible content was manifested in numerous workstation cubicles.

The goal of the third set of tests is to provide input to NIST-developed fire modeling software so that investigators can accurately simulate the complex burning of the combustibles and determine how the fires contributed to the collapses of the WTC buildings.

NIST has completed (1) a series of fire tests of the WTC workstations, including the effects of rubble and aviation fuel on their burning rate and (2) measurements in the Cone Calorimeter to obtain the combustibility properties of the workstation components. The latter have been used as input to the NIST FDS computational model, which has been used to predict the burning behavior in the former tests.

The workstation mockup was the same as one used by Marsh & McLennan Companies, a tenant of WTC 1. The firm occupied the floors where the hijacked aircraft hit the tower. The mockup (Fig. 2) was an 8 ft by 8 ft, four-sided cubicle that incorporated a laminated particle-board desk surface on three sides, a bookcase holding 70 lb of paper products, a largely plastic chair, a computer system, and nylon-faced carpet tiles. An additional 65 lb of paper products were distributed throughout the office setting.

Four other tests were conducted on similar workstation mockups. In two of them, jet fuel was intentionally spilled on the furnishings in order to simulate a unique and potentially influential contribution to the fires from the fuel-laden aircraft.

During the fire test, the workstation was subjected to a 2 MW burner adjacent to the outside of one wall panel, simulating the burning of a neighboring cubicle (Fig. 3). A ceiling 9 ft above the floor retained the hot combustion gases, enhancing the “reflection” of heat back to the exposed surfaces of the workstation. The peak heat release rate from the workstation in this test was about 8 MW, occurring at 8.5 min after the start of the test. The fire consumed 386 lb of combustible materials in 33 min.

Figure 2. Two views of WTC 1 workstation.

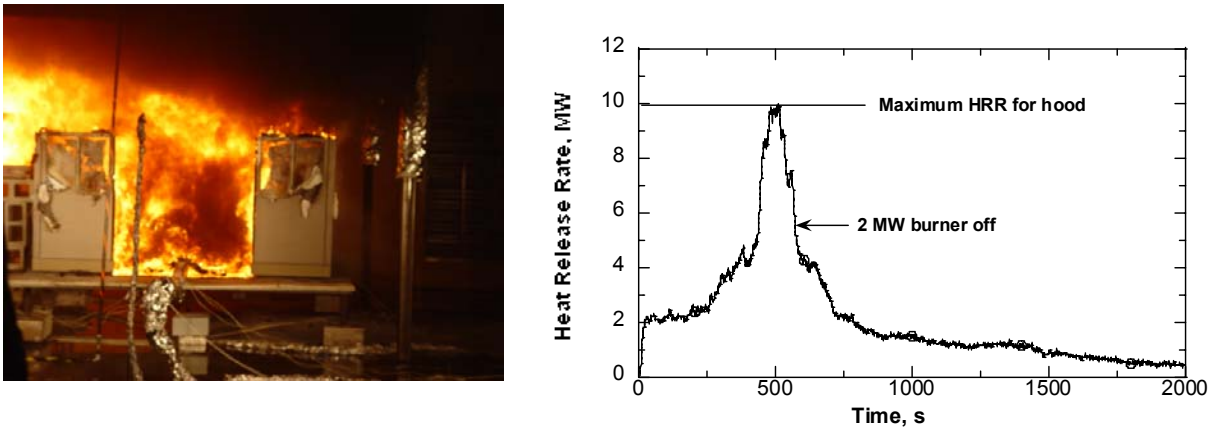


Figure 3. Full involvement of workstation fire near peak heat release rate.

NIST is now conducting the fourth set of fire tests of multiple WTC workstations to validate the model predictions of the sensitivity of fire intensity, duration, and spread to the distribution of the combustibles, the ventilation of the fire, and the effect of jet fuel. These tests will include three workstations, two contiguous and one separated by an aisle, in a large compartment with one wall mostly open. The FDS predictions were completed before conducting the tests and the accuracy of those predictions is now being assessed against the test measurements.

Fire Endurance Testing of the WTC Floor System

The interim findings contained in the May 2003 progress report stated that from the documents reviewed NIST had not been able to determine the technical basis for the selection of fireproofing material for the WTC floor system or how the specified fireproofing thickness would achieve the required 2 hr fire rating.

In addition, NIST found no documentary evidence indicating that a test based on ASTM E 119 had been conducted to determine the fire rating of the WTC floor system. The Port Authority stated that "there are no test records in our files" in response to a NIST question asking "Were tests performed on the fire resistance of the composite floor system during the design or construction phase of the project."

