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June 2004
Progress Report on the Federal Building and Fire Safety Investigation of the World Trade Center Disaster

Volume 1

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List of Acronyms and Abbreviations

AAPOR	American Association of Public Opinion Research
ABC	American Broadcasting Company
ACI	American Concrete Institute
AISC	American Institute of Steel Construction
AISI	American Iron and Steel Institute
ALE	Arbitrary-Lagrangian-Evlerian
AMCBO	Association of Major City/County Building Officials
ANSI	American National Standards Institute
ANSYS	finite element model
ARA	Applied Research Associates, Inc.
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
ASME	American Society of Mechanical Engineers
ASTM	ASTM International
AWS	American Welding Society
BOCA	Building Officials and Code Administrators
BOCA/BBC	BOCA Basic Building Code
BPAT	Building Performance Assessment Team
BPS	Building Performance Study
BSI	British Standards Institution
C/F	cancer free
CATI	computer-assisted telephone interviews
CBR	chemical, biological, and radiological
CBS	Columbia Broadcasting System
CERF	Civil Engineering Research Foundation
CFD	computational fluid dynamics
CIB	International Council for Research and Innovation in Building and Construction
CII	Construction Industry Institute
CNN	Cable News Network

CPP	Cermak Peterka Peterson, Inc.
CPU	central processing unit
CRT	cathode-ray tube
CTB&UH	Council on Tall Buildings and Urban Habitat
CTE	coefficients of thermal expansion
DC/F	BlazeShield DC/F fire protective insulation
DL	dead load
DTAP	dissemination and technical assistance program
EMS	Emergency Medical Service
EMT	Emergency Medical Team
ER&S	Emory Roth & Sons
FBI	Federal Bureau of Investigation
FCA	Flux cored arc
FDNY	New York City Fire Department
FDS	Fire Dynamics Simulator
FE	finite element
FEA	finite element analysis
FEM	finite element model
FEMA	Federal Emergency Management Agency
FMRC	Factory Mutual Research Corp.
FSI	Fire-Structure Interface
FVM	Finite Volume Method
GFI	Government Furnished Information
GG	glass over glass
GHz	gigahertz
GMS, LLP	Gilsanz Murray Steficek, LLP
HAZ	heat affected zone
HNSE	Hugo Nue Schnutzer East
HRR	heat release rate
HVAC	heating, ventilating, and air conditioning
IAQ	indoor air quality
IBC	International Building Code

ICBO	International Conference of Building Officials
ICC	International Code Council
IMTI	Integrated Manufacturing Technology
JFK	John F. Kennedy International Airport
JIS	Japan Industrial Standard
LERA	Leslie E. Robertson Associates
LES	Large Eddy Simulation
LL	live load
LSTC	Livermore Software Technology Corporation
MBC	BOCA National Building Code
MCC	Municipal Code of Chicago
MPI	Message Passing Interface
NBC	National Broadcasting Company
NBFU	National Board of Fire Underwriters
NCSBCS	National Conference of States on Building Codes & Standards, Inc.
NCST	National Construction Safety Team
NEMA	National Electrical Manufacturers Association
NFPA	National Fire Protection Association
NIBS	National Institute of Building Sciences
NIST	National Institute of Standards and Technology
NYC	New York City
NYCBC	New York City Building Code
NYCDOB	New York City Department of Buildings
NYPD	New York City Police Department
NYSBC	New York State Building Construction Code
P.L.	Public Law
PANYNJ	Port Authority of New York and New Jersey
PAPD	Port Authority Police Department
PC&F	Pacific Car and Foundry
PDM	Pittsburg-Des Moines
PONYA	Port of New York Authority
R&D	research and development

RWDI	Rowan Williams Davis and Irwin, Inc.
SBCCI	Southern Standard Building Code
SDL	superimposed dead load
SDO	standards development organization
SEAoNY	Structural Engineers Association of New York
SFPE	Society of Fire Protection Engineering
SFRM	spray-on fire resistant material or sprayed fire resistive materials
SHCR	Skilling, Helle, Christiansen, & Robertson
SI	metric
SLB	short legs back-to-back
SMA	Shielded Metal Arc
SOD	Special Operations Division
SOM	Skidmore, Ownings & Merrill
SPH	Smoothed Particle Hydrodynamics
SQL	Structured Query Language
SWMB	Skilling, Ward, Magnussen, and Barkshire
TL	Truss Lower Chord
TM	Truss Middle Chord
TU	Truss Upper Chord
UBC	Uniform Building Code
UL	Underwriters' Laboratories, Inc.
USC	United States Code
USM	United States Mineral Products Co.
VCBT	Virtual Cybernetic Building Testbed
WABC	WABC-TV New York
WCBS	WCBS-TV New York
WF	wide flange (a type of structural steel shape now usually called a W-shape). ASTM A 6 defines them as "doubly-symmetric, wide-flange shapes with inside flange surfaces that are substantially parallel."
WNBC	NBC4 New York
WNYW	FOX5 New York
WPIX	WPIX-TV New York
WTC	World Trade Center

WTC 1	World Trade Center Tower 1
WTC 2	World Trade Center Tower 2
WTC 7	World Trade Center Building 7

Abbreviations

×	by
±	plus or minus
°C	degrees Celsius
°F	degrees Fahrenheit
μm	micrometer
2D	two dimensional
3D	three dimensional
cm	centimeter
ft	foot
ft^2	square foot
F_y	yield strength (AISC usage)
g	acceleration (gravity)
g	gram
gal	gallon
h	hour
in.	inch
kg	kilogram
kip	a stress unit equal to 1,000 pounds
kJ	kilojoule
kN	kilonewton
kPa	kilopascal
klb	1,000 pounds
ksi	1,000 pounds per square inch
kW	kilowatt
kW/m^2	kilowatts per square meter
L	liter
lb	pound
m	meter
m^2	square meter
mm	millimeter
m/s	meters per second

min	minute
MJ	megajoule
MPa	megapascal
mph	miles per hour
ms	microsecond
Msi	millions pounds per square inch
MW	megawatt
N	newton
Pa	pascal
pcf	pounds per cubic foot
plf	pounds per linear foot
psf	pounds per square foot
psi	pounds per square inch
s	second

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Metric Conversion Table

To convert from	to	Multiply by
AREA AND SECOND MOMENT OF AREA		
square foot (ft^2)	square meter (m^2)	9.290 304 E-02
square inch (in^2)	square meter (m^2)	6.4516 E-04
square inch (in^2)	square centimeter (cm^2)	6.4516 E+00
square yard (yd^2)	square meter (m^2)	8.361 274 E-01
ENERGY (includes WORK)		
kilowatt hour (kW * h)	joule (J)	3.6 E+06
quad (1015 BtuIT)	joule (J)	1.055 056 E+18
therm (U.S.)	joule (J)	1.054 804 E+08
ton of TNT (energy equivalent)	joule (J)	4.184 E+09
watt hour (W * h)	joule (J)	3.6 E+03
watt second (W * s)	joule (J)	1.0 E+00
FORCE		
dyne (dyn)	newton (N)	1.0 E-05
kilogram-force (kgf)	newton (N)	9.806 65 E+00
kilopond (kilogram-force) (kp)	newton (N)	9.806 65 E+00
kip (1 kip=1000 lbf)	newton (N)	4.448 222 E+03
kip (1 kip=1000 lbf)	kilonewton (kN)	4.448 222 E+00
pound-force (lbf)	newton (N)	4.448 222 E+00
FORCE DIVIDED BY LENGTH		
pound-force per foot (lbf/ft)	newton per meter (N/m)	1.459 390 E+01
pound-force per inch (lbf/in)	newton per meter (N/m)	1.751 268 E+02
HEAT FLOW RATE		
calorieth per minute (calth/min)	watt (W)	6.973 333 E-02
calorieth per second (calth/s)	watt (W)	4.184 E+00
kilocalorieth per minute (kcalth/min)	watt (W)	6.973 333 E+01
kilocalorieth per second (kcalth/s)	watt (W)	4.184 E+03

To convert from	to	Multiply by
LENGTH		
foot (ft)	meter (m)	3.048 E-01
inch (in)	meter (m)	2.54 E-02
inch (in)	centimeter (cm)	2.54 E+00
micron (m)	meter (m)	1.0 E-06
yard (yd)	meter (m)	9.144 E-01
MASS and MOMENT OF INERTIA		
kilogram-force second squared per meter (kgf * s^2/m)	kilogram (kg)	9.806 65 E+00
pound foot squared (lb * ft^2)	kilogram meter squared (kg * m^2)	4.214 011 E-02
pound inch squared (lb * in^2)	kilogram meter squared (kg * m^2)	2.926 397 E-04
ton, metric (t)	kilogram (kg)	1.0 E+03
ton, short (2000 lb)	kilogram (kg)	9.071 847 E+02
MASS DIVIDED BY AREA		
pound per square foot (lb/ft^2)	kilogram per square meter (kg/m^2)	4.882 428 E+00
pound per square inch (*not* pound force) (lb/in^2)	kilogram per square meter (kg/m^2)	7.030 696 E+02
MASS DIVIDED BY LENGTH		
pound per foot (lb/ft)	kilogram per meter (kg/m)	1.488 164 E+00
pound per inch (lb/in)	kilogram per meter (kg/m)	1.785 797 E+01
pound per yard (lb/yd)	kilogram per meter (kg/m)	4.960 546 E-01
PRESSURE or STRESS (FORCE DIVIDED BY AREA)		
kilogram-force per square centimeter (kgf/cm^2)	pascal (Pa)	9.806 65 E+04
kilogram-force per square meter (kgf/m^2)	pascal (Pa)	9.806 65 E+00
kilogram-force per square millimeter (kgf/mm^2)	pascal (Pa)	9.806 65 E+06
kip per square inch (ksi) (kip/in^2)	pascal (Pa)	6.894 757 E+06
kip per square inch (ksi) (kip/in^2)	kilopascal (kPa)	6.894 757 E+03
pound-force per square foot (lbf/ft^2)	pascal (Pa)	4.788 026 E+01
pound-force per square inch (psi) (lbf/in^2)	pascal (Pa)	6.894 757 E+03
pound-force per square inch (psi) (lbf/in^2)	kilopascal (kPa)	6.894 757 E+00
psi (pound-force per square inch) (lbf/in^2)	pascal (Pa)	6.894 757 E+03
psi (pound-force per square inch) (lbf/in^2)	kilopascal (kPa)	6.894 757 E+00

To convert from	to	Multiply by
TEMPERATURE		
degree Celsius (°C)	kelvin (K)	T/K = t/ °C + 273.15
degree centigrade	degree Celsius (°C)	t/ °C ≈ t /deg. cent.
degree Fahrenheit (°F)	degree Celsius (°C)	t/ °C = (t/ °F 2 32)/1.8
degree Fahrenheit (°F)	kelvin (K)	T/K = (t/ °F + 459.67)/1.8
kelvin (K)	degree Celsius (°C)	t /°C = T/ K 2 273.15
TEMPERATURE INTERVAL		
degree Celsius (°C)	kelvin (K)	1.0 E+00
degree centigrade	degree Celsius (°C)	1.0 E+00
degree Fahrenheit (°F)	degree Celsius (°C)	5.555 556 E-01
degree Fahrenheit (°F)	kelvin (K)	5.555 556 E-01
degree Rankine (°R)	kelvin (K)	5.555 556 E-01
VELOCITY (includes SPEED)		
foot per second (ft/s)	meter per second (m/s)	3.048 E-01
inch per second (in/s)	meter per second (m/s)	2.54 E-02
kilometer per hour (km/h)	meter per second (m/s)	2.777 778 E-01
mile per hour (mi/h)	kilometer per hour (km/h)	1.609 344 E+00
mile per minute (mi/min)	meter per second (m/s)	2.682 24 E+01
VOLUME (includes CAPACITY)		
cubic foot (ft^3)	cubic meter (m^3)	2.831 685 E-02
cubic inch (in^3)	cubic meter (m^3)	1.638 706 E-05
cubic yard (yd^3)	cubic meter (m^3)	7.645 549 E-01
gallon (U.S.) (gal)	cubic meter (m^3)	3.785 412 E-03
gallon (U.S.) (gal)	liter (L)	3.785 412 E+00
liter (L)	cubic meter (m^3)	1.0 E-03
ounce (U.S. fluid) (fl oz)	cubic meter (m^3)	2.957 353 E-05
ounce (U.S. fluid) (fl oz)	milliliter (mL)	2.957 353 E+01

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PREFACE

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

Goals of the WTC Investigation

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

Objectives of the WTC Investigation

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

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

Authorities and Use of Information in Legal Proceedings

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

Organization of the WTC Investigation

The Investigation includes eight interdependent projects that, in combination, meet the objectives. A detailed description of each of these eight projects is available at http://wtc.nist.gov. The purpose of each project is summarized in Table P–1, and the key interdependencies among the projects are illustrated in Figure P–1.

