

NIST Special Publication 1000-3

May 2003

**Progress Report on the
Federal Building and Fire Safety
Investigation of the
World Trade Center Disaster**

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SUMMARY

The National Institute of Standards and Technology (NIST) announced its 24-month 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 a public update on the progress of the investigation on December 9, 2002. The investigation plan, which reflects comments received in writing and at a June 24, 2002 public meeting held in New York City, and the December 2002 progress report may be found at <http://wtc.nist.gov>.

This public update summarizes the progress made by NIST and the cooperation it has received from a variety of organizations since the December update. This report covers:

- Availability of funding to support the investigation and the other elements of NIST's WTC public-private response plan;
- Status of the implementation procedures for the National Construction Safety Team (NCST) Act under which NIST is conducting the WTC investigation;
- Establishment and first meeting of the NCST Advisory Committee;
- Progress in identifying and collecting materials relevant to the investigation from the building owner, leaseholder, their consultants and contractors, New York City authorities, and other sources, with more information still needed;
- An interim report on the procedures and practices used for the passive fire protection of the floor system in the WTC towers;
- Status report on fire model validation experiments and plans for fire endurance testing of the WTC floor system as part of the balanced use of analytical, experimental, and numerical tools to evaluate alternative collapse hypotheses;
- Summary of approach to assess most probable structural collapse sequence, integrating impact damage, fire dynamics, thermal-structural response, and collapse initiation;
- Status of recovered WTC steel pieces and their analysis;
- Status of photographic and video image collection and analysis;
- Status of first-person data collection effort to study occupant behavior, evacuation, and emergency response and the release of an interim report documenting the data collection methodology;
- Selection of external experts and contractors to support the WTC investigation team; and
- Progress in NIST's concurrent WTC Research and Development (R&D) Program and the Dissemination and Technical Assistance Program (DTAP).

The highlights of this update include:

- An interim report that documents the procedures and practices used for the passive fire protection of the floor system in the WTC towers, from the initial design in the 1960s up until very near their collapse;
- Outline of an approach to assess the most probable structural collapse sequence – that integrates impact damage, fire dynamics, thermal-structural response, and collapse initiation analyses – using a combination of physics-based mathematical modeling, statistical, and probabilistic methods;
- Outline of a three-phased sampling methodology to obtain new data on evacuation and emergency response through face-to-face interviews, telephone interviews, and focus group interviews with occupants, first responders, and families of victims – and a statement about the importance of participation in the interviews;

- A summary of important types of documents obtained by NIST from the owner, leaseholder, insurers, and local authorities and examples of what they contain, and the specific documents and materials that have not yet been located or provided to NIST;
- A summary of NIST's photographic and video image collection efforts, the need for access to unpublished photos and non-broadcast video footage from media sources, and repeat call for specific types of photos and videos to document initial damage and subsequent fire growth;
- A status report on fire model validation experiments and plans for fire endurance testing of the WTC floor system as part of the balanced use of analytical, experimental, and numerical tools to evaluate alternative collapse hypotheses; and
- Establishment of the Advisory Committee pursuant to the National Construction Safety Team Act (P.L. 107-231) signed into law October 1, 2002 by President Bush and the status of implementation procedures for the Act.

Chapter 1. INTRODUCTION

1.1 Goals of 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; and
 - Improved public safety.

1.2 Objectives of WTC Investigation:

The objectives of the NIST 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 injuries and fatalities were so high or low depending on location, including all 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; and
4. Identify, as specifically as possible, areas in current building and fire codes, standards, and practices that warrant revision.

1.3 Authorities and Use of Information in Legal Proceedings:

NIST is a non-regulatory agency of the U.S. Department of Commerce. NIST is conducting this investigation under the authorities of the National Construction Safety Team Act (P.L. 107-231). NIST investigations are focused on fact-finding, not fault-finding. No part of any report resulting from a NIST investigation can 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).

1.4 Liaison with the Professional Community, the Public, and Local Authorities:

NIST is maintaining ongoing liaison with the professional community, the general public, and local authorities during the investigation through briefings and presentations. NIST has established a web site to communicate information related to the investigation <http://wtc.nist.gov>. This information also is available in print; every effort will be made to ensure that those without internet access can receive the same information by mail.

In addition, NIST has assigned a special liaison to interact with the families of building occupants and first responders, including organizations such as the Skyscraper Safety Campaign. NIST recognizes the vital role that those individuals and groups have to play in

providing input to the NIST investigation. NIST also believes that it is appropriate and important to keep these families and organizations informed about the progress of the investigation.

Communications may be sent to NIST via electronic mail, facsimile, or regular mail:

Electronic mail:	<u>wtc@nist.gov</u>
Facsimile:	(301) 975-6122
Regular mail:	WTC Technical Information Repository 100 Bureau Drive Stop 8610 Gaithersburg, MD 20899-8610

1.5 NIST's WTC Public-Private Response Plan:

NIST's WTC public-private response plan consists of three program elements. The first is a 24-month ***building and fire safety investigation*** that is studying the factors contributing to the probable cause (or causes) of collapse of the 110-story WTC towers (WTC 1 and 2) and the 47-story WTC 7 and to the associated fatalities and injuries. What is learned in examining WTC 1, 2, and 7 is expected to benefit new and existing buildings.

Parallel to the investigation is a ***research and development (R&D) program*** that is designed to (i) facilitate the implementation of recommendations resulting from the WTC investigation, and (ii) provide a technical foundation that supports improvements to building and fire codes, standards, and practices that reduce the impact of generic extreme threats to the safety of buildings, their occupants and emergency responders. This program addresses work in critical areas such as structural fire safety, mitigation of progressive collapse, building vulnerability reduction tools, equipment standards for first responders, and human behavior, emergency response, and mobility. It includes verification of computer analysis tools and experimental validation of analytical results. The rate at which the recommendations of the investigation can be implemented will depend to some degree on the level of funding available to the R&D program.

An industry-led ***dissemination and technical assistance program (DTAP)*** is the third part of the NIST response plan. The DTAP is designed to engage leaders of the construction and building community in the implementation of proposed changes to practices, standards, and codes. Also, it 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.

1.6 Funding Status for the WTC Public-Private Response Plan:

On September 9, 2002, \$16 million in funding to support the WTC investigation was transferred to NIST by the Federal Emergency Management Agency (FEMA). These funds were made available from Public Law 107-206, the Supplemental Appropriations Act for Further Recovery From and Response to the Terrorist Acts on the United States.

In FY 2002, total funding of \$19.4 million was allocated to support NIST's WTC response plan, *including* the above \$16 million for the investigation and another \$3.4 million from funds redirected by NIST to support the overall response plan.

In FY 2003, Congress appropriated an increase of \$3 million to support selected portions of the WTC response plan, focused on the R&D and DTAP program elements.

In FY 2004, the President's budget requests an increase of \$4 million to continue support for selected portions of the WTC response plan, focused on the R&D and DTAP program elements. This request is currently pending in Congress.

Chapter 2. IMPLEMENTATION OF LEGISLATIVE AUTHORITIES

2.1 National Construction Safety Team Act Implementation:

The National Construction Safety Team Act (P.L. 107-231) (“NCST Act” or “Act”) signed into law October 1, 2002, by President Bush establishes NIST as the lead agency to investigate building failures. The Act, modeled in many respects after the National Transportation Safety Board (NTSB) for investigating transportation accidents, provides NIST with significant additional authorities. The NCST Act applies to the NIST WTC investigation in response to the attacks of September 11, 2001.

The NCST Act provides for the establishment of investigative teams to assess building performance and emergency response and evacuation procedures in the wake of any building failure that has resulted in substantial loss of life or that posed significant potential of substantial loss of life. The purpose of investigations conducted under the Act is to improve the safety and structural integrity of buildings in the United States. The Act gives NIST the responsibility to dispatch teams of experts within 48 hours, where appropriate and practical, after major building disasters. Investigation teams will include outside experts.

Consistent with NIST’s public-private WTC response plan, the Act gives the teams an explicit mandate to:

- Establish the likely technical cause of building failures;
- Evaluate the technical aspects of procedures used for evacuation and emergency response;
- Recommend specific changes to building codes, standards, and practices;
- Recommend any research or other appropriate actions needed to improve the structural safety of buildings, and/or changes in emergency response and evacuation procedures; and
- Make final recommendations within 90 days of completing an investigation.

NIST will report to Congress on actions taken as a consequence of its recommendations.

The Act gives NIST and its teams comprehensive investigative authorities to:

- Access the site of a building disaster;
- Subpoena evidence and witnesses;
- Access evidence such as records, documents, materials, and artifacts; and
- Move and preserve evidence.

The Act also authorizes NIST to confer with employees and request the use of services, records, and facilities of state and local governmental authorities.

The Act requires NIST to develop and update procedures for the establishment and deployment of teams and publish them in the Federal Register. NIST published an interim final rule in the Federal Register on January 30, 2003. It sought public comment on general provisions regarding implementation of the act and on provisions establishing procedures for the collection and preservation of evidence obtained, including the issuance of subpoenas, and the protection of information created as part of investigations. It also included provisions on guiding the disclosure of information and guiding the teams in moving and preserving evidence. These general provisions and procedures were published first because they are necessary to the conduct of the WTC investigation, already under way; they became effective immediately upon

publication. The comment period for this interim final rule closed on March 3, 2003. Only two comments were received. A final rule is in preparation.

A proposed rule is currently drafted and will be published in the Federal Register in the near future. It sets forth procedures (1) regarding conflicts of interest related to service on a team; (2) defining the circumstances under which the Director will establish and deploy a team; (3) prescribing the appropriate size of teams; (4) guiding the conduct of investigations; (5) identifying and prescribing appropriate conditions for provision by the Director of additional resources and services that teams may need; (6) to ensure that investigations under the Act do not impede, and are coordinated with, any search and rescue efforts being undertaken at the site of the building failure; (7) for regular briefings of the public on the status of the investigative proceedings and findings; and (8) providing for coordination with federal, state, and local entities that may sponsor research or investigations of building failures.

During the past four months, other steps were taken to plan and prepare for the implementation of the NCST Act. NIST staff took an Aviation Industry Training Program at the National Transportation Safety Board's (NTSB) Academy to get an overview of the process and procedures used by NTSB for investigating major aircraft accidents. A copy of the NTSB internal procedures was also obtained and was useful in preparing the Federal Register notices described above.

In preparation for the collection of information from eyewitnesses, survivors, and first responders of the WTC building failures and future investigations, staff of the NTSB Academy gave a training class to approximately 30 NIST staff in late March on interviewing techniques and dealing with people experiencing psychological trauma. The instructor provided the academic foundation for the material as well as numerous examples from NTSB investigations.

In preparation for establishing memoranda of understanding with other agencies who may cooperate in future investigations, NIST staff met with representatives of the Bureau of Alcohol, Tobacco, and Firearms (ATF), Federal Insurance and Mitigation Administration (FIMA) and the U.S. Fire Administration (USFA) within the Federal Emergency Management Agency (FEMA), the U.S. Geological Survey (USGS), the National Science Foundation (NSF), and the Occupational Safety and Health Administration (OSHA). Future visits are anticipated to the National Institute of Occupational Safety and Health (NIOSH), the Environmental Protection Agency (EPA), the National Oceanic and Atmospheric Administration (NOAA), the Centers for Disease Control and Prevention (CDC), the United States Chemical Safety and Hazard Investigation Board, and numerous private sector organizations.

Congress anticipated the NCST Act to be applicable to building failures caused by earthquakes. The Act specifies that the NIST Director develop implementing procedures that "provide for coordination with Federal, State, and local entities that may sponsor research on investigations of building failures, including research conducted under the Earthquake Hazards Reduction Act of 1977." In addition, the Committee Report 107-530 published by the House Science Committee on June 25, 2002, states that "The Director should clearly define how earthquake researchers and Teams will carry out their responsibilities in a coordinated fashion in cases where building failures have been caused by an earthquake."

NIST's responsibilities under the NCST Act have been incorporated in the recently completed plan to coordinate post-earthquake investigations issued by the four agencies comprising the National Earthquake Hazards Reduction Program. These agencies include the Federal Emergency Management Agency, the United States Geological Survey, the National Science

Foundation, and NIST. The plan (USGS circular #1242) states that, within 48 hours, NIST will examine the relevant factors associated with building failures that occur as a result of the earthquake and will make reasonable efforts to consult with the other NEHRP agencies prior to determining whether to conduct an investigation under the Act. Any NIST investigation conducted under the authority of the Act will be limited to failures of one or more buildings or failures of one or more class or type of buildings selected by NIST.

2.2 Establishment and First Meeting of the NCST Advisory Committee:

The National Construction Safety Team (NCST) Advisory Committee was established in accordance with Section 11 of the National Construction Safety Team Act (P.L. 107-231) and the Federal Advisory Committee Act (5 U.S.C. app.2). The Charter for the Advisory Committee was approved on November 5, 2002. This Advisory Committee will provide advice to the NIST Director on the WTC investigation and on other NIST investigations under the Act. Both the Act and the Charter for the Advisory Committee may be found at the NIST NCST web site at <http://www.nist.gov/ncst> and are provided for reference in Appendix 1 and 2, respectively.

The NCST Advisory Committee functions to advise the Director of NIST on carrying out investigations of building failures conducted under the authorities of the NCST Act that became law in October 2002, including advice on the composition and function of investigation teams and other responsibilities under the act. On January 1 of each year, the Committee will provide to the Secretary of Commerce, through the Director of NIST's Building and Fire Research Laboratory and the NIST Director, a report for submission to the Committee on Science of the House of Representatives and to the Committee on Commerce, Science, and Transportation of the United States Senate. The report will include an evaluation of NCST activities, along with recommendations to improve the operation and effectiveness of investigation teams and an assessment of the implementation of the recommendations of teams and of the Advisory Committee.

A Federal Register notice was published on November 12, 2002, requesting nominations of members to serve on the NCST Advisory Committee. NIST received 84 nominations. On March 20, 2003, NIST Director Arden L. Bement, Jr., announced the appointment of eight experts to serve on the NCST Advisory Committee. The announcement of two other experts to the 10-member committee was made on April 28, 2003.

The Committee members were selected for their technical expertise and experience, established records of distinguished professional service, and their knowledge of issues affecting teams established under the Act. Their areas of expertise include structural engineering, metallurgy, fire protection, firefighting, human behavior, architecture, building regulations, and the insurance industry. Short biographies of the members are provided in Appendix 3.

Members of the Committee are not compensated for their services, but are allowed travel and per diem expenses while performing duties of the Committee while away from the home or regular places of business. The term of office of each member of the Committee is three years. The initial members have staggered terms so that the Committee will have approximately 1/3 new or reappointed members each year. A person who has completed two consecutive full terms of service on the Committee shall be ineligible for appointment for a third term during the one year period following the expiration of the second term. The Director of NIST will appoint

the Chair from among the members of the Committee, and the Chair's tenure will be at the discretion of the Director of NIST.

Portions of the NCST Advisory Committee meetings will be open to the public; other portions will be closed in accordance with statutory exemptions. Specifically, it has been determined that portions of Advisory Committee meetings that involve discussions regarding the proprietary information and trade secrets of third parties, data and documents that may also be used in criminal cases or lawsuits, matters the premature disclosure of which would be likely to significantly frustrate implementation of a proposed agency action, and data collection status and the issuance of subpoenas may be closed in accordance with 5 U.S.C. 552b(c)(4), (5), (9)(B), and (10), respectively.

The NCST Advisory Committee is required to meet at least once per year but the Committee may meet more frequently for the duration of the WTC Investigation. Additional meetings may be called whenever one-third or more of the members so request it in writing or whenever the Chair or the Director of NIST requests a meeting.

The NCST Advisory Committee held its first meeting on April 29-30, 2003. This session was largely organizational and included a review of the Committee's objectives and duties. The Committee was provided an update on the WTC Investigation and the Rhode Island Nightclub Fire Investigation, the two investigations that NIST is currently conducting under the Act. These investigations are expected to be a focus of the Advisory Committee's activities in the near future. In addition, the Committee discussed procedures to implement the Act. Approximately one hour was reserved for public comments, and speaking times were assigned on a first-come, first-served basis as described in the Federal Register Notice announcing the meeting.

Chapter 3. PROGRESS ON WTC INVESTIGATION

3.1 Technical Approach of Investigation and Scope of Progress Report

The technical approach of the federal building and fire safety investigation, described in the final investigation plan (<http://wtc.nist.gov>) released August 2002, includes the following phases:

- **Identification of Technical Issues and Major Hypotheses Requiring Investigation:** opportunity for public input (e.g., public meeting; website; Federal Register notice) in developing investigation plan; consultations with experts in structural and fire protection engineering and in construction, maintenance, operation and emergency response procedures of tall buildings); findings and recommendations of BPAT study and technical issues identified by other experts; analysis of inputs to establish priorities for investigation; review by Federal Advisory Committee.
- **Data Collection:** inputs from building owners and operators, local authorities, designers, consultants, and contractors; data and information collected by the BPAT study; building and fire protection design documents, records, plans, and specifications; construction, maintenance, operation records, building renovations and upgrades; video and photographic data; field data; interviews and other oral and written accounts from building occupants, families of victims, emergency responders, building operators, and other witnesses; emergency response records including audio communications; and other records.
- **Analysis and Comparison of Building and Fire Codes and Practices:** analysis and comparisons of codes, standards, and specifications used for WTC buildings; comparison of codes with codes in other jurisdictions; review and analysis of practices used for design, construction, operation, maintenance, repair, renovations, and upgrades.
- **Collection and Analysis of Physical Evidence:** structural steel, material specimens and other forensic evidence to the extent they have been collected or are otherwise available; analysis of metallurgical and mechanical properties of steel to evaluate its quality and to estimate temperature conditions in the buildings before collapse.
- **Modeling, Simulation, and Scenario Analysis:** aircraft impact on structures and estimated damage to interior and core structures and residual structural capacities; role of jet fuel and building contents in resulting fire; fire dynamics and smoke movement; thermal effect on structures and the effectiveness of fireproofing; effect of fire on structural response and vulnerability and the role of connections, flooring system, and core and exterior columns; occupant behavior and response including influence of communications and barriers to egress; evacuation issues including egress, control/fire panels, emergency response, and communications; fire protection system design and vulnerability; hypotheses for structural collapse including evaluation of system vulnerability to progressive collapse; probable collapse mechanisms and associated uncertainties.
- **Testing to Re-Create Scenarios and Failure Mechanisms:** reduced and real-scale tests to provide additional data and verify simulation predictions, especially for the effects of fires.
- **Technical Findings and Recommendations:** preparation of interim and final reports; peer review by established NIST Editorial Review Board; augmented NIST review to include

senior management and legal; review of key reports by Federal Advisory Committee; finalize and disseminate via published reports, web, and media.

- **Identify Needs for Changes to Codes and Standards:** identify specific areas in need of change to codes, standards, and practices based on findings of investigation (note: specific recommendations and actions for proposed changes to codes, standards, and practices will be made via the R&D and DTAP programs).

The investigation includes eight projects that provide focus for the technical work. They are:

- Project #1: Analysis of Building and Fire Codes and Practices
- Project #2: Baseline Structural Performance and Aircraft Impact Damage Analysis
- Project #3: Mechanical and Metallurgical Analysis of Structural Steel
- Project #4: Investigation of Active Fire Protection Systems
- Project #5: Reconstruction of Thermal and Tenability Environment
- Project #6: Structural Fire Response and Collapse Analysis
- Project #7: Occupant Behavior, Egress, and Emergency Communications
- Project #8: Fire Service Technologies and Guidelines.

The projects are interdependent, and when considered together meet the NIST investigation objectives identified in Section 1.2 of this report. 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 1, and the key interdependencies among the projects are illustrated in Figure 1.

This report summarizes the progress made by NIST and the cooperation it has received from a variety of organizations since the December 2002 progress report. It covers the following areas (investigation project numbers are indicated in parenthesis) with emphasis on the WTC towers:

- Status of Data Collection Efforts (All projects)
- Procedures and Practices for Passive Fire Protection of WTC Floor System (Projects #6, #1)
- Fire Model Validation Experiments and Fire Testing of WTC Floor System (Projects #5, #6)
- Assessing the Most Probable Structural Collapse Sequence (Projects #6, #2, #5, #3)
- Status of Steel and its Analysis (Project #3)
- Photographic and Videographic Image Collection and Analysis (Project #5)
- First-Person Data on Occupant Behavior, Evacuation, and Emergency Response (Projects #7, #8)
- Selection of External Experts and Contractors to Support WTC Investigation (All projects)

Complete details underpinning the summary reports for the second, fourth, and seventh items contained in the following sections are available in Appendices 4, 5, and 6. These appendices should be consulted for additional details and clarification.

Table 1. Federal Building and Fire Safety Investigation of the World Trade Center Disaster

Technical Area	Project #	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, & 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, & 7.
Investigation of Active Fire-Protection Systems	4	Investigate the performance of the active fire-protection systems in WTC 1, 2, & 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, & 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, & 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 R&D needs that advance the safety of the fire service in responding to massive fires in tall buildings.

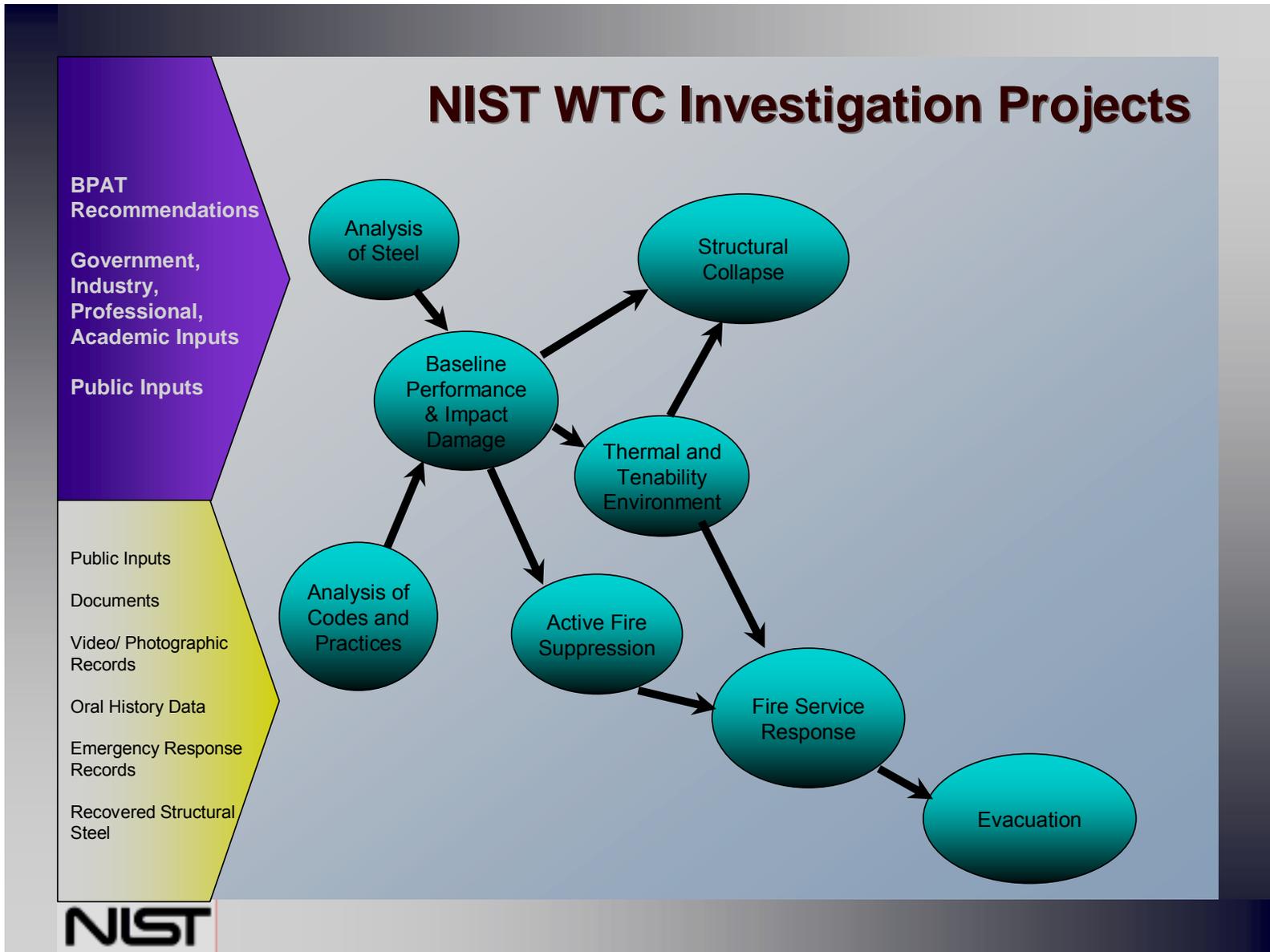


Figure 1 The eight projects in the federal building and fire safety investigation of the World Trade Center disaster

3.2 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.

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 Department of Design and Construction (DDC); the New York City Department of Buildings (DOB); and the New York City Office of Emergency Management (OEM). In addition, the Occupational Safety and Health Administration (OSHA) provided correspondence sent to it regarding the evacuation experience of WTC occupants on September 11, 2001.

NIST also has received information from Silverstein Properties ("Silverstein") 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; March & McLennan (a tenant of WTC 1), and Roger Morse Associates. 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.

The documents described above and other information relate to the design, construction, operation, inspection, maintenance, repair, alterations, emergency response and evacuation of the WTC complex.

NIST has a number of requests for materials that are currently pending with several organizations, including those listed above. NIST is working with these organizations to gain access to important information, specifically that related to emergency response and evacuation on September 11, 2001, including communication and operational records. It is vital that this information be made available to NIST.

The important documents and materials that have not yet been located and/or provided, in addition to those identified in the December 2002 progress report, include:

- The 911 tapes and logs from NYPD and FDNY, from one hour before the first aircraft struck WTC 1 until two hours after WTC 7 collapsed;
- Transcripts of about 500 FDNY interviews of surviving personnel from the incident;
- All supporting documents for the McKinsey & Company's FDNY study;
- Detailed information on the FDNY communication system and radio repeater network;
- FDNY training practices for operations in high rise buildings;
- A complete set of NYPD records identified in request lists submitted by NIST to NYPD; and

- Contents of the aircraft that struck the WTC towers such as cabin furnishings, cargo, etc. that contributed to the intensity of the fires.
- Descriptions of the most recent partitions and furnishings in most of the tenant spaces in the three buildings.
- Reports of critical UL tests performed for the supplier of the fireproofing materials.

Important documents that have not been located include the original contract specifications for WTC 1 and 2 that were completed in the 1970s, and a complete set of tenant alterations, construction logs, and maintenance logs for WTC 1, 2, and 7. The WTC tower specifications provided to NIST were used to procure materials from individual suppliers, such as steel and concrete. They are not the project specifications for the entire structure prepared by the Port Authority. These would include items from site preparation and foundation to erection and finishing of the buildings, including fire protection. If the original project specifications cannot be located, it may be possible to reconstruct them partially from individual subcontract and materials purchase specifications and from individual reports for design and fire protection, etc. NIST is working with the Port Authority and its consultants and contractors (including former employees) to locate the complete set of project specifications.

In addition, the complete as-built drawings of the WTC towers and WTC 7 are not available. NIST has a copy of the original contract drawings for the WTC tower *structures* that were revised to document significant changes during construction and early tenant modifications. NIST also has supplementary drawings that document the majority of the WTC tower *structural* tenant modifications. These modifications were mostly openings to the floor framing system throughout the WTC towers and WTC 7 to meet the needs of tenants, and strengthening of the interior core columns of the WTC towers in the upper stories to accommodate additional gravity loads. In many instances, the steel straps used to brace the floor systems to the columns were inadvertently damaged during such modifications, and repairs were made to restore structural integrity.

NIST continues to be interested in documents related to the ability of the WTC towers to withstand the abnormal load condition of a Boeing 707 aircraft impact that was considered in the original design (this assessment is part of Project #2). A property risk assessment report prepared for Silverstein Properties prior to leasing the WTC towers in 2001 identifies the scenario of an aircraft striking a tower as one of the “maximum foreseeable losses.” The assessment states:

“This scenario is within the realm of the possible, but highly unlikely. ...In the event [of] such an unlikely occurrence, what might result? The structural designers of the towers have publicly stated that in their opinion that either of the Towers could withstand such an impact from a large modern passenger aircraft. The ensuing fire would damage the ‘skin’ in this scenario, as the spilled fuel would fall to the Plaza level where it would have to be extinguished by the NYC Fire Department.”

A three-page document from March 1964 contains calculations to estimate the “period of vibration due to plane crash at 80th floor,” but it provides no details on the ability of the WTC towers to withstand such an impact on the towers. NIST will continue to work with the Port Authority’s structural contractor to locate and obtain documents related to the WTC towers ability to withstand aircraft impact.

The Port Authority and Silverstein Properties have previously informed NIST that many of the documents cited above were destroyed in the collapse of WTC 1, which housed documents for

the Port Authority, and in the collapse of WTC 7 and WTC 1, which housed documents for Silverstein Properties.

The WTC investigation team continues to review and analyze the valuable and voluminous information already in its possession. One example is the significant differences in estimates of design wind loads on the WTC towers resulting from two competing wind tunnel experiments conducted in 2002 by independent groups of experts as part of the WTC insurance litigation. This information is required to establish the baseline structural performance of the WTC towers under design gravity and wind loads (Project #2).

Experts for the insurance companies state that their wind tunnel

“studies and analyses ... indicate that the wind loads on an individual tower in the two-tower configuration are roughly 66 percent greater than the forces for which the towers were apparently designed. ... Thus, with respect to wind loads, the reliability of the towers in the twin tower configuration falls below current state-of-the-practice for significant structures.”

This statement is based on comparing resultant base overturning moments for 50 year wind speeds to the overturning moment reported in the June 1971 *Civil Engineering* article (pp. 66-70) by Lester S. Feld, the Port Authority’s project administrator for structural steel and concrete.

Experts for Silverstein Properties, the WTC leaseholder, however, stated that they “believe that the Feld article lacks sufficient substance to constitute the basis of any opinion concerning the wind resistance design and level of performance of the Towers.” They suggest the need for “conducting independent evaluation or analysis of the performance of the Towers” instead of relying on the numbers in the 1971 *Civil Engineering* article. They further state that the results from the wind tunnel studies in the single-tower configuration conducted by experts for the insurance companies are 28 percent to 44 percent higher than the results of the wind tunnel studies commissioned by the leaseholder.

As part of the effort to establish the baseline structural performance of the WTC towers, NIST wind engineering experts have completed a preliminary review of these studies. This review indicates that the load estimates from the competing wind tunnel experiments differ by significant amounts. NIST will request the two groups of external experts to provide details and clarifications of the procedures that were used to conduct the respective wind tunnel tests and to estimate the loads from such measurements. That information will be used to determine the adequacy of the wind loads applied in the original design and to document the differences in procedures and practices used to estimate design wind loads for high-rise buildings.