While the benefits of conducting a full-scale fire endurance test were realized, apparently no tests were conducted on the specific floor system used in the WTC towers. Such project-specific testing was and is

not normal practice but may be conducted when circumstances warrant it, for example, in a new or unique application.

A composite bar joist floor system with spray-applied fireproofing represented an innovative application in the 1960s. Four additional factors contributed to the uniqueness of the system: (1) the use of bar joists in the floor system of high-rise buildings such as the WTC towers; (2) the long unsupported span of the floor system (about 60 ft in the long direction, about 35 ft in the short direction); (3) the role of the floor system in ensuring stability of the WTC structural system; and (4) the floor diaphragm action required to transfer lateral (wind) loads to the columns.

NIST engineers are working with experienced engineers from *Underwriters' Laboratories, Inc.* (http://wtc.nist.gov/solicitations/wtc_awardQ0281.htm) to determine the fire endurance rating of typical WTC floor systems under both *as-built* and *specified* conditions under the fire conditions prescribed in ASTM E 119. In addition, NIST is using the tests to study the effects of fireproofing thickness, scale, or size of the tested assembly, and thermal restraint at the ends of the assemblies.

The tested composite floor assemblies include the concrete slab on metal deck, two pairs of main joists integrated with the concrete slab to provide composite action, two bridging joists, and fireproofing applied on steel with primer paint. Four tests are being conducted:

- A 17 ft span with ends of the assembly restrained from thermal expansion in a typical furnace representing current U.S. practice. This test will use the ***1/2 in. fireproofing thickness specified by the Port Authority*** when the towers were built.
- A 17 ft span with ends of the assembly restrained from thermal expansion in a typical furnace representing current U.S. practice. This test will use the ***3/4 in. fireproofing thickness representing the as-built condition*** of the buildings before the process, still under way on September 11, 2001, was initiated to upgrade the thickness to 1-1/2 in.
- A 35 ft span with ends of the assembly restrained from thermal expansion in a ***furnace twice the typical size and representing a full-scale 35 ft assembly.*** This test will use the 3/4 in. fireproofing thickness representing the as-built condition in the buildings before the process, still under way on September 11, 2001, was initiated to upgrade the thickness to 1-1/2 in.
- A 35 ft span with ***ends of the assembly not restrained from thermal expansion*** in a furnace twice the typical size and representing a full-scale 35 ft assembly. This test will use the 3/4 in. fireproofing thickness representing the as-built condition in the buildings before the process, still under way on September 11, 2001, was initiated to upgrade the thickness to 1-1/2 in.

Additional rods and double angle structural members are placed within the furnace in each test to ***evaluate the effect of different fireproofing thicknesses up to 1-1/2 in.***

COLLECTION AND ANALYSIS OF PHOTOGRAPHIC AND VIDEO IMAGES

Photographic and video images of damage and fires in the WTC towers and WTC 7 are critical for guiding the Investigation on the initial conditions for modeling the fires, the rates of fire spread through the buildings, and the floors on which the structural collapse may have begun.

NIST has collected such materials in a variety of ways, including direct contacts with individuals and organizations, public appeals, transfer of material from other organizations, and video recordings from

broadcast television. Many individuals contacted NIST based on news coverage of earlier updates and provided a large number of important photographs and videos. NIST very much appreciates the public response and the reporting that made it possible.

NIST has assembled the collected visual material into a searchable computerized database. **The database now contains 6,194 photographs representing more than 185 photographers and 5,726 digitized video clips from 150 hours of videotape representing more than 20 individuals, news organizations, and documentaries.** The collection has been catalogued, cross-referenced, and expanded through the end of November 2003.

The NIST Investigation continues to lack photographs of the south side of WTC 7; the modeling of the initiation and progress of the fires in that structure depends on obtaining such evidence. Those who are aware of or are in possession of such photographs and videos are encouraged to contact NIST by e-mail at wtc@nist.gov, facsimile 301-975-6122, or regular mail at the WTC Technical Information Repository, NIST, 100 Bureau Drive Stop 8610, Gaithersburg, Maryland, 20899-8610. NIST has hired a visual media expert, Mr. Valentine Junker, to assist with contacting potential sources of material and arranging for and facilitating transfer of appropriate photographs and video to NIST. Mr. Junker is located in the New York area and can be reached by telephone at 917-596-2509 or e-mail at val@nist.gov.

A key NIST focus is to determine accurate times for the images contained in the database. The May 2003 progress report describes how NIST is conducting this work. For the vast majority of digital materials NIST is able to assign times that are accurate to within 3 seconds.