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

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

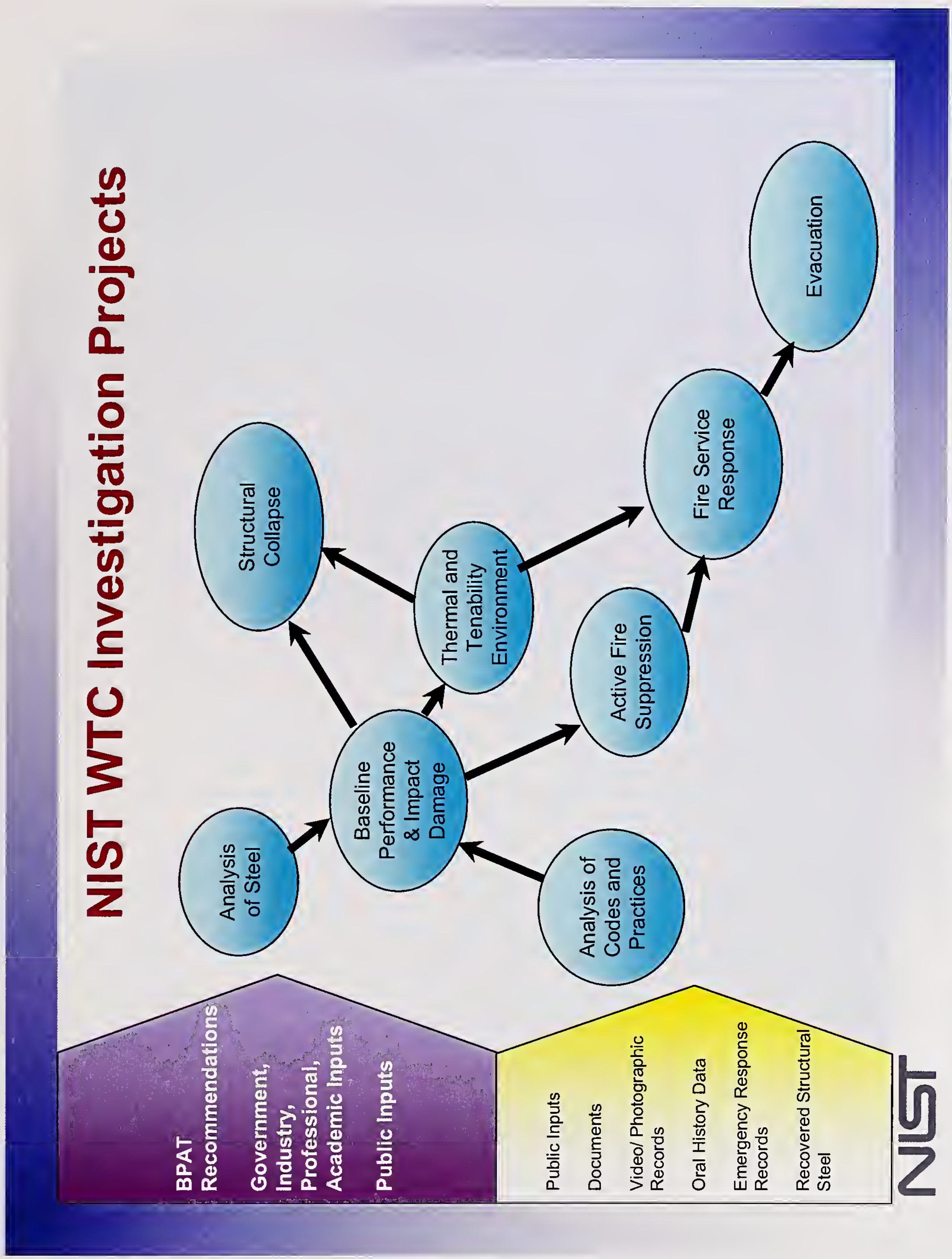

Figure P–1. The eight projects in the federal building and fire safety investigation of the WTC disaster.

NIST's WTC Public-Private Response Plan

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

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

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

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

EXECUTIVE SUMMARY

Background

In response to the terrorist attacks of September 11, 2001, the National Institute of Standards and Technology (NIST) initiated a formal federal building and fire safety investigation of the World Trade Center disaster on August 21, 2002. NIST issued two written updates on its WTC investigation activities (December 2002 and December 2003) and a detailed technical progress report in May 2003.

In addition, NIST held a public meeting in New York City on February 12, 2004 to solicit comments on (1) specific technical aspects of the investigation, (2) additional information that NIST might consider in the time remaining; and (3) areas that NIST should consider, within the scope of its investigation, in making recommendations for specific improvements to building and fire practice, standards, and codes, and their timely adoption.

The present report provides details of the technical progress made since the May 2003 report was published. NIST expects to release the draft of the final investigation report for public comment in December 2004. NIST's investigation is still ongoing. Current findings may be revised and additional findings will be presented in the December 2004 report. **NIST is not making any recommendations at this time. All recommendations will be made in the final report.**

Status of Progress

This report includes:

- A comprehensive summary of interim findings and accomplishments for each of the independent investigation objectives.

- A working hypothesis for the collapse of the WTC towers that identifies the chronological sequence of major collapse events and allows for different possible load redistribution paths and damage scenarios currently under analysis. The hypothesis will be refined on the basis of these analyses to determine the most probable collapse sequence for each building.

- A working hypothesis for the collapse of the 47-story WTC 7 based on an initiating event, a vertical progression at the east side of the building, a subsequent horizontal progression from the east to the west side of the building, and global collapse.

- Key visual observations on the building, fire, and smoke conditions in all three WTC buildings (the WTC towers and WTC 7) from analysis of a large collection of photographic and videographic images.

- A summary of major progress in building comprehensive models for analyzing the most probable collapse sequence, from aircraft impact to collapse initiation, and simplified analytical models with results to supplement those from detailed models.

- Results from experimental work to (1) analyze the recovered WTC structural steel, (2) support the fire dynamics and thermal modeling, and (3) conduct fire endurance testing of typical floor systems of the WTC towers based on ASTM E 119.

- Reports on the inventory and identification of the steels recovered from the WTC buildings and on the contemporaneous (1960s era) structural steel and welding specifications used to construct the WTC towers.

- First-person interviews of nearly 1,200 WTC occupants, first responders, and families of victims to collect data on occupant behavior, evacuation, and emergency response with some early results from analysis of that data.

- Review of the New York City 911 tapes and logs and the transcripts of about 500 interviews with Fire Department of New York (FDNY) employees involved in WTC emergency response activities with analysis still in progress.

- Preliminary analysis of emergency responder communication tapes recorded by the Port Authority, including the high-rise radio repeater, and by the New York Police Department (NYPD), including internal department operations.

- Analysis of building and fire codes and practices, including: a review of available documents related to the design, construction, operation, maintenance, and modifications to the three WTC buildings; and a comparison of selected building regulatory and code requirements.

- Analysis of the design, capabilities, and performance of the installed active fire protection systems for all three WTC buildings (i.e., fire alarm, sprinkler, and smoke management systems) with documentation of the fire history of the WTC towers.

- Progress on both the research and development and the dissemination and technical assistance programs related to the WTC Investigation.

- Seventeen appendices with detailed interim reports on specific technical tasks within the eight investigation projects where significant progress has been made.

NIST has received large amounts of data and information related to the design, construction, operation, inspection, maintenance, repair, alterations, emergency response, and evacuation of the WTC complex. NIST has received considerable cooperation from the Port Authority of New York and New Jersey (PANYNJ or Port Authority), the City of New York, the National Commission on Terrorist Attacks Upon the United States (9-11 Commission), designers, leaseholders, contractors, suppliers, insurers, news media, tenants, first responders, survivors, and families of victims.

NIST has received all of the essential information it needs for the WTC Investigation. NIST has made a few requests for materials that are lost, currently pending, or not yet located; NIST is making efforts to assemble this information from various sources since much of it was lost when the buildings collapsed. NIST continues to pursue other materials that can further clarify some aspects of the Investigation.

The Web site http://wtc.nist.gov provides comprehensive information on the WTC investigation and related work to improve the safety of buildings, their occupants, and first responders.

Investigation Objectives and Key Questions

The key interim findings are summarized below in subsections that relate to the investigation objectives contained in the NIST investigation plan (see Chapter 1 for a comprehensive discussion of all interim findings). The investigation objectives are:

1. To determine (a) why and how the WTC 1 and WTC 2 collapsed following the initial impact of the aircraft, and (b) why and how the 47-story WTC 7 collapsed.
2. To determine why the loss of life and injuries were so low or so high depending on location, including technical aspects of fire protection, occupant behavior, evacuation, and emergency response.
3. To determine the procedures and practices which were used in the design, construction, operation, and maintenance of the WTC buildings.
4. To identify, as specifically as possible, areas in national building and fire codes, standards, and practices that warrant revision.

Among the specific questions that NIST is investigating within the above four objectives are the following:

- How and why did WTC 1 stand nearly twice as long as WTC 2 before collapsing (103 min versus 56 min), though they were hit by virtually identical aircraft?
- What factors related to normal building and fire safety considerations not unique to the terrorist attacks of September 11, 2001, if any, could have delayed or prevented the collapse of the WTC towers?
- Would the undamaged WTC towers have remained standing in a normal major building fire?
- What factors related to normal building and fire safety considerations, if any, could have saved additional WTC occupant lives or could have minimized the loss of life among the ranks of first responders on September 11, 2001?
- How well did the procedures and practices used in the design, construction, operation, and maintenance of the WTC buildings conform to accepted national practices, standards, and codes?

Context for Findings

When reviewing these interim findings, the following should be considered:

- Buildings are not specifically designed to withstand the impact of fuel-laden commercial airliners. While documents from the PANYNJ indicate that the impact of a Boeing 707 flying at 600 mph, possibly crashing into the 80th floor, was analyzed during the design of the WTC towers in February/March 1964, the effect of the subsequent fires was not considered. Building codes do not require building designs to consider aircraft impact.

- Buildings are not designed for fire protection and evacuation under the magnitude and scale of conditions similar to those caused by the terrorist attacks of September 11, 2001.

- The load conditions induced by aircraft impact and the extensive fires on September 11, 2001, which triggered the collapse of the WTC towers, fall outside the norm of design loads considered in building codes.

- Prior evacuation and emergency response experience in major events did not include the total collapse of tall buildings such as the WTC towers and WTC 7 that were occupied and in everyday use; instead, that experience suggested that major tall building fires result in burnout conditions, not global building collapse.

- The PANYNJ was created as an interstate entity, under a clause of the U.S. Constitution permitting compacts between states, and is not bound by the authority of any local, state, or federal jurisdiction, including local building and fire codes. The PANYNJ's longstanding policy is to meet and, where appropriate, exceed the requirements of local building and fire codes.

Collapse of the WTC Towers

Working Hypothesis. The following chronological sequence of major events led to the eventual collapse of the towers; specific load redistribution paths and damage scenarios are currently under analysis to determine the most probable collapse sequence for each building:

- Aircraft impact damage to perimeter columns, resulting in redistribution of column loads to adjacent perimeter columns and to the core columns via the hat truss;

- After breaching the building's exterior, the aircraft continued to penetrate into the buildings, damaging core columns with redistribution of column loads to other intact core and perimeter columns via the hat truss and floor systems;

- The subsequent fires, influenced by the post-impact condition of the fireproofing, weakened columns and floor systems (including those that had been damaged by aircraft impact), triggering additional local failures that ultimately led to column instability; and

- Initiation and horizontal progression of column instability resulted when redistributing loads could not be accommodated any further. The collapses then ensued.

The working hypothesis (see Chapter 1 and Appendix Q for a detailed description) is consistent with all evidence currently held by NIST, including photographs and videos, eyewitness accounts, and emergency communication records. In addition to evidence of hanging floor slabs on the east and north faces of WTC 2 that were reported previously, new evidence has been found showing inward bowing of perimeter columns several minutes (less than 10 min) prior to collapse in both WTC towers. Inward bowing of about a quarter to a third of the perimeter columns was observed in photographs on the south face of WTC 1 and the east face of WTC 2 in regions that contained active fires. Further, initiation of global collapse was first observed by the tilting of building sections above the impact regions of both WTC towers. WTC 1 tilted to the south (observed via antenna tilting in a video recording) and WTC 2 tilted to the east and south and twisted in a counterclockwise motion.

Discussed below are interim findings for several factors relevant to the condition and collapse of the WTC towers, including the innovative structural system, aircraft impact and the ensuing fires, post-impact condition of the fireproofing, and the quality and properties of the structural steel used in the WTC towers. In addition to the role played by these factors in the collapse of the WTC towers, NIST continues to investigate the relative roles of the perimeter and core columns and the composite floor system, including connections.

Innovative Structural System. The WTC tower structures represented an innovative structural system when they were built, incorporating many new and unusual features. Among them, two features require additional consideration: the composite floor system, using open-web bar joist elements, to provide lateral stability and diaphragm action, and the use of wind tunnel testing to estimate lateral wind loads—which were a major governing factor in the design of the WTC tower structures.

The performance of the former under fire conditions, which is relevant to evaluating the collapse of the WTC towers, was of some concern to the building owner and designers throughout the life of the buildings. The concern stemming from the latter, identified by the leaseholder and insurers in litigation after September 11, 2001, is representative of the still evolving state-of-knowledge in the field of wind engineering and is relevant to establishing the baseline performance of the WTC towers and to assessing the practices and procedures used in design.

The fire protection of a truss-supported floor system by directly applying spray-on fireproofing to the steel trusses was innovative and not consistent with prevailing practice at the time the WTC towers were designed and constructed. The fireproofing thickness required to meet the 2 h fire rating evolved from the specified 1/2 in. when the WTC towers were built to 1-1/2 in. for use in upgrading the fireproofing some years prior to September 11, 2001. Unrelated to the WTC buildings, a model code evaluation service recommended in June 2001 a minimum thickness of 2 in. for a similar floor system. This three to four fold difference in specifying the fireproofing thickness to meet the required fire rating for a structural assembly is extraordinarily large and confirms the lack of technical basis in the selection of thickness.