3.3 Procedures and Practices for Passive Fire Protection of WTC Floor System:

One of the four objectives of the NIST investigation is to determine what procedures and practices were used in the design, construction, operation, and maintenance of the WTC towers and WTC 7. A key focus is on acceptance procedures and practices for innovative systems, technologies, and materials, and for variances from requirements of building and fire code provisions. This documentation of historical information is expected to be of value to the professional community in identifying and adopting changes to procedures and practices that may be warranted.

NIST is releasing today an interim report that documents the procedures and practices used to provide the passive fire protection for the floor system of the WTC towers (Appendix 4). The report traces the history of the fireproofing of the WTC towers within the broad context of applicable building codes, construction classifications, fire ratings, standardized testing, and inspections. The primary focus is on the floor system, which was innovative in its day and for which there was little, if any, service knowledge. In particular, there was little fire safety and maintenance experience with the spray-on fireproofing of the trusses. NIST is also reviewing documents related to the fireproofing of other structural components in the WTC towers and will include that information in future reports.

This report summarizes the factual data contained in the many documents reviewed by NIST. The report documents a few instances where there are conflicting data or data that need some interpretation. To the maximum extent possible the facts are presented without interpretation.

Nothing in this report should be understood to imply that the floor trusses played a critical role in the collapse of the WTC towers. This issue is a key component of another NIST investigation objective, viz., to determine why and how WTC 1 and 2 collapsed following the initial impacts of the aircraft and why and how WTC 7 collapsed. Any findings and conclusions related to the role of the floor trusses in the most probable collapse sequence must await the results of that work.

NIST continues to seek, receive, and review additional data related to the fireproofing of the floor systems of the WTC towers. This includes maintenance and inspection records for the WTC towers from different sources, reports of critical UL tests performed for the fireproofing materials supplier, and information on the ability of the fireproofing material to withstand shock, impact, and vibration. Further, since nearly 40 years have elapsed from the initial design of the WTC towers and some documentation was stored in the towers, it is inevitable that some factual data has been lost or is missing from the documents reviewed by NIST.

Accordingly, NIST welcomes written comments from organizations and individuals possessing specific factual information related to the contents of this report. Such information may be sent to NIST via e-mail to wtc@nist.gov, fax to (301) 975-6122, or by mail to WTC Technical Information Repository, 100 Bureau Drive Stop 8610, Gaithersburg, MD 20899-8610. NIST will review all such information and update this report as needed.

The major findings of this interim report of the fireproofing of the WTC floor system are summarized below (readers should refer to the report in Appendix 4 for additional details):

Applicable Building Codes, Building Classification, and Fire Rating Requirements. Early in the design phase (May 1963), the Port Authority adopted the New York City Building Code for the design and construction of the WTC towers. The 1961-1962 revision to the 1938 New York City Building Code was in effect at the time.

In September 1965, the Port Authority instructed its designers to revise plans to comply with the second and third drafts of what became the 1968 edition of the New York City Building Code. In accordance with the 1968 Code, the WTC towers were identified as occupancy group E – Business, and classified as Construction Class IB. Construction Class IB required that the columns and floor systems of the towers have a 3 hour and 2 hour fire endurance, respectively. By comparison, the 1961-1962 revision to the 1938 code would have required a 4 hour rating for the columns and a 3 hour rating for the floor systems.

By the 1990s, both towers had been retrofitted with sprinklers as required by the New York City Local Law No. 5, which was effective in 1973. Based on the 1999 revision of the New York City Building Code, sprinklered buildings could be classified as Construction Group IA, IB, and IC. While it was possible to lower the fire rating requirements for the WTC towers to Class IC, they remained classified as Class IB. Construction Class IC would have required that the columns and floor systems of the towers have a 2 hour and 1-1/2 hour fire endurance, respectively.

Fireproofing Material, Thickness Requirements, and Measured Data. The open-web bar joists that supported the floors of WTC 1 were initially fireproofed with an asbestos-based spray-on material, Cafco Blaze-Shield Type D. No information about the required thickness was specified in either project specifications or drawings to achieve the required 2 hour rating. The Port Authority directed the fireproofing contractor to apply 1/2 in of fireproofing to the bar joists.

After fireproofing of the first 38 floors of WTC 1 was completed using asbestos-containing Cafco Type D, the fireproofing material was changed to Cafco Blaze-Shield Type D C/F, a non-asbestos product. There are no records specifying any changes in the thickness requirements to protect the bar joists using the new product, Blaze-Shield D C/F.

A few sample area data sheets, from surveys conducted in 1990 in support of litigation related to the asbestos-based fireproofing, reported that the fireproofing thickness on the floor joists was consistently about 1/2 in. Measurements taken in 1993 on two floors (Floors 23 and 24) of WTC 1 provide some quantitative data on actual applied thickness of fireproofing. Results indicate an average thickness of fireproofing from a relatively small sample (16 random trusses from two floors out of a total of 220 possible floors) to be 0.74 in, with a minimum average (of six measurements) value of 0.52 in and a maximum average value of 1.17 in for each of the tested bar joists. Four of the 32 bar joists had average thicknesses that varied between 0.52 in and 0.56 in. These measurements suggest that the minimum thickness exceeded 1/2 in.

A study performed by the Port Authority in 1995 concluded that 1-1/2 in of fireproofing was required for chords and web members of the bar joists. The Port Authority issued guidelines in 1999 for fireproofing repairs, replacement, and upgrades adopting the 1-1/2 in thickness requirement for the bar joists. By 2000 about 30 floors had been upgraded. Floors 92-100 of WTC 1 as well as floors 77-78, 88-89, 92, 96-97 of WTC 2 had been upgraded. Construction audit reports suggest that the minimum thickness requirement was met. Cafco Blaze-Shield II was used for the upgrade, not Blaze-Shield D C/F.

A property condition report prepared for the Port Authority in 2000 concluded that the rating of the structural fireproofing in the WTC towers and subgrade had been judged to be “an adequate 1 hour rating considering the fact that all Tower floors are now sprinklered” and noting the ongoing program to upgrade the fireproofing thickness to 1-1/2 in to achieve a 2 hour fire rating.

Adhesion of Fireproofing, and Ability to Withstand Shock, Impact, and Vibration.

Problems with adhesion of Cafco Type D were reported during construction of the WTC towers. A more recent report, issued in 2000, also indicates that, in the majority of the cases, the existing fireproofing required so much patching that it was more effective to replace it with new fireproofing material. The construction audit reports associated with upgrading the fireproofing to 1-1/2 in thickness suggest that the minimum bond strength requirement of 150 psf was met. NIST has not received any records that document the shock, vibration, and impact properties of the specific fireproofing materials used in the WTC towers.

Need for Fire Endurance Testing. The fire protection of bar joist-supported floor systems by directly applying spray-on fireproofing to the joists was relatively innovative at the time the WTC towers were designed and constructed. 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.

In 1966, Emery Roth & Sons, the Architect of Record, and, in 1975, Skilling Helle Christiansen Robertson, the Structural Engineer of Record, stated that the fire rating of the floor system of the WTC towers could not be determined without testing.

The fire rating of structural materials and assemblies is determined through standard testing in accordance with ASTM E119, "Standard Test Methods for Fire Tests of Building Construction and Materials, American Society for Testing and Materials." Based on the 1961 edition of ASTM E119, floors being tested would pass the fire endurance test if the test assembly sustained the applied load and if the temperature on the unexposed surface (top of slab) would not rise more than 250 °F above its initial temperature. More recent versions of the ASTM E 119 differentiate between testing thermally restrained and unrestrained floor assemblies, and incorporate criteria for fire rating based on limiting temperatures of the steel members for both types of assemblies.

Fire Testing of a Similar Floor System. In 1970, an ASTM E 119 test of a 10-inch deep joist-supported floor system (with 2-3/4 in concrete slab) was conducted, with a span shorter than what was employed in the WTC towers. This test was not related directly to the WTC construction, and the tested floor assembly differed in several respects from that used in the WTC towers. The floor assembly achieved a 3 hour rating based on structural capacity and temperature criteria for the unexposed surface, but measurements indicated that the bottom chords of the joists reached 1200 °F (650 °C) within about 105 minutes and the diagonal webs reached 1200 °F in about 150 minutes. Although temperature criteria for steel was stated to have become common practice in a 1954 NIST report and was used as an alternative testing procedures at this time, they were not required by ASTM E 119. In addition, measurements showed that the floor assembly sagged 3 in (or 1.5 percent of span) at 120 minutes and 4-3/4 in (or 2.4 percent) at 180 minutes. There is no record to suggest that the test results formed the technical basis for the fire protection requirements for the WTC floor system.

Status and Actions. From the documents reviewed, NIST has not been able to determine the technical basis for the selection of fireproofing material for the joists, and the determination of the thickness of fireproofing to achieve a 2 hour rating. NIST intends to carry out testing to assess the fire rating and behavior of a typical fireproofed floor assembly under the fire conditions prescribed in ASTM E 119. In addition, information contained in this report (e.g., on fireproofing material and thickness, and fire rating) will be used in conducting the ASTM E 119 tests and to analyze thermal-structural response of the WTC towers. NIST also intends to compare the fire protection requirements of the NYC Building Code with national model codes.

3.4 Fire Model Validation Experiments and Fire Testing of WTC Floor System

NIST is using a combination of analytical, experimental, and numerical tools to analyze alternative collapse hypotheses. Among the key factors that need to be considered are:

- the speed, direction, orientation, and point of impact of each aircraft;
- the dispersion of the jet fuel following impact;
- the mass, nature, and locations of other combustibles, including building furnishings and those from the aircraft interior and cargo bays;
- the mass of the steel, concrete, heavy machinery, and non-structural building materials and contents, that shared in absorbing the energy imparted during aircraft impact;
- the effects of debris fragments on the structure, fireproofing, interior partitions, and other building systems, and subsequent gravity load effects on structural stability;
- the performance of the steel components and connections, at the high rates of loading during aircraft impact and at elevated temperatures during subsequent fires, and the associated failure criteria;
- the performance of the fireproofing at high temperatures and the extent to which the fireproofing may have been missing or knocked off during aircraft impact; and
- the growth and spread of fire and the resulting temperature of the structural steel as a function of time and location, including the coupling of the fire dynamics and thermal-structural response analyses.

In its re-construction of the thermal and tenability environment, NIST is taking into account:

- the fire load provided by the building contents, jet fuel and combustible aircraft contents (WTC 1 & 2), and fuel storage tanks (WTC 7);
- the ventilation available for combustion; and
- the inter-compartment 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 mechanical properties of steel (columns, spandrels, trusses, truss seats, welds, and fasteners) at high strain rates to support aircraft impact damage analysis;
- the thermal-insulation properties of the fireproofing materials as a function of temperature and the ability of the fireproofing materials to withstand shock and impact;
- the mechanical properties of steel (columns, trusses, truss seats, bolts, welds) at high temperatures to support the analysis of structural response to fires;
- fire tests to study the floor truss-to-column connections and the load-transfer between the steel truss and the concrete deck in the composite floor system;
- fire tests in large compartments to measure the heat release and transfer rate to compartment gases and steel specimens (steel truss and columns, with and without fireproofing) for validating fire dynamics and thermal-structural analyses, including the coupling between the two analyses;
- office work station fire tests, based on descriptions of furnishings used in WTC 1 office space, to generate a data base 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; and
- fire endurance testing of a typical floor system and individual steel members under the fire conditions prescribed in ASTM E 119.

NIST is also reviewing previously completed tests on open-web steel truss systems, including their performance under gravity loads and fire. The past performance of open-web steel trusses in fires is being documented using available fire incident and insurance investigation reports.

The progress on experimental validation of fire modeling and thermal-structural analysis is summarized below, as are the plans for fire endurance testing of the WTC floor system under the fire conditions prescribed in ASTM E 119. The status of the WTC steel and its analysis, including experiments, is summarized in a separate section of this progress report.

Progress on Experimental Validation of Fire Modeling and Thermal-Structural Analysis.

Reconstructing the fires and their impact on the structural members in the WTC buildings requires extensive use of computational models. There is little direct information about the fires within the buildings. Available information is based on photographic evidence at the building perimeters and from testing a few pieces of steel to determine the heat that was endured. The modeling enables examination of alternative possible fire growth patterns in the unobserved portions of the buildings. Each of these patterns will lead to predictions that can then be compared with the observations to identify the most likely fire growth and spread rates.

The building fires will be modeled using the NIST Fire Dynamics Simulator/Smokeview software package. The thermal response of the steel structure will be modeled using finite element thermal-structural software. The Fire Dynamics Simulator (FDS) is the first large-domain CFD fire model that predicts and visualizes the spread, growth and suppression of a fire based on the underlying scientific principles governing fluid motion. The model numerically solves the governing conservation equations of mass, momentum and energy for low-speed, thermally-driven flows with an emphasis on smoke and heat transport from fires. FDS has been in use for nearly a decade and has been validated against experimental data for a variety of applications. The companion software package, called Smokeview, animates in three dimensions the FDS-generated movement of smoke particulates, heat fluxes, temperatures and fluid velocities within a building.

A series of large-scale experiments was conducted in the NIST Large-scale Fire Laboratory from March 10 to March 26, 2003, to (a) assess the accuracy with which FDS predicts the thermal environment in a burning compartment and (b) establish a data set to assess the accuracy of the prediction of the temperature rise of structural steel elements.

Four steel components, similar in geometry and cross-sectional dimensions but not exact replicates of those used in the WTC towers: two trusses, one thin-walled column, and a simple rod (Figure 2), were placed within a steel-frame compartment (3 m by 7 m by 4 m) lined with calcium silicate board. The components were either left bare or had sprayed-on fire protective insulation material in each of two insulation thicknesses; 17 mm (3/4 in) and 34 mm (1-1/2 in).

The fire was generated using one of two liquid hydrocarbon fuels introduced by a two-nozzle spray burner onto a 1 m by 2 m pan. The fuels were selected to produce medium-soot fires (heptanes) and high-soot fires (heptanes with toluene).

Fresh air entered the compartment through openings located 1 m above the floor (Figure 3). Heat and combustion products were emitted through openings located 2 m above the floor on the other end of the enclosure (Figure 4). A description of the tests appears in Table 2.

The compartment was heavily instrumented so that all of the energy released by the fire could be accounted for and reported in terms of heat losses to the walls, through the openings, etc.

With the large number of measurements, it was possible to go beyond the traditional point-by-point comparison and discover why the model either under- or over-predicted a given measurement. The heat flux and completeness of combustion (CO, CO₂) measurements allow evaluation of the overall energy budget, and subcomponents of the model.

Table 2. Test Matrix

Test	Heat Release Rate (MW)	Fuel	Steel Insulation Thickness (mm)	Test Duration (min)
1	2.0	Heptanes	None	15
2	2.4	Heptanes/toluene	None	15
3	2.0	Heptanes/toluene	None	15
4	3.0	Heptanes	17, 34	15
5	3.0	Heptanes	17, 34	50
6	3.0	Heptanes	17, 17	50

The instrumentation for the tests generated up to 352 channels of data. Many of the channels recorded temperatures measured by thermocouples on the surface of the walls and ceiling, within the walls, on the surface of the steel components, and at the surface of the spray-applied insulation. Heat flux gauges were placed strategically around the compartment to measure the transport of radiant energy.

Following the establishment of baseline signals from all the measurement devices, the burner was ignited and continued burning at a steady rate (Figure 5). The test continued until the temperature at any steel surface approached approximately 600 °C.

Prior to each test a prediction of the thermal environment in the compartment was determined using FDS, as well as the steel temperature rise for the predicted thermal environment using ANSYS finite element analysis thermal models. NIST is in the process of comparing the predicted and experimental results. Valuable preliminary results are:

- The predicted and measured times for the bottom of the bare steel joist to reach 600 °C agreed to within 15 percent
- Despite significant differences in the sootiness of the flames from the two fuels, both types of fires produced similar temperature rises at the ceiling surface. However, the bottom of the steel joist above the fire plume reached 600 deg C twice as fast in the sootier fire, even though there was a larger temperature gradient along the joist length.
- The model predicted the non-symmetric shape of the fire plume, caused by obstructions to uniform air flow within the compartment.

Using Smokeview, visual comparison of the test results and the model predictions will determine how well FDS captures both the fire phenomena and the thermal patterns in the compartment. Quantitative analysis of the data will determine the numerical accuracy of the predictions. Similar analysis will be performed to assess the accuracy of the finite element modeling of the thermal patterns within the bare and insulated steel components.

NIST is in the process of gathering information on the two WTC towers (e.g., their design; the nature and mass of furnishings; for the towers, the damage from the incident aircraft and the combustibles they introduced) to construct the environment in which the fires burned on September 11, 2001. Similar information is being gathered on the design and contents of WTC 7. To the extent that this information is accurate and complete, NIST will then proceed with

confidence to evaluate alternate hypotheses for the causes of the collapses of the buildings. If not, NIST will be required to rely on generally available knowledge, prior experience, and expert judgment to estimate the combustibles in the buildings.

In addition, NIST intends to conduct office work station fire tests, based on descriptions of the furnishings used in WTC 1 office space, to generate a database on the thermo-physical properties of the materials for use as input to the fire dynamics simulation tool. NIST also intends to conduct fire tests to validate the model predictions of the sensitivity of fire intensity, duration, and spread to the distribution and nature of the combustibles.

Plans for Fire Endurance Testing of WTC Floor System: NIST has issued a solicitation to conduct fire endurance testing of a typical WTC steel-concrete composite floor system and individual steel members under the fire conditions prescribed in ASTM E 119. Details of the testing and instrumentation requirements, including specimen geometry and dimensions, may be found in the solicitation at the web site <http://wtc.nist.gov/contracts>. The testing will seek to assess the effect of insulation thickness and end-point criteria on the resulting fire rating, using the specific spray-on fireproofing materials applied to the WTC floor system.



Figure 2. Insulated steel components in place prior to Test 5. In the foreground are two steel trusses and a steel rod, supported across the lower chord panel points, positioned near the ceiling above the fire pan. The steel column is located between the air inlet and the fire pan. The specimens are similar in geometry but not exact replicates of those in the WTC towers. The tests are designed to validate models to analyze heat flux and temperatures models.



Figure 3. Inlet side of the compartment 5 minutes after ignition in Test 2. The fire is in the background. The foreground shows instrumentation for characterizing the air flow at the inlet. A baffle is located in front of the fire.



Figure 4. View of compartment from air exhaust outlet prior to the start of test 6. The foreground shows instrumentation for characterizing the air flow at the outlet.



Figure 5. View of compartment from air exhaust outlet several minutes after the start of test 6. Note the flame impingement on the steel trusses and bar.

3.5 Assessing the Most Probable Structural Collapse Sequence:

The collapse sequence hypotheses under consideration for the WTC towers recognize that aircraft impact caused damage to perimeter and interior columns and to floor systems. While the full extent of this damage is unknown and can only be estimated through analysis, it led to redistribution of the building loads among the columns (e.g., from the damaged columns to the undamaged columns, aided by the hat truss at the top of the towers) and with the floor systems.

There are several leading hypotheses that have been postulated publicly by experts for the structural collapse sequence between the aircraft impact and the collapse of each WTC tower. These are summarized below to provide context for the subsequent discussion.

One hypothesis suggests that the load carrying columns were weakened by the fires and failed, initiating overall building collapse without the need for any weakening or failure of the steel truss floor system. Another hypothesis suggests that significant portions of one or more floor truss systems sagged, as they were weakened by fires, pulling the columns inwards via the connections to initiate overall building collapse through combined compression and bending failure of the columns. A variation of this hypothesis suggests that the sagging floor system failed in shear at its connections to the columns, leading to overall building collapse initiation through buckling failure of the columns. Load eccentricities introduced by partially damaged floor systems could also have contributed to buckling failure of the columns. Combinations of these hypotheses present other possibilities, including the relative roles of the perimeter and core columns.

Based on an initial assessment of these hypotheses, including the studies conducted as part of the insurance litigation and other relevant data, NIST considers it premature to exclude any of the postulated hypotheses. 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 observed behavior. First, neither tower collapsed immediately upon aircraft impact. Second, the buildings collapsed only after fires had burned and advanced through the buildings for about 56 minutes in the South Tower (WTC 2) and about one hour and 42 minutes in the North Tower (WTC 1).

Any analysis that suggests rapid loss of stability or collapse without the need for a sustained fire would favor a critical collapse-initiating role for structural components damaged by aircraft impact (e.g., columns) and a lesser role for components weakened by fire (e.g., floor trusses and connections). Likewise, any analysis that delays loss of stability to well beyond the observed time-to-collapse for each tower would favor a critical collapse-initiating role for structural components weakened by fire and a lesser role for components damaged by the initial impact of aircraft.

Further, any analysis must explain the difference in the times to collapse of the two WTC towers, considering factors such as details of the aircraft impact (e.g., speed, height of impact above ground, position and orientation with respect to the building and its core) as well as the condition of the fire protection systems (e.g., thickness and extent of fireproofing, and operation of sprinkler system).

Analyzing complex failure sequences of the type posed by the collapse of the WTC towers requires a formal approach to integrate multiple disciplines effectively, to discern which parameters significantly influence the analysis methods, and to determine the most probable sequence of events leading to the initiation of structural collapse.

The objective of the failure analysis for the WTC investigation is to determine the combination of events in each building (WTC towers and WTC 7) that led to the initiation of its collapse, and to answer the following questions:

1. What is the most probable collapse sequence?
2. What confidence levels are associated with the most probable collapse sequence?
3. What is the probability of other possible collapse sequences?
4. What parameters have the strongest influence on the most probable collapse sequence?

While substantial information is available about the design and general condition of the buildings prior to their collapse, much information remains unknown about the level of damage from aircraft impact or debris and the subsequent fires. In determining the most probable collapse sequence for each building, modeling and analysis tools will be used to evaluate possible sequences of events that 'fit' observed events.

NIST is releasing today the details of an integrated approach, combining mathematical modeling, statistical, and probabilistic methods, to identify the most probable of technically possible collapse sequences while accounting for incomplete information in modeling, input parameters, analysis, and observed events (Appendix 5).

The approach, developed with experts in statistical methods and probabilistic analysis of structural systems, combines three assessment methods in parallel:

- Mathematical modeling methods, from the component to subsystem to full-scale level, to simulate the structural response to service loads, aircraft impact, and ensuing fires up until collapse initiation.
- Statistical methods, using experimental design techniques, for identifying and ranking influential parameters and their relative effects on analysis results.
- Probabilistic methods, using event tree and Monte Carlo techniques, for determining the probability of different collapse sequences, and the parameters that contribute to uncertainty propagation from the component to subsystem to full-scale level.

The mathematical modeling approach represents the best understanding of the physics related to the sequence of events—impact damage, fire dynamics, thermal-structural response, and the collapse sequence. With a full understanding of the physics based on best available information, this approach would be sufficient for evaluating these events. However, since there are knowledge and random uncertainties related to the collapse events, the statistical and probabilistic methods are necessary to provide a rational, consistent approach to assess the different collapse sequences.

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. Specifically:

- The *impact damage* analysis models the impact region to determine the probable damage state(s) of the structure and provides initial building conditions for fire dynamics and thermal-structural response.
- The *fire dynamics* analysis determines 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 *thermal-structural* analysis determines the probable structural response to the identified fire paths, identifies the probable sequences of component damage or failure, and provides the initial conditions for analyzing the stability of the structural system.
- The *collapse initiation* analysis determines the most probable collapse sequence from each of the identified component failure sequences via a stability analysis of the structural system.

Simplified models for impact damage, fire dynamics, thermal-structural response, and collapse initiation analysis will be developed, validated, and used to the extent possible in the full-scale analyses to enable efficient estimation of probabilities and collapse sequences in the available time frame and budget.

3.6 Status of Steel and its Analysis:

NIST has in its possession nearly 250 pieces of World Trade Center steel. The vast majority of the pieces are of significant size and include perimeter prefabricated column-spandrel elements, rectangular box beams, wide flange sections, truss sections, and channels. NIST also has in its possession several smaller pieces, such as bolts. NIST has catalogued 235 pieces of World Trade Center steel as of March 28, 2003. This includes a database with photographic records and member markings. 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 specimens to NIST. NIST believes that this collection of steel from the WTC towers is adequate for purposes of the investigation.

The NIST analysis of recovered WTC steel includes:

- 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; and
- comparing measured steel properties with applicable material specifications.

The steel in NIST's possession includes 28 perimeter column panels for which locations have been identified in the towers, several from the impact zones; and 11 core columns for which locations have been identified in the towers, including two from the impact zones. Figure 6 shows the identified perimeter columns, and one core column, mapped onto a schematic of the north face of WTC 1 (the North Tower) with damage from aircraft impact.

Based on a correlation of information on the grades of steel used in the WTC towers and identifying marks on the recovered steel, it has been possible to locate 10 of the 14 steel strengths specified for the perimeter columns and 10 of the 12 steel strengths specified for the spandrel beams. NIST has samples of all 14 grades of steel used in the perimeter column-spandrel panels, since there is an overlap of the steel strengths used in the columns and spandrels.

NIST also has samples of core columns (wide flange and built-up box columns) of two grades of steel. Ninety-nine percent of the core columns were fabricated from these two grades of steel.

Further, NIST has samples of both strengths of steel that were specified for the floor trusses; two strengths each for the rods and the angles that comprised the bar joists.

Approximately 250 chemical analyses have been conducted using spark emission spectroscopy. The analyses indicate that the majority of the perimeter columns were made of ASTM A 441 or WEL-TEN steels. These columns were fabricated from steel obtained from Yawata Iron and Steel, now Nippon Steel.

Nippon Steel representatives have assisted NIST by providing useful information to the investigation, including the proprietary specifications for their steels. So far, tests by NIST indicate that the higher strength steels are micro-alloyed steels (similar to modern pipeline steels) or CrMo steels that would meet U.S. specifications for heat resisting steels.

NIST also has identified the fabricators of the steel floor trusses (Laclede Steel) and has met with representatives of the firm. The firm has been fully cooperative in providing information on the steels used and the design and tests of the trusses. Laclede documents show that the trusses were fabricated with ASTM A 36 and ASTM A 242 steels and that Laclede's A 36 steel was routinely made at yield strengths of 50 ksi to 55 ksi (well in excess of the 36 ksi specified minimum yield strength). The other two types of steel have minimum yield strengths of 50 ksi.

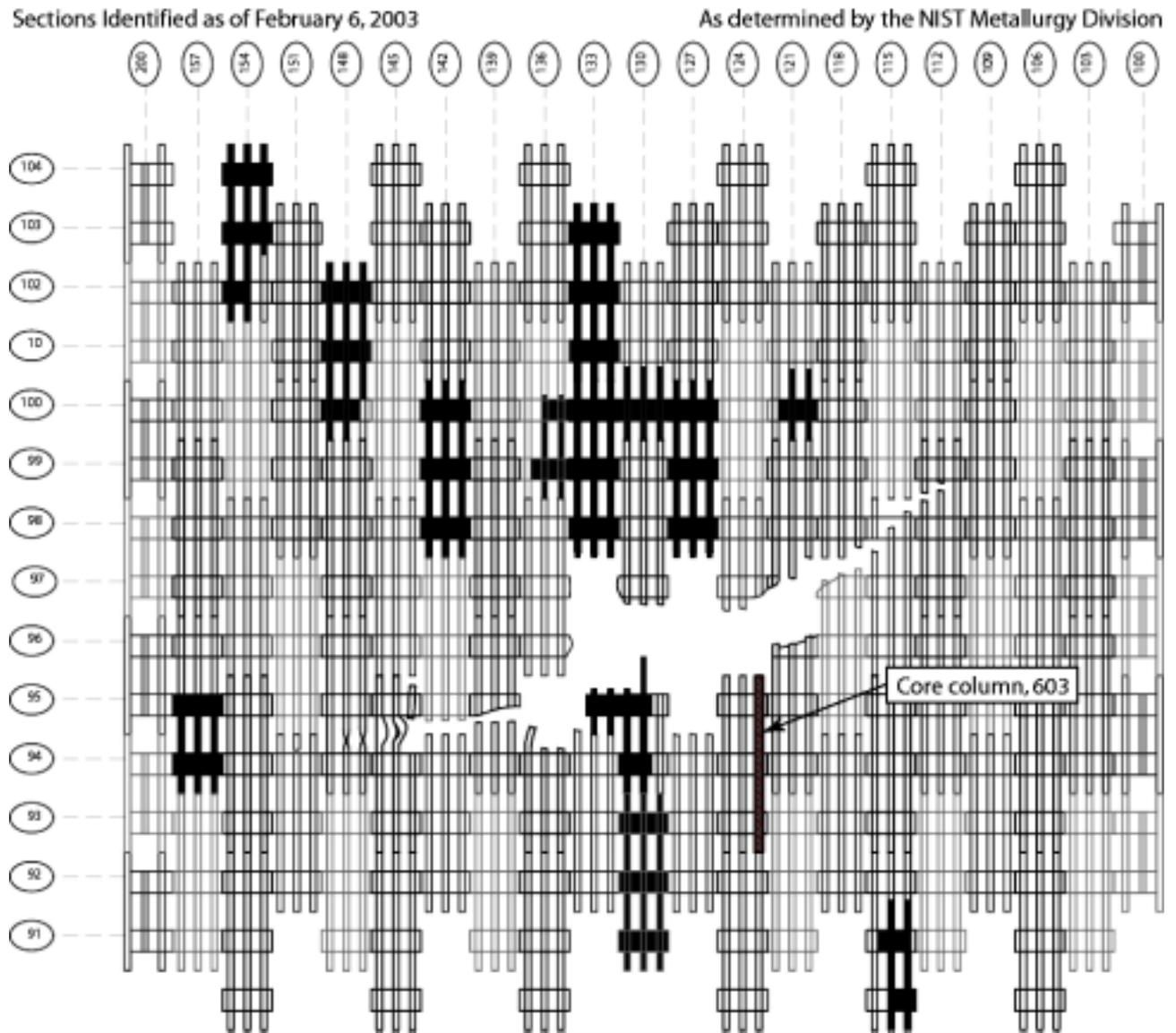


Figure 6. Schematic of north face of WTC 1 (North Tower) showing the location of (darkened) pieces of steel identified by NIST and in its possession. Note that core column 603 is located in the core but is shown here projected onto the north face.