On an interim basis, NIST has determined the following exact times for the major events of September 11, 2001:

- WTC 1 Plane Strike: **8:46:31 a.m.**
- WTC 2 Plane Strike: **9:02:59 a.m.**
- WTC 2 Collapse Initiation: **9:58:59 a.m.**
- WTC 1 Collapse Initiation: **10:28:25 a.m.**
- WTC 7 Collapse Initiation: **5:20:52 p.m.**

NIST has analyzed the material in the visual database to determine, on a window-by-window basis, such properties as whether windows are present or missing (important for estimating the amount of air available to feed the fires) and whether smoke and/or fire are observed. **Detailed mappings for the fires, smoke, and the condition of the windows have been developed at several specific times for both the WTC towers and work is under way for WTC 7.**

The complete data set has been entered into Smokeview, a NIST-developed software program used in conjunction with the NIST FDS modeling software, which has the capability to display time-dependent animations of fire, smoke, and changes in building geometry. The integration of the visual maps into the Smokeview-FDS software system provides NIST with a pivotal capability to establish the timeline of fire events and paths, and the changing ventilation conditions, for use in assessing thermal tenability, reconstructing the fire environment, and analyzing the thermal-structural response to fires.

From the analysis of the visual images to date, NIST has observed the following significant events for WTC 1:

- The region of aircraft impact on the north face ranged from floors 94 through 99.
- Initial damage and subsequent fire development are highly asymmetric (plane strike centered on north face):
  - Fireballs on north, east, and south faces following plane strike.
  - Fires "damped down" shortly after initial fireballs.
  - Significant damage and early fire growth on north face, center of east face, and western side of south face
  - Fires on east side of south face are not observed until after 10 a.m.
- Rapid and extensive fire spread on 97th floor of west face starting at 8:56:08 a.m.; by 9 a.m. large fires on 96th and 97th floors on north face, center of east face on 94th and 97th floors, and west side of south face on 96th floor.
- Fires develop and start to spread across east face of 92nd floor after 9 a.m.
- Areas of "typical" fire spread observed:
  - Fires moving to south on east face of 92nd, 94th, 96th, and 97th floors
- Areas of sudden fire development observed:
  - Some associated with flashover in offices (e.g., northeast corner on 96th floor around 9:19 a.m.).
  - Some occur in open areas (west side of 96th floor on north face around 9:54 a.m.).
  - Fires burning on all four faces of 98th floor at 10 a.m.
  - Large fire appeared suddenly on south side of west face of 104th floor shortly after 10 a.m.
  - Large fires grew on multiple floors of east side of south face after 10:10 a.m.
  - Sudden release of smoke from 92nd floor on north face at 10:18:48 a.m. followed by rapid appearance of flame over much of floor.

From the analysis of the visual images to date, NIST has observed the following significant events for WTC 2:

- The region of aircraft impact on the south face ranged from the 77th through the 85th floors.
- Initial damage and fire locations are highly asymmetric (plane strike off center to the east on south face):
  - Fireballs on north, east, and south faces following plane strike.
  - Large sections of curtain wall removed on north and east faces, broken column on north face.
  - No visible damage to west face.
  - Fires did not "damp" down to low level seen in WTC 1 following fireballs.

  - Large debris piles seen in northeast corners of 80th and 81st floors and close to center of north face on 79th floor.
  - Small fires only on south face, extensive fires on 81st, 82nd, and 83rd floors of east face.
  - Fires located on debris piles on east and north faces burn for long period.
  - "Cold" area between debris piles on the north face that is roughly 45 ft wide and covers the 80th, 81st, and 82nd floors.
- Fires are less active than observed for WTC 1, but there are changes:
  - Heavy flames erupt on 83rd floor of north face just to the right of the "cold" area at 9:29:10 a.m.; at 9:35:45 a.m. suddenly appear on this floor near the center of the face.
  - Heavy smoke and flames suddenly appear on east face over large extent of 79th and 80th floors around 9:35:45 a.m. and decrease abruptly around 9:36:30 a.m., fires then slowly grow back.
  - Flames appear on the 82nd floor just to right of the cold spot on the north face around 9:54 a.m.
  - Flames spread across most of 79th floor on north face prior to collapse.
  - Release of heavy smoke and fire over western half of 80th floor on the south face starting at 9:56:37 a.m.
- Evidence for collapsed floors:
  - Photographs and videos show a hanging object that appears to be the 83rd floor draped across windows on the 82nd floor; this object sinks lower at later times.
  - Similar objects, likely localized portions of 81st, 82nd, and 83rd floors, are visible through windows on the east side of the north face.
  - Molten material pours from the upper region of window 80-255 starting at 9:51:52 a.m.