While the benefits of conducting a full-scale fire endurance test to determine the required fireproofing thickness were recognized by the building designers, no tests were conducted on the floor system used in the WTC towers to establish a fire endurance rating. NIST has awarded a contract to Underwriters Laboratories (UL) to determine the fire resistance rating of typical WTC floor systems under both as-specified and as-built conditions. The tests, expected to be conducted in August 2004, are also designed to evaluate the effects of test scale, fireproofing thickness, and thermal restraint.

Further, use of the "structural frame" approach, in conjunction with the prescriptive fire rating, would have required the floor system trusses, the core floor framing, and perimeter spandrels in the WTC towers—essential to the stability of the building as a whole—to be 3 h fire-rated as the columns were required to be rated by the 1968 New York City (NYC) Building Code. This approach, which appeared in the Uniform Building Code (a model building code) as early as 1953, was carried into the 2000 International Building Code (one of two current national model codes). Neither the 1968 edition of the NYC Building Code which was used in the design of the WTC towers, nor the 2001 edition of the code, adopted the "structural frame" requirement.

Results of two sets of wind tunnel tests conducted for the WTC towers in 2002 by independent laboratories, and voluntarily provided to NIST by the parties to an insurance litigation, show large differences, of as much as about 40 percent, in resultant forces on the structures, i.e., overturning moments and base shears. In addition, the wind loads estimated from these tests are about 20 percent to 60 percent higher than those apparently used in the original design of the WTC towers, also obtained from wind tunnel testing. NIST is conducting an independent analysis to establish the baseline performance of the WTC towers under the original design wind loads and will compare those wind load estimates with then-prevailing code requirements. Wind loads were a major governing factor in the design of structural components that made up the frame-tube steel framing system.

Relative Roles of Aircraft Impact and Fires. The two WTC towers withstood the initial impact of virtually identical aircraft (Boeing 767-200ER) during the terrorist attacks of September 11, 2001. The robustness of the perimeter frame-tube system and large dimensional size of the WTC towers helped the buildings withstand the aircraft impact. The WTC towers displayed significant reserve capacity, vibrating immediately following impact with amplitudes that were about half the amplitudes for design wind conditions expected by the building designers and an oscillation period nearly equal to that measured for the undamaged building.

Preliminary aircraft impact damage analysis indicates that the impact of a fuel-filled wing section results in extensive damage to the exterior wall panel, including complete failure of the perimeter columns. A normal impact of the exterior wall by an empty wing segment produces significant damage to the perimeter columns, not necessarily complete failure. Also, engine impact against an exterior wall panel results in a penetration of the exterior wall and failure of impacted perimeter columns. The residual velocity and mass of the engine after penetration of the exterior wall is sufficient to fail a core column in the event of a direct impact.

Fires played a major role in further reducing the structural capacity of the buildings, initiating collapse. While aircraft impact damage did not, by itself, initiate building collapse, it contributed greatly to the subsequent fires by:

- Compromising the sprinkler and water supply systems;
- Dispersing jet fuel and igniting building contents over large areas;
- Creating large accumulations of combustible matter containing aircraft and building contents;

- Increasing the air supply into the damaged buildings that permitted significantly higher energy release rates than would normally be seen in ventilation limited building fires, allowing the fires to spread rapidly within and between floors; and

- Damaging ceilings that enabled "unabated" heat transport over the floor-to-ceiling partition walls and to structural components.

The jet fuel, which ignited the fires, was mostly consumed within the first few minutes after impact. The fires that burned for almost the entire time that the buildings remained standing were due mainly to burning building contents and, to a lesser extent, aircraft contents, not jet fuel.

By contrast, typical office furnishings were able to sustain intense fires for at least an hour on a given WTC floor. The typical WTC office floor using modern workstation furnishings had on average about 4 pounds per square foot (psf) of combustible materials on floors without unusual file rooms, film storage, etc. Further, the mass of aircraft solid combustibles was significant relative to the building combustibles in the immediate impact region of both WTC towers.

Consistent with available photographic and videographic evidence, computer simulations conducted by NIST have been able to capture the broad patterns of fire movement around the floors, with the flames in a given location lasting for about 20 min before spreading to adjacent, yet unburned combustibles. This spread is generally continuous due to the relatively even distribution of combustibles and the paucity of interior partitions. There are some observed instances where fires persisted over longer durations in regions with accumulated combustible debris and other instances of sudden or interrupted fire spread.

Applying the 1968 NYC Building Code, the WTC towers were required to have 1 h fire-rated tenant separations, but the code did not impose any minimum compartmentation requirements (e.g., 7,500 ft^2) to mitigate the horizontal spread of fire in buildings with large open floor plans. The sprinkler option was chosen for the WTC towers in preference to the compartmentation option in meeting the subsequent requirements of Local Law 5, adopted by New York City in 1973. The affected floors in the WTC towers were mostly open—with a modest number of perimeter offices and conference rooms and an occasional special purpose area. Some floors had two tenants, and those spaces, like the core areas, were partitioned (slab to slab). Photographic and videographic evidence confirms that even non-tenant space partitions (such as those that divided spaces to provide corner conference rooms) provided substantial resistance to fire spread in the affected floors. For the duration of about 50 min to 100 min prior to building collapse that the fires were active, the presence of undamaged 1 h fire-rated compartments may have assisted in mitigating fire spread and consequent thermal weakening of structural components.

Role of Fireproofing Conditions. NIST has developed a rigorous technical approach (see Appendix I for details) to evaluate the role fireproofing conditions may have played in the collapse of the WTC towers. The approach considers both the thickness and variability of fireproofing and the extent to which fireproofing may have been damaged due to aircraft impact.

In general, the floor systems in WTC 1 subject to aircraft impact and subsequent fires on September 11, 2001 had upgraded or thicker fireproofing (1.5 in. specified), while the affected floors in WTC 2 had the original fireproofing (0.5 in. specified).

The response of a structural component to fires is sensitive to variability in fireproofing thickness along its length. For the original fireproofing in the WTC towers, the as-applied fireproofing thickness on the floor trusses (0.75 in. average and 0.4 coefficient of variation) was found to be thermally equivalent to a uniform thickness of 0.6 in., which is greater than the specified minimum thickness of 0.5 in. For the upgraded fireproofing in some floors of the WTC towers, the as-applied upgraded fireproofing thickness (2.5 in. average and 0.24 coefficient of variation) was found to be thermally equivalent to a uniform thickness of 2.2 in., which is greater than the specified minimum thickness of 1.5 in. An alternative criterion for determining the equivalent thickness is currently being examined to confirm these findings.

Based on simplified analytical models, it was found that acceleration of a structural element, on the order of 100 to 150 times the acceleration due to gravity (or 100 g to 150 g), would be required to dislodge fireproofing similar to that used in the WTC towers with a typical thickness of about 1 in. from the structural component. Experiments are underway to verify the results of these simplified analyses. Similarly, analytical studies are underway to estimate the magnitude of accelerations of the structural members due to aircraft impact, from which the regions where fireproofing may have been dislodged will be identified. Those results are being used to analyze the role of the post-impact condition of the fireproofing, including its thickness, on the collapse of the WTC towers.

Analysis of Recovered WTC Steel. NIST has 236 pieces of steel in its possession; this collection of steel is adequate for purposes of determining the quality and properties of steel for the investigation. The regions of impact and fire damage were emphasized in the selection of steel pieces for the investigation. As a result, pieces of all 14 specified steel grades for exterior panels in the WTC towers are available, as well as the two specified grades that represent 99 percent of the core columns and both specified grades for the steel trusses that comprised the composite floor truss system.

Analysis of steel recovered from the WTC towers, based on stampings on the steel and mechanical tests, indicates that the correct specified materials were provided for the specified elements. When these data were combined with pre-collapse photographic images of damaged steel, it was found that aircraft impacted pieces of steel recovered from WTC 1 were in the precise locations as specified in the design drawings. Metallography and mechanical property tests indicate that the strength and quality of the steel used in the towers was as specified, typical of the era, and likely met all qualifying test requirements.

The room-temperature strength of the steel used in the towers met the relevant standards and, in many instances, exceeded the requirements by 5 percent to 10 percent. Work is ongoing to analyze the performance of the steel building components under impact and fire conditions up to initiation of global building collapse.

Collapse of the 47-Story WTC 7 Building

Working Hypothesis. The working hypothesis for the collapse of the 47-story WTC 7 building, if it remains viable upon further analysis, suggests that it was a classic progressive collapse including: an initiating event, a vertical progression at the east side of the building, a subsequent horizontal progression from the east to the west side of the building, and global collapse. The chronological sequence of major events under analysis is:

- An initial local failure at the lower floors (below Floor 13) of the building due to fire and/or debris induced structural damage of a critical column (the initiating event), which supported a large span floor bay with an area of about 2,000 ft^2;

- Vertical progression of the initial local failure up to the east penthouse, as large floor bays were unable to redistribute the loads, bringing down the interior structure below the east penthouse; and

- Horizontal progression of the failure across the lower floors (in the region of Floors 5 and 7, that were much thicker than the rest of the floors), triggered by damage due to the vertical failure, resulting in disproportionate collapse of the entire structure.

Visual Observations. The working hypothesis (see Chapter 1 and Appendix L for a detailed description) is consistent with all evidence currently held by NIST, including photographs and videos, eyewitness accounts, and emergency communication records. Specifically, the evidence indicates:

- The sequence of failures associated with the sinking of the east penthouse roof structure into the building, the near simultaneous window breakage along the east side of the north face, the sinking of the other roof structures, the near simultaneous breakage of a second set of windows along the west side of the north face, and the entire north façade above the 13th floor appearing to drop as an intact unit.

- Structural damage on the south face and southwest corner from WTC 1 debris that included (1) a multi-story gash across approximately a quarter to a third of the lower portion of the south face and extending inwards to the core, (2) approximately two columns in the southwest corner and related floor areas missing from Floors 8 to 18, and (3) severed spandrels between exterior columns near the southwest corner from the roof level for at least 5 to 10 floors.

- The sequence of fires in WTC 7—which began soon after WTC 1 collapsed—was observed (1) on the south face and near the southwest corner on Floors 22, 29, and 30, (2) across Floors 11 and 12 on the east face, from the south to the north, (3) on Floors 7 and 12 along the north face, (4) on Floors 8 and 13, with the fire on Floor 8 moving from west to east and the fire on Floor 13 moving from east to west, and (5) finally, on Floors 7, 8, 9, and 11 near the middle about half an hour before collapse; Floor 12 was burned out by this time. Interview responses indicate that there was no water in the standpipe system supplying the sprinklers in WTC 7.

Fuel System for Emergency Power. Based on a review of the fuel system for emergency power in WTC 7, Floor 5—which did not have any exterior windows and contained the only pressurized fuel distribution system on the south, west and north floor areas—is considered a possible fire initiation location, subject to further data and/or analysis that improve knowledge of fire conditions in this area.

Evacuation and Emergency Response

Building Population Characteristics. Based on information and data gathered during the first-person interviews of WTC surviving occupants:

- It is estimated that 17,400 occupants (± 1,200) were present in the WTC towers on the morning of September 11, 2001. The initial population of each tower was similar: 8,900 (± 750) in WTC 1 and 8,500 (± 900) in WTC 2. Of those present on September 11, 2001, 16 percent were also present during the 1993 bombing.

- About 6 percent of the surviving occupants reported a pre-existing limitation to their mobility. These limitations included obesity, heart condition, needing assistance to walk, pregnancy, asthma, being elderly, chronic condition, recent surgery or injury, and other.

- About 7 percent of the surviving occupants reported having special knowledge about the building. These included fire safety staff, floor wardens, searchers, building maintenance, and security staff. Searchers assist the floor wardens in facilitating evacuation.

Evacuation. Two-thirds of surviving occupants reported having participated in a fire drill in the 12 months prior to September 11, 2001, while 17 percent reported that they received no training during that same period. Of those participating in fire drills, 93 percent were instructed about the location of the nearest stairwell. Overall, slightly over half of the survivors, however, had never used a stairwell at the WTC prior to September 11, 2001.

Approximately 87 percent of the WTC tower occupants, including more than 99 percent of those below the floors of impact, were able to evacuate successfully. Two-thousand one-hundred fifty-nine building occupants (1,560 in WTC 1 and 599 in WTC 2) and an additional 433 first responders, including security guards but not aircraft passengers and crew or bystanders, were reported to have lost their lives on September 11, 2001.

Rough initial estimates indicate that about 20 percent or more of those who were in the WTC towers and lost their lives may have been alive in the buildings just prior to their collapse. This estimate, which will be refined as data analysis is completed, assumes that nearly all of the first responders and 76 building occupants below the floors of impact, but none of the people at or above the floors of impact, may have been alive. It is estimated that there were a total of 2,592 building occupants and first responders who were in the WTC towers and lost their lives.

Overall, about 7,900 survivors evacuated WTC 2 in 73 min (i.e., from the instant the WTC 1 was struck by aircraft until WTC 2 collapsed) while about 7,500 survivors evacuated WTC 1 in 103 min. Thus, the overall evacuation rate in WTC 2 (108 survivors per min) was about 50 percent faster than that in WTC 1 (73 survivors per min). Functioning elevators allowed many survivors to evacuate WTC 2 prior to aircraft impact. Most of the elevators in WTC 1 were not functioning, and survivors could only use the stairways. The stairwells, with partition wall enclosures that provided a 2 h fire-rating but little structural integrity, were damaged in the region of the aircraft impacted floors.

- After the first airplane struck WTC 1 and before the second airplane struck WTC 2, the survivors in WTC 2 were twice as likely as those in WTC 1 to have already exited the building (41 percent versus 21 percent). The rate of evacuation completion in WTC 2 was twice the rate in WTC 1 during that same period.