Noteworthy results since the December 2002 progress report are summarized below. To date, the following samples have been tested to determine **room temperature mechanical properties** (these are required to compare the actual properties of the steel used with the specifications and to analyze the baseline structural performance under gravity and wind loads):

- Perimeter Columns: 82 samples from 10 different specified yield strengths in various columns, including flanges and webs.
- Truss Rods: Six truss rod samples from two different diameter truss rods have been tested.
- Truss Angles: Seven truss angle samples have been tested from 2 different gage truss angles.
- Truss Seats: Six truss seat samples from one outer truss seat have been tested.
- Welds: Four weld samples from a perimeter column web/flange fillet weld have been tested.
- All-Weld-Metal: Two “all-weld-metal” samples have been tested
- Spandrel: Five samples have been tested from one spandrel.

A comparison of measured yield strength to yield strengths specified on the steel design drawings was made on all column, spandrels, trusses, and truss seats tested to date. Yield strengths were found to satisfy the applicable specifications, and in most cases to be well in excess of specified minimum values.

The perimeter columns with specified yield strengths from 50 to 100 ksi are now fairly well characterized at room temperature, although additional tests will be conducted to measure the variability in the properties of the steels.

The yield strengths of the all-weld metal samples were 85 ksi, significantly higher strengths than the base metals to which they were attached. The base metals were flanges and webs from a perimeter column in WTC 1 (column 155, floors 101 to 104) and had average measured yield values of 65 ksi, well in excess of the specified base metal minimum yield strength of 55 ksi. Several transverse tensile tests (across a weld, and thus including parts of two plates, a weld, and the adjacent heat affected zone) were used to assess the net section strength after fabrication. The yield strength values were about 68 ksi, also well above the specified base-metal minimum yield value of 55 ksi. This is a preferred condition, where weldments do not introduce a weakening of the structure.

A test matrix has been developed for high temperature tensile tests and creep tests. Preliminary tensile tests have been conducted at temperatures between 400 °C and 750 °C to determine **high temperature mechanical properties**. The high temperature results, as expected, demonstrate that the yield and ultimate strengths decrease with increasing temperature beyond 400 °C.

To date, more than 40 tensile specimens have been tested to determine **high strain rate mechanical properties**. Targeted strain rates were 10 000, 20 000, and 30 000 percent elongation per second. The actual strain rates, yield strengths, and ultimate strengths were measured and the yield and ultimate values typically increased with increasing strain rate. Approximately 100 additional specimens are being prepared for testing. The specimens in this part of the effort are from perimeter columns, spandrels, and core columns.

In addition, the Kolsky bar apparatus, an advanced testing method, has been prepared for high strain rate compression testing of WTC materials and is awaiting calibration verification before testing proceeds. The compressive and tensile testing rates will overlap so that the data can be

compared. NIST plans to test specimens of all of the exterior column strengths and inner core column strengths in the area of impact using this device.

As part of the *forensic thermometry* effort to identify methods to measure the temperature excursions of the steel, burn tests of paint on column specimens have been completed for three different columns, all of which exhibited identical behavior upon exposure to high temperatures (Figure 7). When heated to 250 °C and cooled to room temperature, the paint exhibits a “mud crack” pattern resulting from the mismatch in thermal expansion coefficients between the metal and the coating. At this temperature there would be little or no visible discoloration or damage to the primer paint. Little change is noticed with exposure to temperatures as high as 650 °C. Thus steel that shows little visible evidence of discoloration or damage to the primer paint still could have experienced high temperature levels due to the fires.

Above 650 °C, rapid formation of an oxide scale between the paint and metal leads to delamination of the paint from the metal. The degree of delamination, and the weakness of the interface, is somewhat dependent on the time of exposure to high temperatures (longer exposure leads to slightly weaker adhesion). Above 750 °C, the scale formation is so massive that it leads to complete delamination and spalling of the paint, which blows off easily with bursts of air. At these high temperatures there would be visible discoloration and damage to the primer paint (and the steel would likely have softened significantly). However, these changes may not be distinguishable from changes due to corrosion or abrasion. Observations of the condition of the primer paint could be used, however, to detect pieces that did not exceed 250 °C, and those that exceeded 250 °C but did not exceed 750 °C.

The examination of residual stresses and metastable phases in welds have yielded two possible additional tests for detecting high temperature exposure. Measured stress profiles across weldments show that the weld stress relaxes gradually upon heating to temperatures between 300 °C and 600 °C. Using calibration techniques, it would be possible to characterize temperature exposure with an estimated 50 °C accuracy. Regarding metastable phases, irreversible phase transformations from an unidentified phase were seen at roughly 400 °C in differential scanning calorimetry studies of weld metal. If the phase can be identified as a common one for ferrous weldments, this technique could act as a “litmus” test for this temperature.

Annealing of hardened washers, used with bolts, to induce softening by removing residual stresses has not yielded clear results to date. So far, variation in hardness between washers, whether due to variations during fabrication or plastic deformation during installation, has been of a larger magnitude than any decrease in hardness due to annealing (the variation in hardness of the washers is not an indication that they did not meet standards). Similarly, microstructural analysis indicates there are very limited microstructural changes unless the steel is heated to the eutectoid temperature (≈ 725 °C).



No burn
faint cracks from drying of paint 1 mm



250 °C for an hour
mud cracks much more visible



700 °C for an hour
mud cracks partially obscured by formation of
whiteish “sandy” phase on surface
delamination easy with finger



1000 °C for an hour
massive spalling of paint, falls off
thick scale forms between paint and steel

Figure 7. Sample results from burn tests of paint on WTC column specimens, indicating little visible evidence of discoloration or damage to the primer paint until the steel experiences high temperature levels.

3.7 Photographic and Video Image Collection and Analysis:

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. Preliminary observations discussed demonstrate the importance of such visual evidence.

Many individuals contacted NIST based on news coverage of our December 2002 update. As a result a large number of important photos and videos were provided to NIST. NIST very much appreciates the public response and the reporting that made it possible.

The NIST investigation continues to lack photos of the south side of WTC 7, yet the efficiency of the modeling of the initiation and progress of the fires depends heavily on obtaining such evidence. It has been suggested that the south side of WTC 7 was struck by debris from the collapse of WTC 1, and that burning debris may have ignited the fires that led to the ultimate collapse of WTC 7. Some eyewitness accounts describe fires on many floors of WTC 7 while photos show only localized fires on other sides of the building.

The NIST investigation team also continues to seek photographic and video images that can help it better document the initial damage and subsequent fire growth in the WTC towers. NIST is especially interested in images from the south and west faces of the WTC towers, images that show the airplanes as they approach and/or enter the towers, and photographs and videos that provide close-up details of fire conditions in the three buildings. The public and media organizations can significantly assist in this public safety investigation by sharing published and unpublished high quality photos and video footage.

Those who are aware of or are in possession of such materials 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, MD 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.

NIST is assembling the collected visual material into a searchable computerized database. The collection is constantly being expanded, catalogued, and cross-referenced. The database now contains over 3 100 photographs taken by 66 professional or amateur photographers and over 3 400 video clips from publicly available news coverage, news agencies, and 25 individual videographers.

NIST has received significant visual material from the Associated Press, New York 1 News, and WNBC in New York. NIST appreciates the willingness of these news organizations to assist the investigation. In addition, NIST staff has reviewed similar materials from the New York Police Department and the Fire Department of New York and is making arrangements to have the materials of interest to the investigation transferred to NIST. NIST remains very interested in obtaining similar materials from other media organizations as well as individual professionals and amateurs, and efforts to do so are ongoing.

A key NIST focus is to determine accurate times for the images contained in the database. This effort is aided by the availability of digital photographs and videos that incorporate timestamps.

While the clocks in the various photographic devices are quite accurate, it is uncommon for them to be set exactly to the true time. It is thus necessary to adjust recorded times to place them on a common time line. Typically, time shifts are determined by visual comparison with materials for which accurate times have been determined. A variety of visual cues are used including shadows, smoke and fire patterns, and specific events such as falling objects. In some cases more imaginative approaches are required. An example is the use of a clock on Trinity Church that appears in a number of photos by different photographers.

For the vast majority of digital materials NIST is able to assign times that are accurate to within 2 seconds. Times for analog materials (e.g., photographic film and video tape) are typically more difficult to determine, but this is becoming easier as the quantity of material available for comparison increases. The availability of a searchable database has proven to be invaluable for this process. The time uncertainty is assessed and recorded for all visual items.

NIST has now begun to characterize and analyze the photographic and video evidence currently in the database. Initial analyses suggest that close-up photographs of the aircraft impact on each of the towers can be used to determine important parameters such as exactly where each aircraft struck and its orientation, as well as the in-flight deformation of the loaded wings of the aircraft as it entered the buildings.

Eyewitness accounts from September 11th refer to the movement of the towers after being struck by the airplanes. The plane strikes are expected to result in bending of the towers from their bases followed by a swaying of the towers analogous to the motion of a pendulum. This motion should damp out slowly with time. A video of the plane strike on WTC 2 provided to NIST shows oscillations with initial amplitude of many tens of inches. This movement has been accentuated to allow quantitative determination of its period and duration using image analysis. Estimates indicate a period of oscillation of 11.29 ± 0.01 seconds that was detectable for over 4 minutes in the North-South direction.

This oscillation period is consistent with measurements that are available from WTC 1, accounting for the difference in orientation of the core in the two buildings, which yielded a period of 10.9 seconds in the East-West direction (averaged over a 9 year period that ended in 1993) and 11.6 seconds in the North-South direction (averaged over a 14 year period that also ended in 1993). Further analysis is planned to provide a better estimate of the oscillation amplitude. These results provide insight into the effects of aircraft impact on the immediate structural condition of WTC 2 and to validate the aircraft impact damage analysis in Project #2.

NIST also used the video to estimate that the speed of the plane that struck WTC 2 was 560 ± 5 miles per hour. This information is required as input to analyze the aircraft impact damage to the tower. By way of comparison, the Federal Aviation Administration and the National Transportation Safety Board, using radar and video data, had estimated the speed of the plane to be 586 miles per hour, while a researcher at the Massachusetts Institute of Technology, by analyzing photographic and video images using different methods, estimated that the plane was traveling at 537 miles per hour.

Material in the visual database is being used to determine on a window-by-window basis such properties as whether windows are present or missing and whether smoke and/or fire are observed. A preliminary analysis of the four faces of WTC 1 has been assembled for two times (8:47 am and 9:00 am). Comparison of the two sets of results (Figure 8) shows that the fires grew rapidly at certain locations during this time period. A number of windows broke open between the two times, significantly increasing the amount of air available to feed the fires.

Similar detailed mappings will be developed at several specific times for both towers and WTC 7. These will be pivotal in establishing 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.

Preliminary analysis also suggests that significant structural changes were occurring in both towers prior to their collapses. For example, photos and videos of the east face of WTC 2 (Figure 9) show what appears to be a floor assembly from the 83rd floor hanging across a number of windows on the 82nd floor. Early views show the structure hanging near the upper part of the windows, but over time it sinks further and is later observed near the base of the windows.

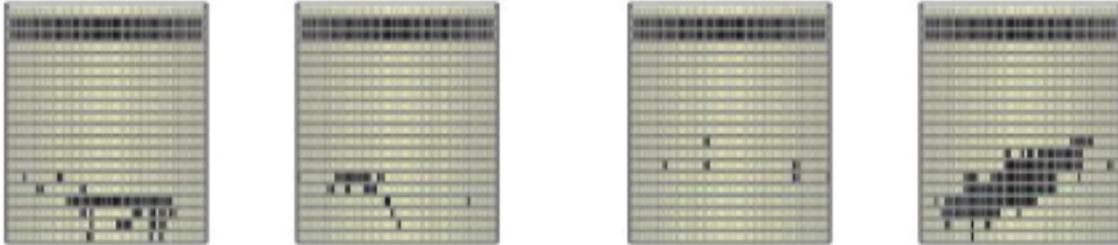
In WTC 1, several videos clearly show the sudden appearance of a line of smoke on the north face at the 92nd floor and extending over most of the width of the building. The smoke appears suddenly, approximately 9 minutes and 31 seconds before the collapse of this tower. Concurrent with this event, smoke and fire appear at more isolated locations on the 93rd, 95th and 96th floors of the north face, as well as at locations on the east and west faces.

These observations must be considered further within the context of information provided to NIST from the NYPD aviation unit, which suggests that at 10:16 fire began moving downward (about 12 minutes before the collapse), at 10:21 WTC 1 was leaning to the south (about 7 minutes before collapse), and at 10:28 the tower began coming down.

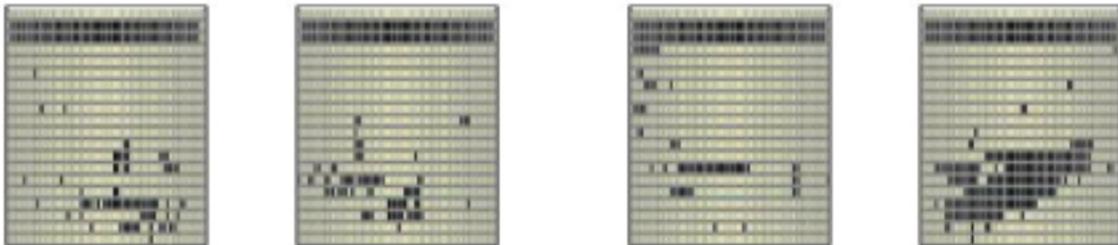
The preliminary results described here demonstrate the value and importance of the visual record of the WTC disaster for understanding the technical causes for the collapses of the towers and WTC 7. However, NIST is aware of a great deal of visual material that has not been made available to the investigation, and believes that additional material exists which has not been identified. The quality of the analyses based on visual material will be greatly enhanced if NIST is able to collect the most relevant material. Each contribution to the NIST database will improve the quality and usefulness of the final result.

Visual Data of Broken Windows on the North Tower

8:47 AM



9:00 AM



East

South

West

North

Figure 8. Visual data of broken windows on floors 87-110 of WTC 1 (North Tower) at two different times (13 minutes apart) on September 11, 2001. Data were obtained through analysis of video and photographic images and is estimated to be accurate to about 2 minutes. Floors 108 and 109 near the top were mechanical floors and had vented windows; whether these were open or not remains to be confirmed.



Photo by Allen Muarabayashi, 9:47:05 am \pm 5 s

Figure 9. East face of the WTC 2 (South Tower). Image shows what appears to be a floor assembly from the 83rd floor hanging across a number of windows on the 82nd floor.

3.8 First-Person Data on Occupant Behavior, 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, and others with operational or command authority on September 11, 2001.

The data accumulated from this effort will be used to evaluate occupant behavior and evacuation and emergency response technologies and practices for tall buildings. This includes decision-making and situation awareness, time-constrained evacuation strategies, communications, fire protection and firefighting, the role of fire wardens and fire safety directors, and issues concerning people with disabilities. 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.

NIST believes that it is possible to learn from the WTC disaster, and to improve public safety, through the collection and analysis of first-person accounts, but this is an ambitious undertaking and it will need the active participation of WTC employers and survivors in its interviews, surveys and focus groups.

NIST recently released a white paper (Appendix 6) describing a first-person data collection methodology that includes face-to-face interviews, telephone interviews, and focus group interviews. This multi-faceted approach is designed to increase confidence in the findings, enable systematic hypothesis testing and generalization, probe specific information of particular value to the investigation, and enhance memory recall and accuracy.

The data collection will be conducted by a yet-to-be-selected contractor and is expected to begin this summer as soon as the necessary pre-work is complete. The contract solicitation closed on March 28, 2003 and NIST is in the process of making the selection.

In addition, NIST is cooperating with the Centers for Disease Control and Prevention (CDC), Columbia University's Mailman School of Public Health, and the New York City Department of Health and Mental Hygiene. Each of these organizations is conducting complementary evacuation studies, and working together to enumerate the population of the WTC towers. Using information provided by the Port Authority and Silverstein Properties, NIST has developed a list of tenant companies and identified their locations within each of the WTC buildings for use in enumerating the population. In partnership with NIST and the other agencies, Columbia University organized a public meeting in New York City on April 8, 2003 to present study plans to the public and to elicit the active participation of WTC employers and occupants.

Before NIST can begin actual data collection, instruments and protocols must be developed, contractor staff must be trained, approval of survey instruments must be granted by the Office of Management and Budget for compliance with the Paperwork Reduction Act. In addition, NIST and the appropriate Institutional Review Board (IRB) must approve the plans to assure compliance with federal requirements for protecting human subjects. NIST will use established procedures to review all survey and interview questions and data collection methods, along with procedures for maintaining privacy and confidentiality of respondents, before proceeding with these data collection efforts.

The white paper identifies specific populations and the size of samples to be included in the data collection effort. The exact numbers and populations may be modified to better suit the

investigation as additional details of the methodology are finalized by NIST with the panel of experts and the survey contractor.

NIST plans to have the contractor perform up to 750 face-to-face interviews. These will include occupants of the two WTC towers and WTC 7, especially those near the floors of impact and in elevators or lobbies; people with disabilities who were inside the WTC buildings; first responders from FDNY, NYPD, the Port Authority Police Department (PAPD), and the firm that provided security to the WTC complex; and people with safety responsibilities such as floor wardens and fire safety directors. Families of victims who communicated with occupants inside the WTC towers before they collapsed will be interviewed to obtain information about the evacuation of the victims and determine the environment above the floors of impact.

The interview protocol is planned to include three steps:

- an uninterrupted open-ended narrative account where the participant recounts his or her “story” chronologically to the interviewer;
- a structured narrative account where the participant reviews the story in cooperation with the interviewer to elicit the logical sequence of actions by identifying cues that initiate an action, the action itself, and the reason for taking the action; and
- follow-up open-ended probes for specific information of value to the investigation.

NIST plans to have the contractor collect data via telephone interviews of up to 800 occupants and persons with responsibility within the WTC towers using a standardized set of questions. Stratification requires two stages. Stage one is an area sample of floors. The first stratification criterion is Tower 1 or Tower 2. The second stratification criterion is height. WTC 1 and 2 will be segmented into three zones according to the location of the mechanical floors. These zones will approximately represent the top (floors 77 – 91 in Tower 1 and floors 77 – 107 and 110 in Tower 2), middle (floors 43 – 74 in Towers 1 and 2), and lower (floors 9 – 40 in Towers 1 and 2) thirds. The third stratification criterion is tenant size. The tenant size criterion represents a floor as one of two levels: large tenant floor (a single tenant occupies greater than 40% of the usable square footage of a floor) or small tenant floor (all other tenant-occupied floors). The second stage is a random sample without replacement of occupants from the floors in the first stage.

Focus groups will elicit accurate group representations of specific events or themes (e.g., the experience of unique types of people in unique places in the buildings). Occupant focus groups in approximately five specialized categories will be conducted by the contractor with between five to 10 participants per group. Examples of such specialized groups include:

- people with special responsibilities (floor wardens, fire safety directors, etc);
- people on a specific floor such as the 78th floor of WTC 2 and the 91st floor of WTC 1 – just below impact;
- people in the lobbies of WTC 1 and WTC 2; and
- people who escaped from above the floors of impact in the WTC towers.

First responders will constitute a second set of focus groups, and will include FDNY, NYPD, and PAPD. Ten first responder focus groups will be conducted with five participants per group, the typical size of an operating unit such as a fire department company.

3.9 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. Over two dozen NIST experts will be involved over the course of the investigation.

In addition, NIST is augmenting 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 being 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.

The bulk of the planned contract solicitations have already appeared or will appear shortly. Several of those solicitations are now closed. A status report of the eleven solicitations that have been posted is provided in Appendix 7. Summaries of the four contract awards that have been made are provided in Appendix 8. Details of the solicitations may be found at the NIST WTC contracts web site <http://wtc.nist.gov/solicitations>. In addition, an administrative services contract was awarded to Science Applications International Corporation (SAIC) in August 2002 to support the two-year investigation.

In most cases, NIST is relying on full and open competition to fulfill these requirements. Proposal solicitations are posted on the Federal Business Opportunities (FedBizOpps) web site <http://www.fedbizopps.gov>. NIST posts direct links to solicitations at the WTC contracts web site <http://wtc.nist.gov/solicitations>. This site is updated with new solicitations and email notifications are sent, usually within 24 hours of a FedBizOpps posting. Persons interested in receiving email notification of new solicitations, modifications, or awards may register for the service on this page. More than 230 individuals have registered to receive email notifications.

The solicitations are based on statements of work prepared by NIST as a result of a careful and deliberate process to identify and define in detail the specific technical areas in which external expertise is needed to carry out each investigation project. The final investigation plan released August 21, 2002 with descriptions of the eight component projects is available at the above referenced NIST WTC web site.

Competitive solicitations are listed on FedBizOpps for a minimum period of 15 days. More complex procurements may be kept open longer to give potential offerors sufficient time to prepare their proposals. The solicitation contains all necessary information for an offeror to prepare a proposal, including the statement of work, the criteria against which the proposal will be evaluated, and applicable terms and conditions. Offerors may direct questions to the Contract Specialist.

All proposals received in response to a WTC Investigation competitive solicitation are evaluated on a best value basis. When proposals are received by NIST, the technical, business, and cost proposal sections are separated by the Contract Specialist. The technical proposal is distributed to a team of at least three independent evaluators who have been approved by the Lead Investigator in consultation with the responsible investigation Project Leader. Each reviewer conducts an independent review of each proposal received and evaluates it against the stated criteria.

When independent reviews are complete, a consensus review is conducted. This meeting is conducted by the Contract Specialist and includes the independent reviewers and a consensus reviewer (also approved by the Lead Investigator in consultation with the responsible investigation Project Leader). The independent reviewers share their scores for each of the proposals and reach consensus on any elements of the evaluation where individual scores vary. Based upon this consensus review, proposals are ranked based solely on their technical merit.

Following the technical review, proposals are evaluated for cost reasonableness. This evaluation is conducted by the technical reviewers and is to determine if the proposed cost is reasonable, realistic, and complete relative to the statement of work. The government determines best value based on technical and cost factors, and recommends that proposal for award. The Lead Investigator is briefed on the outcome of the review process.

The Contracting Officer makes the selection decision with review of the Office of the NIST Counsel and, where required, by the Commerce Department's Contract Law Division. Unsuccessful offerors are notified in writing that they were not selected. They may submit a written request within 3 days for a debriefing on their proposal.

All offerors responding to WTC Investigation solicitations are required to identify potential conflicts of interest and provide mitigation plans as a part of their business proposal. This information is reviewed by the Office of the NIST Counsel. The Office of the NIST Counsel will, in consultation with other parties as appropriate, determine if a conflict of interest exists and approve appropriate actions to take in order to mitigate the conflict and assure the integrity of the work to be performed by the contractor.

In a limited number of cases, NIST may choose to issue a contract on a sole source basis consistent with all federal procurement laws and acquisition regulations. For the WTC Investigation, NIST may issue a sole source contract where there is only one uniquely qualified source that can meet the requirements of the statement of work or when there is an urgent and compelling need to issue such an award.

NIST posts its intent to award sole source contracts on FedBizOpps for 15 days before making the award. Announcements of NIST's intent to award a sole source contract are posted on the NIST WTC web site. During this period, any organization that feels it is qualified to meet the requirement may submit a capability statement for review by NIST. Of its contract actions to date on the investigation, NIST has issued two sole source contracts as listed in Appendix 8.

NIST has identified the need within some of the investigation projects for outside experts to perform specific tasks that assist NIST in the formulation of its technical approach, conduct independent third-party reviews, assist in the analysis of data and modeling results, and provide other such technical assistance. NIST has used full and open competition in two such cases to acquire such expertise. 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 investigation. The choice between contracting versus direct hire is made on a case by case basis.

Chapter 4. UPDATE ON WTC R&D PROGRAM

4.1 Update on WTC Research and Development Program:

The WTC research and development (R&D) program is designed to (i) facilitate the implementation of recommendations resulting from the WTC investigation, and (ii) provide a technical foundation that supports improvements to building and fire codes, standards, and practices that reduce the impact of generic extreme threats to the safety of buildings, their occupants and emergency responders. The program involves experimentation, analysis, testing, computational verification, experimental 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 U.S.

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 thirteen R&D projects underway in support of these four outcomes (private sector and academic experts are contributing to several of these projects):

<u>Projects</u>	<u>Outcomes</u>			
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
A. Fire Safety Design and Retrofit of Structures	X	X		
B. Prevention of Progressive Collapse	X			
C. Fire Protective Coatings for Structural Steel		X		
D. Method of Fire Resistance Determination		X		
E. Fire Simulation Tools		X	X	
F. Emergency Use of Elevators			X	
G. Occupant Behavior and Egress			X	
H. Equipment Standards for First Responders			X	X
I. Technologies for Building Operations Air Cleaners			X	X Photocatalytic
K. Standard Building Information Models				X
L. Cost-effective Risk Management Tools				X
M. High Temperature Steels	X	X		

Working with the engineering profession and industry representatives, NIST is continuing to develop and refine a national plan to understand and mitigate structural progressive collapse that will lead to a draft best practices guide by the end of this year. A similar effort is underway to provide guidance on best practices for the fire safety design of steel and concrete structures. Both of these studies are in support of the desired outcome of increased structural integrity.

A report by Hughes Associates, Inc.,¹ analyzing the needs and existing capabilities for full-scale fire resistance testing was released in December. It reviews the high rise building failures throughout the world that have been initiated by fire, and the current capabilities of fire testing laboratories. The authors conclude that to provide reliable structural fire protection for buildings,

¹ Beitel, J., and Iwankiw, N., "Analysis of Needs and Existing Capabilities for Full-scale Fire Resistance Testing," NIST GCR 02-843, December 2002.

new specialized research facilities are required for real-scale structural elements and their connections that will lead to a capability to predict the performance of building frames under fire and mechanical loads in a more quantitative fashion. Such facilities would lead to the desired outcome of enhanced fire resistance of structures. These would also support research activities that are underway to provide the technical basis for accurate measurement methodologies for inclusion of the fire resistance properties of walls, floors, and ceilings in building fire simulations and performance-based design.

The technical and procedural means to supplement occupant egress by stairs, for evacuation of occupants with disabilities, and for first responder access is the objective of project F. A contract has been issued to John H. Klote Inc., an expert in elevators and smoke movement within buildings, to review the current state of emergency use of elevators. Reliable predictions of the time for egress from a high rise building are important to the proper design of stairways and elevators. A grant has been made to Ove Arup & Partners Massachusetts, Inc., in which they will be studying the uncertainty in existing models and the impact of that on predicted outcomes.

The objectives of the five projects in direct support of science-based building and equipment standards and operation guidelines can be summarized as follows:

- To develop standard building information models which facilitate the simulation of building system behavior during adverse events.
- To develop analysis tools and guidance for the assessment and subsequent reductions in the vulnerability of buildings to chemical/biological/radiological attacks.
- To obtain a comprehensive understanding of the fundamental properties and mechanisms controlling the effectiveness of photocatalytic air cleaners, as well as the impacts of installed systems, in eliminating harmful chemical and biological agents.
- To establish facilities and science-based exposures for measurement of firefighter equipment performance attributes essential to support informed fire service procurement decisions.
- To develop a user-friendly tool for building owners and managers to aid in the selection of cost-effective strategies for the management of terrorist and environmental risks.

A full description of all the projects mentioned here, and progress as it is made, is available at the following web site: http://www.bfrl.nist.gov/goals_program/HS_goal.htm. Achieving the desired outcomes of the WTC R&D program will require a continuous investment and sustained effort. The rate at which the desired outcomes are achieved is a function of the available funds, the technical obstacles that are encountered, and the success of the Dissemination and Technical Assistance Program (DTAP).

Chapter 5. UPDATE ON WTC DTAP PROGRAM

5.1 Update on WTC Dissemination and Technical Assistance Program (DTAP):

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.

Noteworthy efforts since the December 2002 progress report include an effort to develop and deliver a standard information model and critical building information database through the National Alliance for Building Regulatory Reform in the Digital Age, a public-private partnership to enhance public safety and homeland security in buildings. The work of the alliance focuses on the use of information technology and the development and use by state and local jurisdictions of products, guidelines, model processes and procedures that enable jurisdictions to better respond to natural and manmade disasters and reduce the regulatory cost of construction by up to 60 percent.

From July 2001, through the end of June 2002, the National Alliance completed the first of three phases of its operations. During that period, the Alliance established its Steering Committee and Technology and Planning and Coordinating Task Forces. They, in turn, established their structure, adopted mission statements, action timetables, and developed their first products and guidelines. These products then were made available to the construction and information technology communities and to state and local governments via the Alliance's website.

Among the products available on the website are: an initial listing of existing software currently being used by state and local governments in their building regulatory processes; model streamlining processes using information technology; an outline of steps which need to be taken to review and restructure the architecture of the building regulatory process; and in the wake of the World Trade Center disaster, a detailed outline of the components of a secure, nationwide, state-maintained database for first responders of as-built designs, evacuation plans, and other key contact information related to building safety.

Beginning in the first quarter of calendar year 2003, NIST supported the Alliance to begin completing Phase II of their Action Plan; developing model streamlining processes and procedures, drafting new architecture for building regulatory systems, and building and testing a prototype of a proposed first responder database. Specifically the Alliance:

- Expanded the existing website database inventory of hardware and software currently being used in state and local jurisdictions.
- In conjunction with the National Association of State Chief Information Officers (NASCIO), developed criteria for jurisdictions to use when determining which set of hardware and software to acquire for use in their building regulatory system.
- Assembled a team to finalize the design of the proposed prototype of a secure, nationwide, state-maintained database of as-built designs, evacuation plans, and other key building contact information for first responders. This involved expanded discussions with the Department of Homeland Security, Federal Emergency Management Agency, State Homeland Security Directors, NASCIO, and national organizations representing the first

responder community. The secure database will be interoperable, will be linked and coordinated with other first responder databases (e.g., medical), and will be usable by multiple levels of first responders (paid departments and volunteers).

As previously reported, NIST was a sponsor of a November 13-15, 2002, Capital Projects Technology Roadmap Workshop organized by the non-profit industry-led FIATECH Consortium. A key focus of this workshop was to update a recently developed industry roadmap to assure coverage of homeland security issues and to develop specific project plans for implementing R&D to achieve the goals defined in the roadmap. The workshop drew representatives from a range of construction interests, including industry, research, academia, and regulators. The roadmap is now publicly available at <http://www.fiatech.org>.

In addition, NIST has funded an effort to identify best practices related to the security of capital projects for critical industries in the U.S. infrastructure and to provide a basis for assessing the impacts of these practices on cost, schedule, and safety. The study is led by the Construction Industry Institute (CII), a non-profit research organization representing the nation's top 100 facility owners and contractors.

The study will focus on chemical manufacturing, oil production and refining, natural gas processing and distribution, power generation and distribution, water treatment, and possibly other critical industries needed to support the nation's infrastructure. Information collected as part of a series of regional workshops and field site visits will be used to:

- establish a basis for identifying best practices related to the security of infrastructure capital facilities; and
- provide the basis for assessing the impacts of these practices on key project outcomes of cost, schedule, and safety.