FIRST-PERSON DATA COLLECTION ON EVACUATION AND EMERGENCY RESPONSE

NIST's study of the WTC evacuation and emergency response requires a systematic collection of first-hand data from survivors, family members who were in touch with victims after the aircraft impacts on the buildings, and others with operational or command authority on September 11, 2001.

Among the areas for which the interview data could facilitate improvements are the following:

- Occupant behavior and evacuation technologies and practices for tall buildings
- Decision-making and situation awareness (for both evacuees and first-responders)
- The design of egress systems
- The role of floor wardens and fire safety directors
- The evacuation of people with disabilities
- Firefighting technologies and practices for tall buildings

- Command, control, and communication systems for emergency response
- The content, timing, and quality of emergency communications (among occupants and authorities, within and outside buildings, and for intra- and inter-group communications)

Additionally, observations of fire and smoke conditions or structural damage from within the building will be sought to assist in this and other aspects of the Investigation.

Buildings are not normally designed for fire protection and evacuation under extreme conditions. There is a critical lack of information on which to base evacuation and emergency response practice, standards, and codes under such conditions. NIST believes that it is possible to learn from the tragic WTC events and to improve public safety through the collection and analysis of first-person accounts. This is an ambitious undertaking and needs the active participation of WTC survivors, current and retired first responders, and families in its first-person interviews.

NIST has developed a comprehensive protocol for collecting and analyzing first-person accounts from survivors, family members of victims, and first responders working in cooperation with three outside experts: Dr. Dennis Mileti, Dr. Guylene Proulx, and Dr. Norman Groner (http://wtc.nist.gov/solicitations/wtc_awards.htm). The protocol is geared toward enhancing recall of directly experienced events and combines face-to-face interviews, telephone interviews, and focus group interviews to assist in documenting the building evacuation, understanding occupant decision making, building safety operations, and the events of the day associated with the emergency response, as well as collecting observations of fire, smoke, and building damage.

NIST investigators are conducting some of the interviews; they are also working with a group of contractors led by *NuStats Partners LLP* (http://wtc.nist.gov/solicitations/wtc_awardr0013.htm) to conduct the majority of the field interviews. **In all, NIST plans to conduct up to 500 face-to-face interviews, 800 telephone interviews, and 15 focus group interviews. These include face-to-face interviews with up to 150 first responders—100 from FDNY, 25 from NYPD, and 15 from the Port Authority—and up to 350 face-to-face interviews with occupants, families, and retired first responders.**

NIST established a toll-free number (877-221-7828) for survivors, families, and retired first responders to volunteer to participate in the face-to-face interviews. NIST also set up a Web site (https://wtc.nist.gov/family) for families of WTC victims to volunteer to participate in the face-to-face interviews. In addition, NIST set up a toll-free anonymous tip line (888-804-7581) and an e-mail (wtc@nist.gov) for individuals wishing to provide information. NIST also is contacting WTC occupants directly for the telephone interviews using lists of individuals issued security badges by the Port Authority.

As of November 17, 2003, NIST had been contacted by 260 individuals volunteering for the face-to-face interviews. Based on initial screening, 167 individuals were of interest for the interviews, including 26 family members.

NIST has now received all necessary approvals and has commenced the first-person data collection from occupants, families, and first responders. The approvals include:

- Paperwork Reduction Act approval for the telephone interviews of WTC occupants from the Office of Management and Budget (OMB No. 0693-0044).

- Essex Institutional Research Board review and approval and NIST review and approval of the "research on human subjects" protocol submitted by NuStats for the first-person data collection from WTC occupants and families.
- Agreement with the City of New York for conduct of interviews with FDNY and NYPD first responders. The National Commission on Terrorist Attacks Upon the United States (also known as the 9-11 Commission) will cooperate with NIST in the interview process.
- Agreement with the Port Authority of New York and New Jersey for conduct of first responder interviews with its staff.

In addition, NIST has committed to protecting the personal privacy and confidentiality of individual respondents to the maximum extent permitted by law.