- Soon after WTC 2 was struck by the airplane until about 20 min before each building collapsed, the survivors in WTC 2 and WTC 1 had exited at about the same rate (the prior evacuation rate of WTC 1).

- During the last 20 min before each building collapsed, the evacuation rate in both buildings had slowed to about one-fifth the immediately prior evacuation rate. This suggests that for those seeking and able to reach and use undamaged exits and stairways, the egress capacity (number and width of exits and stairways) was adequate to accommodate survivors.

Preliminary results from application of existing computer egress models for a full capacity evacuation of a single WTC tower with 25,000 occupants and visitors indicate a movement time of 2 h and 15 min. This is a minimum time estimate; the simulation assumed that there was no survivor delay, continual movement on the stairs, and no damage to the egress system. It was also assumed that elevators were not available. The egress model estimate for a September 11, 2001 capacity evacuation under the same assumptions is about 50 min, which is 2.5 times less than the time estimate for evacuating 25,000 people.

Given that the actual evacuation time on September 11, 2001 was about 100 min without elevator use, a full capacity evacuation of each WTC tower with 25,000 people would have required about 4 h (2.5 times 100 min). To achieve a significantly faster total evacuation at full capacity would have required increases in egress capacity (number and width of exits and stairways).

In addition to the full evacuation of the WTC towers on September 11, 2001, a full evacuation was ordered during the 1993 bombing at the WTC site and during a 1977 terrorist threat associated with bombings in two remote midtown Manhattan buildings. Sufficient data do not exist on the frequency with which full evacuations are conducted in buildings not at risk for terrorist attacks and whether this frequency has increased since September 11, 2001 among the general population that did not directly experience the events on that day.

Roof Evacuation. A preliminary evaluation indicates that the PANYNJ's standard occupant evacuation procedures and drills required the use of stairways to exit at the bottom of the WTC towers. The standard procedures were to keep the doors to the roof locked with a key being required to gain roof access. The PANYNJ reports that it never advised tenants to evacuate upward.

There were at least two decedents who had tried to get to the roof and found the roof access locked to both the WTC towers. In addition, a PANYNJ employee trapped on Floor 105 of WTC 2 was unable to walk down the stairs, or go to the roof as instructed on radio by another PANYNJ employee.

The NYPD aviation unit arrived at the WTC site soon after WTC 1 was attacked. Despite repeated attempts to examine the possibility of roof rescue, smoke and heat conditions at the top of the WTC towers prevented the conduct of safe roof evacuation operations.

Considering the capacity of typical helicopters and travel times, it is not clear what fraction of the large number of occupants could have been evacuated from the WTC towers prior to their collapse had roof rescue been possible on September 11, 2001.

Emergency Communication Systems. A partial analysis of emergency responder communications (see Appendix P for details) has been completed, including:

- Audio communications tapes recorded by the PANYNJ, including a recording of the FDNY's city-wide high-rise Channel 7 (Port Authority Police Department's [PAPD] Channel 30) radio repeater that was located at the WTC.
- Audio tapes copied from original NYPD communications tapes, including NYPD internal department operations.

FDNY communications recordings from the WTC location on September 11, 2001, are not available because the primary field communication truck was in the shop for repairs. A back-up field-communications van used in its place—which did not have a recording capability—was destroyed when the WTC towers collapsed.

The best record of radio communications reflecting fire department operations came from the FDNY Channel 7/PAPD Channel 30 and first person accounts provided by FDNY personnel during their interviews. The PANYNJ installed the radio repeater system for use by FDNY after the 1993 bombing.

The analysis of the emergency responder communication tapes indicates that:

- After the first aircraft struck WTC 1, there was an approximate factor of 5 peak increase in traffic level over the normal level of emergency responder radio communications, followed by an approximate factor of 3 steady increase in the level of subsequent traffic.
- A surge in communications traffic volume made it more difficult to handle the flow of communications and delivery of information.
- Roughly a third to a half of the radio messages transmitted during these radio traffic surge conditions were not complete messages or understandable.
- FDNY's city-wide high-rise Channel 7 (PAPD Channel 30) radio repeater at the WTC site was operating.
- NYPD aviation unit personnel reported critical information about the impending collapse of the WTC towers several minutes prior to their collapse. No evidence has been found to suggest that the information was further communicated to all emergency responders at the scene.

Several FDNY personnel at the incident site did not think that the high-rise radio repeater was working. This is based on radio communications tests that were conducted by two chief officers working inside WTC 1 when the first command post was being set up in that lobby. Following this radio test, a chief officer involved in the test chose to use different channels for command and tactical communications during the incident. However, as FDNY operations increased in WTC 2, it was determined by FDNY members that the high-rise repeater was functioning, and use of the channel developed.

While the preliminary analysis indicates that the repeater was operating, there also appears to have been some type of malfunction with the communications equipment that was detected, but not identified, by

FDNY officers during the initial test. NIST continues to evaluate the repeater system and its operations, as well as the handheld radios, which were used on September 11, 2001. These findings will be updated and additional findings will be documented when the investigation is complete.

Command and Control. Based on face-to-face interviews, NIST has determined that first responders—including key incident commanders—did not have adequate information (voice, video, and data) on, nor an overall perspective of, the conditions in the WTC buildings and what was happening elsewhere at the WTC site. Interagency information sharing was inadequate.

The three FDNY suitcase-based, magnetic Command Boards that were set up at the incident site—on which a record is kept of the identification of the units on site, their assignment, location, and activities—were damaged and lost with the collapse WTC 2. Since there was no back-up capability for the Command Boards, all information related to command, control, and accountability was lost.

Active Fire Protection Systems. Investigation of the design, capabilities, and performance of the active fire protection systems in the WTC towers and WTC 7 indicates that:

- The smoke management systems in the WTC towers were not activated during the fires on September 11, 2001. It was determined that the likelihood of these systems being functional was very low due to the damage inflicted by the aircraft impacts.

- The analysis of smoke flow in WTC 1 and WTC 2 on September 11, 2001 shows that HVAC (heating, ventilation, and air-conditioning) ductwork was a major path for vertical smoke spread in the buildings. Fire dampers were installed in the systems, but not smoke dampers that could have provided a barrier to hot gas and smoke penetration into the vertical HVAC shafts. However, smoke dampers were not available when the towers were built.

- Modeling results show that stair pressurization systems would have provided minimal resistance to the passage of smoke in WTC 1 and WTC 2 had they been installed on September 11, 2001. While the existence of such systems was known when the WTC towers were built, the alternative smoke purge system used in the WTC towers was considered to be equivalent.

- The fire alarm system in WTC 7 sent only one signal (at 10:00:52 a.m. shortly after the collapse of WTC 2) to the monitoring company indicating a fire condition. The signal did not contain any specific information about the location of the fire within the building. Since the system was placed on TEST for a period of 8 h beginning at 6:47:03 a.m. on September 11, 2001, alarm signals would not have been shown on the operator's display; instead, they would have to be recorded into the history file.

- The resistance to failure of the fire alarm system communications paths between the fire command station and occupied WTC tower floors could have been enhanced if fiber optic communications cable had been used instead of copper lines. Fiber optic cable is not susceptible to electric short-circuits and would have provided full communications with fire alarm system components, including voice communications systems, to the point where the cable was severed. Electric shorts in the voice communications disable that communication system over the entire cable length affected by the electric short-circuit. During initial design of the system, the PANYNJ requested, but did not receive, approval of the City of New York for use of fiber optic communication cable in the system. The NYC code required copper wiring.

- There was adequate multiple point redundancy in the water supply to the sprinkler system, and the water flow rate exceeded the minimum requirement by a considerable margin. However, the potential for single point failure of the water supply to the fire sprinklers existed at each floor due to lack of redundancy in the sprinkler riser system that provided only one water supply connection on each floor. While this lack of redundancy may not have had an impact on September 11, 2001 because the sprinkler system was damaged by aircraft impact, it could have made a difference in other building emergencies.

Procedures and Practices

The 110-story WTC towers were among the world's tallest buildings, while the 47-story WTC 7 represented a more typical tall building. These buildings provide case studies to document, review, and, if needed, improve the procedures and practices used in the design, construction, operation, and maintenance of tall buildings. This investigation objective is independent of other objectives which are focused specifically on the consequences of the attack on September 11, 2001, viz., the building collapses, evacuation, and emergency response. While some findings under this objective are directly relevant to the events of September 11, 2001, others are concerned with general building and fire safety procedures and practices.

Applicable Building Codes. Although not required to conform to NYC codes, the PANYNJ adopted the provisions of the proposed 1968 edition of the NYC Building Code, more than three years before it went into effect. The 1968 edition allowed the PANYNJ to take economic advantage of less restrictive provisions compared with the 1938 edition that was in effect when design began for the WTC towers in 1962. The 1968 code:

- Eliminated a fire tower[1] as a required means of egress;
- Reduced the number of required stairwells from 6 to 3 and the size of doors leading to the stairs from 44 in. to 36 in.;
- Reduced the fire rating of the shaft walls in the building core from 3 h to 2 h;
- Changed partition loads from 20 psf to one based on weight of partitions per unit length (that reduced such loads for many buildings including the WTC buildings); and
- Permitted a 1 h reduction in fire rating for all structural components (columns from 4 h to 3 h and floor framing members from 3 h to 2 h).

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[1] A fire tower (also called a smoke-proof stair) is a stairway that is accessed through an enclosed vestibule that is open to the outside or to an open ventilation shaft providing natural ventilation that prevents any accumulation of smoke without the need for mechanical pressurization.

The NYC Department of Buildings reviewed the WTC tower drawings in 1968 and provided comments to the PANYNJ concerning the plans in relation to the 1938 NYC Building Code. The architect-of-record submitted to the PANYNJ responses to those comments, noting how the drawings conformed to the 1968 NYC Building Code.

In 1993, the PANYNJ and the NYC Department of Buildings entered into a memorandum of understanding that restated the PANYNJ's longstanding policy to assure that its facilities in the City of New York meet and, where appropriate, exceed the requirements of the NYC Building Code. The agreement also provided specific commitments to the NYC Department of Buildings regarding procedures to be undertaken by the PANYNJ to assure that buildings owned or operated by the PANYNJ are in conformance with the Building Standards contained in the NYC Building Code.

In 1993, the PANYNJ adopted a policy providing for implementation of fire safety recommendations made by local government fire departments after a fire safety inspection of a PANYNJ facility and for the prior review by local fire safety agencies of fire safety systems to be introduced or added to a facility. Later that year, the PANYNJ entered into an agreement with FDNY which reiterated the policy adopted by the PANYNJ and set forth procedures to assure that new or modified fire safety systems are in compliance with local codes and regulations.

Standards, Codes, and Regulations. NIST has reviewed the then-prevailing and current standards, codes, and regulations relevant to assessing the procedures and practices used in the design, construction, operation, and maintenance of the WTC buildings. That review raises the following issues that merit further consideration (see Chapter 1 for a discussion and WTC-related rationale):

- Code provisions that would detail procedures to analyze and evaluate data from fire resistance tests of other building components and assemblies to qualify an untested building element.

- Code provisions that would require the conduct of a fire resistance test if adequate data do not exist from other building components and assemblies to qualify an untested building element.

- Regulations that would adopt code provisions using the "structural frame" approach to fire resistance ratings which requires structural members, other than columns, that are essential to the stability of the building as a whole to be fire protected to the same rating as columns.

- Code provisions that would ensure that structural connections are provided the same degree of fire protection as the more restrictive protection of the connected elements.

- Code provisions and standards that would establish whether the minimum mechanical and durability related properties of spray-applied fire resistive materials (SFRM) are sufficient to ensure acceptable in-service performance in buildings. While minimum bond strength requirements exist, there are no serviceability requirements for such materials to withstand typical shock, impact, vibration, or abrasion effects over the life of a building.

- Rigorous field application and inspection provisions and regulatory requirements that would assure that the as-built condition of the passive fire protection, such as SFRM, conforms to conditions found in fire resistance tests of building components and assemblies.

- Rigorous provisions and regulatory requirements for in-service inspections of passive fire protection during the life of the building.

- Early installation of sprinklers in existing buildings, not as an option in lieu of compartmentation.

- Standards and code provisions that would provide minimum structural integrity for the means of egress (stairwells and elevator shafts) in the building core which are critical to life safety.

- Standards and code provisions that would permit the installation of fire-protected elevators and their use for routine emergency access by first responders or as a secondary method (after stairwells) for emergency evacuation of building occupants.

- Explicit standards and code provisions for structural integrity that would mitigate progressive collapse.

- Standards and code provisions for conducting wind tunnel tests and for the methods used in practice to estimate design wind loads from test results.

- Regulatory requirements for retention of documents related to the design, construction, operation, maintenance, and modifications of buildings, including retention off-site. For example, there are few, if any, requirements for retention of documents throughout the service life of a building.

Fire Safety and Egress Design Methods. Historical fire loss data over more than half a century, for different high-rise building occupancies, suggests that prescriptive requirements in standards and codes have considerable built-in conservatism to adequately protect building occupants. As a result, there has been a trend in recent decades to reduce fire rating and egress requirements, sometimes in conjunction with addition of other new and complementary fire protection requirements (e.g., detectors and sprinklers). The lower fire rating requirements when combined with the considerable increases in building design efficiency that have been achieved, have also led to reductions in the thermal mass of buildings—an indicator of how much heat energy a building can absorb passively without damage.