The study, which began last fall, is making excellent progress. The steering team and practice development team are working an aggressive schedule to produce a "security rating index." This index will assess how well security has been addressed during planning and delivery of a project. The index will also permit security issues impacts on project outcomes to be benchmarked. A report on the findings is expected to be presented at the CII Annual Conference in July 2003.

Public Law 107–231
107th Congress

An Act

To provide for the establishment of investigative teams to assess building performance and emergency response and evacuation procedures in the wake of any building failure that has resulted in substantial loss of life or that posed significant potential of substantial loss of life.

Oct. 1, 2002
[H.R. 4687]

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE.

This Act may be cited as the “National Construction Safety Team Act”.

National
Construction
Safety Team Act.
15 USC 7301
note.

SEC. 2. NATIONAL CONSTRUCTION SAFETY TEAMS.

15 USC 7301.

(a) **ESTABLISHMENT.**—The Director of the National Institute of Standards and Technology (in this Act referred to as the “Director”) is authorized to establish National Construction Safety Teams (in this Act referred to as a “Team”) for deployment after events causing the failure of a building or buildings that has resulted in substantial loss of life or that posed significant potential for substantial loss of life. To the maximum extent practicable, the Director shall establish and deploy a Team within 48 hours after such an event. The Director shall promptly publish in the Federal Register notice of the establishment of each Team.

Federal Register,
publication.

(b) **PURPOSE OF INVESTIGATION; DUTIES.**—

(1) **PURPOSE.**—The purpose of investigations by Teams is to improve the safety and structural integrity of buildings in the United States.

(2) **DUTIES.**—A Team shall—

(A) establish the likely technical cause or causes of the building failure;

(B) evaluate the technical aspects of evacuation and emergency response procedures;

(C) recommend, as necessary, specific improvements to building standards, codes, and practices based on the findings made pursuant to subparagraphs (A) and (B); and

(D) recommend any research and other appropriate actions needed to improve the structural safety of buildings, and improve evacuation and emergency response procedures, based on the findings of the investigation.

(c) **PROCEDURES.**—

(1) **DEVELOPMENT.**—Not later than 3 months after the date of the enactment of this Act, the Director, in consultation with the United States Fire Administration and other appropriate Federal agencies, shall develop procedures for the establishment and deployment of Teams. The Director shall

Deadline.

update such procedures as appropriate. Such procedures shall include provisions—

(A) regarding conflicts of interest related to service on the Team;

(B) defining the circumstances under which the Director will establish and deploy a Team;

(C) prescribing the appropriate size of Teams;

(D) guiding the disclosure of information under section 8;

(E) guiding the conduct of investigations under this Act, including procedures for providing written notice of inspection authority under section 4(a) and for ensuring compliance with any other applicable law;

(F) identifying and prescribing appropriate conditions for the provision by the Director of additional resources and services Teams may need;

(G) to ensure that investigations under this Act do not impede and are coordinated with any search and rescue efforts being undertaken at the site of the building failure;

(H) for regular briefings of the public on the status of the investigative proceedings and findings;

(I) guiding the Teams in moving and preserving evidence as described in section 4 (a)(4), (b)(2), and (d)(4);

(J) providing for coordination with Federal, State, and local entities that may sponsor research or investigations of building failures, including research conducted under the Earthquake Hazards Reduction Act of 1977; and

(K) regarding such other issues as the Director considers appropriate.

Federal Register, publication.

(2) PUBLICATION.—The Director shall publish promptly in the Federal Register final procedures, and subsequent updates thereof, developed under paragraph (1).

15 USC 7302.

SEC. 3. COMPOSITION OF TEAMS.

Each Team shall be composed of individuals selected by the Director and led by an individual designated by the Director. Team members shall include at least 1 employee of the National Institute of Standards and Technology and shall include other experts who are not employees of the National Institute of Standards and Technology, who may include private sector experts, university experts, representatives of professional organizations with appropriate expertise, and appropriate Federal, State, or local officials. Team members who are not Federal employees shall be considered Federal Government contractors.

15 USC 7303.

SEC. 4. AUTHORITIES.

(a) ENTRY AND INSPECTION.—In investigating a building failure under this Act, members of a Team, and any other person authorized by the Director to support a Team, on display of appropriate credentials provided by the Director and written notice of inspection authority, may—

(1) enter property where a building failure being investigated has occurred, or where building components, materials, and artifacts with respect to the building failure are located, and take action necessary, appropriate, and reasonable in light of the nature of the property to be inspected to carry out the duties of the Team under section 2(b)(2) (A) and (B);

(2) during reasonable hours, inspect any record (including any design, construction, or maintenance record), process, or facility related to the investigation;

(3) inspect and test any building components, materials, and artifacts related to the building failure; and

(4) move such records, components, materials, and artifacts as provided by the procedures developed under section 2(c)(1).

(b) AVOIDING UNNECESSARY INTERFERENCE AND PRESERVING EVIDENCE.—An inspection, test, or other action taken by a Team under this section shall be conducted in a way that—

(1) does not interfere unnecessarily with services provided by the owner or operator of the building components, materials, or artifacts, property, records, process, or facility; and

(2) to the maximum extent feasible, preserves evidence related to the building failure, consistent with the ongoing needs of the investigation.

(c) COORDINATION.—

(1) WITH SEARCH AND RESCUE EFFORTS.—A Team shall not impede, and shall coordinate its investigation with, any search and rescue efforts being undertaken at the site of the building failure.

(2) WITH OTHER RESEARCH.—A Team shall coordinate its investigation, to the extent practicable, with qualified researchers who are conducting engineering or scientific (including social science) research relating to the building failure.

(3) MEMORANDA OF UNDERSTANDING.—The National Institute of Standards and Technology shall enter into a memorandum of understanding with each Federal agency that may conduct or sponsor a related investigation, providing for coordination of investigations.

(4) WITH STATE AND LOCAL AUTHORITIES.—A Team shall cooperate with State and local authorities carrying out any activities related to a Team's investigation.

(d) INTERAGENCY PRIORITIES.—

(1) IN GENERAL.—Except as provided in paragraph (2) or (3), a Team investigation shall have priority over any other investigation of any other Federal agency.

(2) NATIONAL TRANSPORTATION SAFETY BOARD.—If the National Transportation Safety Board is conducting an investigation related to an investigation of a Team, the National Transportation Safety Board investigation shall have priority over the Team investigation. Such priority shall not otherwise affect the authority of the Team to continue its investigation under this Act.

(3) CRIMINAL ACTS.—If the Attorney General, in consultation with the Director, determines, and notifies the Director, that circumstances reasonably indicate that the building failure being investigated by a Team may have been caused by a criminal act, the Team shall relinquish investigative priority to the appropriate law enforcement agency. The relinquishment of investigative priority by the Team shall not otherwise affect the authority of the Team to continue its investigation under this Act.

(4) PRESERVATION OF EVIDENCE.—If a Federal law enforcement agency suspects and notifies the Director that a building failure being investigated by a Team under this Act may have

been caused by a criminal act, the Team, in consultation with the Federal law enforcement agency, shall take necessary actions to ensure that evidence of the criminal act is preserved.

15 USC 7304.

SEC. 5. BRIEFINGS, HEARINGS, WITNESSES, AND SUBPOENAS.

(a) **GENERAL AUTHORITY.**—The Director or his designee, on behalf of a Team, may conduct hearings, administer oaths, and require, by subpoena (pursuant to subsection (e)) and otherwise, necessary witnesses and evidence as necessary to carry out this Act.

(b) **BRIEFINGS.**—The Director or his designee (who may be the leader or a member of a Team), on behalf of a Team, shall hold regular public briefings on the status of investigative proceedings and findings, including a final briefing after the report required by section 8 is issued.

(c) **PUBLIC HEARINGS.**—During the course of an investigation by a Team, the National Institute of Standards and Technology may, if the Director considers it to be in the public interest, hold a public hearing for the purposes of—

(1) gathering testimony from witnesses; and

(2) informing the public on the progress of the investigation.

(d) **PRODUCTION OF WITNESSES.**—A witness or evidence in an investigation under this Act may be summoned or required to be produced from any place in the United States. A witness summoned under this subsection is entitled to the same fee and mileage the witness would have been paid in a court of the United States.

(e) **ISSUANCE OF SUBPOENAS.**—A subpoena shall be issued only under the signature of the Director but may be served by any person designated by the Director.

(f) **FAILURE TO OBEY SUBPOENA.**—If a person disobeys a subpoena issued by the Director under this Act, the Attorney General, acting on behalf of the Director, may bring a civil action in a district court of the United States to enforce the subpoena. An action under this subsection may be brought in the judicial district in which the person against whom the action is brought resides, is found, or does business. The court may punish a failure to obey an order of the court to comply with the subpoena as a contempt of court.

15 USC 7305.

SEC. 6. ADDITIONAL POWERS.

In order to support Teams in carrying out this Act, the Director may—

(1) procure the temporary or intermittent services of experts or consultants under section 3109 of title 5, United States Code;

(2) request the use, when appropriate, of available services, equipment, personnel, and facilities of a department, agency, or instrumentality of the United States Government on a reimbursable or other basis;

(3) confer with employees and request the use of services, records, and facilities of State and local governmental authorities;

(4) accept voluntary and uncompensated services;

(5) accept and use gifts of money and other property, to the extent provided in advance in appropriations Acts;

(6) make contracts with nonprofit entities to carry out studies related to purpose, functions, and authorities of the Teams; and

(7) provide nongovernmental members of the Team reasonable compensation for time spent carrying out activities under this Act.

SEC. 7. DISCLOSURE OF INFORMATION.

15 USC 7306.

(a) **GENERAL RULE.**—Except as otherwise provided in this section, a copy of a record, information, or investigation submitted or received by a Team shall be made available to the public on request and at reasonable cost.

Records.

(b) **EXCEPTIONS.**—Subsection (a) does not require the release of—

(1) information described by section 552(b) of title 5, United States Code, or protected from disclosure by any other law of the United States; or

(2) information described in subsection (a) by the National Institute of Standards and Technology or by a Team until the report required by section 8 is issued.

(c) **PROTECTION OF VOLUNTARY SUBMISSION OF INFORMATION.**—Notwithstanding any other provision of law, a Team, the National Institute of Standards and Technology, and any agency receiving information from a Team or the National Institute of Standards and Technology, shall not disclose voluntarily provided safety-related information if that information is not directly related to the building failure being investigated and the Director finds that the disclosure of the information would inhibit the voluntary provision of that type of information.

(d) **PUBLIC SAFETY INFORMATION.**—A Team and the National Institute of Standards and Technology shall not publicly release any information it receives in the course of an investigation under this Act if the Director finds that the disclosure of that information might jeopardize public safety.

SEC. 8. NATIONAL CONSTRUCTION SAFETY TEAM REPORT.

15 USC 7307.

Not later than 90 days after completing an investigation, a Team shall issue a public report which includes—

Deadline.

(1) an analysis of the likely technical cause or causes of the building failure investigated;

(2) any technical recommendations for changes to or the establishment of evacuation and emergency response procedures;

(3) any recommended specific improvements to building standards, codes, and practices; and

(4) recommendations for research and other appropriate actions needed to help prevent future building failures.

SEC. 9. NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY ACTIONS.

15 USC 7308.

After the issuance of a public report under section 8, the National Institute of Standards and Technology shall comprehensively review the report and, working with the United States Fire Administration and other appropriate Federal and non-Federal agencies and organizations—

(1) conduct, or enable or encourage the conducting of, appropriate research recommended by the Team; and

(2) promote (consistent with existing procedures for the establishment of building standards, codes, and practices) the

appropriate adoption by the Federal Government, and encourage the appropriate adoption by other agencies and organizations, of the recommendations of the Team with respect to—

- (A) technical aspects of evacuation and emergency response procedures;
- (B) specific improvements to building standards, codes, and practices; and
- (C) other actions needed to help prevent future building failures.

15 USC 7309. **SEC. 10. NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY ANNUAL REPORT.**

Deadline. Not later than February 15 of each year, the Director shall transmit to the Committee on Science of the House of Representatives and to the Committee on Commerce, Science, and Transportation of the Senate a report that includes—

- (1) a summary of the investigations conducted by Teams during the prior fiscal year;
- (2) a summary of recommendations made by the Teams in reports issued under section 8 during the prior fiscal year and a description of the extent to which those recommendations have been implemented; and
- (3) a description of the actions taken to improve building safety and structural integrity by the National Institute of Standards and Technology during the prior fiscal year in response to reports issued under section 8.

15 USC 7310. **SEC. 11. ADVISORY COMMITTEE.**

(a) ESTABLISHMENT AND FUNCTIONS.—The Director, in consultation with the United States Fire Administration and other appropriate Federal agencies, shall establish an advisory committee to advise the Director on carrying out this Act and to review the procedures developed under section 2(c)(1) and the reports issued under section 8.

Deadline. (b) ANNUAL REPORT.—On January 1 of each year, the advisory committee shall transmit to the Committee on Science of the House of Representatives and to the Committee on Commerce, Science, and Transportation of the Senate a report that includes—

- (1) an evaluation of Team activities, along with recommendations to improve the operation and effectiveness of Teams; and
- (2) an assessment of the implementation of the recommendations of Teams and of the advisory committee.

(c) DURATION OF ADVISORY COMMITTEE.—Section 14 of the Federal Advisory Committee Act shall not apply to the advisory committee established under this section.

15 USC 7311. **SEC. 12. ADDITIONAL APPLICABILITY.**

The authorities and restrictions applicable under this Act to the Director and to Teams shall apply to the activities of the National Institute of Standards and Technology in response to the attacks of September 11, 2001.

SEC. 13. AMENDMENT.

Section 7 of the National Bureau of Standards Authorization Act for Fiscal Year 1986 (15 U.S.C. 281a) is amended by inserting “, or from an investigation under the National Construction Safety Team Act,” after “from such investigation”.

SEC. 14. CONSTRUCTION.

15 USC 7312.

Nothing in this Act shall be construed to confer any authority on the National Institute of Standards and Technology to require the adoption of building standards, codes, or practices.

SEC. 15. AUTHORIZATION OF APPROPRIATIONS.

15 USC 7313.

The National Institute of Standards and Technology is authorized to use funds otherwise authorized by law to carry out this Act.

Approved October 1, 2002.

LEGISLATIVE HISTORY—H.R. 4687:

HOUSE REPORTS: No. 107-530 (Comm. on Science).

CONGRESSIONAL RECORD, Vol. 148 (2002):

July 12, considered and passed House.

Sept. 9, considered and passed Senate, amended.

Sept. 17, House concurred in Senate amendment.



Appendix 2

U.S. DEPARTMENT OF COMMERCE CHARTER OF THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY NATIONAL CONSTRUCTION SAFETY TEAM ADVISORY COMMITTEE

ESTABLISHMENT:

In accordance with the requirements of Section 11 of the National Construction Safety Team Act (P. L. 107-231), hereinafter referred to as the Act, the Secretary of Commerce hereby establishes the National Construction Safety Team Advisory Committee, hereinafter referred to as the Committee, pursuant to the Federal Advisory Committee Act, 5 USC App. 2.

OBJECTIVES AND DUTIES:

The Committee will act in the public interest to:

1. Advise the Director of the National Institute of Standards and Technology, hereinafter referred to as the NIST, on carrying out the Act by:
 - a. Providing advice on the functions of National Construction Safety Teams, hereinafter referred to as Teams, as described in section 2(b)(2) of the Act.
 - b. Providing advice on the composition of Teams under section 3 of the Act.
 - c. Providing advice on the exercise of authorities enumerated in sections 4 and 5 of the Act.
 - d. Providing such other advice as necessary to enable the Director to carry out the Act.
2. Review and provide advice on the procedures developed under section 2(c)(1) of the Act.
3. Review and provide advice on the reports issued under section 8 of the Act.
4. Function solely as an advisory body, in accordance with the provisions of the Federal Advisory Committee Act.

MEMBERS AND CHAIRPERSON:

1. The Director of NIST shall appoint the members of the Committee, and they will be selected on a clear, standardized basis, in accordance with applicable Department of Commerce guidance. Members shall be selected on the basis of established records of distinguished service in their professional community and their knowledge of issues affecting the National Construction Safety Teams. Members shall serve as Special Government Employees. Members serve at the discretion of the NIST Director.
2. Members shall reflect the wide diversity of technical disciplines and competencies involved in the National Construction Safety Teams investigations. Members will be drawn from industry and other communities having an interest in the National Construction Safety Teams investigations, such as, but not limited to, universities, state and local government bodies, non-profit research institutions, and other Federal agencies and laboratories.

3. The Committee shall consist of not fewer than 5 nor more than 10 members. The term of office of each member of the Committee shall be three years, except that vacancy appointments shall be for the remainder of the unexpired term of the vacancy and that the initial members shall have staggered terms such that the committee will have approximately 1/3 new or reappointed members each year. Members who are not able to fulfill the duties and responsibilities of the Committee will have their membership terminated.
4. Any person who has completed two consecutive full terms of service on the Committee shall be ineligible for appointment for a third term during the one year period following the expiration of the second term.
5. The Director of NIST shall appoint the Chair from among the members of the Committee. The Chair's tenure shall be at the discretion of the Director of NIST.

ADMINISTRATIVE PROVISIONS:

1. The Committee shall report to the Director of NIST.
2. The Building and Fire Research Laboratory (BFRL) within NIST will provide staff support for the Committee.
3. The Committee shall meet at least once per year at the call of the Chair. Additional meetings may be called whenever one-third or more of the members so request it in writing or whenever the Chair or the NIST Director requests a meeting.
4. Members of the Committee shall not be compensated for their services, but will, upon request, be allowed travel and per diem expenses in accordance with 5 U.S.C. 5701 et seq., while attending meetings of the Committee or subcommittees thereof, or while otherwise performing duties at the request of the Chair, while away from their homes or regular places of business.
5. The Committee shall provide an annual report through the Director of BFRL and the Director of NIST, to the Secretary of Commerce for submission to the Committee on Science of the House of Representatives and to the Committee on Commerce, Science, and Transportation of the Senate, to be due at a date to be agreed upon by the Committee and the Director of NIST. Such report will provide an evaluation of National Construction Safety Team activities, along with recommendations to improve the operation and effectiveness of National Construction Safety Teams; and an assessment of the implementation of the recommendations of the National Construction Safety Teams and of the Committee. In addition, the Committee may provide reports at strategic stages of an investigation, at its discretion or at the request of the Director of NIST, through the Director of the BFRL and the Director of NIST, to the Secretary of Commerce, to be due on dates to be agreed upon by the Committee and the Director of NIST.
6. The Committee may establish subcommittees subject to the provisions of the Federal Advisory Committee Act and the Department of Commerce *Committee Management Handbook*. Subcommittee members shall be selected from the parent committee.
7. The annual cost of operating the Committee is estimated at \$ 250,000, which includes 0.5 work years of staff support.

8. The Committee shall not act in the absence of a quorum, which shall consist of a simple majority of the members of the Committee not having a conflict of interest in the matter being considered by the Committee, except that, if the number of members on the Committee is even, half will suffice.
9. NIST will report to the Committee actions taken in response to recommendations by the Committee.

DURATION:

While the duration of the Committee is continuing, the Charter shall be renewed every two years from the date of filing.


11-05-02

Chief Financial Officer
and Assistant Secretary for Administration

Biographies of NCST Advisory Committee Members

John M. Barsom

President, Barsom Consulting, Ltd, Pittsburgh, PA.

Term Expires: March 31, 2005

From 1967 to 1998, Barsom worked at U.S. Steel Research Laboratory in Monroeville, Pa., where he was named a Research Fellow, the company's highest technical position, and served as director of materials technology. He is a specialist in fracture mechanics, failure analysis of structures and equipment, accident reconstruction, integrity and life extension of structures and equipment, properties and behavior of steels and welds, and behavior of fabricated components under various loading conditions. Barsom has degrees in physics, mathematics, and mechanical engineering from the University of Pittsburgh.

John L. Bryan

University of Maryland, Professor Emeritus, and Consultant, Fire Protection and Life Safety, Frederick, MD.

Term Expires: March 31, 2004

Until his retirement in 1993, Bryan spent 37 years as a professor in and chairman of the Department of Fire Protection Engineering at the University of Maryland. He has broad experience as a consultant in fire protection, life safety, and fire investigation. Bryan has 26 years of fire and rescue experience with several fire departments, including the Bethesda-Chevy Chase (Md.) Rescue Squad, the Glen Echo (Md.) Fire Department, and the Stillwater (Okla.) Fire Department. Bryan has degrees from Oklahoma State University and American University.

David Collins

President, The Preview Group, Cincinnati, OH

Term Expires: March 31, 2004

Collins has 30 years experience in architectural practice, as a building code official, in building code and regulatory issues, and in the analysis of existing buildings. He is an active participant in building and fire code development organizations, including the International Code Council and the National Fire Protection Association. He also serves as manager of the codes advocacy program of the American Institute of Architects. He has degrees from Purdue University and the University of Cincinnati, and is a registered architect. Collins is a Fellow of the American Institute of Architects.

Glenn P. Corbett

Professor, Public Management-Fire Science, John Jay College of Criminal Justice, New York, NY.

Term Expires: March 31, 2006

Corbett has extensive experience in different facets of fire protection, including teaching fire science at the John Jay College of Criminal Justice and acting as administrator of engineering services at the San Antonio (Texas) Fire Department, as fire protection engineer at the Austin (Texas) Fire Department, and as loss prevention consultant at A.B.C. Loss and Fire Prevention Corp. (East Orange, N.J.). Corbett was an auxiliary firefighter at the Paterson (N.J.) Fire

Department and currently is First Captain at the Waldwick (N.J.) Volunteer Fire Department. He has degrees from Worcester Polytechnic Institute and John Jay College of Criminal Justice.

Philip J. DiNenno

President, Hughes Associates, Inc., Baltimore, MD.
Term Expires: March 31, 2005

At Hughes Associates, DiNenno is responsible for planning, executing, and analyzing fire protection design, research, and development projects. DiNenno also served as a fire protection engineer at Benjamin/Clarke Associates and Professional Loss Control Inc. He developed and taught a course on mathematical modeling of fire development and smoke movement at the University of Maryland. He has a degree in fire protection engineering from the University of Maryland.

Paul M. Fitzgerald

formerly Executive Vice President, FM Global, Johnston, RI.
Term Expires: March 31, 2006

Currently residing in Holliston, Mass., Fitzgerald has served in a wide variety of executive and technical positions at FM Global, one of the world's largest commercial and industrial property insurance and risk management organizations specializing in property protection. Fitzgerald's positions have included president and chief executive officer and chair of the board of directors for both Factory Mutual Engineering and Factory Mutual Research. He has degrees from Tufts University and Babson College.

Robert D. Hanson

University of Michigan, Professor Emeritus, Walnut Creek, CA.
Term Expires: March 31, 2006

Hanson has been a civil engineering faculty member at the University of Michigan since 1966 and was chair of the department for eight years. Hanson has extensive experience as an expert in earthquake engineering and steel structures and an advisor to organizations such as the United Nations Educational, Scientific and Cultural Organization; International Institute for Seismology and Earthquake Engineering, Tokyo, Japan; and the Federal Emergency Management Agency. He has degrees in civil engineering from the University of Minnesota and the California Institute of Technology. Hanson is a member of the National Academy of Engineering.

Charles Thornton

Chairman and Principal, Thornton-Tomasetti, Inc., New York, NY
Term Expires: March 31, 2005

Thornton has overall responsibility for engineering, design, and research and development activities, as well as strategic planning. His 40 years of experience at the firm have included involvement in the design and construction of billions of dollars worth of projects in the U.S. and overseas, ranging from hospitals, arenas and high-rise buildings to airports, transportation facilities and special structure projects. Many of these projects have set industry standards for innovative thinking and creativity. In addition, he has extensive experience in conducting failure investigations. He has degrees in civil engineering from Manhattan College and New York University, and is a registered professional engineer in 14 states and the District of Columbia. Thornton is a member of the National Academy of Engineering.

Kathleen J. Tierney

Professor, Department of Sociology and Criminal Justice, and
Director, Disaster Research Center, University of Delaware, Newark, DE.

Term Expires: March 31, 2004

At the University of Delaware, Tierney teaches courses on collective behavior, social movements, sociology of disaster, and qualitative research. She also is director of the University's Disaster Research Center, the first social science research center in the world devoted to the study of disasters. The center conducts field and survey research on group, organizational, and community preparation for, response to, and recovery from natural and technological disasters and other community-wide crises. Tierney has degrees in sociology from Youngstown State University and Ohio State University.

Forman A. Williams

Professor, Department of Mechanical and Aerospace Engineering, and
Director, Center for Energy Research, University of California at San Diego, CA.

Term Expires: March 31, 2005

Williams has taught engineering physics and combustion at the University of California since 1988. Prior to 1988, he taught at many prestigious colleges and universities around the world, including California Institute of Technology, University of London, Harvard University, Universite de Provence, and Princeton University. Williams has degrees from Princeton University and the California Institute of Technology. He is a member of the National Academy of Engineering.

Interim Report on Procedures and Practices Used for Passive Fire Protection of the Floor System of the World Trade Center Tower Structures: Interim Report

Introduction

One of the four primary objectives of the National Institute of Standards and Technology (NIST) Federal Building and Fire Safety Investigation of the World Trade Center (WTC) Disaster is to determine what procedures and practices were used in the design, construction, operation, and maintenance of the WTC towers and WTC 7. A key focus is on acceptance procedures and practices for innovative systems, technologies, and materials, and for variances from requirements of building and fire code provisions. This documentation of historical information is expected to be of value to the professional community in identifying and adopting changes to procedures and practices that may be warranted.

This interim report documents the procedures and practices used to provide the passive fire protection for the floor system of the WTC tower structures.¹ It traces the history of the fireproofing within the broad context of applicable building codes, construction classifications, fire ratings, standardized testing, and inspection. A primary focus is on the floor system, which was innovative in its day and for which there was little, if any, service knowledge, and in particular, on the fireproofing of the trusses. NIST is also reviewing documents related to the fireproofing of other structural components in the WTC towers and will include that information in future investigation reports.

This report is issued as part of the ongoing federal building and fire safety investigation into the World Trade Center building collapses. NIST is conducting this investigation under the authorities of the National Construction Safety Team Act (P.L. 107-231). No part of any report resulting from a NIST investigation can 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).

The report summarizes factual data contained in documents reviewed by NIST. Most of these documents were provided to NIST by the Port Authority of New York and New Jersey and its contractors and consultants. Additional data were provided by Laclede Steel Company, the firm that supplied the floor trusses for the WTC towers, and Isolatek International, formerly United States Mineral Products Co. (USM), the manufacturer of the fireproofing material.² This report documents a few instances where there are conflicting data or data that need some interpretation. To the maximum extent possible, the facts are presented without interpretation.

The report begins by discussing the applicable building codes and the building classification system, which dictates the fire rating required for structural members and assemblies. The structural system for the World Trade Center towers was constructed predominantly of steel, which, in general, requires protection from fire to maintain its strength and stiffness. The report

¹ In this report, World Trade Center Tower 1 (North tower) will be referred to as WTC 1, while World Trade Center Tower 2 (South tower) will be referred to as WTC 2.

² 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.

focuses on the spray-on fireproofing and the procedures and practices used in its selection and application. Additionally, the report discusses the procedures and practices used to determine whether tests were needed to evaluate the fire endurance of the structural elements, and it presents the results from one such test.

Nothing in this report should be understood to imply that the floor trusses played a critical role in the collapse of the WTC towers. This issue is a key component of another NIST investigation objective, viz., to determine why and how WTC 1 and 2 collapsed following the initial impacts of the aircraft and why and how WTC 7 collapsed. Any findings and conclusions related to the role of the floor trusses in the most probable collapse sequence must await the results of that work.

NIST continues to seek, receive, and review additional data that includes maintenance and inspection records for the WTC towers from different sources, reports of critical UL tests performed for the fireproofing materials supplier, and information on the ability of the fireproofing materials to withstand shock, impact, and vibration. Further, since nearly 40 years have elapsed from the initial design of the WTC towers and some documentation was stored in the towers, it is inevitable that some factual data have been lost or are missing from the documents reviewed by NIST.

Accordingly, NIST welcomes written comments from organizations or individuals possessing factual information related to the contents of this report. Such information may be sent to NIST via e-mail to wtc@nist.gov, fax to (301) 975-6122, or by mail to WTC Technical Information Repository, 100 Bureau Drive, Stop 8610, Gaithersburg, MD 20899-8610. NIST will review all such information and update this report as needed.

Applicable Building Code

The World Trade Center towers were built by the Port of New York Authority, which in 1972 became known as the Port Authority of New York and New Jersey and is hereafter referred to as the Port Authority. As an interstate agency created under a clause of the U.S. Constitution permitting compacts between states, the Port Authority was not bound by the authority having jurisdiction, namely the New York City Department of Buildings. It was not required to comply with the New York City Building Code or any other building code.

In May 1963, the Port Authority instructed its consulting engineers and architects to comply with the New York City Building Code.³ In the areas where the Code was not explicit or where technological advances made portions of the Code obsolete, it directed that design may be based on acceptable engineering practice. At that time, the 1938 edition of the New York Building Code (NYBC) was in effect, and a revised code was being drafted. In September 1965, the Port Authority instructed the designers of the WTC towers to revise the design plans to comply with the second and third drafts of the NYBC revision.⁴ The revised Building Code became effective in December 1968.

³ Letter dated May 15, 1963 from Malcolm P. Levy (Chief, Planning Division, World Trade Department) to Minoru Yamasaki (Minoru Yamasaki & Associates)

⁴ Letter dated September 29, 1965 from Malcolm P. Levy (Chief, Planning Division, World Trade Department) to Minoru Yamasaki (Minoru Yamasaki & Associates)

In 1993, the Port Authority and the New York City Department of Buildings entered into a memorandum of understanding⁵ to establish procedures to be followed by the Port Authority for any building construction project undertaken by the Port Authority or any of its tenants at buildings owned or operated by the Port Authority and located in the City's jurisdiction. While the long-standing policy of the Port Authority was to guarantee that its buildings meet or exceed the New York City Code requirements, the 1993 agreement restated the commitment. Among other key points, it was agreed that:

- Each project would be reviewed and examined for compliance with the Code;
- All plans would be prepared, sealed, and reviewed by New York State licensed professional engineers or architects; and,
- The Port Authority engineer or architect approving the plans would be licensed in the State of New York and would not have assisted in the preparation of the plans.

A supplement⁶ to this memorandum of understanding was executed in 1995. The supplement added that the person or firm performing the review and certification of plans for WTC tenants should not be the same person or firm providing certification that the project had been constructed in accordance with the plans and specifications.