The WTC Investigation of evacuation and emergency response is based on multiple sources of data. The first-person data collection is a key component of the overall effort. Other sources of documentary, electronic, and photographic data include:

- Existing published first-person accounts of WTC evacuation; more than 725 accounts have been collected and analyzed in cooperation with the *National Fire Protection Association* (http://wtc.nist.gov/solicitations/wtc_awardw0471.htm).
- Communications tapes from the Port Authority and NYPD with 1,000 plus hours of recordings.
- Filings with the Occupational Safety and Health Administration by survivors and families of victims; more than 50 written statements.
- Documents from the Port Authority, FDNY, NYPD, and others on design of egress and emergency communication systems; modifications to these systems; WTC evacuation history; WTC evacuation planning and drills; emergency response preparedness; occupant communication records; identification of units dispatched to the WTC; data on their response; information on unit operations at the incident; equipment on hand at the incident; emergency response technologies used at the incident; etc
- Photographic and video data on occupant behavior, evacuation, and emergency response from various sources.

NIST has hired three experts (Vincent Dunn, John Hodgens, and Kevin Malley) with knowledge and experience of emergency response operations for high-rise buildings in New York City gained as former FDNY employees. These consultants are assisting with identification of important emergency response issues and in analyzing and clarifying the information gathered.

NIST is developing a detailed chronology of events related to the emergency response and evacuation. This chronology contains information on the dispatch of emergency responders, their response and activities at the incident, radio and telephone communications related to responder operations at the incident, public address communications to the occupants, the evacuation experience of the occupants, and information concerning the conditions of WTC 1, 2, and 7 as the incident unfolded.

The history of evacuation of the WTC and the first-person accounts will support computer egress modeling. NIST has obtained three existing computer models that will be used to better understand the evacuation experience on September 11, 2001.

NIST investigators have sorted and categorized the communications data and are analyzing the contents to better define the events of September 11, 2001, and to document the performance of the emergency communications system.

From the initial analysis of the communications data from the Port Authority, NYPD, and FDNY Channel 30, **NIST has found the following noteworthy information relating to the events of September 11, 2001**:

- Dispatch/arrival of emergency response units:
  - By 8:48 a.m. 26 FDNY units dispatched
  - By 8:52 a.m. 5 NYPD units dispatched
  - By 9:00 a.m. 66 FDNY units dispatched
  - By 9:15 a.m. 121 FDNY units dispatched 30 FDNY units call in arrival
  - By 9:59 a.m. 171 FDNY units dispatched 74 FDNY units call in arrival
  - By 10:29 a.m. 214 FDNY units dispatched 103 FDNY units call in arrival
- Evacuation and emergency response information:
  - PAPD Desk receives two orders from a PAPD officer calling for evacuation of building by 8:48 a.m.
  - FDNY establishes command post in the lobby of WTC 1 by 8:50 a.m.
  - PATH trains were bringing in people into the WTC at 8:56 a.m.
  - One incoming message was received at the PAPD Desk and two outgoing general messages were issued by the PAPD Desk for the evacuation of WTC 1 and WTC 2 and then "all buildings in the complex" within the 3-1/2 min period before the second plane struck at 9:03 a.m.
  - An FDNY Fire Chief makes radio call ordering all units in WTC 1 to come down to the lobby at 9:32 a.m.
  - At and below the 79th floor of WTC 2, firefighters were evacuating occupants, assisting the injured, and fighting fires at 9:57 a.m.
  - Numerous emergency responders ascending in WTC 1 and 2 call in on their radios that they must stop and rest before climbing higher.
- Condition of WTC towers:
  - At 9:30 a.m., an FDNY Fire Chief inside WTC 1 feels the building move and makes the decision that the building is no longer safe.
  - At 9:49 a.m., NYPD helicopters provide a radio report stating that "large pieces" are falling from WTC 2.
  - At 10:07 a.m., NYPD aviation units warn that WTC 1 may collapse.
  - At 10:20 a.m., an NYPD aviation unit reports that WTC 1 is leaning to the south.

From the initial analysis of the communications data from the Port Authority, NYPD, and FDNY Channel 30, **NIST has found the following noteworthy information relating to the emergency communication systems**:

- Radio systems appeared to work well during normal operations before the attacks with one exception. An open or keyed mike on a handie-talkie transmitted a carrier wave, disrupting communications on one PAPD radio channel (W). After the attack, the NYPD Central, Special Operations Division radio channel experienced similar disruptions.
- The radio communications systems experienced surge load conditions after the attack. Traffic volume made it difficult to handle the flow and delivery of information. Multiple, concurrent radio transmissions on the same frequency, or doubling, made it more difficult. It is estimated that roughly a third to a half of the communications were not complete due to surge load conditions.

ANALYSIS OF BUILDING AND FIRE CODES AND PRACTICES

NIST is obtaining, reviewing, and analyzing applicable building and fire code provisions and project documents and determining the procedures and practices that were used in the design, construction, operation, and maintenance of the structural and fire safety systems of the WTC towers and WTC 7.