The empirical rules and test methods used in prescriptive design, which have evolved with experience over the years, do not lend themselves readily to evaluate whether the performance of building fire safety and egress systems is risk-consistent, considering both the hazards and the consequences of the hazards. Performance-based methods that explicitly define the design objectives and specific design-basis fire hazards or evacuation events are better suited to risk analysis, enabling appropriate protection to be provided where it is needed.

The increasing use of performance-based methods, as an alternative to prescriptive design, in fire safety and egress design, raises the following issues that merit further consideration (see Chapter 1 for a detailed discussion and rationale related to the WTC investigation):

- Considering fire as a design condition in structural design, including evaluation of the fire performance of the structure as a whole system. This design approach is already being used in building design practice for earthquake and wind hazards (e.g., a two-level design that includes an operational event with a 10 percent probability of occurrence in 50 years and a life safety event with a 2 percent probability of occurrence in 50 years).

- Detailed procedures to select appropriate design-basis fire scenarios for performance-based design of the sprinkler system (e.g., a frequent but low severity fire), compartmentation (e.g., a moderate severity but less frequent fire), and passive protection of the structure (e.g., a maximum credible fire).

- Validated and verified tools for use in performance-based design practice to analyze the dynamics of building fires and their effects on the structural system that would allow engineers to evaluate structural performance under alternative fire scenarios and fire protection strategies. While considerable progress has been made in recent years in advancing the tools that will help to improve the fire-safe design of new structures and analyze conditions of existing structures, significant work remains to be done before adequate tools are available for use in routine practice.

- The technical basis to establish whether the construction classification and fire rating requirements are risk-consistent. Specifically, it is not apparent how the current height and area tables in building codes consider the technical basis for the progressively increasing risk to an occupant on the upper floors of tall buildings that are much greater than 200 ft in height. The maximum fire rating in current codes applies to any building more than about 12 stories in height.

- Sprinklers improve safety in most common building fires and prevent them from becoming large fires. The technical basis to establish the "sprinkler trade-off" in current codes, considering fire safety risk factors such as: (1) the complementary functions of sprinklers and fire-protected structural elements, (2) the different design-basis fire scenarios for which each system is designed to provide protection, and (3) the need for redundancy should one system fail to function as intended is not available. The sprinkler trade-off provides an economic incentive to encourage installation of sprinklers by allowing a lower fire rating for sprinklered buildings.

- The design of egress systems to achieve a target performance (e.g., evacuation rate or time) for a given occupant population by adequately considering travel distance, remoteness requirements, and human factors such as occupant size, stairwell environmental conditions, visibility, and congestion.

Building Practices. While the PANYNJ entered into agreements with the NYC Department of Buildings in the 1990s with regard to conformance of PANYNJ buildings constructed in New York City to the NYC Building Code, the PANYNJ did not yield jurisdictional authority for regulatory and enforcement oversight to the NYC Department of Buildings. The PANYNJ was created as an interstate entity, under a clause of the U.S. Constitution permitting compacts between states, and is not bound by the authority of any local, state, or federal jurisdiction.

The architect is responsible for specifying the fire protection in current building practice. The structural engineer is not required to evaluate and certify that the passive fire protection is adequate to protect the structural system. In accordance with established practice, the structural engineer was not responsible for the passive fire protection in the design of the WTC tower structures. In addition, there is no requirement to involve a fire protection engineer in the design and evaluation of a building's fire protection system. In some cases, architects retain fire protection engineers to assist with the fire protection design for a building. There are only a few academic degree programs or continuing education programs that qualify engineers (or architects) to evaluate the fire performance of structures. The current state-of-practice is not sufficiently advanced for engineers to routinely analyze the performance of a whole structural system under a prescribed design-basis fire scenario.

Approach to Recommendations

In the United States, state and local governments are responsible for promulgating and enforcing building and fire regulations. With some exceptions, the state and local regulations are based on national model building and fire codes developed by private sector organizations. The model codes, in turn, reference voluntary consensus standards developed by a large number of private sector standards development organizations (SDOs) accredited by the American National Standards Institute (ANSI).

NIST is a non-regulatory agency of the U.S. Department of Commerce. NIST does not set building codes and standards, but provides technical support to the private sector and other government agencies in the development of U.S. building and fire practices, standards, and codes. NIST recommendations are given serious consideration by private sector organizations that develop national standards and model codes – which provide minimum requirements for public welfare and safety.

The NIST building and fire safety investigation of the WTC disaster has not yet formulated recommendations. However, in formulating its recommendations, NIST will consider the following:

- Findings from the first three independent investigation objectives related to building performance, evacuation and emergency response, and procedures and practices.
- Whether findings relate to the unique circumstances surrounding the terrorist attacks of September 11, 2001, or to normal building and fire safety considerations, including evacuation and emergency response.
- What technical solutions are needed, if any, to address potential risks to buildings, occupants, and first responders, considering both identifiable hazards and the consequences of those hazards?
- Whether the risk is in all buildings or limited to certain building types (e.g., height and area, structural system), buildings that contain specific design features, iconic/signature buildings, or buildings that house critical functions.

NIST urges organizations responsible for building and fire safety at all levels to carefully consider the interim findings contained in this report. NIST welcomes comments from technical experts and the public on the interim findings presented herein. Comments can be sent by e-mail to wtc@nist.gov, facsimile to (301) 975-6122, or regular mail to WTC Technical Information Repository, Stop 8610, 100 Bureau Drive, Gaithersburg, MD 20899-8610.

In its final report, a draft which is expected to be released in December 2004, NIST will recommend appropriate improvements in the way buildings are designed, constructed, maintained and used. It will be important for those recommendations to be thoroughly and promptly considered by the many organizations responsible for building and fire safety. As part of NIST's overall WTC response plan, the Institute has begun to reach out to these organizations to pave the way for timely, expedited consideration of recommendations stemming from this investigation. NIST also has expanded its research in areas of high priority need.

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Chapter 1
INTERIM FINDINGS AND ACCOMPLISHMENTS

1.1 INTRODUCTION

In response to the terrorist attacks of September 11, 2001, the National Institute of Standards and Technology (NIST) initiated a formal federal building and fire safety investigation of the World Trade Center (WTC) disaster on August 21, 2002. At the same time, NIST also released the final plan for its investigation.

NIST has received large amounts of data and information related to the design, construction, operation, inspection, maintenance, repair, alterations, emergency response, and evacuation of the WTC complex. A summary is included in Section 2.1. NIST has received considerable cooperation from the Port Authority of New York and New Jersey (PANYNJ or Port Authority), the City of New York, the National Commission on Terrorist Attacks Upon the United States (9-11 Commission), designers, leaseholders, contractors, suppliers, insurers, news media, tenants, first responders, survivors, and families of victims.

NIST has received all of the essential information it needs for the WTC Investigation. NIST has a few requests for materials that are lost, currently pending, or not yet located; NIST is making efforts to re-create this information from various sources since much of it was lost when the buildings collapsed. NIST continues to pursue other materials that can clarify some aspects of the Investigation.

The interim findings summarized in this progress report are based on information contained in public updates issued by NIST in December 2002 and December 2003, a previous progress report issued in May 2003, and work completed since the last progress report. (Previous updates and progress reports may be found at http://wtc.nist.gov.)

NIST expects to release the draft of the final investigation report for public comment in December 2004. **NIST is not making any recommendations at this time. All recommendations will be made in the final report.** These interim findings and the working hypothesis for the collapse of the WTC towers and WTC 7 are subject to refinement or change as further information becomes available prior to release of the final investigation report. The final report will include any recommendations that NIST considers appropriate based on these and other findings yet to be made.

NIST welcomes comments from technical experts and the public on the interim findings presented herein. Comments may be sent by e-mail to wtc@nist.gov, facsimile to (301) 975-6122, or regular mail to WTC Technical Information Repository, Stop 8610, 100 Bureau Drive, Gaithersburg, MD 20899-8610.

The interim findings are presented in four subsections that relate to the investigation objectives listed below. They are then subdivided according to the technical areas to which they relate. NIST findings are presented in *italics* to distinguish them from narrative text throughout this section.

The stated objectives contained in the NIST investigation plan are:

1. To determine (a) why and how the WTC 1 and WTC 2 collapsed following the initial impact of the aircraft, and (b) why and how the 47-story WTC 7 collapsed.

2. To determine why the loss of life and injuries were so low or so high depending on location, including technical aspects of fire protection, occupant behavior, evacuation, and emergency response.

3. To determine the procedures and practices which were used in the design, construction, operation, and maintenance of the WTC buildings.

4. To identify, as specifically as possible, areas in national building and fire codes, standards, and practices that warrant revision.

1.2 COLLAPSE OF THE WTC TOWERS

Working Hypothesis

NIST is investigating possible collapse scenarios to establish the sequence of events that led to the collapse of the WTC towers following the initial impact of the aircraft. The objectives of the NIST analysis are to determine the most probable sequence of events from the moment of aircraft impact until the initiation of global building collapse and to identify the factors that have the strongest influence on the most probable sequence.

NIST has developed a working hypothesis to explain the collapse initiation of the WTC towers. The working hypothesis (summarized below and in Appendix Q) identifies the chronological sequence of major events as the WTC tower structures redistributed loads from structural element to structural element to accommodate the aircraft impact and subsequent fire damage until no further load redistribution was possible to maintain overall stability, thus, leading to collapse. The hypothesis:

- Is based on analysis of the available evidence and data, consideration of a range of hypotheses (including those postulated publicly by experts), and a newly enhanced understanding of structural and fire behavior.

- Is consistent with all evidence currently held by NIST, including photos and videos, eyewitness accounts, and emergency communication records.

- Allows for multiple load redistribution paths and damage scenarios for each building, currently under analysis.

- Will be further refined based on the results of NIST's continuing analyses to identify specific load redistribution paths and damage scenarios that are possible for each building, from which the most probable collapse sequence will be identified.

NIST welcomes comments from technical experts and the public on the working hypothesis. Among the key questions that NIST continues to investigate within the framework of the working hypothesis are the following:

- How and why did WTC 1 stand nearly twice as long as WTC 2 before collapsing (103 min versus 56 min), though they were hit by virtually identical aircraft?
- What were the relative roles of the perimeter and core columns[1] and the composite floor system,[2] including connections, in initiating the collapses?
- What was the post-impact condition of the fireproofing, especially the extent to which fireproofing may have been damaged due to aircraft impact?
- What factors related to normal building and fire safety considerations not unique to the terrorist attacks of September 11, 2001, if any, could have delayed or prevented the collapse of the WTC towers?

In evaluating the working hypothesis for the collapse of the WTC towers, NIST is also considering the following factors:

- The relative contributions of aircraft impact damage and subsequent fires;
- How safe each building was immediately after aircraft impact but before fire weakened the structures, i.e., to what extent the capacity of the buildings to carry design loads[3] was reduced;
- Whether the undamaged towers would have remained standing in a "maximum credible fire";[4] and
- The role compartmentation (i.e. areas divided by fire-rated walls) may have played, i.e., what would have happened if the floors had been separated into 7,500 or 10,000 ft^2 compartments with 1 h fire-rated partition walls or separations.

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[1] The perimeter columns were designed to carry both gravity and wind forces and acted together as a framed-tube system. The core columns were designed to carry only gravity loads and were not required to provide frame action.

[2] The composite floor truss system, which included long-span open-web bar joist elements, was designed to carry floor loads to the supporting core and perimeter columns. It also acted as a diaphragm that distributed wind forces to the perimeter columns of the framed-tube system and provided lateral stability to the perimeter columns.

[3] The design of the WTC towers was governed by gravity and lateral wind loads.

[4] A maximum credible fire for the WTC towers is assumed to have the following characteristics: the sprinkler system is compromised, overwhelmed, or not present; there is no active firefighting; combustible building contents averaging 10 psf (in the range of about 5 psf to 20 psf for conventional office buildings); floor-to-floor fire spread to next upper floor at 30 min or 60 min; and ventilation from windows broken by fire and a total of 50 ft^2 of air leakage between floors.

Finding 1a.1: *The following chronological sequence of major events led to the eventual collapse of the towers; specific load redistribution paths and damage scenarios for each building continue to be refined:*

- Aircraft impact damage to perimeter columns, resulting in redistribution of column loads to adjacent perimeter columns and to the core columns via the hat truss;
- After breaching the building's exterior, the aircraft continued to penetrate into the buildings, damaging core columns with redistribution of column loads to other intact core and perimeter columns via the hat truss and floor systems;
- The subsequent fires, influenced by the post-impact condition of the fireproofing, weakened columns and floor systems (including those that had been damaged by aircraft impact), triggering additional local failures that ultimately led to column instability; and
- Initiation and horizontal progression of column instability resulted when redistributing loads could not be accommodated any further. The collapses then ensued.

Aircraft Impact. Buildings are not specifically designed to withstand the impact of fuel-laden commercial airliners. However, PANYNJ documents indicate that the impact of a Boeing 707 flying at 600 mph, possibly crashing into the 80th floor, was analyzed during the design of the WTC towers in February/March 1964. While NIST has not found detailed evidence of the analysis, the documents in NIST's possession state that the postulated aircraft collision would have resulted in only local damage that would not cause collapse or substantial damage to the WTC towers. The effect of the fires due to jet fuel dispersion and ignition of building contents was not considered. The loss of life in the immediate area of aircraft impact was recognized, but the loss of life due to the growth and spread of fires and smoke was not considered. Building codes do not require building designs to consider aircraft impact.