In 1993, "in order to maintain and enhance the safety" of its facilities, the Port Authority also "adopted a policy providing for the implementation of fire safety recommendations made by local government fire departments after a fire safety inspection of a Port Authority facility."⁷ Later that year, the Port Authority and the Fire Department of the City of New York (FDNY) entered into a memorandum of understanding to restate the Port Authority's commitment to the policy.⁸ The agreement included the following statements:

- "FDNY, acting through its Bureau of Fire Prevention ("BFP"), shall have the right to conduct fire safety inspections at any Port Authority facility located in the City of New York."
- "BFP will issue a letterhead report of its fire safety findings and recommendations for corrective action with respect to any deficiencies forming a part of such findings addressed to the Port Authority's General Manager of Risk Management operations."
- "The Port Authority policy is and will continue to be to assure that such new or modified fire safety systems are in compliance with local codes and regulations."

To provide context for the information in this report, an overview of concepts used in U.S. building regulations for structural fire resistance is presented in Appendix 4-A.

⁵ Memorandum of Understanding Between the New York City Department of Buildings and the Port Authority of New York and New Jersey, 1993.

⁶ Supplement to Memorandum of Understanding Between the New York City Department of Buildings and the Port Authority of New York and New Jersey, 1995.

⁷ Memorandum of Understanding Between the Fire Department of the City of New York and The Port Authority of New York and New Jersey, Executed as of December 30, 1993.

⁸ Ibid

Building Classification and Fire Rating Requirements

Compliance with the New York City Building Code affected, among other things, the assigned building classification and thus the required fire rating of the WTC towers and their structural members. It should be recalled that the NYBC was under revision during the design of the WTC towers.

The 1968 New York City Building Code established the occupancy classification based on the use of the building. It divided occupancy into nine groups, A through I, as follows:

- A-High Hazard;
- B-Storage ;
- C-Mercantile;
- D-Industrial;
- E-Business;
- F-Assembly;
- G-Educational;
- H-Institutional; and,
- I-Residential.

As office buildings, the WTC towers were classified as Occupancy Group E.⁹

Additionally, there were other factors (see Appendix A) that determined the “classification” of a building and, consequently, its required fire rating: combustible versus noncombustible construction, sprinklered versus unsprinklered spaces, and building height and floor area limitations. The 1968 Code identified two construction groups: Noncombustible Construction (Group I) and Combustible Construction (Group II). The WTC towers were classified as Construction Group I because their walls, exitways, shafts, structural members, floors, and roofs were constructed of noncombustible materials. At the time of design and construction, the towers were not sprinklered.

The drafts and final version of the 1968 New York City Building Code established five subgroups within Construction Group I. Each construction subgroup required a specific fire rating as follows for Business Occupancy [Ref. 1]:

- Construction Group IA: 4 hour protected¹⁰
- Construction Group IB: 3 hour protected
- Construction Group IC: 2 hour protected
- Construction Group ID: 1 hour protected
- Construction Group IE: unprotected

To provide perspective, the 1961-1962 revision to the 1938 New York City Building Code (the last revision prior to the 1968 edition of the Code) required that the 110 story towers be

⁹ Letter dated May 14, 1969 from Malcolm P. Levy (Chief, Planning Division, World Trade Department) to Milton Gerstman (Tishman Realty & Construction Company, Inc.)

¹⁰ Fire endurance is a rating, given in hours, as established in accordance with the American Society for Testing and Materials (ASTM) Standard E 119 – Standard Test Methods for Fire Tests of Building Construction and Materials. Fire endurance is also referred to as fire rating or fire index.

classified as “Class 1 – Fireproof Structures,”¹¹ which includes office buildings [Ref. 2]. This meant that the columns were required to have a 4 hour fire endurance while the floor system was required to have a 3 hour fire endurance.

In the 1968 Building Code, area and height limitations for unsprinklered buildings of Construction Group I with a Business Occupancy were as presented in Table 1 [Ref. 1]. The WTC towers, WTC 1 and WTC 2, had a roof height of 1368 ft and 1362 ft,¹² respectively, and each tower had a floor area of approximately 43 100 ft². As Table 1 indicates, the WTC towers could be classified as either Class IA or Class IB.

It was the practice at the time, and continues to be the practice, for the architect to establish the building classification, fire rating of members and systems, and fireproofing requirements. Emery Roth & Sons (ER&S), the Architect of Record for the towers, classified the WTC towers as Class IB since there was “no economic advantage in using Class IA Construction.”¹³

Table 1 - Area and height limitations for unsprinklered buildings for Construction Group I with a Business Occupancy (NYC Building Code 1968)

	Class IA	Class IB	Class IC	Class ID	Class IE
Area	No Limit	No Limit	No Limit	17 500 ft ²	10 500 ft ²
Height	No Limit	No Limit	85'-0"	75'-0"	40'-0"

According to the 1968 Code, construction Class IB classification provided, in part, the following fire protection requirements:

- Enclosure of vertical shafts, exits, passage-ways, and hoistways shall have a 2 hour fire endurance;
- Columns, girders, trusses, other than roof trusses, and framing supporting one floor shall have a 2 hour fire endurance;
- Columns, girders, trusses, other than roof trusses, and framing supporting more than one floor shall have a 3 hour fire endurance; and
- Floor construction including beams shall have a 2 hour fire endurance.
- Roof construction including beams, trusses, and framing including arches, domes, shells, cable supported roofs, and roof decks (for buildings over one story in height) shall have a 2 hour fire endurance.

Generally, fire ratings would appear on the application submitted for approval to the New York City Department of Buildings. In the case of the towers, however, no plans or forms were filed since the Port Authority was not subject to the New York City Building Code.¹⁴

¹¹ This Code used numerals instead of alphabets for classification.

¹² The policy of NIST is to use the International System of Units (metric units) in all its publications. In this document, however, to preserve original references and quotes, units are presented using the inch-pound system throughout the report.

¹³ Memorandum dated January 15, 1987 from Lester S. Field (Chief Structural Engineer, World Trade Department) to Robert J. Linn (Deputy Director for Physical Facilities, World Trade Department)

¹⁴ *Ibid*

Correspondence from ER&S indicates that in early 1969 the Port Authority had rewritten the fireproofing specifications for the WTC towers.¹⁵ In the process of rewriting, the following key paragraph specifying the fire rating requirements for the structural members was apparently omitted (reasons for the omission are not documented in available records):

“Finished thicknesses of applied material over the various component steel parts requiring fireproofing shall be great enough to qualify the fireproofed parts for a three (3) hour rating (support beams, steel deck work) and a four (4) hour rating for all pick-up girders, if any, and columns.”

ER&S continued, “We cannot be expected to accept responsibility for specifications which have been revised in such a manner; that which we originally stated clearly and simply, has become a meaningless document.”

In 1973, New York City Local Law No. 5 amended the New York City Building Code (effective January 18, 1973). Local Law No. 5 required, in part, retrofit of existing unsprinklered office buildings 100 ft or higher and having HVAC systems that serve more than the floor on which the equipment is located. The retrofit could be done by subdividing the floor area into compartments of specified square footage by fire separations (1 hour or 2 hour fire rated depending on the size of the compartment) or by providing sprinkler protection.¹⁶ Owners of unsprinklered buildings were required to comply according to the following time frame from the effective date of the law:

- At least 1/3 of the non-complying floor area shall be completed in 5 years;
- At least 2/3 of the non complying floor area shall be completed in 10 years; and,
- The entire building shall be completed in 15 years.

By the 1990s, WTC 1 and 2 had been retrofitted with active fire protection systems (sprinklers) [Ref. 3].

The 1999 revision of the New York City Building Code placed a 75 ft height limitation on unsprinklered buildings of Construction Groups IA, IB, IC, and ID. Sprinklered buildings, however, had no height limitations for Construction Group IA, IB, and IC. Thus the WTC towers could have been reclassified as Class IC (2 hour protected) [Ref. 4]. As Class IC, the columns and floor systems would have required 2 hour and 1-1/2 hour fire ratings, respectively.

In preparation for leasing the WTC to Silverstein Properties, a condition assessment was carried out in 2000. The report¹⁷ presented to the Port Authority by Merritt & Harris, Inc. states that the WTC towers were classified as Class IB – noncombustible, fire-protected, retrofitted with sprinklers in accordance with New York City Local Law 5/1973.

Fireproofing Method and Materials

Classification of a building leads to its overall fire endurance rating and ratings of the various structural components. The New York City Building Code does not prescribe how the required

¹⁵ Letter dated February 11, 1969 from Douglas Fernández (Emery Roth & Sons, Architect of Record) to Joseph A. Schwartzman (The Port of New York Authority).

¹⁶ Communication from New York City Department of Buildings to NIST dated April 4, 2003.

¹⁷ *Property Condition Assessment of World Trade Center Portfolio*, prepared by Merritt & Harris, Inc., December 2000.

fire endurance rating is to be achieved. Rather, the fire protection method is established by the Architect of Record and it depends, in part, on the structural materials used in the construction.

In the case of the WTC towers, the primary structural material was steel. Steel, in general, requires passive fire protection to achieve the fire ratings prescribed in the Code. The Port Authority, in agreement with all appropriate parties, chose to fireproof the main structural components such as columns, spandrel beams, and bar joists with spray-on fireproofing. This fireproofing technique was an established method for protecting columns, beams, and walls. In the 1960s, however, composite steel joist-supported floor systems were usually fireproofed using “lath and plaster” or fire-rated ceiling tiles.¹⁸

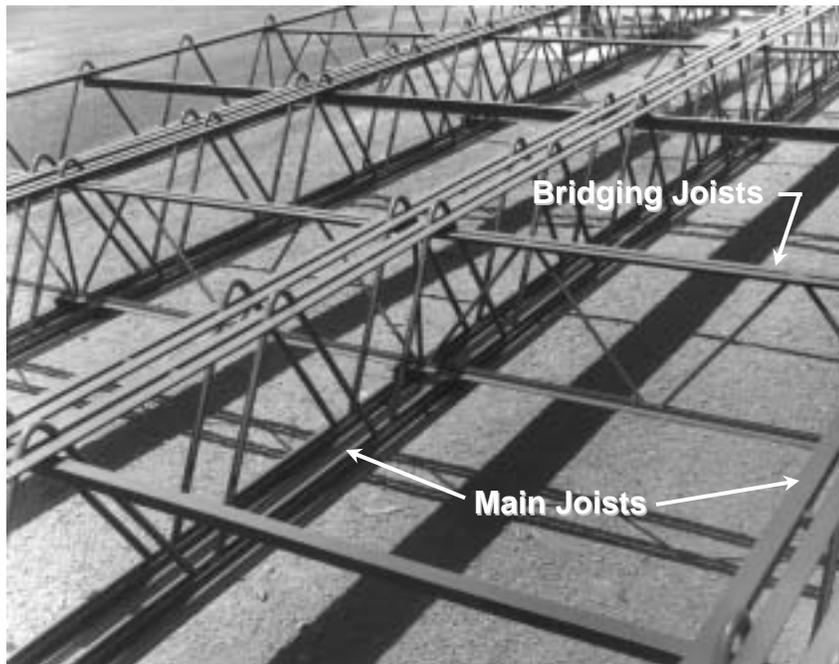


Figure 1 Mock up of bar joist lay-out for floor system
(Photograph circa 1967 provided by Laclede Steel)

The floor system used in the towers consisted of open-web bar joists acting as a composite system with a 4 in thick reinforced lightweight concrete slab over metal decking. The main composite joists, which were used in pairs,¹⁹ were spaced at 6 ft-8 in on center (o.c.) and had a nominal clear span of either 60 ft or 35 ft. The steel bar joists were fabricated with double-angles, for the top and bottom chords, and round bars for the webs. Additionally, the floor system included bridging joists (perpendicular to main joists) spaced 13 ft-4 in o.c. Figure 1 illustrates the bar joist system as presented in a mock-up fabricated by Laclede Steel, the manufacturer of the composite bar joists. Figure 2 shows the basic configuration of the bar-joist floor system.

¹⁸ Harold E. Nelson, personal communication; also Underwriters' Laboratories, Inc., Building Materials List, January 1968.

¹⁹ Terms, such as trusses, open-web joists, and composite joists have been used by various parties to designate the bar joists used to support the floor system. For consistency, and to agree with standard terminology for these structural members, generally, the term “bar joists” is used where possible in this document. In quotes referring to bar joists with an alternative term, the original terminology has been preserved.

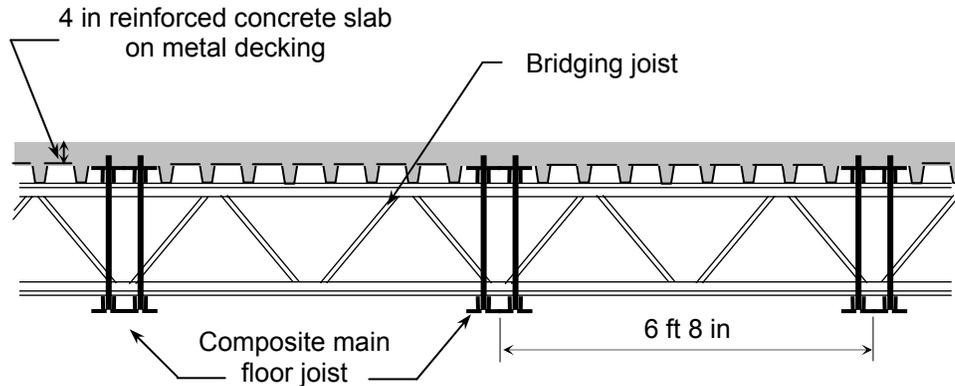


Figure 2 - Schematic floor system viewed perpendicular to the main steel joists (not to scale)

The use of “demountable ceilings” was considered as a possible fireproofing method by the Port Authority and its consultants as early as 1963; other efficient and economical fireproofing methods, however, were sought.²⁰ By late 1965, the use of spray-on fireproofing applied directly to the bar-joists “appears to have been selected.”²¹

Since application of spray-on fireproofing to slender steel members was an innovative fire protection method, the Port Authority arranged for demonstrations to establish its feasibility for the World Trade Center. The demonstrations also aimed to provide information on the amount of material loss that could be expected when spraying the slender bar joist elements.²² In August of 1967, application of Zonolite’s Monokote was demonstrated to the Port Authority’s engineers (Figure 3) at the Madison plant of Laclede Steel. After observing the demonstrations, Laclede Steel stated,

“With the successful application of spray-on insulation an entire new scheme of fire safe building construction is possible for steel joists in that the fire protection of the joists would permit the installation of low cost acoustical ceilings with access to utility lines that have not be[en] possible in the two hour rated buildings before.”²³

and

“In any event, the fireproofing of joists seems to be a problem now solved, and in the World Trade Center as well as in other steel joist structures, we may be sure

²⁰ Report on WTC Fire dated April 1, 1975 from Skilling Helle Christiansen Robertson (SHCR) to the Port Authority.

²¹ *Ibid*

²² Office memorandum dated August 10, 1967 by A. Carl Weber (Vice President Research & Engineering, Laclede Steel, Co.)

²³ Office memorandum dated August 10, 1967 by A. Carl Weber (Vice President Research & Engineering, Laclede Steel, Co.)

that an economical fireproofing can be effected in the field without the expense of heavy ceiling construction.”²⁴



Figure 3 Demonstration of Monokote spray-on fireproofing circa 1967 at Laclede Steel Co. (Madison, Il.)

(Photograph provided by Laclede Steel)

A similar demonstration of the USM’s Cafco Blaze-Shield Type D was conducted in September 1967.²⁵

Cafco D was selected by the Port Authority and, in March 1969, the contract for fireproofing was awarded to Mario & DiBono Plastering Co., Inc.²⁶ At this time, NIST is not aware of the rationale for selecting Cafco Type D.

Fireproofing Thickness Requirements and Measured Data

The thickness of fireproofing material necessary to achieve the required fire endurance was being assessed in 1965, more than three years prior to the award of the fireproofing contract. Correspondence stated that “the one-inch thick material meets the 3 hour requirements of both the new code and Underwriter’s [Underwriters’ Laboratory Inc. (UL)].”²⁷ Follow-on correspondence stated the following:

²⁴ *Ibid*

²⁵ Memorandum dated September 20, 1967 from R.M. Monti (The Port of New York Authority) to Malcolm P. Levy (The Port of New York Authority)

²⁶ Report on WTC Fire dated April 1, 1975 from SHCR to the Port Authority.

²⁷ Letter dated December 14, 1965 from Julian Roth (ER&S) to Malcolm P. Levy (The Port of New York Authority).

“Although the one-inch spray-on fireproofing meets the 3 hour requirements of both the proposed Building Code and Underwriters, advance information from manufacturers indicates that if the truss were required to be fire-tested, then two inches of material would be required for the light angle members. We are therefore revising our working drawings to indicate a one inch thickness of spray-on fireproofing around the top and bottom chords of the trusses, and two-inch thickness for all other members of the trusses.”²⁸

Neither of these communications identified the manufacturer or type of fireproofing material.

In October 1969, nearly four years after the previously cited correspondence, the Port Authority stated, in a letter to the fireproofing contractor, that

“All Tower beams, spandrels, and bar joists requiring spray-on fireproofing are to have a ½” [1/2 in] covering of Cafco.

The above requirements must be adhered to in order to maintain the Class 1-A Fire Rating of the New York City Building Code.”²⁹

To date, NIST has not been able to ascertain the technical basis for this recommendation.

USM’s technical literature dated 1966-1967, included a table indicating that 1/2 in of Cafco Type D would provide a 4 hour rating for beams, girders and spandrels, citing authority of UL tests (ASTM E 119).³⁰ The 1966-1967 USM literature does not address bar joists. By way of comparison, the product catalog recommends 2-3/16 in of Cafco Type D for light columns (columns lighter than W14×228) to achieve the same 4 hour rating.

In the early 1970s, asbestos-based products were no longer permitted to be used. Since asbestos fiber was a key component of Cafco Type D, manufacture of this material was discontinued in the early 1970s. The use of Cafco Type D was discontinued at the 38th floor of WTC 1.³¹ The asbestos-containing material was “subsequently encapsulated with a spray-on hardening material.”³² Fireproofing of the remaining floors of WTC 1 and all of WTC 2 was carried out using Cafco Blaze-Shield Type D C/F, a product that contained mineral wool in place of the asbestos fibers. There is no record that the required thickness of the fireproofing was evaluated following the change of fireproofing material. Correspondence between Underwriters’ Laboratories and the Port Authority indicates, however, that the thermal properties of Cafco Type D C/F were equal to or better than those of Cafco Type D.³³

In February 1975, a fire took place in WTC 1, spreading from the 9th to the 19th floor.³⁴ Most of the damage occurred on the 11th floor where the fire affected 9000 ft². Due to the fire, some of the bar joists in the 12th and 13th floors were damaged to some extent. The fire did not damage

²⁸ Letter dated December 23, 1965 from Julian Roth (ER&S) to Malcolm P. Levy (The Port of New York Authority).

²⁹ Letter dated October 30, 1969 from Robert J. Linn (Manager, Project Planning, The World Trade Center) to Mr. Louis DiBono (Mario & DiBono Plastering Co., Inc.).

³⁰ 1966-1967 Cafco Blaze-Shield fireproofing product literature, U.S. Mineral Products Co.

³¹ Letter dated March 14, 1983 from Daniel J. Censullo (Manager, WTC Operations, The World Trade Center) to Jerry Silecchia (National Cleaning Contractors, Inc.)

³² *Ibid*

³³ Letter dated April 24, 1970 from S.W. Bell (Assistant Engineer, Fire Protection Department, Underwriters’ Laboratories, Inc.) to R. Monti (Construction Manager, World Trade Center, Port of New York Authority).

³⁴ One World Trade Center Fire - February 13, 1975, report by The New York Board of Fire Underwriters.

any of the main bar joists; though it caused buckling of some top chord members, bridging bar joists, and deck support angles.³⁵

After the 1975 fire in WTC 1, the Port Authority contracted Skilling Helle Christiansen Robertson (SHCR) to assess the resulting structural damage and to report, in general, on the fire resistivity of the floor system. The SHCR transmittal letter for the resulting report stated that it was “intended to provide background ... as to the development of the fire-resistive standards for World Trade Center and looks also at the adequacy of existing systems.”³⁶

In the transmittal letter,³⁷ SHCR indicated that it held itself “as a reporter of facts -- as presented in communications gleaned from the files of Port Authority,” the architects, and its own files; and that it did “not purport to have any special expertise not commonly held by other structural engineers.” Furthermore, the letter stated that “The only way to assure the existence of the fire safety of floor systems is to be found through the participation of a fire safety engineer and/or fire testing.”

The report suggested that the required thickness of Cafco for the various structural members could have been determined from catalog information.³⁸ As mentioned previously, Cafco’s catalog from 1967 indicated that the product had been tested by Underwriters’ Laboratories, and that for beams, girders, and spandrels, a thickness of 1/2 in of Cafco Blaze-Shield Type D provided a 4-h rating;³⁹ the catalog did not provide any information on the fireproofing of bar joists.

Table 2 summarizes the “fire retardant ratings” for Cafco Blaze-Shield products applied directly to beams, girders and spandrels circa 1960-1972. The information is primarily based on ASTM fire endurance tests. The table also presents the thermal conductivity, k , for some of the fireproofing (the higher the value of k , the lower the thermal insulation).

Two items are particularly noteworthy. First, the thickness requirement was nearly halved for Cafco D from 1965 to 1966 based on two different test results. Second, the 1966-1967 fire ratings, based on two different test results, show both the Standard and Cafco D product using the same thickness to achieve 2 and 4 hour ratings, respectively. NIST is working to gain access to these critical documents so that it can review the test results that formed the basis of the thickness requirements for the ratings.

³⁵ Report on WTC Fire dated April 1, 1975 from SHCR to the Port Authority.

³⁶ Cover letter for SHCR’s WTC-Fire Report dated April 1, 1975 from Leslie E. Robertson (SHCR) to Malcolm P. Levy (Chief, Planning and Construction, Port Authority of New York & New Jersey).

³⁷ *Ibid*

³⁸ Report on WTC Fire dated April 1, 1975 from SHCR to the Port Authority.

³⁹ 1966-1967 Cafco Blaze-Shield fireproofing product literature, U.S. Mineral Products Co.

Table 2 - Information presented in the Sweets Catalogs regarding Caeco Blaze Shield Products applied directly to beams, girders, or spandrels (with protected deck) circa 1960-1972.

Year	Caeco Product	Reported Thermal Conductivity k (Btu-in/(h·ft ² ·°F)) ^{†§}	Hour Rating (h)	Fireproofing Thickness (in)	Authority	UL Design No.
1960	Blaze Shield	0.26	4	2 1/8	UL test R3749-3	
			3	1 7/16	UL test CR193-2	
			2	1 1/8	UL test CR193-3	
			1	3/4	Extr.BMS-92 [‡]	
1965	Blaze Shield	0.27	4	1	ULI [*] #R3749-8	
			3	7/8	ULI# R3789-2	
			2	1/2	ULI# R3749-6	
	Blaze Shield Type D	None	4	7/8	ULI# R3749-11	
1966	Blaze Shield Type D	None	4	1/2	ULI# R3749-13	
1966-1967	Blaze Shield Standard	0.27	3	7/8	ULI# R3789-2	
			2	1/2	ULI# R3749-6	
	Blaze Shield Type D	0.34	4	1/2	ULI# R3749-13	
1968	Blaze Shield Standard	0.27	2	1/2	ULI# R3749-6	
	Blaze Shield Type D	0.34	4	9/16	ULI# R3749-20	
			4	1/2	ULI# R3749-13	
1970	Blaze Shield Type D	None	4	9/16		98-3 HR
			4	1/2		86-3 HR
			2	1/2		54-2 HR
1971	Blaze Shield D C/F	0.29	4	1/2		86-3 HR
			4	9/16		98-3 HR
			2	5/16		310-2 HR
1972	Blaze Shield D C/F	0.29	4	1/2		86-3 HR
			4	9/16		98-3 HR
			2	5/16		310-2 HR

[†] U.S. Mineral Products catalogs incorrectly report units of thermal conductivity as Btu-in/hr/ft²/°F.

[§] Thermal conductivities are reported only at ambient temperature.

[‡] Reported to be extrapolations based on formulae contained in National Bureau of Standards Report BMS-92.

^{*} Underwriters' Laboratory Inc.

The SCHR report stated further that fireproofing of the top chord of the bar joists was not necessary, except for the corner 60 ft × 35 ft quadrants of the buildings where the floor system acted as a two-way system in bending. Additionally, it was stated that fireproofing of the bridging system and the slab metal deck were not required for the following reasons.⁴⁰

- In the one-way portion of the floor, “the concrete slab becomes the dominant element of the top chord.” Thus if the shear knuckle remains intact, “the structural integrity of the top chord is not required.” Additionally, “the structural steel top chord provides only a small increment in the diaphragm strength,” so the fireproofing may be omitted.
- The bridging joists were used “for reduction in floor ‘tremor’ and to reduce the effects of differential deflections associated with gravity loads.” Bridging joists were “not required as a part of the structural system” and, therefore, fireproofing could be omitted on the bridging joists.

The report also addressed the performance of the floor system in the 1975 fire, stating,

“The fire of February, while reported in the press to have been very hot, did not damage a single primary, fireproofed element. Some top chord members (not needed for structural integrity), some bridging members (used to reduce floor tremor and the like), and some deck support angles (used only as construction devices) were buckled in the fire – all were un-fireproofed steel.”

In February 2003, the Port Authority informed NIST that the top chord and bridging trusses were fireproofed.⁴¹ NIST has recently received and is in the process of reviewing a large number of photographs from inspections conducted on the fireproofing in the towers. The results of that review will be incorporated into an update of this report.

Information on the in-place fireproofing thickness for the floor system first appears in Sample Area Data Sheets from 1990.⁴² The data sheets commented on the state of the in-place fireproofing. As an example, the data sheet for floor 29 of WTC 1 states the following for the South West quadrant of the floor:

“Fluffy spray-on fireproofing coating the support beams, joists, and deck above the ceiling. The thickness of the material on the beams and joists was consistently about 1/2”. Regarding the deck it ranged from very sparse [*sic*] in areas to 1/4” in other areas. The areas we sampled were coated with a light green encapsulant.”

Similar statements were recorded for the remaining quadrants of the floor.

Information regarding quantitative inspection of existing fireproofing appears in documentation from 1994. That year, the Port Authority performed a series of thickness measurements of the existing fireproofing on floors 23 and 24 of WTC 1. Six measurements were taken from “both flanges and web” of each of 16 random bar joists on each floor at those locations where the fireproofing was not damaged or absent.

⁴⁰ Report on WTC Fire dated April 1, 1975 from SCHR to the Port Authority.

⁴¹ Response to NIST’s Questions to the Port Authority on Fire Resistance of the WTC Floor System, March 7, 2003.

⁴² Sample Area Data Sheets dated March 14, 1990. Port Authority of N.Y. and N.J. Litigation Sampling Program. Tower 1, Floor 29.

The averages of six measurements per joist that were recorded on the two floors are presented in Table 3. Measured average thickness varied between 0.52 in and 1.17 in and for the 32 measurements (16 on each floor) the overall average was 0.74 in. Four of the 32 floor joists, had an average thicknesses between 0.52 in and 0.56 in. These measurements suggest that the minimum thickness exceeded 1/2 in.

This same report stated that, on the 23rd floor, “truss members located adjacent to the outside walls (within 3 ft.) are devoid of fireproofing material. Visual inspection on the 24th floor was not possible, as this area still has a lowered ceiling in place.”⁴³

Table 3 - Average fireproofing thickness from six measurements on each of 16 random floor joists on floors 23rd and 24th of WTC 1 (Data provided by the Port Authority)

Fireproofing Thickness (in)	
Floor 23 (in)	Floor 24 (in)
0.60	0.76
0.53	0.60
0.70	0.90
0.76	0.72
0.88	0.64
0.89	0.80
0.83	0.68
1.17	0.65
0.88	0.67
0.71	0.77
0.82	0.96
0.52	0.66
0.69	0.65
0.52	1.11
0.64	0.95
0.52	0.56

The issue of the fireproofing thickness requirements was revisited in 1995. That year, the Port Authority performed a study to establish the requirements for applying spray-on fireproofing to the joists in the case of new construction (alterations conducted when tenants vacated the space) in the towers. The study estimated the fireproofing requirements for the bar joists of the towers based on “the fireproofing requirements for Design No. G805 contained in the Fire Resistance Directory” of Underwriters’ Laboratories. The study concluded that 1-1/2 in of spray-on mineral fiber fireproofing, “when applied directly to the chords and web members,” was sufficient to achieve the required 2 hour rating for the bar joists.⁴⁴

⁴³ Memorandum dated March 17, 1994 from S.M. Solomon (Chief of Chemical/Environmental Testing, Port Authority of New York and New Jersey) to E. Ramabhusanam.

⁴⁴ White paper titled “Fireproofing Requirements for World Trade Center Tenant Floor Joist Construction that Requires Installation Due to Asbestos Removal or Local Removal to Facilitate Construction” transmitted by way of memorandum from Joseph Englot (Chief Structural Engineer, Port Authority) to Peter Sweeney (Engineering Program Manager, Port Authority) on August 18, 1995.

In 1999, the Port Authority established “guidelines regarding fireproofing repairs, replacement, and upgrades” for the towers.⁴⁵ The guidelines for tenant spaces may be summarized as follows:

- For full floors undergoing new construction or renovation, the bar joists should be fireproofed with 1-1/2 in of spray-on mineral fiber fireproofing. Refireproofing requires removal of existing material and controlled inspection.
- For “tenant spaces less than a full floor undergoing new construction or renovation,” the floor trusses “need only meet the original construction standard. Fireproofing shall be inspected and patched as required to the greater of 3/4 in or to match existing” if it has already been upgraded to 1-1/2 in.

While the primary material used to fireproof the floor system was Cafco Blaze-Shield D C/F, small areas with damaged fireproofing were patched using the Monokote fireproofing material instead of Cafco.⁴⁶ For patching, Monokote was troweled-on rather than sprayed.

A report presented in 2000 indicates, however, that, in the majority of the cases, the existing fireproofing required so much patching that it was more effective to replace it.⁴⁷ The same report states that proper spray-on application of 1-1/2 in of Cafco Blaze-Shield took between 2 and 3 passes. When fewer passes were used, the material usually failed the adhesion tests conducted after application.

Internal memoranda from USM, dating from 1960 to 1969, warned of the poor adherence or bond performance of Cafco Blaze-Shield, and specifically Cafco Type D. Tests performed in 1960 apparently indicated poor bond characteristics of Cafco Blaze-Shield as manufactured in the plant compared with laboratory mixtures.⁴⁸

In March 1968, the Port Authority investigated the adherence of Cafco Type D under field conditions. Based on letters from both USM and Mario & DiBono relative to an “on-the-job” application of Cafco spray-on insulating material in January 1968 to evaluate the ability of the material to adhere to the steel and to itself, the Port Authority was able to state that “this material can be applied successfully to the exterior steel under adverse weather conditions.”⁴⁹ The Port Authority transmitted⁵⁰ this information to the New York City Department of Buildings in January 1970 along with a USM report on the material and techniques in the application and the USM product catalog. Adhesion problems with Cafco Type D, however, were reported in December 1969 during construction of the World Trade Center.