Specifically, NIST is documenting the building and fire code requirements adopted for the WTC buildings along with the requirements for other buildings in New York City and Chicago in the same time period. NIST is also documenting new or innovative technologies and materials, if any, that were incorporated in the design and construction of the buildings, and the criteria and procedures used to accept these technologies and materials. In addition, NIST is documenting major modifications to the structural and fire safety and egress systems following the major fire in 1975 and after the 1993 bombing.

To investigate the collapse of the WTC buildings, it is necessary to re-create the state of the buildings prior to the 9/11 attacks. Since the WTC towers and WTC 7 were totally destroyed, the state of the buildings is recreated based on available design, construction, and maintenance documents. Documents provided by the Port Authority, design firms, contractors, and suppliers related to the design, construction, and maintenance of the buildings are being reviewed.

NIST investigators are conducting a detailed review of the extraordinarily large volume of documents in NIST's possession, or to which it has gained access, and synthesis of their content in cooperation with a group of contractors led by *Rolf Jensen & Associates, Inc.* (http://wtc.nist.gov/solicitations/wtc_awardQ0721.htm). The group has many years of experience in evaluating building code provisions, evaluating fire safety systems, and designing high-rise buildings in New York City. The overall effort includes five tasks (and a number of subtasks) to document the following:

- The design and construction of structural system
- The design and construction of fire protection and egress systems
- The fuel system for emergency power in WTC 7
- The requirements of selected building regulatory systems and codes
- The maintenance and modifications to the structural, fire protection and egress systems

Work is progressing concurrently on all five tasks with significant progress having been made on the third and fourth tasks.

INVESTIGATION OF ACTIVE FIRE PROTECTION SYSTEMS

NIST is investigating the design, capabilities, and performance of the installed active fire protection systems in WTC 1, 2, and 7 and their role in fire control, emergency response, and fate of occupants and responders.

Three systems are being investigated: the fire sprinkler system, including the fire standpipes and preconnected hoses; fire alarm system; and the smoke management systems.

For the sprinkler system, NIST is:

- Documenting the design and installation of the fire sprinkler system, standpipe system, and preconnected hoses;
- Documenting the design and capacity of the water supply systems to the fire sprinklers, including provisions for redundancy;
- Identifying and documenting differences in the design of the water supply, fire sprinkler system, standpipe system, and preconnected hoses between WTC 1, 2, and 7;
- Documenting the normal operation and effect of the fully functional fire sprinkler system, standpipe system, and preconnected hoses for fire control; and
- Assessing the probable performance of the fire sprinkler system, standpipe system, and preconnected hoses on September 11, 2001.

NIST investigators are working with experienced engineers from *Hughes Associates, Inc.* (http://wtc.nist.gov/solicitations/wtc_awardQ0463.htm) to carry out this aspect of the Investigation.

For the fire alarm system, NIST is:

- Documenting the design and installation of the fire alarm systems;
- Documenting the normal expected operation and effect of the fully functional active fire alarm systems, including provisions for redundancy;
- Documenting modifications made to fire alarm systems in WTC 1 and 2 after the 1993 bombing; and
- Assessing the probable performance of the active fire alarm systems on September 11, 2001.

NIST investigators are working with engineers from *Rolf Jensen & Associates, Inc.* (http://wtc.nist.gov/solicitations/wtc_awardQ0721.htm) with relevant expertise to carry out this aspect of the Investigation.

For the smoke management system, NIST is:

- Documenting the design and installation of the smoke management systems,
- Describing the normal operation in fire emergencies, and
- Assessing the probable performance of the smoke management systems on September 11, 2001.

NIST investigators are working with engineers from *Hughes Associates, Inc.* http://wtc.nist.gov/solicitations/wtc_awardQ0835.htm with relevant expertise to carry out this aspect of the Investigation.

To provide a context in which to understand the fire performance of the three buildings, **NIST has completed a review of the history of postoccupancy fire incidents in these buildings prior to September 11, 2001.** This included a review of 434 Bureau of Operations Fire Reports (1970-2001) and 87 Bureau of Fire Investigation Records (1977-2001) from FDNY. **NIST has identified 12 significant fires in these buildings—those that were large enough to activate more than one sprinkler or, if sprinklers were not present, estimated to be so from other information. These 12 fires are in addition to the well-known fire incidents in WTC 1 in 1975 and the 1993 bombing.** Extensive records maintained by the PANYNJ about fire incidents in the buildings were lost when the WTC offices were destroyed.