Role of the Hat Truss System

The purpose of the hat truss was to support gravity and wind loads on the antenna. It was not designed to resist lateral forces on the towers, and, in an undamaged state, it did not have a significant role in carrying gravity loads. Lateral loads due to wind were distributed to the framed-tube system via diaphragm action of the floor system. The hat truss was connected to each perimeter face at only four points, all at the same level (at the 108th floor just below the concrete floor slab). The 47 core columns were connected to diagonal elements, heavier transfer beams, or smaller beam elements of the hat truss. Most of the core columns extended to the roof level, but four core columns, which were only minimally connected to the hat truss, terminated at Floor 110. The hat truss provided minimal redistribution of loads (less than 10 percent) from perimeter columns to core columns. Most of the load redistributed due to aircraft impact damage occurred on the external face through vierendeel action.

Finding 1a.2: *The two WTC towers withstood the initial impact of virtually identical aircraft (Boeing 767-200ER) during the terrorist attacks of September 11, 2001. The robustness of the perimeter frame-tube system and large dimensional size of the WTC towers helped the buildings withstand the aircraft impact. The WTC towers displayed significant reserve capacity, vibrating immediately following impact with amplitudes that were about half the amplitudes for design wind conditions expected by the building designers. WTC 2, which collapsed first and in about half the time as WTC 1, vibrated for over 4 min at an oscillation period nearly equal to that measured for the undamaged building. The lightly damped (about 1.2 percent of critical damping) oscillation had an initial amplitude of approximately 20 in at the roof level, where expected sway was about 3 ft to 4 ft under design wind conditions.*

Aircraft Impact Damage to Perimeter Columns. Based on the above information, structural damage to perimeter columns as a result of aircraft impact of the framed-tube system appears to have played a minimal role in initiating the collapse. Perimeter column bowing prior to collapse occurred on other faces (i.e., fire floors on the south face of WTC 1 and east face of WTC 2) that were not severed by the aircraft.

Aircraft Impact Damage to Core Columns. The core columns were designed to carry only gravity loads and not required to provide frame action. The aircraft trajectory at impact suggests damage to the core columns occurred as follows:

WTC 1—The aircraft was traveling about 450 mph and hit the tower near the center of the north face damaging Floors 93 to 99. The aircraft fully entered the core area and severed or damaged central core columns in the north-south direction. Aircraft and building debris accumulated in the remaining core area and south-side floor areas as contents were displaced from the point of impact.

WTC 2—The aircraft was traveling about 550 mph and hit the tower near the southeast corner of the building damaging Floors 77 to 85. Core columns to the south and east were severed or damaged. Aircraft and building debris accumulated in the core area and floor areas to the east and north.

Severed core columns redistributed their loads in three ways, depending on how many and which core columns were severed.

1. Isolated core columns were severed. Severed column and tributary floor loads, at and above the point of impact, were redistributed locally at each floor to adjacent intact core columns via core floor framing. This was limited by shear/bending capacity of floor-framing connections to adjacent columns.

2. Critical (e.g., corner) core columns and/or several other core columns were severed. The severed column and tributary floor loads, at and above impact floors, redistributed to intact core columns via the hat truss. Significant hat truss deflections may have occurred if there was adequate connection capacity since the severed core columns and the associated floors were hanging from the hat truss which was not designed to carry such loads. This was limited by the tensile capacity of bolted splices in the severed core columns, tensile/compression capacity of hat truss members, and tensile capacity of column connections to the hat truss.

3. Extent of core column failures precluded redistribution through the hat truss and/or exceeded redistribution capacity of the hat truss. Severed column and associated floor loads, at and above floors of impact, redistributed to intact core and perimeter columns via the core and composite truss floor system. Floors were subjected to combined bending and diaphragm action (e.g., consider the scenario of no core columns in the floor span direction to visualize this action). The overall capacity of the floors was limited by shear capacity of floor-to-column connections (including perimeter columns) and tensile/bending capacity of composite truss floor connections to core or perimeter columns. Significant sagging of the hat truss system may have occurred if its capacity was exceeded.

Relative Roles of Fires and Aircraft Impact

Finding 1a.3: *Fires played a major role in further reducing the structural capacity of the buildings, initiating collapse. The tower structures withstood the initial aircraft impacts and remained stable. While aircraft impact damage did not, by itself, initiate building collapse, it contributed greatly to the subsequent fires by:*

- Compromising the sprinkler and water supply systems;
- Dispersing jet fuel and igniting building contents over large areas;
- Creating large accumulations of combustible matter containing aircraft and building contents;
- Increasing air supply into the buildings (through broken windows and holes in the sides of the buildings, and between floors due to damaged floors, vertical shafts, and columns) that permitted significantly higher energy release rates than would normally be seen in ventilation-limited building fires, allowing the fires to spread rapidly within and between floors; and
- Damaging ceilings that enabled "unabated" heat transport over the floor-to-ceiling partition walls and to the floor trusses, spandrels, and tops of columns.

Finding 1a.4: *The jet fuel, which ignited the fires, was mostly consumed within the first few minutes after impact. The fires that burned for almost the entire time that the buildings remained standing were due mainly to burning building contents and, to a lesser extent, aircraft contents, not jet fuel.*

Thermal Effects on Columns and Floors. Some floors in WTC 2 experienced partial collapse due to aircraft impact. For example, partially collapsed floor slabs were visible on the east and north faces. This included failures at the edges with perimeter columns causing floor edge sagging. Based on photographs or videographs there is no visible evidence of partially collapsed floors in WTC 1.

> **Role of Fireproofing**
>
> The post-impact condition of the fireproofing played a key role in the structural response to fires. The post-impact condition of the fireproofing depends on the condition of the fireproofing prior to aircraft impact and the extent to which fireproofing was damaged due to aircraft impact. The fire-affected floors in WTC 1 had, in general, upgraded or thicker fireproofing (1.5 in. specified) while, in general, those in WTC 2 did not have upgraded fireproofing (0.5 in. specified).

Fires may have had the following thermal effects:

- Core columns and core floors may have been further weakened, with reduced ability to carry and/or redistribute load, causing such loads to be redistributed to other core and perimeter columns consistent with the residual reserve capacities of these columns and the transfer mechanisms (i.e., hat truss and floor system).
- The floor system may have been further weakened, either along the span of the floor system or localized at connections with columns. The weakening floor system may have pulled the perimeter columns inward (observed on the south face of WTC 1 and the east face of WTC 2 minutes prior to building collapse) and then initiated connection failures at perimeter or core columns.

- Perimeter columns may have been further weakened, with reduced ability to carry loads. Thermal effects could also cause inward bowing of perimeter columns due to differential temperatures between the inner and outer faces of the columns. The loads that could no longer be carried by the weakened columns would have been redistributed to adjacent perimeter columns.

Column Instability and Collapse Initiation. The perimeter columns were designed as part of a framed-tube system to carry both gravity and wind forces. Instability of perimeter columns resulted from a combination of (1) redistributed loads from the core columns via the floor system and possibly the hat truss, (2) inward bowing due to thermally-weakened and sagging floors, (3) increased unsupported length due to failed floors, and (4) thermal effects directly on the perimeter columns.

The instability of a few perimeter columns was observed to propagate across the entire face and around the corners just before or during collapse initiation. The initiation or spread of perimeter column instability also may have been facilitated by the hoop stress demand on the framed-tube system exceeding the capacity of the spandrels (horizontal steel plates) that tied the perimeter columns together (e.g., at the northeast corner of WTC 2).

The initiation of global collapse for both towers was first observed by the tilting of the sections above the impact regions of both WTC towers. The tilting and the propagation of column instability are synchronous processes that initiated global collapse. The tilting may have caused forces such as shear and torsion to spread the column instability laterally.

Issues Being Investigated. Over the next few months, NIST will continue to investigate the following technical issues and modify its working hypothesis as needed. Findings on these issues will be included in the final report.

- Aircraft impact damage to structural components, fireproofing, and hat truss connections.
- Distribution of aircraft/building contents.
- Thermal effects on core columns and core floors, especially extent of fires and growth history.
- Thermal effects on welded perimeter columns, especially temperature gradients on columns.
- Extent of load redistribution to intact core columns and their reserve capacity to accommodate thermal loads.
- Capacity of hat truss connections to perimeter columns, especially to meet the demands of aircraft impact and any torsional effects.
- Capacity of hat truss to accommodate the load redistribution from severed columns.
- Capacity of bolted splices in the severed core columns to carry loads to the hat truss.
- Relative magnitude of the load redistribution provided by the local core floor, hat truss, and the core-truss floor system for each tower.

- Axial/shear/bending capacity of floor connections to core and perimeter columns.
- Effect of localized fires on floor truss connections.
- Mechanisms to propagate instability laterally in the perimeter columns (e.g., shear and torsion forces induced by a rigid body movement)
- Capacity of spandrels, including splices, to carry shear transfer in the framed-tube system, especially at the corners.
- Role of bolted splices on instability of perimeter columns.
- Outward bowing of perimeter columns due to thermal expansion of floors.
- Effect of uneven floor thermal expansion on perimeter column instability due to potential biaxial bending.
- Comparison and reconciliation of working hypothesis with observed facts (photographs and videos, eyewitness accounts, emergency communication records).
- Examination of other possible or probable hypotheses.

Visual Observations

Photographic and video images of damage and fires in the WTC buildings are providing critical guidance for the investigation. NIST has collected and assembled the visual materials into a searchable computerized database. The database now contains well in excess of 6,000 photographs representing the work of more than 185 photographers, and 150 hours of video from most of the major media outlets and more than 20 individuals.

Based on an analysis of this visual evidence, NIST has identified significant events for WTC 1 and WTC 2 related to aircraft impact, fire development, and building damage, and work is progressing on WTC 7. As part of this analysis, NIST has developed detailed mappings and time-dependent visualizations for fire, smoke, and window conditions of the WTC towers, and similar efforts are nearing completion for WTC 7.

Finding 1a.5: *On the east face of WTC 2, what appears to be the 83rd floor slab was seen hanging across window openings over a large fraction of the 82nd floor. The object was observed in a number of photographs and videos very shortly after the plane strike and found to sag further prior to collapse. On the north face of WTC 2, shorter lengths of what appear to be the 81st, 82nd, and 83rd floor slabs were seen hanging through the windows in the floors below. There was no visible evidence of floors sagging in WTC 1. NIST continues to investigate what role aircraft impact and subsequent fires had on causing such floor failures.*

Finding 1a.6: *Several minutes (less than 10 min) prior to building collapse, inward bowing of about a quarter to a third of the perimeter columns was observed in photographs on the south face of WTC 1 and the east face of WTC 2 in regions that contained active fires.*

Finding 1a.7: *At 9:36 a.m. an occupant of WTC 2 called the New York City 911 telephone operator and reported that a floor in the 90's had collapsed underneath them and that they were now on the 105th floor. The NYPD aviation unit observed the following events with respect to WTC 2. At 9:49 a.m., they reported "large pieces" falling from WTC 2. At 9:58 a.m., it was reported that the south tower was coming down. With respect to WTC 1, at 10:06 a.m., an advisory was transmitted by the aviation unit that it wasn't going to take much longer before the north tower comes down and to pull emergency vehicles back from the building. At 10:20 a.m., the unit reported that the top of the (north) tower might be leaning. At 10:21 a.m., they reported that the north tower was buckling on the southwest corner and leaning to the south. At 10:27 a.m., a report was made that the roof was going to come down very shortly.*

Finding 1a.8: *The initiation of global collapse was first observed by the tilting of building sections above the impact regions of both WTC towers. WTC 1 tilted to the south (observed via antenna tilting in a video recording), and WTC 2 tilted to the east and south and twisted in a counterclockwise motion. The primary direction of tilt was around the weak axis of the core (north-south for WTC 1 and east-west for WTC 2). An earlier building performance study, performed by a private-public sector team with funding support from the Federal Emergency Management Agency (FEMA), concluded that the core failed first in WTC 1 based on vertical movement of the antenna observed in a video recording from due north that did not capture the antenna tilt due to the angle from which the video was shot. NIST is reevaluating this conclusion based on new visual information available from a different angle.*

Analysis of Recovered WTC Steel

NIST believes the collection of steel in its possession is adequate for purposes of analyzing the quality and properties of steel for the Investigation. NIST has 236 pieces of steel in its possession. The regions of impact and fire damage were emphasized in the selection of steel pieces for the investigation. As a result, NIST has all 14 specified steel grades for the exterior panels in the WTC towers, 2 specified grades that represent 99 percent of the core columns, and both specified grades for the steel trusses that comprised the composite floor truss system.

Finding 1a.9: *Analysis of steel recovered from the WTC towers, based on stampings on the steel and mechanical tests, indicates that the correct specified materials were provided for the specified elements. When these data were combined with pre-collapse photographic images of damaged steel, it was found that aircraft impacted pieces of steel recovered from WTC 1 were in the precise locations as specified in the design drawings.*

Finding 1a.10: *Metallography and mechanical property tests indicate that the strength and quality of the steel used in the towers was as specified, typical of the era, and likely met all qualifying test requirements. Further metallographic and fractographic analyses on the pieces from the impact zone are being considered.*

Finding 1a.11: *The room-temperature strength of the steel used in the towers met the relevant standards and, in many instances, exceeded the requirements by 5 percent to 10 percent. Ten different steel companies fabricated structural elements for the WTC towers, using steel supplied by at least eight different suppliers; four fabricators supplied the major structural elements from the 9th to the 107th floors. Work is ongoing to analyze the performance of the steel building components under impact and fire conditions up to initiation of global building collapse.*

Reconstruction of the Fires

NIST has completed three series of large-fire tests to enhance and validate the fire dynamics and thermal modeling tools being used in the WTC investigation, including:

- Single office workstation cubicle fire tests, based on descriptions of furnishings used in the WTC 1 office space, to generate a database on the thermo-physical properties of the materials for input to the fire dynamics simulation tool. The effects of debris and jet fuel on these fires were also investigated.