In the 1990s, the bar joists of several floors were upgraded to have 1-1/2 in of fireproofing as tenants vacated their space. The Port Authority provided the information presented in Table 4 from Construction Audit Reports regarding the status of fireproofing upgraded as of 2000 in the

⁴⁵ Memorandum dated March 24, 1999 from Alan L. Reiss (Director, World Trade Department) to John Castaldo and Kent Piatt (Port Authority).

⁴⁶ Buro Happold Report “World Trade Center - Fire Engineering of Steelwork, Phase 1 Report,” February 2000.

⁴⁷ *Ibid.*

⁴⁸ U.S. Mineral Products Co., inter-office memorandum dated July 29, 1960 from F.M. Stumpf to R.E. Schelemmer.

⁴⁹ Memorandum dated March 6, 1968 from F.H. Werneke (Assistant Construction Manager, The World Trade Center) to R.M. Monti (Construction Manager, The World Trade Center)

⁵⁰ Letter dated January 14, 1970 from Malcolm P. Levy (Port Authority) to Joseph Ferro (Deputy Commissioner, Department of Buildings, New York, City).

aircraft impacted region of the WTC towers. Port Authority documents also state that the material used for the upgrade was Blaze-Shield II and not Blaze-Shield D C/F.⁵¹

The documents state that tests of upgraded fireproofing were performed in accordance with ASTM Standard E 605 “Standard Test Methods for Thickness and Density of Sprayed Fire-Resistive Material (SFRM) Applied to Structural Members” [Ref. 5] and ASTM E 736 “Standard Test Method for Cohesion/Adhesion of Sprayed Fire Resistance Materials Applied to Structural Members” [Ref. 6].

ASTM E 605 requires that thickness measurements be taken at “One bay per floor or one bay for each 10 000 ft², whichever provides the greater number of tests.” “Thickness determinations for the following structural elements shall be conducted in each randomly selected bay: one selected area of metal deck, concrete slab, or wall section; one column; and one beam (joist or truss).” For each preselected joist, one 12 in length should be laid out and seven thickness measurements taken at each end of the 12 in length. The seven measurements are to be taken at the web, top chord, and bottom chord of joists.

Table 4 documents the test date with the thickness, bond strength, and density for each test area on a given floor reported in the Construction Audit Reports provided by the Port Authority. The specified minimum requirements are 1-1/2 in for thickness, 150 psf for bond strength, and 15 pcf for density. The reported thickness for each test area, with few exceptions, is based on measurements taken from the “bottom of truss” only, deviating from the requirements of ASTM E 605. Since the audit reports do not include the details of the individual thickness measurements, it is not possible to determine if the procedures complied in other respects with ASTM E 605. There is no record of whether the top chord and bridging trusses were fireproofed throughout the floors in the upgrades. The data in Table 4 suggests that the minimum thickness requirement of 1-1/2 in and minimum bond strength requirement of 150 psf were met.

In 2000, Buro Happold, an engineering consultant was commissioned by the Port Authority to “conduct a fire-engineering assessment of the fire-proofing requirements of the open-web, steel joists that support the floors in the tenant areas of Towers 1 and 2 of the World Trade Center.”⁵² The report focuses on the requirements of the fire resistance of the floor system of the towers. This report stated that Cafco Blaze-Shield D C/F was used on the majority of the bar joists. Based on calculations and risk assessment, the consultant concluded that

- “The structural design has sufficient inherent fire performance to ensure that the fire condition is never the critical condition with respect to loading allowances.
- A single coat application is possible.
- Significant savings are possible.
- The target reduction of fiber content and increased long term durability can be achieved.
- Alternative materials should be considered.”

⁵¹ Memorandum related to Test of Fire Resistive Material from Construction Audit Reports dated November 24, 1999 from Dorian Bailey (Staff Services Engineer, Port Authority) to Edward McGinley (Port Authority)

⁵² Buro Happold report “World Trade Center - Fire Engineering of Steelwork, Final Report,” July 2000.

Table 4 - Recorded locations with upgraded fireproofing
(Data provided by the Port Authority)

WTC Tower	Floor Number	Specific Location / Tenant	Date of Report	Fireproofing thickness (in)	Adhesion/ Cohesion (lb/ft ²)	Density (lb/ft ³)
1	79	Multiple tenant floor	11/24/99	2.4	333	16.6
1	80	Multiple tenant floor				
1	81	Multiple tenant floor	10/24/96	2.7	270	19.0
1	81	Multiple tenant floor	7/16/99	2.3, 2.4, 3.0	352, 463, 315	17.4, 17.6, 17.4
1	83	Suite 8331	12/15/99	2.2	259	16.0
1	85	Multiple tenant floor	12/24/97	3.5, 2.9, 2.9	162, 180, 288	28.7, 23.7, 18.6
1	85	Multiple tenant floor	6/12/99	2.9	278	15.8
1	85	Multiple tenant floor Suite 8563	8/16/99	2.8	259	16.4
1	86	Julien Studley Inc. (7000 ft ²)				
1	92	Full floor	4/2/97	3.0, 2.8, 2.8	360, 324, 360	20.3, 15.4, 18.0
1	93	Full floor	8/28/98	1.8, 2.0, 1.8, 2.2, 1.8, 1.9, 2.9	117 (153) [†] , 207, 216, 234, 162, 180, 216	14.2, 16.6, 16.1, 18.4, 15.1, 17.4, 21.3
1	94	Full floor	12/27/96	4.3, 3.8, 4.3	486, 504, 288	21.2, 20.5, 20.1
1	95	Full floor	8/24/98	2.2, 2.4, 3.3	270, 306, 198	18.0, 20.1, 20.4
1	96	Full floor	10/22/98	3.0, 3.2, 3.2	486, 288, 324	20.5, 19.8, 19.9
1	97	Full floor	10/22/98	2.6, 2.2, 2.2	360, 468, 468	26.5, 20.0, 23.9
1	98	Full floor	11/19/98	2.9, 2.8, 2.5	407, 351, 518	31.3, 16.8, 19.6
1	99	Full floor	11/20/98	2.8, 2.2, 2.2	204, 222, 204	18.8, 16.6, 18.4
1	100	Full floor	11/20/98	2.8, 3.2, 3.4	278, 278, 333	16.4, 17.3, 19.9
1	102	Full floor	9/28/99	3.2, 3.2, 2.1	333, 333, 315	16.5, 16.9, 15.9
2	77	Full floor	6/9/98	2.7, 2.1, 2.6	351, 198, 297	19.4, 19.4, 17.2
2	78	Full floor	4/3/98	2.5, 2.8	288, 270	17.0, 18.1
2	88	Full floor	7/5/00	1.9, 2.4, 2.1	167, 333, 157	18, 16, 15
2	89	Full floor	5/5/99	2.8, 2.7, 3.0	370, 333, 270	22.4, 15.8, 15.3
2	92	Full floor	2/26/98	2.8, 3.0, 2.7	342, 360, 297	19.7, 21.1, 19.7
2	96	Full floor				
2	97	Full floor				
2	98	?				
2	99	Half floor	7/28/97	2.1, 3.0	315, 252	19.5, 22.7
2	99	Half floor	4/3/98	1.8, 1.7	306, 270	21.9, 19.5

[†] Repeated test

As quoted, the report states that significant savings could be possible by reducing the fiber content and considering alternative materials. The report suggested that the thickness of the fireproofing could be reduced to 1/2 in if the material properties are taken to be those at ambient temperature. The report recognized the lack of available temperature-dependent material data for Blaze-Shield D C/F. Thus, considering the uncertainties in the material properties and having the understanding of material degradation with temperature and time, Buro Happold recommended a thickness of 1.3 in of fireproofing for the bar joists.

Later, in December 2000, the final draft of the *Property Condition Assessment of World Trade Center Portfolio*, prepared by Merritt & Harris, Inc., was presented to the Port Authority⁵³. The report stated that, based on existing fireproofing conditions, “The rating of the structural fireproofing in the Towers and subgrade has been judged to be an adequate 1 hour rating considering the fact that all Tower floors are now sprinklered.” The report also noted the ongoing program, established by the Port Authority to upgrade the fireproofing thickness to 1-1/2 in in order to achieve a 2 hour fire rating.

Need for Fire Endurance Testing

The fire rating of structural materials and assemblies is determined through testing. In the United States, for example, fire rating may be determined in accordance with ASTM E 119, “Standard Test Methods for Fire Tests of Building Construction and Materials.” This standard was first published in 1917 as a tentative standard ASTM C 19 and was first adopted as ASTM E 119 in 1933. Since its introduction, the test method has been modified and updated many times, though its essential character has remained unchanged.

In the case of the WTC towers, the need to perform fire rating tests of the floor components was raised several times during the design stage as well as after completion of the towers. No evidence has been provided to NIST to indicate that a test was ever conducted to determine the fire endurance of the WTC floor system fireproofed with Cafco Blaze-Shield. The end-point criteria are an important consideration in assessing if an assembly passes or fails the test.

Early in 1965, the Port Authority requested its consultants to design a steel deck that when used with a lightweight aggregate concrete could pass a 3 hour test performed in accordance with ASTM E 119.⁵⁴ This correspondence stated that after completion of the design, the Port Authority would review the need for conducting fire testing of the floor deck.⁵⁵

In its response to the Port Authority, Worthington Skilling Helle & Jackson indicated that the proposed deck system for the towers would probably not meet the 3 hour endurance requirement although it would meet the minimum thickness requirements of the New York City Building Code.⁵⁶

The 4 in concrete slab over metal deck had 3 in penetrating electrical header ducts in the slab, floor inserts for electric and telephone raceways, and knock-outs for lighting. In 1966, ER&S wrote to the Port Authority that “with so many penetrations of the floor system the fire rating of

⁵³ *Property Condition Assessment of World Trade Center Portfolio*, prepared by Merritt & Harris, Inc., December 2000.

⁵⁴ Memorandum dated April 20, 1965 from Malcolm P. Levy (Chief, Planning Division, World Trade Center) to File.

⁵⁵ *Ibid*

⁵⁶ Letter dated April 26, 1965 from Leslie E. Robertson (Worthington Skilling Helle & Jackson) to Malcolm P. Levy (Chief, Planning Division, World Trade Center).

the floor construction is of an indeterminate value unless tested. It is doubtful if it will meet a 3 hour test.”⁵⁷

Regarding the fireproofing of the bar joists, a December 1965 letter from ER&S to the Port Authority indicated that the fire protection of the WTC floor system would involve “the use of a maximum thickness of one inch spray-on fireproofing material around the individual components of the floor trusses.”⁵⁸ It was further stated that

“one inch thick material meets the 3 hour requirements of both the new code and Underwriter’s [Underwriters’ Laboratories, Inc.] using previously approved assemblies tested by the ‘load criteria’ but ignoring the more stringent time-temperature-rate-of-rise criteria which is an alternate testing procedure not required by the new code or by Underwriter’s, and which we do not consider necessary.”⁵⁹

In the above statement, “time-temperature-rate-of-rise criteria” refers to end-point criteria based on maximum temperatures of steel in the structural component under test. While ER&S did not consider the alternate end-point criteria necessary, a study involving 18 fire tests of bar joists with concrete slabs and gypsum ceilings carried out at the National Bureau of Standards (NBS), now NIST, in 1954 [Ref. 7] stated

“Although not required by the ASTM Standard Test Methods, additional data were obtained relative to the following criteria, which have become *common practice* [italics added here for emphasis], apply to tests of ceilings or were considered of known interest:

- The times at which the main steel structural members attained average temperatures of 925 °F and 1000 °F at one level, or
- The time at which a main steel-structural member attained a temperature of 1200 °F at any one point.”

In the NBS tests, the behavior of the bar joist floor system made it challenging to determine the time at which the floor could no longer sustain the design load. Based on visual estimates of the rate of change on floor deflections or on how the hydraulic pressure varied in the loading system, the researchers established that the floor no longer sustained the design load once a 3 in deflection was reached. The bar joists had a span length of 13 ft-4 in, so the deflection-to-span ratio is 1.9 percent.

In 1965, when ER&S made the above statements, the latest version of the ASTM fire endurance test was the one adopted in 1961 (ASTM E 119-61) [Ref. 8]. Based on ASTM E 119-61, floors being tested should be loaded “in a manner calculated to develop theoretically, as nearly as practicable, the working stresses in each member contemplated by the design” while being exposed to the established temperature history. The floor assembly would pass the fire endurance test if it sustained the applied load and if the temperature on the unexposed surface (top of slab) would not rise more than 250 °F above its initial temperature, nor would there be passage of hot gases or flames through the slab.

⁵⁷ Letter dated July 25, 1966 from Harry J. Harman (ER&S) to Malcolm P. Levy (Port of New York Authority).

⁵⁸ Letter dated December 14, 1965 from Julian Roth (ER&S) to Malcolm P. Levy (Chief, Planning Division, World Trade Center).

⁵⁹ *Ibid*

Versions of ASTM E 119 since 1971 differentiate between testing thermally restrained and unrestrained floor assemblies. According to Appendix A4 of ASTM E 119-73, a restrained condition is “one in which expansion at the support of a load carrying element resulting from the effects of fire is resisted by forces external to the element.” In an unrestrained condition the element is free to expand and rotate at its supports.

While the conditions of acceptance for restrained assemblies is based on structural failure and temperature limitations on the unexposed surface of the slab, the conditions of acceptance for unrestrained floor assemblies are based on limitations in the temperature of the steel members, as well as the unexposed surface of the floor system, and the structural failure of the assembly.

For example, ASTM E 119-73 [Ref. 9] included among the conditions of acceptance for unrestrained floor assemblies with bar joists that the average temperature recorded by all joist thermocouples should not exceed 1100 °F during the classification period. Note that these maximum average temperatures differ from the NBS end-point criterion used in the 1954 test series.

Also in December 1965, ER&S notified the Port Authority that “one-inch thick spray-on fireproofing meets the 3 hour requirements of both the proposed Building Code and Underwriters,” however, “advanced information from manufacturers indicates that if the truss were required to be fire-tested, then two inches of material would be required for the light angle members.”⁶⁰

Fire Testing of a Similar Floor System

In 1970, a fire endurance test of construction similar to the WTC floor system was conducted and reported to W.R. Grace & Co., manufacturer of Monokote⁶¹. The fire endurance test was conducted by the Underwriters’ Laboratories, Inc. (UL) following the procedures of the ASTM E 119.

The test involved a floor system constructed with bar joists supporting a 2-3/4 in composite concrete slab. The bar joists were 10 in deep (Laclede composite joists type 10H5C), spaced 3 ft-6 in o.c. with a 16 ft-10 in span. The corrugated steel deck supporting the concrete slab was protected with 1/2 in of Monokote fireproofing while all the joist members were protected with 1-1/2 in of the same product. The floor assembly was loaded to provide a maximum working stress of 30 000 psi in the bar joists.

The floor assembly achieved a 3 hour fire endurance as certified by UL. The rating was based on the criteria of acceptance that required that the average temperature of the unexposed surface (top of the slab) not increase more than 250 °F above the initial temperature and that the system support the applied load. Temperature measurements of the steel indicated that 1200 °F (650 °C) was reached on the bottom chord of the bar joists within about 105 minutes. The diagonal webs reached 1200 °F in about 150 minutes.

⁶⁰ Letter dated December 23, 1965 from Julian Roth (ER&S) to Malcolm P. Levy (Chief, Planning Division, World Trade Center).

⁶¹ Report of 3 Hour Fire Endurance Assembly with Mono-kote Spray-Applied Cementations Fireproofing and Laclede Composite Joists dated July 1969 [March 1970] from Thomas P. Feit (Manager, Technical Services, Zonolite, W.R. Grace & Co.).

In addition, measurements showed that the floor assembly attained a 3 in deflection (1.5 percent of the 16 ft-10 in span) at 120 minutes and that it had sagged 4-3/4 in (or 2.4 percent) at 180 minutes.

As previously mentioned, in 1975, SHCR assessed the damage caused by the fire in WTC 1 and reviewed available documentation regarding fireproofing of the floor joists. In March 1975, the Port Authority provided SHCR with a copy of the UL fire endurance test using Monokote.

Based on the fire endurance of the floor system protected with Monokote and extrapolating from the thermal conductivities of Monokote and Cafco, SHCR justified the use of 1/2 in Cafco Blaze-Shield on the floor bar joists of the WTC towers to achieve a 2 hour rating. For the calculation, SHCR used 0.27 Btu·in/(h·ft²·°F) and 0.61 Btu·in/(h·ft²·°F) as the thermal conductivities of Cafco and Monokote, respectively.

SHCR stated, however, that the theoretical extrapolations from the results of Monokote's fire endurance to the 1/2 in of Cafco "must be viewed with caution."⁶² In the summary of the report, SHCR stated, "Without benefit of a full-scale fire test we cannot establish a rating for the floor assembly."

In 1966, ER&S, the Architect of Record, and in 1975, SHCR, the Structural Engineer of Record, stated that the fire rating of the floor system of the WTC towers could not be determined without testing.

Summary

This interim report documents the procedures and practices used for passive fire protection of the floor system of the WTC towers.

Early in the design phase (May 1963), the Port Authority adopted the New York City Building Code for the design and construction of the WTC towers. The 1961-1962 revision to the 1938 NYBC was in effect at that time. In September 1965, the Port Authority instructed its designers to revise plans to comply with the second and third drafts of what became the 1968 edition of the NYBC.

Because the New York City Building Code was being revised, the plans for fire protection of the structural steel underwent continuous modification. While available records that were reviewed suggest that the fireproofing of the columns, beams, and spandrels was not a subject of concern, fireproofing of the floor bar joists was the focus of continuous reassessment and revision.

The WTC towers were identified as occupancy group E – Business, and classified as Construction Class IB in accordance with the 1968 New York City Building Code. This classification required that the columns and floor systems of the towers have a 3 hour and 2 hour fire endurance, respectively.

In 1969, the fireproofing contract for WTC 1 and 2 was awarded. It is unclear if the thickness of spray-on fireproofing was made part of the original specifications.

The bar joists that supported the floors of WTC 1 were initially fireproofed with an asbestos-based spray-on material, Cafco Blaze-Shield Type D. No information about the required

⁶² Report on WTC Fire dated April 1, 1975 from SHCR to the Port Authority.

thickness was specified in either project specifications or drawings to achieve the required 2 hour rating. The Port Authority directed the fireproofing contractor to apply 1/2 in of fireproofing to the bar joists.

In 1970, Underwriters' Laboratories conducted an ASTM E 119 test of a joist-supported floor system, with a span shorter than what was employed in the WTC towers. This test was not related directly to the WTC construction and the tested floor assembly differed in several respects from that used in the WTC towers. Specifically, the trusses were 10 in deep, the slab was 2-3/4 in thick and the fireproofing was that of a different manufacturer.

While the floor assembly achieved a 3 hour rating based on structural capacity and temperature criteria for the unexposed surface, measurements indicated that the bottom chords of the trusses reached 1200 °F (650 °C) within about 105 minutes and the diagonal webs reached 1200 °F in about 150 minutes. In addition, measurements showed that the floor assembly sagged 3 in (or 1.5 percent) at 120 minutes and 4-3/4 in (or 2.4 percent) at 180 minutes. There is no record to suggest that the test results formed the technical basis for the fire protection requirements for the WTC floor system.

Documents indicate that the metal floor decking, bridging joists, and top chords of the main joists were not required to be fireproofed. Structural assessments performed by SHCR after the 1975 fire indicated that the steel decking, bridging joists, and the top chords of the main trusses were not fireproofed. The Port Authority, however, has informed NIST that the top chords of the main joists and the bridging joists were fireproofed. NIST is in the process of reviewing limited photographic evidence from inspections on floor trusses from different sources. The results of that review will be incorporated into an update of this report.

After fireproofing of the first 38 floors of WTC 1 was completed using asbestos-containing Cafco Blaze-Shield Type D, the fireproofing material was changed to Cafco Blaze-Shield Type D C/F, a non-asbestos product. There are no records specifying any changes in the thickness requirements to protect the bar joists using the new product, Blaze-Shield D C/F.

A few sample area data sheets, from surveys conducted in 1990 in support of litigation related to the asbestos-based fireproofing, reported that the fireproofing thickness on the joists was consistently about 1/2 in. Measurements taken in 1993 on two floors (Floors 23 and 24) of WTC 1 provide some quantitative data on actual applied thickness of fireproofing. Results indicate an average thickness of fireproofing from a relatively small sample (16 random bar joists from two floors out of total of 220 possible floors) to be 0.74 in, with a minimum average (of six measurements) value of 0.52 in and a maximum average value of 1.17 in for each of the tested bar joists. Four of the 32 bar joists had average thicknesses that varied between 0.52 in and 0.56 in. These measurements suggest that the minimum thickness exceeded 1/2 in.

By the early 1990s, both towers had been retrofitted with sprinklers as required by New York City Local Law No. 5, which was effective in 1973. Based on the 1999 revision of the NYBC, sprinklered buildings could be classified as Construction Group IA, IB, and IC. While it was possible to lower the fire rating requirements to Class IC, the towers remained classified as Class IB, according to a property condition assessment prepared by Merritt & Harris. Construction Class IC would have required the columns and floor systems of the towers to have a 2 hour and 1-1/2 hour endurance, respectively.

A study conducted by the Port Authority in 1995 concluded that 1-1/2 in of fireproofing was required for chords and web members. The Port Authority issued guidelines in 1999 for

fireproofing repairs, replacement, and upgrades adopting the 1-1/2 in thickness requirement for the bar joists. By 2000, about 30 floors had been upgraded. Floors 92-100 of WTC 1 as well as floors 77-78, 88-89, 92, 96-97 of WTC 2 had been upgraded. Construction audit reports suggest that the thickness requirements were met. Documents indicate that Blaze-Shield II was used for the upgrades, not Blaze-Shield D C/F.

In 2000, the Merritt & Harris property condition assessment concluded that the rating of the structural fireproofing in the WTC towers and subgrade provided an “adequate 1 hour rating” considering that the floors were sprinklered and that there was an ongoing program to upgrade the fireproofing thickness to 1-1/2 in. The same year, a study completed by Buro-Happold recommended a fireproofing thickness of 1.3 in on the bar joists to achieve the required 2 hour rating.

Problems with adhesion of Cafco Type D were reported during construction of the WTC towers. A more recent report also indicates that, in the majority of the cases, the existing fireproofing required so much patching that it was more effective to replace it with new fireproofing material. The construction audit reports associated with upgrading the fireproofing to 1-1/2 in thickness suggest that the minimum bond strength requirement of 150 psf was met. NIST has not received any records that document the shock, vibration, and impact properties of the specific fireproofing materials used in the WTC towers.

The fire protection of bar joist-supported floor system by directly applying spray-on fireproofing to the joists was relatively innovative at the time the WTC towers were designed and constructed. 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.

In 1966, ER&S, the Architect of Record, and in 1975, SHCR, the Structural Engineer of Record, stated that the fire rating of the floor system of the WTC towers could not be determined without testing.

There are no records that provide the technical basis for the amount and type of fireproofing material for the bar joists from the time of the original design. Specifically, the technical basis remains unknown for the selection of fireproofing material for the joists, and the determination of the thickness of fireproofing to achieve a 2 hour rating.

NIST continues to seek, receive, and review additional data related to the subject of this report. This includes maintenance and inspection records for the WTC towers from different sources, critical UL test reports for Cafco fireproofing products, and information on the ability of the fireproofing material to withstand shock, impact, and vibration. In addition, since nearly 40 years have elapsed from the initial design of the WTC towers and some documentation was stored in the towers, it is inevitable that some factual data have been lost or are missing from the documents reviewed by NIST.

NIST welcomes written comments from organizations or individuals possessing specific factual information related to the contents of this report. Such information may be sent to NIST via e-mail to wtc@nist.gov, fax to (301) 975-6122, or by mail to WTC Technical Information Repository, 100 Bureau Drive, Stop 8610, Gaithersburg, MD 20899-8610.

Specific types of information of interest that will help address outstanding issues include those related to fireproofing thickness requirements and the technical basis for such requirements, fireproofing of the bridging joists and top chords of the main joists, and fireproofing of the joist-

to-column seated connections and the joists in the vicinity of the connections. NIST will review all such information and update this report as needed.

NIST also intends to carry out testing to assess the fire rating and behavior of a typical fireproofed floor assembly under the fire conditions prescribed in ASTM E 119. In addition, information contained in this report (e.g., on fireproofing material and thickness, and fire rating) will be used in conducting the ASTM E 119 tests and to analyze thermal-structural response of the WTC towers. NIST also intends to compare the fire protection requirements of the NYBC with national model codes.

References

1. New York City Building Code (1968).
2. Administrative Building Code of the City of New York (1961-1962).
3. World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations. Federal Emergency Management Agency, May 2002.
4. New York City Building Code (2001).
5. ASTM E 605-93 "Standard Test Methods for Thickness and Density of Sprayed Fire-Resistive Material (SFRM) Applied to Structural Members."
6. ASTM E 736-00 "Standard Test Method for Cohesion/Adhesion of Sprayed Fire Resistance Materials Applied to Structural Members"
7. Ryan, J.V. and Bender, E.W. (1954) "Fire Endurance of Open-Web Steel-Joist Floors with Concrete Slabs and Gypsum Ceilings." *Building Materials and Structures Report 141*, National Bureau of Standards.
8. ASTM E 119-61 "Standard Test Methods for Fire Tests of Building Construction and Materials."
9. ASTM E 119-73 "Standard Test Methods for Fire Tests of Building Construction and Materials."

Appendix 4-A

Overview of Concepts Used in U.S. Building Regulations for Structural Fire Resistance

Origins and Intent

Prevention of fire-induced collapse of buildings is regulated generally through limits on the height and the area per floor as a function of the types and degree of fire resistance of materials used in the structural elements. These material characteristics are categorized as *types of construction*, e.g., Type I through V, and the associated limits are contained in so-called *heights and areas tables*, which are a cornerstone of most (prescriptive) building codes, worldwide.

The origins of the regulation of building construction are in insurance regulations developed in the late 19th century to limit property losses in fires [Ref. A.1]. Thus the intent of building height limits is to restrict taller buildings to non-combustible structural members and the greatest fire resistance (as measured in the ASTM E 119 test method) is assigned to members supporting multiple floors. The primary concern with combustible structural members is that they can become ignited by an exposing fire and can continue to burn (often in concealed spaces) even after the exposing fire has been extinguished, leading to collapse. The intent of increased fire resistance for members supporting multiple floors is directly related to the higher risk of property loss in the event of failure of multiple floors.

The other important height factor is the definition of a high-rise building. This is based generally on the height above which fire department ladders will not reach, requiring that fires be fought from inside, which is significantly less effective (and more dangerous for the firefighters). In an exterior attack, hose streams can be brought to bear from several sides and so-called master streams can apply large volumes of water. An interior attack is limited to hand-held hoses supplied from standpipes and working from interior stairways. Traditionally high-rise buildings have been defined as those that exceed 22 m (75 ft or 6 stories above grade) in height, but some newer codes increase this height to 30 m (100 ft) as modern fire department ladders are taller.

The intent of floor area limits is less obvious, but is generally attributed to limiting property risk and to limiting the size (area involved on any floor) of the fire to that which can be dealt with by the fire department, with the number of people and equipment typical of an initial response.

Construction Types

Construction types (or groups) are defined in the model building codes and in NFPA 220 [Ref. A.2] and, while there are some variations in categories, they are reasonably consistent. The main categories are Type I (fire resistive), Type II (non-combustible), Type III (combustible), Type IV (heavy timber) and Type V (ordinary).

Types I and II are constructed with non-combustible exterior and interior bearing walls and columns, where fire resistance ratings are greatest for Type I, and Type II is any (non-combustible) construction not meeting Type I requirements. Type III is where exterior bearing walls are non-combustible and interior bearing walls and some columns may employ approved combustible materials. Type IV is known as *heavy timber*, which utilizes large, solid cross section wooden members such as in post-and-beam construction. Type V is traditional wood

frame construction. Common non-combustible structural elements employ steel or reinforced concrete. Combustible structural elements are usually solid- or engineered-wood, and laminates.

Combustibility of the materials in the structural element is determined in accordance with ASTM E 136 [Ref. A.3] in which the material is placed in a furnace at 750 °C (a “typical” fire temperature). Some minor surface burning (e.g., from paint or coatings) is allowed in the first 30 seconds but there cannot be any significant energy released as determined by more than 30 °C (54 °F) increase in the furnace temperature, and the sample cannot lose more than half its initial mass. Materials that pass are designated non-combustible and the rest are combustible. In 1973, an in-between category of “limited combustible” was added to ASTM E 136 to regulate some structural materials.

Within each construction type are several sub-categories determined by the fire resistance ratings of the columns (vertical structural elements that support predominantly gravity loads), beams (horizontal structural elements that support predominantly live loads), and floor supports. In some codes these sub-categories are identified by letters following the type (e.g., 1B or 3A) [Ref. A.4] or by a set of three numbers that represent the fire resistance required (in hours) of the columns, beams, and floors, respectively (e.g., Type 1 (3,3,2)) [Ref. A.5].

Fire Resistance of Structural Elements

The building elements that support loads are to be protected against failure for a specified period (rating) when exposed to a standard ASTM E119 test. The intent of these code requirements is lost to history but recent development of performance-based codes has resulted in discussion of the current intent with regard to structural stability in fire. The intent is for the building to withstand design loads (including fire) without local structural collapse until occupants can escape and the fire service can complete search and rescue operations. Further, in high-rise buildings, local collapse is to be prevented while the fire service undertakes suppression operations.

With regard to total collapse, the intent of the code is for this not to occur for any design load (including design fires), but it is recognized that such might occur in an extreme event. In this case, it should not occur until the building has been evacuated of both occupants and firefighters.

The codes specify maximum fire resistance for columns and elements supporting multiple floors, and somewhat less resistance for columns supporting single floors, for beams, and for floors. For example, the NFPA Building Construction and Safety Code [Ref. 5] requires exterior bearing walls or columns supporting one or more floors to have the same fire resistance rating, but for interior bearing walls or columns the fire resistance rating is one hour less if only a single floor is supported. Historically similar requirements were found in the BOCA Basic Building Code and the SBCCI Standard Building Code. ICBO's Uniform Building Code and the successor⁶³ to the three model building codes, the International Building Code, incorporated the concept of a structural frame, discussed below.