To gather facts about fire alarm system performance and possibly gain some insight into fire events in WTC 7, NIST obtained the central station monitoring record for the building from AFA Protective Systems, Inc. The record shows that an alarm was received at 10:00:52 a.m. on September 11, 2001. This corresponds closely to the time of collapse for WTC 2. It is unknown at this time whether this alarm was triggered by fire or dust from the collapse. All of the records from the fire alarm systems recorded and stored in WTC 1, 2, and 7 were lost in the collapse of those buildings.

UPDATE ON WTC RESEARCH AND DEVELOPMENT PROGRAM

The associated WTC research and development (designated the **Safety of Threatened Buildings R&D Program**) is designed to (1) facilitate the implementation of recommendations resulting from the WTC Investigation, and (2) provide a technical foundation that supports improvements to building and fire codes, standards, and practices that reduce the impact of extreme threats to the safety of buildings, their occupants and emergency responders. The program involves laboratory experimentation, analysis, large-scale testing, computational verification, validation, and demonstration of improved tools to guide the building and fire safety communities, and to support the voluntary consensus process that is used to develop building and fire codes and standards in the United States.

There are four major outcomes sought by this program:

1. Increased structural integrity
2. Enhanced fire resistance of structures
3. Improved emergency egress and access
4. Science-based building and equipment standards and operation guidelines

NIST has 11 R&D projects under way in support of these outcomes. Private sector and academic experts are contributing to several of these projects.

Project	Outcomes			
	1	2	3	4
Mitigation of Progressive Collapse	X			
Fire Safety Design and Retrofit of Structures	X	X		
High Temperature Steels	X	X		
Fire Protection Coatings for Structural Steel	X	X		
Methods of Fire Resistance Determination		X	X	

Project	Outcomes			
	1	2	3	4
Emergency Use of Elevators			X	
Occupant Behavior and Egress			X	
Equipment Standards for First Responders			X	X
Technologies for Building Operations				X
Standard Building Information Models				X
Cost-effective Risk Management Tools				X

A description of the FY 2003 WTC R&D program is available at http://www.bfrl.nist.gov/goals_programs/03prgmSTB.htm.

A description of selected component projects within the FY 2003 WTC R&D program is available at http://www2.bfrl.nist.gov/projects/goalslist.asp?program=STB#4.

Recent activities related to two projects are highlighted below.

Fire Safety Design and Retrofit of Structures

Current building design practice does not consider fire as a design condition for purposes of evaluating structural performance. Instead, structural fire endurance ratings are specified in building codes. In addition, there is no accepted set of verified tools to evaluate the fire performance of entire structures and to achieve engineered fire safety.

While current prescriptive methods appear to work satisfactorily in typical fires, the adequacy of such methods in extreme fires is unknown. The expectation from conventional design practice and experience is that extreme fires should result in a burnout condition without collapse; and that passive fire protection should be sufficient to achieve this condition, if sprinklers are not to be designed for such extreme events as is current practice.

Current design practice for earthquake and wind hazards does consider extreme conditions. The intent of building codes is that collapse, if inevitable in such extreme events, should not occur until the building is evacuated of both occupants and first responders. There appears to be widespread recognition of the need to establish the performance-based technical framework for structural-fire design similar to earthquake and wind design.

NIST has initiated an R&D project to develop and implement significantly improved standards, tools, and practical guidance for the fire safety design and retrofit of structures. The project seeks to integrate knowledge of modern fire science and fire protection engineering with knowledge of modern structural reliability methods and structural engineering.

NIST worked with the Society of Fire Protection Engineers to organize and conduct a workshop to develop a detailed roadmap identifying the R&D gaps to be filled to meet industry needs. The October 2-3, 2003, workshop was attended by 60 fire protection and structural engineers, academics, researchers, trade association representatives, architects and building officials. It focused on U.S. practice and codes and standards within the context of recent international developments, especially in the European Union.

Ten detailed white papers were prepared and presented at the workshop by leading national and international experts. They covered the following topics:

- Analysis Tools and Design Methods: Current Best Practices
- Challenges Facing Engineered Structural Fire Protection
- Design Fire Scenarios
- Evaluation and Retrofit of Existing Buildings for Structural Fire Safety
- Evaluation and Retrofit of Buildings for Improved Structural Response to Fire
- Framework for Structural Fire Engineering and Design Methods
- International Status of Design Standards for Structural Fire Safety
- The American Institute of Architects Codes Advocacy Program
- Relationship between Structural Fire Protection Design and Other Elements of Fire Safety Design
- Thermal and Structural Analysis Methods and Tools – Gaps in Knowledge and Priority Areas for Research from a Practice Perspective

Workshop attendees supported the development of a best-practices manual for structural fire protection, including design and analysis tools, to add to the knowledge base and aid building officials in evaluating the adequacy of performance-based rather than "prescriptive" designs. Others said they would welcome a "one-stop" Web site to provide the latest information on the subject.