- Fire tests of multiple WTC workstation cubicles to validate the model predictions of the sensitivity of fire intensity, duration, and spread to the distribution and nature of the combustibles, effect of ventilation on the fire, and the effects of debris and jet fuel.

- Fire tests to measure the thermal environment (heat release and transfer rate to compartment gases) in a burning compartment and to establish a data set to validate the prediction of the temperature rise of structural steel components (similar to WTC steel trusses and columns, with and without fireproofing).

In addition, NIST has completed a series of experiments on ceiling tile systems similar to those present in the WTC towers. Shake table experiments were conducted to determine the magnitude of impulses that could result in damage to the ceiling tile systems, increasing the accessibility of the fire energy to the ceiling/floor membranes.

NIST has significantly enhanced the capabilities of computational tools for fire dynamics and thermal modeling and validated their predictions during the investigation. The tools can now be applied with greater confidence to recreate possible fires from the complex arrays of combustibles that existed in the WTC buildings, given initial damage conditions and descriptions of combustibles that have been collected by NIST. Key enhancements include: underventilated fire scenarios, charring materials such as those comprising much of the office furniture, fire spread, dimensional resolution in the vicinity of structural components, time-efficient computations for large simulations, and visualization of large data sets. These tools will help to improve the fire-safe design of new structures and analyze conditions of existing structures.

Finding 1a.12: *Unlike the jet fuel that was mostly consumed in only a few minutes, typical office furnishings were able to sustain intense fires for at least an hour on a given WTC floor. NIST has obtained generic and, in some cases, specific information about the furnishings in the WTC offices. In addition, NIST has obtained descriptions of the combustible contents of the aircraft. This includes cabin materials, aircraft components, and cargo bay contents. Based on a review of this information, NIST has found that:*

- *The typical WTC office floor, using modern workstation furnishings, had on average about 4 pounds per square foot (psf) of combustible materials on floors without unusual file rooms, film storage, etc. For conventional office buildings, the weight of combustibles varies from a combustible load commensurate with that in the WTC to about 10 psf to 20 psf when there are extensive bookcases, file storage, etc.*

- *The mass of the aircraft solid combustibles was significant relative to the mass of the building combustibles in the immediate impact region of each of the WTC towers.*

Following the experimental validation of the NIST Fire Dynamics Simulator for the WTC application, an extensive series of simulations of the fire floors in all three buildings is well underway. Input to the simulations includes the information gathered on the layouts of the floors, ventilation through the broken windows (as observed in the visual collection), the nature and loading of the combustible contents of the buildings, and preliminary (visual) estimates of damage to the towers from the aircraft impact. Alternative estimates of possible damage conditions in the interiors of the buildings are examined parametrically.

Consistent with available photographic and videographic evidence, these simulations have been able to capture the broad patterns of fire movement around the floors, with the flames in a given location lasting for about 20 min before spreading to adjacent, yet unburned combustibles. This spread is generally continuous due to the relatively even distribution of combustibles and the paucity of interior partitions and tends to be controlled by the air supply available through broken windows. There are some observed instances where fires persisted over longer durations in regions with accumulated combustible debris and other instances of sudden or interrupted fire spread. To the extent that these fires are locally of high intensity and duration and occur in a vicinity where they could contribute to structural weakening, they are being examined further via additional simulations.

Applying the 1968 NYC Building Code, the WTC towers were required to have 1 h fire-rated tenant separations, but the code did not impose any minimum compartmentation requirements (e.g., 7,500 ft^2) to mitigate the horizontal spread of fire in buildings with large open floor plans. The affected floors in the WTC towers were mostly open—with a modest number of perimeter offices and conference rooms and an occasional special purpose area. Some floors had two tenants, and those spaces, like the core areas, were partitioned (slab to slab). Photographic and videographic evidence confirms that even non-tenant space partitions (such as those that divided spaces to provide corner conference rooms) provided substantial resistance to fire spread in the affected floors. Exit access corridors had a 2 h fire-rating with 1 1/2 h fire-rated doors. Enclosures for vertical exits, exit passageways, hoistways, and shafts were required to be 2 h.

Finding 1a.13: *Laboratory experiments show that impulses like those estimated for the aircraft impact caused serious damage to the ceilings in the WTC towers. This is consistent with the accounts of survivors from floors below the impact region. This damage enables "unabated" heat transport over the floor-to-ceiling partition walls and to the steel trusses, spandrels, and tops of columns.*

Structural Response and Collapse Analysis

NIST has developed and adopted a comprehensive approach to identify the most probable of technically possible collapse sequences, from aircraft impact to collapse initiation. The approach:

- Combines mathematical modeling, well-established statistical and probability-based analysis methods, laboratory experiments, and analysis of photographic and videographic evidence.

- Allows for evaluation and comparison of possible collapse sequences based on different damage states, fire paths, and structural responses.

- Accounts for variations in models, input parameters, analyses, and observed events.

NIST has defined detailed requirements for this complex series of analyses, formulated detailed modeling approaches to capture important structural behavior, made significant progress in developing and evaluating the adequacy of the models, and obtained results from preliminary analyses using the models. The objective of the analyses is to simulate highly-complex failure modes at the component level, subsystem level, and over the entire structure due to aircraft impact and the subsequent fires. In many instances, NIST is testing the limits of current engineering software. Most such systems are used in general practice for design purposes, not for high-fidelity modeling and failure analysis of complex systems.

The computational models developed by NIST include:

- A detailed model of a typical truss-framed floor of the WTC towers with over 40,000 elements and 166,000 degrees of freedom.
- A detailed model of a typical beam-framed floor of WTC towers with over 12,000 elements and 35,000 degrees of freedom.
- A detailed global model of WTC 1 with over 80,000 elements and 218,000 degrees of freedom (with 17 flexible and other rigid diaphragm floors).
- A similar detailed global model of WTC 2 with over 78,000 elements and 200,000 degrees of freedom.
- A model of a typical turbofan engine of the Boeing 767-200ER aircraft with over 60,000 elements and 100,000 nodes.
- A comprehensive model of the Boeing 767-200ER aircraft, including engines, airframe, landing gear, fuel tanks, passenger cabin, and cargo bay, with over 530,000 elements and 740,000 nodes.

The first four models described above are being used to evaluate the baseline performance of the WTC towers under design gravity and wind loads. They also serve as *reference* models for other phases of the investigation involving analyses of aircraft impact damage and response of the thermally-insulated WTC structures to the subsequent fires.

Finding 1a.14: *The WTC tower structures represented an innovative structural system when they were built. The structural system incorporated many new and unusual features, including:*

- *First frame-tube framing system for a high-rise steel building.*
- *Composite floor system, using open-web bar joist elements, to provide lateral stability and diaphragm action.*
- *First extensive use of prefabricated perimeter panels (3 columns wide by 3 stories high) in steel construction with bolted butt-plate column splices.*

- *Uniform perimeter column geometry (14 in x 14 in cross-section) over most of the height of the 110-story buildings.*

- *First use of more than 14 different grades of specified steel in a tall building, with 14 grades specified for the uniform perimeter column geometry.*

- *Use of deep spandrel plates as beam elements connecting perimeter columns, enabling frame-tube action by providing lateral bracing around the structure.*

- *First use of wind tunnel testing to estimate the lateral wind loads in the design of a super tall building.*

- *First use of structural dampers to control dynamic motion in tall buildings, especially those due to winds (10,000 viscoelastic dampers were installed in each building connecting the floor trusses to the perimeter frame-tube system).*

- *Use of specially designed prefabricated panels to transfer forces at the chamfered corners of the frame-tube system.*

Finding 1a.15: *NIST has completed a preliminary stability analysis of the WTC towers. The findings from the preliminary analysis, if they remain viable upon further more detailed analysis, suggest that:*

- *For global instability of the WTC tower to occur under service loading conditions, five floors must have separated completely from all columns if the columns are at room temperature or four full floors must separate if the columns are uniformly heated to 600 ℃. Linear stability analysis indicates that some individual core columns begin buckling with fewer "failed" floors at both temperatures without significantly affecting global stability.*

- *For typical truss-framed floors under service loading conditions, if fifteen core columns are assumed severed due to aircraft impact, tension is induced in those columns by the floor immediately above the failure location of the columns. The tension force increases as more floor loads are picked up by the columns as they approach the hat truss at the roof level. The increase in tension load is limited by the tensile capacity of the column splice. When the tensile load exceeds the column splice capacity at a certain floor level, the splice fails, and all floors below the failed splices must redistribute their own loads directly to neighboring undamaged core columns. When fewer (only eight) core columns are assumed severed, the tension forces in the core columns are smaller due to the larger stiffness of the damaged floor area for eight severed columns, relative to that for 15 severed columns. The stiffer floor area redistributed more of the floor loads directly to neighboring undamaged core columns. The extent to which the severed core columns assist in transferring loads via the hat truss without failure of the column splices is sensitive to the relative magnitudes of the floor loads, column tension force, and column splice capacity.*

- *WTC 1 maintained stability after aircraft impact, with the highest stressed elements being the perimeter columns next to the region where columns and spandrels were severed on the north face of the tower. The analysis assumed eight columns in the core were severed due to aircraft impact. A "pushdown" analysis was used for evaluating structural stability accounts*

> *for geometric and material nonlinearities with plastic hinges. WTC 1 also maintained stability with remaining residual reserve capacity when additional perimeter columns were removed on the south face to represent the inward bowing observed in videos a few minutes prior to collapse. However, loss or weakening of additional core columns, weakening of additional perimeter columns, or loss of additional floors would be needed for global collapse of the tower to occur.*

NIST has completed a series of preliminary aircraft impact analyses using component-level models of tower perimeter and core columns with wing section and engine component models as impactors. These models were used to develop the simulation techniques required for the global analysis of the aircraft impacts into the WTC towers.

Finding 1a.16: *A 500 mph engine impact against an exterior wall panel results in a penetration of the exterior wall and failure of impacted perimeter columns. If the engine does not impact a floor slab, the majority of the engine core remains intact through the exterior wall penetration with a reduction in velocity between 10 percent and 20 percent. The residual velocity and mass of the engine after penetration of the exterior wall is sufficient to fail a core column in the event of a direct impact. Interaction with additional interior building contents prior to impact, or an indirect impact against the core column, could change this result.*

Finding 1a.17: *A normal impact of the exterior wall by an empty wing segment (toward the wing tip region) will produce significant damage to the perimeter columns, but not necessarily complete failure. This is consistent with photographs showing the exterior damage to the towers immediately after impact. Specific details of the damage depend on details of the impact orientation and locations of internal wing components such as control surface actuators and arms.*

Finding 1a.18: *Impact by a fuel-filled wing section (away from the wing tip toward the fuselage) results in extensive damage to the exterior wall panel, including complete failure of the perimeter columns. This is also consistent with photographs of the exterior damage. The resulting debris propagating into the building maintains the majority of the initial momentum of the wing prior to impact.*

NIST has completed detailed preliminary analyses of the response of a single floor truss assembly if it were subjected to a severe fire. These include the response of the truss and its seat connections (to columns) and knuckles (to provide composite action with the concrete floor slab) to service load conditions, uniformly increasing elevated temperatures in the steel, and increasing the temperature gradient in the concrete slab. The truss model includes all potential failure modes that may occur under loading and thermal conditions, though the actual sequence of failure may differ under other fire conditions.

Finding 1a.19: *NIST's preliminary analyses of a single floor truss assembly if it were subjected to a severe fire suggest the following sequence of events:*

- *The floor truss first experiences increasing vertical deflections at mid-span as it pushes (expands) outward and exerts a compressive lateral load on the exterior column. The exterior column begins to displace outward at the floor connection.*

- *Web diagonals begin to buckle at 340 °C, the mid-span deflection continues to increase, but the horizontal displacement of the exterior column begins to decrease. The maximum horizontal displacement of the exterior column is approximately 0.7 in. when the diagonals begin to buckle. (The interior column is assumed to have no lateral displacements at the floor level, as it is braced by the core framing.)*

- *The shear connectors (steel-knuckle-to-concrete slab connections referred to as knuckles) at each end of the truss begin to fail as the steel and bottom surface of the slab reach 400 °C, with such failures moving progressively inward from the truss ends. The failure of web diagonals and knuckles at the ends of the truss reduce the bending rigidity of the floor truss at the ends, further increasing the floor sag and decreasing the lateral outward force exerted on the columns.*

- *The truss bearing angle slips until the bolt is bearing against the edge of the slotted hole. The bolt shears off at the interior seat connection at approximately 500 °C. The floor truss sag increases to 20 in. when the bolt fails.*

- *The interior end of the reinforced slab continues to carry vertical loads as the truss bearing angle continues to slip. At 560 °C, the exterior column begins to be displaced inward as the floor truss continues to sag and exert vertical and horizontal tensile loads.*

- *At 650 °C, the truss slides off the interior seat, followed by the gusset plate fracture at the exterior connection at 660 °C.*

NIST has developed a rigorous technical approach to evaluate the role fireproofing conditions may have played in the collapse of the WTC towers, considering:

- Specified spray-applied fire resistive material (SFRM) and thicknesses for the various structural components.

- The as-built condition of the fireproofing prior to September 11, 2001, including the average SFRM thicknesses applied to different structural components, and variability in the thickness along the length of components.