⁶³ In January of 2003 the three (regional) model building code organizations, International Conference of Building Officials (ICBO), Building Officials and Code Administrators, International (BOCA), and Southern Building Code Congress, International (SBCCI) completed a merger into the International Code Council (ICC). As a part of this merger they agreed to cease publication of their individual model codes and to jointly develop and administer the International Codes.

The fire resistance times have been reduced in recent years as fire sprinklers have become universal in high-rise buildings and common in most other commercial buildings. Where high-rise buildings generally required a 4 hour rating for columns this has been reduced to three hours, and sometimes two hours, based on the parallel mandatory requirement for sprinklers. This reduction in fire rating requirements for structural components is usually referred to as “sprinkler trade-offs.” Some codes, such as the International Building Code and the New York City Building Code, allow a reduction in fire-resistance rating for high-rise buildings that have been retrofitted with sprinklers.

Structural Frame

As early as 1953,⁶⁴ the Uniform Building Code implemented the concept of a structural frame that explicitly identified the importance of beams and trusses to prevent buckling of columns in some structural designs. For example, the 1991 UBC [Ref. A.6] defined the structural frame as “... *the columns and the girders, trusses, and spandrels having direct connections to the columns and all other members which are essential to the stability of the building as a whole.*” Such elements were required to be fire protected to the same rating as the columns. This concept was carried into the International Building Code [Ref. A.4] as footnote a to Table 601, which states:

“The structural frame shall be considered to be the columns and the girders, beams, trusses and spandrels having direct connections to the columns and bracing members designed to carry gravity loads. The members of floor or roof panels which have no connection to the columns shall be considered secondary members and not a part of the structural frame.”

References

- A.1. Bukowski, R.W. (1997) Progress toward a performance-based code system for the United States, Proc FORUM Symposium on Fire Safety Engineering, Tianjin China, 6-7 October 1997.
- A.2. Types of Building Construction, NFPA 220, National Fire Protection Assn, Quincy, MA 02269.
- A.3. Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750 C, ASTM E136, American Society for Testing and Materials, West Conshohocken, PA 19428.
- A.4. International Building Code (2000) International Code Council, Alexandria, VA.
- A.5. Building Construction and Safety Code, NFPA 5000. (2003) National Fire Protection Assn., Quincy, MA.
- A.6. Uniform Building Code (1991) Section 1702, ICBO, Whittier, CA 90601.

⁶⁴ Jon Traw, private communication.

**Assessing the Most Probable Structural Collapse Sequence:
Integrating Impact Damage, Fire Dynamics,
Thermal-Structural Response, & Collapse Initiation**

Introduction

Structures subjected to extreme loads, such as blasts, high-speed impacts, and uncontrolled fires, experience a sequence of events that require complex analyses to determine the probable cause of failure. Analysis of these types of problems requires a formal approach to integrate multiple disciplines effectively, to discern which parameters significantly influence the analysis methods, and to 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:

1. What is the most probable collapse sequence?
2. What confidence levels are associated with the most probable collapse sequence?
3. What is the probability of other possible collapse sequences?
4. What parameters have the strongest influence on the most probable collapse sequence?

This paper presents a formal, integrated approach to identify the most probable of technically possible collapse sequences while accounting for uncertainties in modeling, input parameters, analysis, and observed events. This approach has been developed for use in the ongoing Federal Building and Fire Safety Investigation of the World Trade Center Disaster being conducted by NIST.

The following section summarizes the approach that combines mathematical modeling, statistical, and probabilistic methods to achieve the stated objectives. While the individual techniques are well understood, their integration and detailed implementation are to be refined on the basis of initial analytical findings and results. The development and calibration of simplified, accurate models for impact damage, fire dynamics, thermal-structural response, and collapse initiation analysis is required to enable robust, efficient estimation of uncertainties and collapse sequences in the available time frame and budget.

Similar approaches have been used in probabilistic risk assessment, or PRA, for nuclear power plants and other critical facilities (NUREG-1050, 1984). PRA uses models of plant processes and their combinations, coupled with models of uncertainty, to provide quantitative estimates of risk and to identify factors that contribute significantly to the risk. A typical 'prospective' PRA considers the probability of future extreme events, the system capacity over its expected life, and likely consequences or probabilities of failure. Risk assessment determines whether estimated probabilities of failure are acceptable for specific consequences or failure events. In 'retrospective' failure analysis, however, the consequences are known and the focus is on the actual failure sequence and its probable causes.

Assessment Methods

Method I: Mathematical modeling with mean-centered estimates of parameters.

This method provides an indication of a probable collapse sequence. In conducting a mathematical analysis, all parameter values must be defined and appropriate analytical and numerical tools selected. Experimental work may be required to determine some parameters

that cannot be defined based upon event data, available records, and engineering expertise. As an example, Appendix 5-A describes the types of parameters that are being considered in the investigation of the collapsed WTC buildings. However, a mathematical analysis does not evaluate the sensitivity of the probable collapse sequence to parameter values or the confidence level associated with the identified collapse sequence. The collapse sequence is evaluated by comparing how well it fits the observables. See Appendix 5-B for examples of collapse sequence hypotheses under consideration for the WTC Investigation.

Method II: Statistical analysis, using orthogonal factorial design methods.

This method significantly extends the mathematical modeling by identifying influential parameters and evaluating the sensitivity of the results (collapse sequence and time-to-failure) to ranges of parameter values using orthogonal factorial design methods (Box, Hunter, Hunter, 1978; NIST/Sematech). This method examines analysis results at extremes of parameter values. Ranges of parameter values are based upon experimental data, event observables, available as-built information and records, and engineering expertise. The observed event data, or observables, is used to constrain the analysis problem, improve the estimates of parameters, and evaluate results.

Method III: Probabilistic analysis, using event tree and Monte Carlo techniques.

This method uses event tree and Monte Carlo techniques (Melchers, 1999) for determining the probability of different collapse sequences, and the parameters that contribute to uncertainty propagation. Since these techniques start by quantifying uncertainty of input parameters and initial conditions, and propagate such uncertainty using mathematical modeling, they are generally referred to as uncertainty propagation methods. Uncertainty in parameters is estimated using experimental data, event observables, available as-built information and records, and engineering expertise. Systematic model uncertainties are identified and minimized to the extent possible.

Monte Carlo techniques consist of numerical experiments through repetition of an analysis, or series of analyses, using sets of parameters that are randomly generated from their estimated distributions. The frequency of a numerical result (a possible damage state, collapse sequence, or time-to-failure) out of the total number of simulations provides the probability estimate for that particular result. The most probable failure would have the highest relative frequency. This technique tends to determine results clustered around typical parameter values (the mode), with occasional extreme values in the randomly generated parameter set. The number of Monte Carlo simulations can be reduced by orders of magnitude, from tens- or hundreds-of-thousands to tens or hundreds, using sampling techniques. The sampling focuses analysis results in the region of interest, such as a particular damage state or collapse sequence, by limiting randomly generated parameter sets to ranges that produce results in that region. Observables are used in conjunction with Bayesian updating techniques, where computed results and observed events are compared, to improve the parameter distributions for the analysis.

Event tree models capture a chain of events through enumeration of possible branches, and the probabilities associated with each branch. Branches represent discrete changes in physical state associated with impact damage, fire dynamics, thermal-structural response, and the progression of collapse. While event trees are relatively straightforward for simple events, for more complex problems the ability to identify all possible branches, and assign probabilities to them, becomes strongly dependent upon knowledge about the events and expert judgment. Pruning of branches keeps the size of the event tree manageable, by eliminating branches that do not match observables. Rules for pruning are based upon how well analysis results match

observables. About ten branches are a suggested maximum for each node on the tree, so that the event tree assessment remains manageable.

Integrated Approach

This paper adopts an integrated approach to determine the most probable collapse sequence. It integrates mathematical modeling, statistical, and probabilistic methods that are adapted to each type of analysis – impact damage, fire dynamics, thermal-structural response, and collapse initiation. The ideal analysis outcome is an explicit component-by-component sequence of failure events. This is difficult to achieve given limits in knowledge about the event and in existing analytical tools. In practice, the most probable collapse sequence identified can be expected to adequately capture a level of detail greater than the description provided in Appendix 5-B, with information on likely sequences of failure of sub-systems and groups of components. A 3-step implementation strategy is summarized below and in Figures 5.1 and 5.2.

Step 1:

The first step evaluates each of the assessment methods by applying them to simple problems at the component level. Examples of component level analysis include the response of columns and trusses to impact damage and the dynamics of fire in a single compartment. This step begins the process of identifying some of the important parameters that influence the results and identifies failure mechanisms for components.

In addition, the orthogonal factorial design (OFD) technique and probabilistic methods are applied to all of the component level analysis problems. The effectiveness of the integrated assessment approach for each type of analysis is evaluated. The software tools available for the impact analysis, which model the entire impacted region with the failure criteria embedded in the tool, appear more suitable for initial assessment with the Monte Carlo technique. The tools for the fire dynamics analysis, which model single compartments and require use of technical criteria, event observables, and expert judgment in tracking the fire spread to adjacent compartments, appear more suitable for initial assessment with event tree techniques. This is also the case for thermal-structural response analysis, which mirrors the fire path and must reflect the discrete progression in loss of component stability and load redistribution, and for the collapse initiation analyses.

Step 2:

The second step applies the integrated assessment methods for each analysis to intermediate scale models, such as structural subsystems consisting of several stories or bays and fire spread to adjacent compartments. This step refines the integrated approach developed in Step 1 for identifying the most probable collapse sequence. It also leads to better identification of influential parameters, subsystem-level simplified models, failure mechanisms for subsystem models, and improved definition of possible collapse sequences.

Alternative model simplifications are developed and calibrated for the structural response to fire and impact loads based on the combination of detailed component and subsystem level analyses. Similar simplifications are developed and calibrated for fire dynamics by comparing the results of detailed computational fluid dynamics (CFD) simulations under different postulated interior geometries and fuel loadings.

Step 3:

The third step achieves the stated analysis objectives by implementing the integrated approach at full-scale. Full-scale assessment includes analysis of the event, from the moment of impact to

the initiation of collapse, with propagation of uncertainty to determine the most probable sequence of events leading to collapse initiation. To the extent possible, the simplified models developed and validated in Step 2 will be used for the full-scale analysis. If required, the simplified models are to be integrated with the detailed full-scale models to the maximum extent possible.

The *impact analysis* models the impact region to determine the probable damage state(s) of the structure, 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 analyses, such as fire dynamics and thermal-structural response. These damage states must be consistent with observed phenomena, such as exterior damage and stability of the structure subsequent to impact. Simplified analytical models based on energy and momentum conservation principles and lumped mass-spring systems will provide bounds on structural damage as an independent check on the numerical results. The number of full-scale simulations per structure is estimated to range from 10 to 30, assuming the Monte Carlo technique is applied with sampling. Trade-offs are to be made between highly detailed models (about 4 to 6 per structure) and a larger number of less refined models. The analysis identifies the 2 to 3 most probable damage states per structure.

The *fire dynamics* analysis determines 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 series of branches as the fire moves to adjacent compartments is related to boundary condition (geometry) changes and postulated interior fuel loadings. Examples of such changes include partition failure, ceiling collapse, or window failure. The analysis also considers fires initiating in multiple compartments and following different paths over time. Estimates of uncertainty of the fire spread and heat imparted to the structure are based upon full-scale analysis. The number of probable paths per structure is estimated to range from about 3 to 10. The analysis identifies the 2 to 3 most probable fire paths per structure.

The *thermal-structural* analysis determines the probable response time-histories of the impact-damaged structural system to the identified fire paths, accounting for cumulative heat-induced effects, 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. The time-history of the thermal-structural analysis mirrors the path of the compartment-to-compartment fire spread. Examples of branches for thermal-structural response include weakening or loss of lateral bracing to columns, connection failures, or member failures. The number of thermal-structural simulations for each of the 2 to 3 most probable fire paths is estimated to range from about 5 to 10. The analysis identifies the 3 to 5 most probable thermal-structural response time-histories per structure.

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. Branches for collapse initiation are influenced by the failure criteria used to determine the loss of component stability and the associated redistribution of loads. The stability checks are conducted at discrete times during the thermal-structural response analysis. Collapse initiation is tied to the rate at which components fail, especially those critical to overall stability. This analysis ranks the 3 to 5 probable collapse sequences and times to failure per

structure, from which the most probable collapse sequence is identified. It also identifies the predominant types of member and connection failures.

Selection of Parameters and Observables

The identification of influential parameters and the use of observables to validate the analyses are an important aspect of determining the most probable collapse sequence. No more than an estimated 5 to 10 influential parameters are expected for each of the four analyses – impact damage, fire dynamics, thermal-structural response, and collapse initiation. This would result in a total of about 25 to 50 influential parameters for the entire sequence of events. The number of influential parameters for each analysis will be determined in the second step of the integrated approach.

Observables about the event are obtained from photos, videos, and witnesses. Observables may be quantitative, such as the number of failed exterior columns, or qualitative, such as descriptions of smoke movement.

Steps 1 and 2 provide procedures for using observables in the assessment methods. They include identifying the range of parameter values, pruning branches of event trees that do not simulate observed events, or Bayesian updating of probabilities.

In Bayesian updating, analysis results are evaluated against observables and parameter estimates are improved through a consistent, formal process. Analysis results, based upon the initially estimated parameter distributions, are compared to observed events. If there is a significant difference, the parameter distribution is modified to reflect this new knowledge. The updating process considers the probability of the observables occurring under the initial parameter distribution.

References

Box, G.E.P., Hunter, W.G., Hunter, J.S., “Statistics for Experimenters: An Introduction to Design, Data Analysis, and Model Building”, John Wiley & Sons, 1978

NIST/Sematech, “Engineering Statistics Handbook”, Chapters 4 and 5, <http://www.itl.nist.gov/div898/handbook/index.htm>

NUREG-1050, “Probabilistic risk assessment (PRA) reference document,” *Report NUREG-1050*, U.S. Nuclear Regulatory Commission, Washington, DC, 1984.

Melchers, R.E., “Structural Reliability Analysis and Prediction”, Second Edition, Chapters 3 and 5, John Wiley & Sons, 1999

Selected Bibliography

Buchanon, A., “Structural Design for Fire Safety,” John Wiley & Sons, pp. 174-182, 2001.

Drysdale, D., “An Introduction to Fire Dynamics”, Second Edition, John Wiley & Sons, pp.361-367, 1998.

Levine, H., Tennant, D., Lawver, D., Levy, M., and Abboud, N., "Simplified and Advanced Methodology for Determining the Response of Buildings to Aircraft Impact," Structures Congress and Exposition, American Society of Civil Engineers, Seattle, Washington, 2003.

McGrattan, K.B., Baum, H.R., Rehm, R.G., Hamins, A., Forney, G.P., Floyd, J.E., and Hostikka, S., "Fire Dynamics Simulator (Version 3) - Technical Reference Guide", Nat. Inst. Stds. and Tech. Report NISTIR 6783, Dec., 2002.

Quintiere, J.G., "Fundamentals of enclosure fire zone models", J. Fire Protection Engineering, Vol. 1, pp. 99-119, (1989).

Riera, J. D., "A Critical Reappraisal of Nuclear Power Plant Safety Against Accidental Aircraft Impact," Nuclear Engineering and Design, Vol. 57, pp. 193-206, 1980.

Siegel, R. and Howell, J.R., Thermal Radiation Heat Transfer, Third Ed., Hemisphere, Washington, D.C., pp. 699-722, (1992).

Figure 5.1: Development of Integrated Assessment Approach

Step 1: Evaluate Separate Component Assessments

Analysis	Model Scale	Assessment Method	Purpose
Impact Damage	Columns & trusses	Evaluate OFD + Monte Carlo	Begin to identify influential parameters Determine effectiveness of individual & integrated methods Determine failure mechanism for components
Fire Dynamics	Single compartment	Evaluate OFD + Event Tree	
Thermal-Structural	Columns & trusses		
Collapse Initiation			

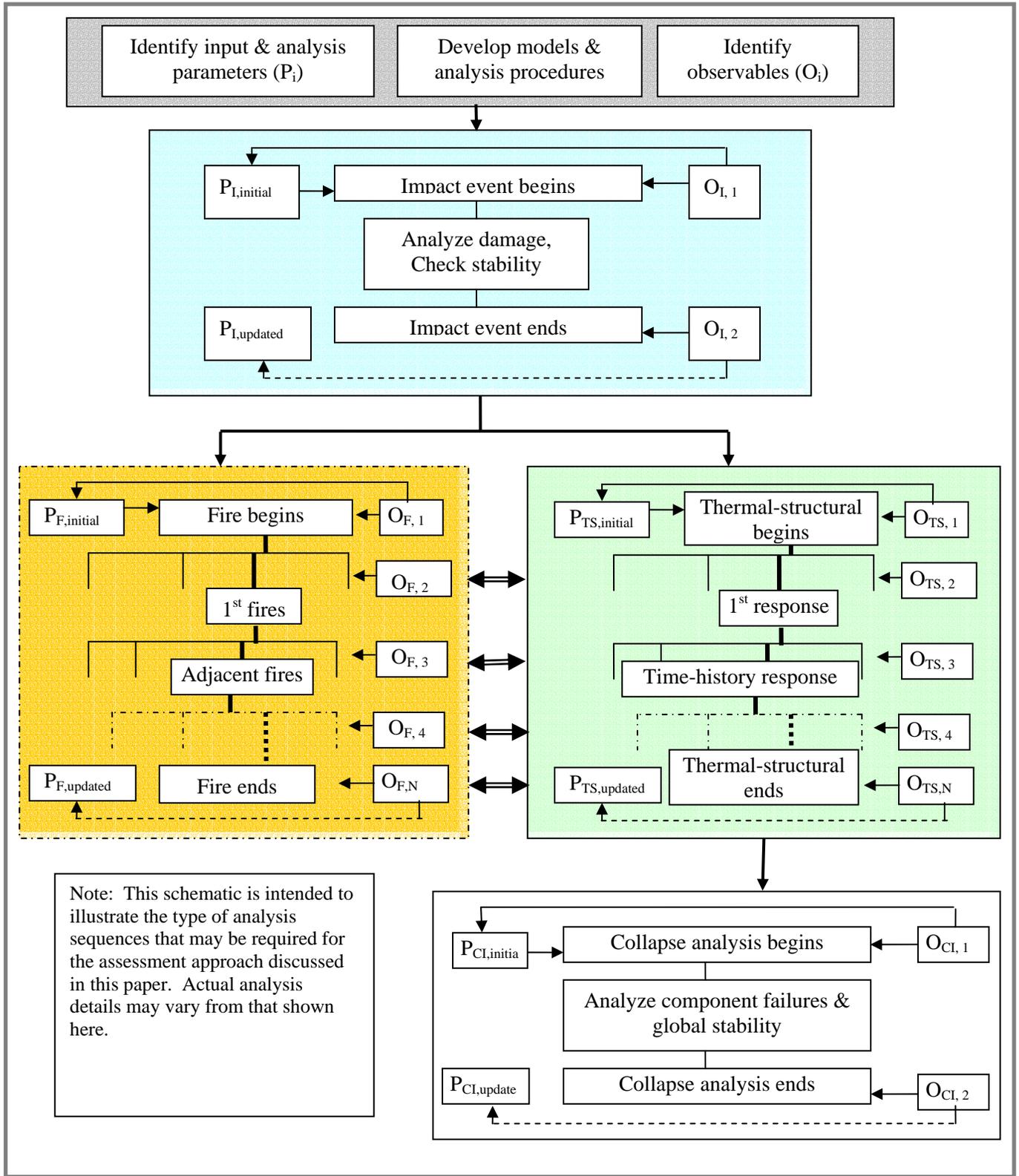
Step 2: Evaluate Integrated Intermediate Assessments

Analysis	Model Scale	Assessment Method	Purpose
Impact Damage	Several stories / bays of structure	Evaluate integrated approach for individual and series of analyses, using: OFD Monte Carlo Event Tree	Refine integrated approach for assessment
Fire Dynamics	Adjacent compartments		Improved identification of influential parameters
Thermal-Structural	Several stories / bays of structure		Simplified subsystem models
Collapse Initiation			Determine failure mechanisms for sub-systems Improved definition of possible collapse sequences

Step 3: Apply Integrated Full-Scale Assessment

Analysis	Model Scale	Anticipated Analyses & # Probable States	Purpose
Impact Damage	Impact region	10-30 analyses/structure ↓ 2-3 damage states/structure	Identify most probable collapse sequence & time-to-failure
Fire Dynamics	Impact region & fire spread compartments	3-10 fire paths/structure ↓ 2-3 most probable/structure	
Thermal-Structural	Impact region & fire spread compartments	5-10 T-S analyses/fire path ↓ 3-5 most probable/structure	Determine confidence level for most probable collapse sequence
Collapse Initiation	Impact region to roof	Ranks 3-5 most probable collapse sequences/structure	Identify other possible collapse sequences ID most influential parameters

Figure 5.2: Modeling the Sequence of Events



Appendix 5-A: Balanced Use of Analytical, Experimental, and Numerical Tools

NIST is using a balance of analytical, experimental, and numerical tools to support or refute possible collapse hypotheses. Among the key factors being considered are:

- the speed, direction, orientation, and point of impact of each aircraft;
- the dispersion of the jet fuel following impact;
- the mass, nature, and locations of other combustibles, including building furnishings and those from the aircraft interior and cargo bays;
- the mass of the steel, concrete, heavy machinery, and non-structural building materials and contents, that shared in absorbing the energy during aircraft impact;
- the effects of debris fragments on the structure, fireproofing, interior partitions, and other building systems, and gravity effects in providing structural stability;
- the performance of the steel components at high strain rates during aircraft impact and at elevated temperatures during subsequent fires, and the associated failure criteria;
- the performance of the fireproofing at high temperatures, and the extent to which the fireproofing may have been missing or knocked off during aircraft impact; and
- the growth and spread of fire and the resulting temperature of the structural steel as a function of time and location.

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

- the fire load provided by the building contents, jet fuel and combustible aircraft contents (WTC 1 & 2), and fuel storage tanks (WTC 7);
- ventilation available for combustion; and
- inter-compartment 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. These studies include:

- the mechanical properties of steel at high strain rates and at high temperatures;
- the thermal-insulation properties of the fireproofing materials and their resistance to shock and impact loads;
- fire tests to study the floor truss-to-column connections and shear transfer between the steel truss and the concrete deck in the composite floor system;
- fire tests in large compartments (12 ft x 12 ft x 24 ft) to measure the heat release and transfer rate to compartment gases and steel specimens (with and without fireproofing);
- office work station fire tests, based on descriptions of furnishings used in WTC 1 office space, to generate a data base on the thermo-physical properties of the materials for 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; and
- fire endurance testing of a typical floor system and individual steel members under the fire conditions prescribed in ASTM E119.

Appendix 5-B: Collapse Sequence Hypotheses and Considerations

The collapse sequence hypotheses under consideration for the WTC Investigation (http://wtc.nist.gov/media/progress_report.htm) recognize that aircraft impact caused damage to perimeter and interior columns and to floor systems. While the full extent of this damage is unknown and can only be estimated through analysis, it led to redistribution of the building loads among the columns (e.g., from the damaged columns to the undamaged columns, aided by the hat truss at the top of the towers) and with the floor systems.

There are several leading hypotheses that have been postulated publicly by experts for the structural collapse sequence between the aircraft impact and the collapse of each WTC tower. These are summarized below to provide context for the subsequent discussion.

One hypothesis suggests that the load carrying columns were weakened by the fires and failed, initiating overall building collapse without the need for any weakening or failure of the steel truss floor system. Another hypothesis suggests that significant portions of one or more floor truss systems sagged, as they were weakened by fires, pulling the columns inwards via the connections to initiate overall building collapse through combined compression and bending failure of the columns. A variation of this hypothesis suggests that the sagging floor system failed in shear at its connections to the columns, leading to overall building collapse initiation through buckling failure of the columns. Load eccentricities introduced by partially damaged floor systems could also have contributed to buckling failure of the columns. Combinations of these hypotheses present other possibilities, including the relative roles of the perimeter and core columns

Based on an initial assessment of these hypotheses, including the studies conducted as part of the insurance litigation and other relevant data, NIST considers it premature to exclude any of the postulated hypotheses. 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 observed behavior. First, neither tower collapsed immediately upon aircraft impact. Second, the buildings collapsed only after fires had burned and advanced through the buildings for about 56 minutes in the South Tower (WTC 2) and about one hour and 42 minutes in the North Tower (WTC 1).

Any analysis that suggests rapid loss of stability or collapse without the need for a sustained fire would favor a critical collapse-initiating role for structural components damaged by aircraft impact (e.g., columns) and a lesser role for components weakened by fire (e.g., floor trusses and connections). Likewise, any analysis that delays loss of stability to well beyond the observed time-to-collapse for each tower would favor a critical collapse-initiating role for

structural components weakened by fire and a lesser role for components damaged by the initial impact of aircraft.

Further, any analysis must explain the difference in the times to collapse of the two WTC towers, considering factors such as details of the aircraft impact (e.g., speed, height of impact above ground, position and orientation with respect to the building and its core) as well as the condition of the fire protection systems (e.g., thickness and extent of fireproofing, and operation of sprinkler system).

Data Collection Methodology for World Trade Center Evacuation and Emergency Response: Telephone Interviews, Face-to-face Interviews, Focus Groups and Population Sampling

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1. Background

The goal of the National Institute of Standards and Technology's World Trade Center Investigation is to investigate the building construction, the materials used, and the technical conditions that contributed to the outcome of the World Trade Center (WTC) disaster. The results of the Investigation will serve as the basis for improvements in the way buildings are designed, constructed, maintained, and used; improved tools, guidance for industry and safety officials; revisions to codes, standards, and practices; and improved public safety. The primary objectives of the NIST-led technical investigation of the WTC disaster are to:

1. Determine why and how WTC 1 and 2 collapsed following the initial impacts of the aircraft and why and how WTC 7 collapsed;
2. Determine why the injuries and fatalities were so high or low depending on location, including all 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; and
4. Identify, as specifically as possible, areas in building and fire codes, standards, and practices that are still in use and warrant revision.

The NIST Investigation Plan can be found at <http://wtc.nist.gov>, including a description of Projects 7 and 8. Under Project 7, "Occupant Behavior, Egress, and Emergency Communications," first-hand accounts of the events of September 11, 2001 from inside WTC 1, 2, and 7 will be collected. This data collection effort will evaluate the role of occupant behavior and evacuation technologies and practices for tall buildings, including decision-making and situation awareness, time-constrained evacuation strategies, communications, role of floor wardens and fire safety directors, and issues concerning people with disabilities. Additionally, NIST will seek specific observations of fire and smoke conditions and/or structural damage from within the building. Families of the victims, who communicated with loved ones inside the Towers before collapse, will be interviewed to determine the nature of the environment above the floors of impact.

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The nature of the communications between and among different groups within the World Trade Center has been identified as being a potentially significant factor in determining the outcome of the evacuation and emergency response. The project will investigate the content and timing of communications among the occupants and authorities within the buildings, as well as people outside the buildings. The figure below, a hypothetical demonstration of the extraordinary flow of information on the morning of September 11th, reinforces the need to understand the role of information transfer in explaining occupant and responder actions. In addition to the intergroup communications, communications within each group, particularly the building occupants, are potentially important to understanding the events of September 11th.

Emergency Communications



The objectives of Project 8, “Fire Service Technology and Guidelines,” are to build upon work already done by the Fire Department of New York (FDNY) and McKinsey & Company by: (1) fully documenting what happened during the response by the fire services to the attacks on the World Trade Center, up to the time of collapse of WTC 7; (2) identifying issues that need to be addressed in changes to practice, standards and codes; (3) identifying alternative practices and/or technologies that may address these issues; and (4) identifying R&D needs that advance the safety of the fire service in responding to massive fires in tall buildings. Thus, a subset of the emergency responders who were present at the World Trade Center complex will be asked to voluntarily participate in the face-to-face interview or focus group phases of this project. Only first responders who participated in fire suppression, operational, or search and rescue activities prior to the building collapse will be considered for inclusion in the population of face-to-face interviews.

The data collection will be conducted by a yet-to-be-selected contractor and is planned to begin as soon as the necessary pre-work is complete. This includes preparation of the telephone interview schedule, face-to-face interview protocol, focus group protocol, training of contractor

staff, and approval by NIST and the appropriate Institutional Review Board (IRB) to assure compliance with federal requirements for the protection of human subjects. NIST will use established procedures to review all survey and interview questions, data collection methods, and safeguards for maintaining privacy and confidentiality of all instruments before proceeding with these critical data collection efforts.

Note that this paper identifies specific populations and the size of samples to be included in the data collection effort. The exact numbers and populations may be modified to better suit the Investigation as additional details of the methodology are finalized by NIST and the yet-to-be-chosen contractor.

2. Overview of Methodological Approach

A multidisciplinary, triangulated approach, including telephone interviews, face-to-face interviews, as well as focus group interviews has been selected. The multi-methodological approach was selected for several reasons. First, multiple methodologies increase confidence in the conclusions and findings when more than one methodology arrives at the same conclusions. Second, the varied objectives of the Investigation mandate complementary approaches to accomplish all the goals. Finally, concerns associated with the time latency since September 11, 2001 suggest the use of different approaches and techniques in order to increase memory recall and accuracy. A discussion of each methodology and statistical sampling will follow.

NIST intends to solicit experienced contractors to perform the telephone interviews, face-to-face interviews, and focus groups. The contractor will meet or exceed all Federal requirements regarding the Common Rule for the Protection of Human Subjects,¹ including Institutional Review Board (IRB) and NIST approvals. The objective is to perform up to 600 face-to-face interviews of occupants from areas of interest, approximately 150 face-to-face interviews of first responders using selected groups, approximately 800 telephone interviews covering selected floors of WTC 1 and WTC 2. Additionally, NIST will contract for the conduct of up to 10 focus group sessions with first responders, including the Fire Department of New York (FDNY), the New York City Police Department (NYPD), the Port Authority Police Department (PAPD), or other groups identified as having operational or command authority at the World Trade Center on September 11, 2001. Finally, up to five focus group sessions will be conducted with selected building occupants and management. Interviewers and moderators will be thoroughly trained in data collection protocols and procedures, study scope and intent, as well as an understanding of the events September 11, 2001 at the World Trade Center.

2.1 Telephone Interview Format

One of the data collection instruments is the telephone interview. The collection mechanism will be a computer-assisted telephone interview. The primary goal of the telephone interview is to provide qualitative and quantitative occupant behavior and egress data which can be generalized. A secondary goal will be to provide unique, investigative observations, particular to the events at the World Trade Center on September 11th. The telephone interview schedule (script) will be closely linked to the evacuation experience of the occupants.