Workshop participants identified the following actions/research needs as having the highest priority in developing best practices for fire safety design and retrofit of structures (shown with the number of "votes" given by participants as a percentage of the total votes cast; each participant had 10 votes and each percentage below represents about 6 votes):

- Build and use structural-fire experimental facilities in the United States to apply complex structural loads to large scale components at elevated temperature (6 percent)
- Develop more "research quality" experimental data on structural response at elevated temperature (6 percent)
- Quantify level of protection provided by current prescriptive code requirements (5 percent)
- Collect actual fire performance data (5 percent)
- Define failure/limit states for structural response in fire (5 percent)
- Develop guidelines for public and engineering community on evaluation and remediation of structural fire performance of existing buildings (5 percent)
- Specify performance goals in the building code for prescriptive and performance-based options (4 percent)
- Develop performance metrics for multihazard building robustness (3 percent)
- Develop a risk-based methodology for design fires and the data to support it; place into a standard (3 percent)

- Develop standard methods for determining material properties at elevated temperatures (3 percent)
- Investigate fire performance of connections for codes and standards (3 percent)
- Develop benchmark problems for verification of analytical tools (2 percent)
- Specify professional responsibilities for structural fire protection over the life of the building (2 percent)

Emergency Use of Elevators

In the aftermath of the September 11, 2001, terrorist attacks, U.S. fire experts are beginning to advocate the use of elevators in high-rise buildings throughout a fire, both to carry firefighters to the site of the blaze and as a secondary method (after stairwells) for evacuating building occupants. **NIST has joined others to study ways to build "protected" elevators.**

As reported at a recent conference in Malaysia,[1] NIST is working with the elevator industry to develop and test redundant, more reliable elevator-dedicated emergency power systems and waterproof elevator components. NIST is investigating software and sensing systems that can adapt to changing smoke and heat conditions, maintain safe and reliable operation, and not shut down during fire emergencies. Such changes could allow elevators to be operated with remote control from the ground floor during fires, thus freeing urgently needed firefighters from elevator operation duties.

NIST also will use its expertise in virtual reality simulation to test scenarios for coordinating firefighting activities, elevator egress and stairway evacuation. By incorporating elevators into its graphic computer models, NIST will help fire safety experts identify the most effective operational procedures for specific fire conditions. NIST fire researchers hope to collaborate on emergency elevator operations standards with colleagues from around the world. Global standardization should reduce confusion during an emergency, enabling people to take evacuation actions with confidence.

UPDATE ON WTC DISSEMINATION AND TECHNICAL ASSISTANCE PROGRAM

The industry-led dissemination and technical assistance program (DTAP) is designed to engage leaders of the construction and building community in assuring timely implementation of proposed changes to practices, standards, and codes. It also will provide technical guidance and tools to better prepare facility owners, contractors, architects, engineers, emergency responders, regulatory authorities, and occupants to respond to future disasters. The DTAP is crucial for timely adoption and widespread use of proposed changes to practice, standards, and codes resulting from the WTC Investigation and the R&D program.

NIST recently awarded a contract to the National Institute of Building Science (NIBS) to facilitate the implementation and maximize the impact of proposed changes to building and construction related

[1] Richard Bukowski, "Protected Elevators for Egress and Access During Fires in Tall Buildings," in *Proceedings of the CIB-CTBUH Conference on Tall Buildings*, Oct. 20-23, 2003, Kuala Lumpur, Malaysia.

practices, guidelines, standards, and codes that come out of the WTC Investigation and R&D Program. Through a series of specific task orders, NIBS is contracted to organize and/or convene activities that:

- Review the NIST programs to identify issues and opportunities;
- Identify strategies and actions for accomplishing needed changes to relevant practices, guidelines, standards and codes resulting from the heightened emphasis on homeland security and for assuring NIST research efforts are responsive to these needs;
- Assist in the identification and support of potential participants and leaders for the implementation activities associated with specific products to emerge from the WTC R&D program; and
- Assist in implementing the identified strategies through such initiatives as managing and conducting efforts that support codes and standards change, drafting new or assisting in the revision of existing guidelines, initiating information technology initiatives, and conducting and supporting information dissemination efforts.