The questions will flow in a logical order in relation to the chronology of the events, as suggested in the literature.^{2,3} Significant topic areas proposed for the telephone interview include, but are not limited to: occupant demographics and inherent traits, chronology of occupant activity, observations and perceptions during evacuation, and environmental, social, psychological, physiological, information, frequency, and source attributes. As the precise

content of the telephone interviews, face-to-face interviews, and focus groups has not yet been established, these factors are subject to review and change.

NIST will follow standard telephone interview construction techniques.⁴ These techniques suggest that the project team identify the scope and objectives of the telephone interview schedule. The question type and format which best accomplishes the scope and objectives will then be selected. The first draft of the telephone interview schedule will then be reviewed and revised. Cognitive and pilot testing of the telephone interview with the informants will then occur. After further revision, the procedures to administer the study will be specified.

The persons who were in WTC 1 and 2 immediately prior to the first aircraft impact on September 11, 2001, will constitute the population to be sampled in this study segment, hereafter, to be referred to as the “selected floors study.” The sampling plan of the September 11, 2001 occupants is a multi-stage statistically representative sample with two stages. The first stage will stratify floors by area, population, and number of tenants. The second stage will select occupants from the floors selected in the first stage.

Stratifying the population. Stage one is an area sample of floors. The first stratification criterion is Tower 1 or Tower 2. The second stratification criterion is height. WTC 1 and 2 will be segmented into three zones according to the location of the mechanical floors. These zones will approximately represent the top (floors 77 – 91 in Tower 1 and floors 77 – 107 and 110 in Tower 2), middle (floors 43 – 74 in Towers 1 and 2), and lower (floors 9 – 40 in Towers 1 and 2) thirds. The third stratification criterion is tenant size. The tenant size criterion represents a floor as one of two levels: large tenant floor (a single tenant occupies greater than 40% of the usable square footage of a floor) or small tenant floor (all other tenant-occupied floors). The second stage is a random sample without replacement of occupants from the floors selected in the first stage.

Enumerating the population. A population list of all the people in each of these 6 building strata immediately prior to first impact on September 11, 2001 will then be enumerated. It is estimated that a total of 10 000 to 14 000 people were inside WTC 1 and 2 at the time of the first impact,⁵ and there are unsubstantiated accounts of between 4000 and 5000 persons in WTC 7 on the morning of September 11th. For the purposes of sampling and estimation of the number of telephone interviews, face-to-face interviews, and focus groups, this project will assume an initial population of 18 500 occupants. NIST will provide to the contractor an enumeration of persons on the selected floors.

Selecting the sample. The sampling plan for the selected floors study will be constructed such that a total of 800 telephone interviews are obtained from people included in the study. It is assumed that there will be an approximate 30 percent participation rate among those asked to participate. 800 interviews will ensure a 0.05 level of significance and power of 0.80.⁶ The contractor will make every effort to increase participation above 30 percent.

Data collection. This segment of the study will use a computer assisted telephone interview to obtain data from those who choose to participate in the study.

2.2 Face-to-face Interview Format

The objective of the face-to-face interview segment is to gather first-hand accounts and observations of the activities and events inside the buildings on the morning of September 11th. This approach will identify unknown information, evaluate technical hypotheses, and explore conscious and subconscious motivations for occupant and responder behaviors, while allowing

for qualitative comparisons to the telephone interview data. It is estimated that the average face-to-face interview will last approximately two hours, with some lasting significantly longer.

The proposed methodology for the face-to-face interviews is a synthesis of the Behavioral Sequence Interview Technique (BSIT) originally developed by Keating and Loftus,⁷ and the Cognitive Interviewing Method (CIM), originally developed by Fisher⁸ and Geiselman.⁹ These two interviewing methodologies were developed with the purpose of assisting persons in retrieving more comprehensive and accurate memories of incidents, and sharing important attributes. Both approaches begin by allowing the informant to retell an unimpeded account without interruption from the interviewer, and both initially employ a chronological retelling of information. However, BSIT was designed to yield a database of qualitative information that could be subjected to systematic analysis and consolidation, while CIM was designed to facilitate investigative interviews. Since the Investigation is pursuing both goals (i.e., creation of a database of evacuation-related behaviors and an investigatory attempt to capture information relevant to outcomes), the proposed methodology combines these two approaches.

Cognitive interviewing has been the subject of many empirical investigations. Fisher, et al.¹⁰ summarized these findings, demonstrating that the methodology significantly increases the amount of information recalled without affecting rate of errors. Interviewing a large number of informants will allow corroboration of information, thereby compensating for the likely increase in the absolute number of errors. Accordingly, it is likely that this approach will be productive in achieving a holistic view of the building evacuations.

The face-to-face interview methodology, hereinafter referred to as the “areas of interest study,” will involve face-to-face interviews of occupants and first responders who may have, knowingly or unknowingly, observed events important to the completion of the Investigation. The face-to-face interview methodology will be modified as appropriate for interviews of family members of victims who communicated with loved ones inside WTC 1 or 2.

Enumerating the population. The population will include the entire occupant, management, and first responder population of World Trade Center WTC 1, 2, and 7.

Selecting the sample. The areas of interest sample will identify individuals using the snowball quota sample approach whose constituency may resemble individuals selected for the “Specialized Groups Study” sampling methodology (see below). A snowball quota sample approach asks individuals for the names of other people who may meet the selection criteria for the study. These people are subsequently contacted and asked the same question. The process continues until the quota has been reached. The goal is to perform approximately 600 face-to-face interviews with occupants, 30 face-to-face interviews with family members who communicated with victims inside the building during the event, and 150 first responders. The 150 first responders will be divided among the Fire Department of New York (firefighters, company officers, and operational command officers), Port Authority Police Department, New York Police Department, and other responsible parties. Additional individuals may be randomly selected from strata previously defined in the whole buildings study in order to compare the face-to-face interview results with the results of the telephone interviews.

Data Collection. The face-to-face interviews will follow a four step technique, including unimpeded, open-ended narrative, a structured narrative, and technical probes. Each step is described more fully below.

Step 1: Unimpeded open-ended narrative account. Both BSIT and CIM begin the process by asking the participant to chronologically recount his or her “story.” The proposed starting point is when it became apparent that something unusual had occurred on the morning of September

11, 2001. The proposed ending point is when the participant feels that he or she reached a location where they felt safe (or, alternatively, when he or she successfully reached the exterior of the building). Researchers and practitioners involved with cognitive interviewing believe that starting the face-to-face interviews in this manner both improves recall and helps build rapport between the participant and the interviewer. Fisher et al.⁸ also noted that asking questions may interfere with recall because a participant must divide his or her mental resources between recall and listening to the interviewer's questions.

During the open-ended narrative account, the interviewer can record notable information that can be used for the probing phase conducted later. For example, the participant might briefly mention an odd odor to which the interviewer will want to return to determine whether the smell might have been that of jet fuel, smoke, or of some other origin as yet unknown.

Step 2: Structured narrative account. After participants complete their stories, interviewers will prompt them to go through the story again, but this time they will work cooperatively with the interviewer to record entries into a table. This approach is employed by BSIT for three primary reasons: (1) to yield a structured account that can be entered into a database without further processing; (2) to avoid the biasing effects of having interviewers ask specific questions; and, (3) to enhance the effort at recall put forward by participants by encouraging their active collaborative participation, an advantage to open-ended formats as noted by Fisher, et al.⁸ Each row of the table will represent a single action in a sentential format, meaning that each action is expressed as a grammatical sentence. The approach is based on the hypothesis that people encode episodic memories in a manner consistent with this format, thus facilitating both recall and data entry. Each column of the table represents three essential components of actions: a cue, an action, and the reason for taking that action. Cues can be either external (e.g., signs of a fire, someone saying something) or internal (e.g., remembering about another means of escape.) Actions are expressed using specific action verbs (i.e., “ran” instead of “went”) and may include artifacts (e.g., a fire extinguisher) used by the informant. Reasons are the intentional, goal-directed base for the action. The interviewer will encourage the participant to use their own words to the greatest extent possible.

A hypothetical example of actions recorded in this manner is:

Cue	Action	Reason
I heard but couldn't see someone yell "I've found a clear path"	So I stumbled in the dark towards where I thought the voice came	So that I could find a way to escape
My path was blocked by debris	So I called out to whoever yelled, "I'm near the reception area. Where are you?"	To try to get a better idea about where the person was

Table 1: Example Tabular Face-to-face interview Data Entry

Experimental findings in psychological research on memory¹¹ suggest that when people perform actions, their abilities to verbally recall those actions are significantly improved. Script theory¹² suggests that people naturally organize their knowledge of actions using narrative sequences of actions structured around their pursuit of goals. However, gaps in the narrative are anticipated, especially given the long period of time that will have elapsed between the event and the

interview. Interviewers will assist the participants to fill in these gaps by asking them to recall events in reverse order, an approach used in CIM. Interviewers will, however, encourage participants to report only those memories about events or incidents which they are confident really occurred to them.

Step 3: Probing for specific information. After completing the structured narrative account, interviewers will ask specific open-ended questions (probes) intended to provide specific information of particular value to the investigation. While some of this information is likely to be part of the structured narrative account, participants may be able to recall other valuable information as well.

Interviewers may use “context reinstatement” from CIM to improve recall of important information, because laboratory experiments have demonstrated that contextual cues enhance recall of related information. Fisher et al. explain that context reinstatement may enhance recall because people use multisensory coding of events. Using this mnemonic method, interviewers will ask participants to “mentally recreate the external environment, and their affective, physiological, cognitive, and emotional states that existed at the time of original event.”⁸

Depending on the population, probes may be used to try to elicit information including, but not limited to:

- Location of the informant at the time of certain marker events (e.g., location in WTC 1 when WTC 2 collapsed)
- Fire conditions (e.g., fire and smoke);
- Other cues of interest (e.g., the smell of jet fuel);
- Presence and activities of persons with disabilities;
- Use of elevators by self or others; and,
- Knowledge of any obstacles to their progress while using the stairs.

Because information about many of these areas of concern requires precise responses, questions for open-ended probes will be developed collaboratively between the contractor and NIST. Responses to probes may be recorded using standardized formats where feasible. For example, all participants who observed smoke may be asked to estimate the smoke density using an encodable scale, such as visibility distance.

2.3 Focus Groups

The goal of the focus group interviews is to elicit accurate group representations of specific events or themes. Williams¹³ reports that in a group setting, people provide cues that evoke memories in others, and that social pressures mediate against reporting misrepresentations of what they recall. Two distinct populations will voluntarily participate in the focus groups: occupants and first responders. The first set of focus group interviews will be the occupant sample. Distinct categories of people will be selected for inclusion in this study, hereafter referred to as the “specialized groups study.” The objective of this study is to capture the experience of people in unique places in WTC 1, 2, and 7. These groups will be defined by the NIST Investigation team. Every effort will be made to include no less than 5 people in each of these categories in this study, with 10 people constituting the preferred focus group size. NIST anticipates conducting approximately 5 occupant focus groups.

First responders will constitute a second set of focus group interviews. The set of first responders will include FDNY, NYPD, PAPD, and other groups identified as having operational or command authority at the World Trade Center on September 11th. The focus group size will

be determined as an operating unit size, if applicable. An operating unit may be a Fire Department company, for example. This project proposes 10 focus groups, each containing 5 people.

Sample selection. The people selected for inclusion in this study will be selected using non-probability sampling procedures. The contractor will use a snowball quota sample.^{14,15} Respondents contacted or face-to-face interviewed for other reasons will be asked to provide the names and contact information for people they know in each of the categories in the specialized groups study. Names will be collected by the contractor until at least 5 people in each category have agreed to participate in an occupant focus group, with a preference for 10 people. The same process will occur for selection of the first responder samples, with a preference for inclusion of entire operating units (about 5 people per unit).

Data collection. Focus groups will be conducted with the members of each group selected for inclusion in each of the specialized categories included in this study segment. The data collected in this study will produce qualitative and detailed narrative accounts of the experiences of each category of people. The focus group discussion will be moderated by a trained and experienced contractor.

3. Database

The contractor will provide to NIST at the conclusion of the project a database of encoded survey results. Each telephone interview, face-to-face interview and focus group will result in an encoded table of results which can be analyzed using standard data analysis techniques, such as averages, multivariate regression, and statistical significance. The specific identity of the encoding variables will be generated jointly by the contractor and NIST and is subsequent to the actual content of the survey instruments, which will also be developed by the contractor, subject to input and approval from NIST. The number of encoding variables is anticipated to be less than 75. This database will need to be consistent with an analysis of third-party and media accounts which NIST will generate and code independently of any contractors. Analysis of all data and any conclusions derived therein will be the sole responsibility of NIST. However, it is anticipated that a database expert from the survey contractor will assist NIST after database delivery in developing an understanding of the structure, architecture, limitations, and use of the database.

4. Latency and Accuracy of Recall

The accuracy of participants' memories of events is a consideration, especially given the period of time that will have elapsed between the September 11 attacks and the data gathering activities. Empirical investigations reveal that greater amounts of information are recalled using CI methods without increasing the rate of errors. For example, as compared to traditional epidemiological interviews, Fisher et al. were able, with CI methods, to elicit many more responses and more precise responses from people asked to recall daily physical activities from 35 years earlier.

NIST will address latency in two ways. First, multiple participants who would have experienced similar situations will be used to corroborate as much of the information as possible. Thus, information that cannot be reconciled with other evidence may be discounted although consensus does not establish validity. Second, the proposed investigative approaches are expected to increase the accuracy of the data collected. In a review of research, Pezdek and

Taylor¹⁶ concluded that people retain fairly accurate memories of directly experienced events. They hypothesized that participation in events leads to coherent well-structured narrative memories. Because NIST will only be asking about directly experienced events, and will be asking participants to recall events in a manner compatible with their naturally occurring internal representations, the accuracy of recall should be acceptable.

5. Protection of Human Subjects

This data gathering effort will ensure that all precautions required by the Common Rule for the Protection of Human Subjects are met or exceeded by the contractor. Participation in any part of this project by any person will be strictly voluntary. Interviewers will be trained to establish a rapport with participants based on a compassionate interest in their story and will ensure participants that information provided will be of value in preventing casualties in future building emergencies. During the briefing, interviewers will provide information to participants about where and how to receive counseling without charge, and that participants may stop the interview at any time without explanation. Interviewers will also be trained to recognize signs of post-traumatic stress. Similar services will be offered to participants of focus groups and to people taking the telephone interview. Finally, the contractor will take the necessary precautions to ensure the safety of contract employees administering, collecting, or otherwise involved in this data collection effort.

6. Additional Data Collection

The scenario may arise where an individual critical to developing an understanding of the events of September 11, 2001 may be unavailable or unidentified during the period of performance of the Contractor. Thus, NIST will obtain NIST Institutional Review Board (IRB) approval to conduct a limited number of face-to-face interviews with individuals deemed by NIST likely to contribute significantly to the outcome of the Investigation. The scope, objectives, and procedures used in the additional data collection will be similar to the scope, objectives, and procedures used by the contractor. Telephone interviews and focus groups will not be conducted in this additional data collection effort. It is anticipated that the number of face-to-face interviews conducted by NIST will be less than 10 percent of the number of face-to-face interviews conducted by the contractor. The contractor will incur no duties or obligations related to the additional data collection.

7. Conclusions and Summary

Table 1 summarizes the NIST Investigation survey method. NIST proposes a triangulated, multidisciplinary survey methodology to analyze and document the events of September 11, 2001 at the WTC 1, 2, and 7. The three strategies include telephone interviews, face-to-face interviews, and focus groups. The triangulated approach was selected in order to increase confidence in the conclusions, complete dual objectives of generalization and investigation, and increase memory recall and accuracy. The methodology and enumeration are summarized below.

The data collection will be conducted by a yet-to-be-selected contractor and is planned to begin as soon as the necessary pre-work is complete. This includes preparation of the telephone interview schedule, face-to-face interview protocol, focus group protocol, training of contractor staff, and approval by NIST and the appropriate IRB to assure compliance with federal requirements for the protection of human subjects. NIST will use established procedures to review all survey and face-to-face interview questions, data collection methods, and safeguards

for maintaining privacy and confidentiality of all instruments before proceeding with these critical data collection efforts. As additional details of the survey methodology are finalized, populations to be included in this project may be modified.

The telephone interview approach is described as the selected floors study. Participants will include occupants and persons with safety responsibility in WTC 1 and 2. Approximately 800 participants are required to achieve 0.05 level of statistical significance and power of 0.80. In stage one of stratification, WTC 1 and 2 will each be stratified into three zones, low, medium, and high. Each zone will be further stratified into large tenant floors and small tenant floors. Participants will represent a random sample without replacement of occupants from the floors selected in the first stage.

The areas of interest study will be conducted with face-to-face interviews of up to 600 people. The potential respondents will include:

- up to 200 people near floors of impact,
- up to 150 floor wardens, fire safety directors and persons with responsibility,
- up to 100 people in elevators or lobbies,
- up to 100 people from WTC 7,
- up to 30 family members of victims who called out of the towers, and
- up to 20 people with disabilities.

The Behavioral Sequence Interview Technique and Cognitive Interview Method will be combined in the face-to-face interview sessions. This approach will maximize the investigative return in order to identify unknown information, evaluate technical hypotheses, and explore conscious and subconscious motivations for occupant and responder behaviors, while allowing for comparisons to the telephone interview data. NIST will also conduct face-to-face interviews with members of the Fire Department of New York, Port Authority Police Department, New York Police Department, and others having operational responsibilities. This approach will face-to-face interview approximately 150 people, with the population being stratified among firefighters, company officers, and operational command officers.

The third approach will employ focus groups. NIST anticipates creating five focus groups of building occupants with approximately 10 people per group. The population will be generated using the snowball quota sample approach. Additionally, NIST will create approximately 10 focus groups with first responders, with each focus group containing approximately five individuals. The population will be generated using the snowball quota sample approach.

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- ¹ 15 CFR Subtitle A (1-1-99 Edition) Part 27.
- ² Dillman, D. 1978. *Mail and Telephone Survey*. New York: Wiley Press.
- ³ Lindzey, D., Aronson, E., (Eds). 1985. *The Handbook of Social Psychology*, 3rd Ed. New York: McGraw-Hill.
- ⁴ Shaughnessy, J.J, Zechmeister, B.E. 1994. *Research Methods in Psychology*, 3rd Ed. New York: McGraw-Hill, Inc.
- ⁵ Cauchon, D. December 20, 2001. *For many on Sept. 11, survival was no accident*. USA Today.
- ⁶ Kalton, G. 1983. *Introduction to Survey Sampling. Quantitative Applications in the Social Sciences Series*. London: Sage Publications.
- ⁷ Keating, J. P.; Loftus, E. L. Post Fire Interviews. 1984. *Development and Field Validation of the Behavioral Sequence Interview Technique. Final Report. NBS GCR 84-477*. Washington, DC: National Bureau of Standards.
- ⁸ Fisher, R.P., Falkner, K.L., Trevisan, M., McCauley, M.R. 2000. *Adapting the cognitive interview to enhance long-term (35 years) recall of physical activities*. Journal of Applied Psychology, 85(2), 180-189.
- ⁹ Geiselman, R.E., Fisher, R., Mackinnon, D. and Holland, H. 1986. *Enhancement of eyewitness memory with the cognitive interview*. American Journal of Psychology, 99. 385-401.
- ¹⁰ Fisher, R.P., Brennan, K.H., and McCauley, M.R. 2002. *The Cognitive Interview Method to Enhance Eyewitness Recall*. In Eisen, M.L., Quas, J.A., and Goodman, G.S. (Eds). *Memory and Suggestibility in the Forensic Interview*. Mahwah, New Jersey: Lawrence Erlbaum.
- ¹¹ Nillson, L. 2000. Remembering actions and words. In E. Tulving and F.I.M. Craik (eds.) *The Oxford Handbook of Memory*. New York: Oxford University Press.
- ¹² Schank, R. C., and Abelson, R. 1977. *Scripts, Plans, Goals, and Understanding*. Hillsdale NJ: Erlbaum.
- ¹³ Williams, F.D. 1990. *SLAM: The Influence of S.L.A. Marwill on the United States Army*, in TRADOC. Ft. Monroe, VA: U.S. Army.
- ¹⁴ Blalock, H. 1972. *Social Statistics*. New York: McGraw Hill.
- ¹⁵ Cochran, W.G. 1977. *Sampling Techniques*. New York, John Wiley.
- ¹⁶ Pesdek, K. and Taylor, J. 2002. *Memory for traumatic events in children and adults*. In Eisen, M.L., Quas, J.A., and Goodman, G.S. (Eds). *Memory and Suggestibility in the Forensic Interview*. Mahwah, New Jersey: Lawrence Erlbaum.

Method		Intended Number of Respondents	Intended Response Rate	Sampling Strategy	Population
Telephone Questionnaire	Selected Floors (Occupants)	800	30%	Statistically Representative Area Sampled Floors	WTC 1 and 2
Face to Face Interviews	Areas of Interest (Occupants)	570	N/A	Snowball Quota and Randomly Selected	WTC 1, 2, and 7
	Areas of Interest (Families)	30	N/A	Snowball Quota	WTC 1 and 2
	Areas of Interest (First Responders)	150	N/A	Snowball Quota	FDNY, NYPD, PAPD, others
Focus Groups	Specialized Groups (Occupants)	50	N/A	Snowball Quota	WTC 1, 2, and 7
	Specialized Groups (First Responders)	50	N/A	Snowball Quota	FDNY, NYPD, PAPD, others

Table 2: Summary of Methods

Appendix 7

World Trade Center Investigation Contract Solicitations			
WTC No.	Project No.	Title	Status
1	7	Outside Experts for Occupant Behavior and Evacuation	Awarded 9/30/02 and 10/16/02
2	5, 6, 7	Fire Safety Engineering Expertise	Awarded 12/23/02
3	5	Media, Visual and Database Expert with Experience in Obtaining Visual Materials for the World Trade Center	Cancelled 12/27/02
4	3	Document and Evaluate the Steel Recovered from the WTC Towers	Award Anticipated on 4/23/03
5	7	WTC Investigation Survey Administration and Report Delivery: Questionnaires, Interviews and Focus Group Synopsis	Award Anticipated by 5/30/03
6	2	Development of Structural Databases and Baseline Models for the WTC Towers	Awarded 2/23/03
7	1	Analysis of Building and Fire Codes and Practices	Closed 4/16/03
8	7	World Trade Center Investigation First Person Accounts of Egress	Awarded 4/15/03
9	6	Fire Endurance Testing of the WTC Floor System	Closed 4/23/03
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	Closed 4/25/03
11	2	Analysis of Aircraft Impacts into the WTC Towers	Open

WTC Investigation – Contract Award Summaries

The following contracts have been awarded by NIST for the World Trade Center Investigation.

WTC Solicitation No. 1

Outside Experts for Occupant Behavior and Evacuation (supports WTC Investigation Project 7)

On September 30, 2002 and on October 12, 2002, NIST selected three world-class experts as contractors to augment its investigation team in the area of occupant behavior and evacuation. Chosen from a competitive contract solicitation, these individuals bring extensive expertise, including strengths in psychology and sociology, and experience in the use of state-of-the-art sampling methods and in field data collection strategies. These individuals are:

- Dr. Norman Groner, an independent consultant from California. He has a doctorate in psychology and 25 years experience in the human factors field, much of it in the area of cognitive factors related to fire safety and emergency planning. He also has expertise and experience in interviewing techniques. He is coordinator for the independent World Trade Center Evacuation Initiative.
- Dr. Dennis Mileti, Director of the National Hazards Research and Applications Information Center within the Institute of Behavioral Science at the University of Colorado at Boulder. He has a doctorate in sociology and 28 years experience in risk communication and social psychology of public action. He also has expertise in statistical sampling methods and questionnaire design and methods.
- Dr. Guylène Proulx, Research Officer from the Institute for Research in Construction at the National Research Council of Canada. She has a doctorate in environmental psychology and 15 years experience in evacuation and emergency communications. She also has experience in post-fire egress analysis using questionnaires and interviews. She studied the evacuation of the WTC towers following the 1993 bombing incident.

WTC Solicitation No. 2

Fire Safety Engineering Expertise (supports WTC Investigation Projects 5, 6, and 7)

On December 23, 2002, NIST awarded a firm fixed-price purchase order to Mr. Harold Nelson, formerly a Senior Research Engineer with Hughes Associates, Inc. A graduate of Illinois Institute of Technology, Mr. Nelson has more than 50 years of fire protection engineering expertise, specializing in risk and hazard analysis. He was lead fire protection engineer for the U.S. General Services Administration, and led the team developing new technology for fire safety engineering at the National Bureau of Standards. Mr. Nelson was a participant in the Federal Emergency Management Agency's BPAT study of the World Trade Center disaster.

Mr. Nelson is uniquely qualified to provide the required fire safety engineering expertise for this project. His qualifications include:

- proven ability in fire investigations, including multi-floor fires in high rise buildings with experience in such buildings as One Meridien Plaza Bank.

- participation in the FEMA BPAT study of the Trade Center disaster.
- over 50 years of fire protection engineering expertise, specializing in risk and hazard analysis.
- demonstrated experience in the development of practical fire safety for high-rise buildings.
- specialized experience in human behavior in fires, including egress and fire safety for handicapped persons.
- demonstrated knowledge and experience in the building design, construction, operations and maintenance, and inspection procedures, with particular emphasis in egress. He also has demonstrated knowledge and experience with U.S. building and fire codes, standards, and regulatory system.

The specific tasks to be performed by the contractor and the specific methodologies to be used include:

- Identification of sources of information about the interiors of the three buildings (WTC 1, 2, and 7), the types of fuels present, and the compartmentation.
- Providing insights into the analyses developed during the FEMA World Trade Center Building Performance Study.
- Assistance in formulating hypotheses regarding the dynamics of the fires in the interiors of the buildings;
- Assistance in identifying key aspects of egress and human behavior during the fires;
- Guidance in conceptualizing the floor-to-floor and cross-floor fire spread, and documenting renditions of the concepts.
- Contributing to the selection of pre-fire conditions for modeling the thermal environment using Fire Dynamics Simulator (FDS) and documenting bases for his positions.
- Participation in understanding the relationships between the model predictions and the accumulated photographic evidence and renditions of insights developed.
- Assistance in the design of physical and computational tests to document the accuracy of the modeling predictions.
- Providing documentation of his contributions, which will serve as input to the Final Report.
- Providing a non-binding technical review of the Project 5 report. We don't have dates on any of the other tasks. Contractor deliverables may include summaries of the tasks. The Contractor will not generate conclusions of the Investigation. Contractor deliverables may include summaries of the tasks.

WTC Solicitation No. 6

Development of Structural Databases and Baseline Models for the WTC Towers (supports WTC Investigation Project #2)

On February 23, 2003, a firm fixed-price purchase order was awarded to Leslie E. Robertson Associates (LERA), R.L.L.P.; the firm responsible for the structural engineering of the World Trade Center towers. The project team from LERA includes the engineer of record for the design of the World Trade Center towers, the engineer of record for the repairs made after the 1993 bombing, the engineers of record for modifications based on tenant alterations and ongoing technical work, and the engineers of record for the structural integrity inspections of the towers. This team has detailed knowledge of the design, construction, and intended behavior of the towers over their entire 38 year life span.

This project has three tasks: (1) to digitize structural data from original computer printouts; (2) to develop reference structural analysis models that capture the intended behavior of the structures including modifications as a result of major tenant alterations and the 1993 bombing event; and (3) to analyze the baseline structural response under design wind and gravity loads. This project will not analyze the aircraft impact damage to the towers, the structural response of the towers to the fires, or the collapse sequence of the towers.

There are no existing models of the towers with the level of detail to be developed here. The reference structural models will be used to provide a basis for and comparison with more detailed and refined models to be developed independently in other parts of the NIST investigation for the analysis of (1) aircraft impact damage to the towers, (2) the structural response of the towers to the fires, and (3) the collapse sequence of the towers.

NIST has considered at length the appropriateness of involving LERA, the original structural engineering design firm, in its investigation. NIST has concluded that the firm's unique knowledge of the intended behavior of the original design is important to capture in developing its baseline model, but that LERA's work should be limited and appropriate reviews should be put into place.

Consequently, NIST has implemented rigorous procedures to mitigate potential conflicts of interest, consistent with all federal procurement laws and regulations, and is confident in the integrity and objectivity of the deliverables to be accepted from the contractor. The procedures to mitigate potential conflicts of interest include the following steps:

- The contractor shall have no role in the investigation other than providing NIST with the deliverables associated with the above tasks.
- The contractor shall not provide any findings, conclusions, or recommendations from its work on the three tasks. These are the sole and exclusive responsibility of NIST.
- The scope of work in this contract is limited to the three tasks listed above. It does not involve – in any way – the analysis of aircraft impact damage to the towers, the structural response of the towers to the fires, or the collapse sequence of the towers.
- NIST will conduct a comprehensive, independent review of each of the three tasks performed by the contractor. This review includes line-by-line review of the structural databases as well as extensive in-house verification and validation of the reference structural models and the baseline performance analyses. NIST has in its possession copies of all the original computer printouts, and other structural data and drawings for the towers. The contractor Statement of Work states that the deliverables are subject to review and approval by NIST for each of the tasks.
- NIST also will award a contract to another firm or individual through an open, competitive solicitation to conduct an independent third-party review and critique of each of the three tasks.
 - This review includes random checks of the databases; appropriateness of the models for their intended uses considering model representation and assumptions, level of detail, and model geometry and material properties; and appropriateness of the baseline performance analyses and accuracy of the results.
 - The contractor Statement of Work states that NIST will arrange for a third-party to conduct an independent review of the deliverables before final approval.

- The review will be conducted after LERA completes its work rather than while the work is in process to avoid influencing LERA's product and maintaining the integrity of the independent review.

WTC Solicitation No. 8

World Trade Center Investigation First Person Accounts of Egress (supports WTC Investigation Project #7)

On April 15, 2003, NIST enter into a sole source purchase order with the National Fire Protection Association (NFPA) to provide a data set that includes selected publicly available published first-person accounts of the WTC evacuation. This data set includes approximately 500 existing accounts collected by the NFPA and the National Research Council of Canada (NRCC) since September 11, 2001, along with a matrix of encoding variables that captures important incident details for each account. The NFPA will create a new data set, from the existing data set, to include additional accounts to be supplied by NIST and additional factors of interest to the investigation of the WTC evacuation on September 11, 2001.

The NFPA is uniquely qualified to perform this effort for three reasons: 1) The NFPA is a nonprofit organization specifically chartered to reduce the worldwide burden of fire and other hazards on the quality of life by providing and advocating scientifically-based consensus codes and standards, research, training and education. 2) Part of their charter includes investigations of technically significant fire incidents and fire data analysis. 3) The NFPA has spent more than one year developing their existing database, which would not be publicly available to other possible contenders for this contract.