- The mechanical and thermal properties of the fireproofing materials, including adhesive and cohesive bond strengths, and temperature-dependent heat capacity and thermal conductivity.

- The extent to which fireproofing may have been damaged due to aircraft impact via debris impact and local deformation/acceleration of structural components.

Finding 1a.20: *Available records suggest that the fireproofing of the columns, beams, and spandrels of the WTC towers was not a subject of concern to the building owner and designers, while fireproofing of the floor trusses 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 h and 2 h fire endurance, respectively.*

- *The steel trusses that supported the floors of WTC 1 and WTC 2 were specified to be fireproofed with 1/2 in. of SFRM, although the technical basis for the selection of fireproofing material and its thickness are not known.*

- *In 1999, a decision was made to begin upgrading the fireproofing to a specified 1.5 in. thickness as tenant spaces became unoccupied. In general, the floor systems in WTC 1 subject to aircraft impact and subsequent fires had been upgraded by September 11, 2001; the affected floors in WTC 2 had not.*

- *The fire protection of a truss-supported floor system by directly applying spray-on fireproofing to the steel trusses was innovative and not consistent with prevailing practice at the time the WTC towers were designed and constructed. While the benefits of conducting a full-scale fire endurance test were recognized by the building designers, no tests were conducted on the floor system used in the WTC towers to establish a fire endurance rating.*

Finding 1a.21: *The response of a structural component to fires is sensitive to variability in fireproofing thickness along its length. Such variations can be random in nature or in some instances as stark as bare spots. In the case of random variations, given an average fireproofing thickness and a coefficient of variation, it is possible to identify an equivalent uniform thickness without variation that gives nearly the same time history of temperature rise and component structural response under thermal loads.*

- *For the original fireproofing in the WTC towers, the as-applied fireproofing thickness (0.75 in. average and 0.4 coefficient of variation) on the floor trusses is thermally equivalent to a uniform thickness of 0.6 in. with no variation. This uniform thickness is greater than the specified minimum thickness of 0.5 in.*

- *For the upgraded fireproofing in some floors of the WTC towers, the as-applied upgraded fireproofing thickness (2.5 in. average and 0.24 coefficient of variation) is thermally equivalent to a uniform thickness of 2.2 in. with no variation. This uniform thickness is greater than the specified minimum thickness of 1.5 in.*

- *Thus, it is possible to evaluate if the as-applied average fireproofing thickness and variation on a component is thermally equivalent to a uniform thickness that is at least equal to the minimum fireproofing thickness specified on that component.*

- *For a specified fireproofing thickness, it is also possible to recommend an as-applied average thickness, given the expected variability (coefficient of variation) in quality of fireproofing application.*

NIST is currently examining an alternative performance criterion for determining the equivalent thickness based on restrained conditions to confirm the above finding.

Finding 1a.22: *Based on simplified analytical models, it was found that acceleration of a structural element, on the order of 100 times the acceleration due to gravity (or 100 g), would be required to* *dislodge 1 in thick SFRM from a planar surface. Acceleration on the order of 150 g would be required to dislodge a similar thickness of SFRM from a 1 in. diameter bar. In both cases, SFRM cohesive and adhesive strength properties and densities were typical of those used in the WTC towers. Experiments are underway to verify the results of these simplified analyses. In addition, analytical studies are underway to estimate the magnitude of accelerations of the structural members due to aircraft impact, from which the regions where fireproofing may have been dislodged will be identified.*

1.3 COLLAPSE OF THE 47-STORY WTC 7 BUILDING

Working Hypothesis

A working hypothesis has been developed around four phases of the collapse of WTC 7 that were observed in photographic and videographic records: an initiating event, a vertical progression at the east side of the building, a subsequent horizontal progression from the east to the west side of the building, and global collapse. The working hypothesis will be revised and updated as results of ongoing, more comprehensive analyses become available. NIST welcomes comments from technical experts and the public on this working hypothesis.

Finding 1b.1: *The working hypothesis for the collapse of the 47-story WTC 7, if it remains viable upon further analysis, suggests that it was a classic progressive collapse that included:*

- *An initial local failure at the lower floors (below floor 13) of the building due to fire and/or debris induced structural damage of a critical column (the initiating event), which supported a large span floor bay with an area of about 2,000 ft^2;*
- *Vertical progression of the initial local failure up to the east penthouse, as large floor bays were unable to redistribute the loads, bringing down the interior structure below the east penthouse; and*
- *Horizontal progression of the failure across the lower floors (in the region of floors 5 and 7, that were much thicker than the rest of the floors), triggered by damage due to the vertical failure, resulting in disproportionate collapse of the entire structure.*

WTC 7 Steel

No steel from WTC 7 has been identified from the pieces of recovered WTC steel in NIST's possession. WTC 7 had two specified grades of steel for columns and beams and four grades of steel for cover plates used in built-up columns. The specified grades (ASTM A36, A572 Grades 42 and 50, and A588 Grades 42 and 50) of steel are readily available. Properties were estimated from available test data in the literature.

Visual Observations

Finding 1b.2: *The first exterior sign of structural failure in WTC 7 was the sinking of the east penthouse roof structure into the building. Photographic and videographic records taken from the north have provided information about the sequence of failure events and their relative times. Other key observations* *include window breakage along the east side of the north face, occurring almost simultaneously with the sinking of the east penthouse structure, an approximate 5 s delay before the other roof structures also sank into the building core, a second set of window breakage along the west side of the north face occurring simultaneously with the other roof structure movements, and the appearance of the entire north façade above the 13th floor dropping as an intact unit 8 s after the east penthouse movement was first detected.*

Finding 1b.3: *Witnesses reported structural damage to WTC 7 on its south face and southwest corner from WTC 1 debris. A multi-story gash that extended across approximately a quarter to a third of the south face, in the lower portion of the face, was reported by a number of individuals, though details vary. This damage extended to the core area as two elevator cars were reportedly ejected from the elevator shaft at floor 8 or 9. Reported damage to the southwest corner was confirmed visually in photographic records, which show approximately two columns and related floor areas missing from floors 8 to 18. Multiple photographic and videographic records also appear to show damage on the south face that started at the roof level and severed spandrels between exterior columns near the southwest corner for at least 5 to 10 floors. However, the extent and details of this damage have not yet been discerned, as smoke is present in the photographs.*

Finding 1b.4: *Fires were first observed in WTC 7 after WTC 1 collapsed. Fires, or evidence of fires, were observed initially on the south face and near the southwest corner on Floors 22, 29, and 30. Many of these fires appeared to burn out before 2:00 p.m. Around 2:00 p.m., fires were observed in photographic and videographic records to be burning across Floors 11 and 12 on the east face, from the south to the north. Around 3:00 p.m., fires were observed on Floors 7 and 12 along the north face. The fire on Floor 12 appeared to bypass the northeast corner and was first observed at a point approximately one third of the width of the building from the northeast corner, and then spread both east and west across the north face. Sometime later, fires were observed on Floors 8 and 13 with the fire on floor 8 moving from west to east and the fire on Floor 13 moving from east to west. At this time, the fire on Floor 7 appeared to have stopped progressing near the middle of the north face. The fire on Floor 8 continued to move east on the north face, eventually reaching the northeast corner and moving to the east face. Around 4:45 p.m., a photograph showed fires on Floors 7, 8, 9, and 11 near the middle; Floor 12 was burned out by this time. Interview responses indicate that there was no water in the standpipe system supplying the sprinklers in WTC 7.*

Fuel System for Emergency Power

NIST has reviewed the fuel system for emergency power in WTC 7. There were two 12,000 gal fuel tanks below the first floor loading dock and one 6,000 gal above ground tank on the first floor. These tanks supplied fuel to 275 gal day tanks on floors 5, 7, and 8, and a 50 gal day tank on floor 9. In addition, there were two 6,000–gal tanks located below the first floor loading dock with pressurized pipes leading to floor 5.

Floor 5 did not have any exterior windows but it did have exhaust vents for generators near the south and north corners of the building. Any fires that may have burned on this floor would not have been visible in photographic or videographic records, except for smoke at the exhaust vents, which was not observed. The large opening created by the reported gash in the south face may have so altered the air flow on Floor 5 as to vent any smoke generated on this floor out the south face of the building, where overall smoke conditions prevented photographs or other observations. However, there was a pressurized fuel distribution system on the south, west and north floor areas. Given the variability of damage descriptions for the south face from WTC 1 debris impact, Floor 5 is considered a possible fire initiation location, subject to further data and/or analysis on building conditions that improve knowledge of fire conditions in this area.

Finding 1b.5: *The owner of the two 6,000 gal tanks supplying 5th floor generators through a pressurized piping system contracted with an environmental mitigation firm to recover any remaining fuel and to determine the extent of any contamination from fuel leakage from these tanks several months after the collapse. They reported that the tanks had been damaged by debris and were empty. No residual petroleum product or sludge was found in the tanks or piping. Examination of the gravel below the tanks and the sand below the slab on which the tanks were mounted showed some fuel contamination, but none was found in the organic marine silt/clay layer below. Witnesses also reported that the two 6,000 gal fuel tanks were always kept full for emergencies and were full that day. This finding allows for the possibility, though not conclusively, that the fuel may have contributed to a fire on Floor 5.*

1.4 EVACUATION AND EMERGENCY RESPONSE

Buildings are not designed for fire protection and evacuation under magnitude and scale of conditions similar to those caused by the terrorist attacks of September 11, 2001. Prior evacuation and emergency response experience in major events did not include the total collapse of tall buildings such as the WTC towers and WTC 7 that were occupied and in everyday use. Recent experience with major tall building fires suggests that they typically result in burnout conditions, not global building collapse. The intent of building codes is for buildings to withstand design loads without *local* structural collapse until the occupants can escape and the fire service can complete search and rescue operations. The load conditions induced by aircraft impact and the extensive fires on September 11, 2001, which triggered the collapse of the WTC towers, fall outside the norm of design loads considered in building codes.

NIST is interested in determining what factors related to normal building and fire safety considerations, if any, could have saved additional WTC occupant lives on September 11, 2001, or could have minimized the loss of life among the ranks of first responders. This is being accomplished by addressing the following key questions related to occupant behavior, evacuation, and emergency response:

- How did the evacuation technologies and practices affect the resulting fatalities and injuries?
- How did the first responder technologies and practices affect the resulting fatalities and injuries?
- How did the command, control, and communication systems support the activities of the first responders?
- What were the design, capabilities, and performance of the installed active fire protection systems (i.e., fire alarm, sprinkler, and smoke management systems)?
- What were the physical conditions within the buildings associated with occupant safety, tenability, and emergency responder operations?

- How did building design features affect egress and emergency access?

NIST is using multiple sources of data to investigate occupant behavior, evacuation, and emergency response. These sources include:

- Existing published first-person accounts of WTC evacuation; over 725 accounts collected and analyzed.
- Communication tapes from the PANYNJ and NYPD; 1,000-plus hours of taped recordings.
- Filings with the Occupational Safety and Health Administration by survivors and families of victims; about 60 written statements.
- Documents from the PANYNJ, FDNY, NYPD, and others on design of egress and emergency communication systems; WTC evacuation history; WTC evacuation planning and drills; emergency response preparedness and operational data.
- Photographic and videographic data on occupant behavior, evacuation, and emergency response.
- First-person data collection from WTC survivors, current and retired first responders, and families of victims.
- New York City 911 tapes and logs, and transcripts of about 500 interviews with FDNY employees involved in WTC emergency response activities.

Occupant Behavior and Evacuation

NIST is documenting occupant behavior and evacuation efforts by gathering and analyzing information about:

- Evacuation systems, emergency communications, and human factors;
- Occupant location, evacuation experience, and observed building conditions; and
- Interaction between occupants, first responders, and the buildings.

NIST has completed first-person interviews of nearly 1,200 WTC occupants and first responders to collect data on occupant behavior, evacuation, and emergency response, including:

- 803 telephone interviews with occupants of WTC 1 and WTC 2;
- 228 face-to-face interviews of WTC occupants and families of victims, including 28 near the floors of impact in both WTC towers, 33 persons with responsibility within the buildings, 15 who were in elevators, 13 who had a disability, 8 family members of victims, and 7 occupants from WTC 7; further, 8 interviews were conducted with key personnel present inside WTC 7;

- 108 face-to-face interviews of first responders, including 68 from FDNY, 24 from NYPD, 13 from the Port Authority Police Department (PAPD) and other PANYNJ safety and communications personnel, and 3 other building security and fire safety personnel;

- Six focus groups, including a group each from WTC 1 and WTC 2, maintenance and security personnel, floor wardens, people near/above the floor of impact, and mobility-challenged survivors.

Based on information and data gathered during these interviews with *surviving occupants:*:

Finding 2.1: *It is estimated that 17,400 occupants (± 1,200) were present in the WTC towers on the morning of September 11, 2001. The initial population of each tower was similar: 8,900 (± 750) in WTC 1 and 8,500 (± 900) in WTC 2. Of those present on September 11, 2001, 16 percent were also present during the 1993 bombing.*

Finding 2.2: *The average age of surviving occupants of the WTC towers was mid-forties, with a range of ages from their early twenties to mid-seventies. Occupants were twice as likely to be male (65 percent for WTC 1 and 69 percent for WTC 2) as female.*

Finding 2.3: *Two-thirds of WTC 1 surviving occupants had started working in the building during the previous four years (1998-2001), while half of WTC 2 occupants had begun working there during the same time period. The median residence time in WTC 1 was 2 years, while the median in WTC 2 was 3 years. In WTC 1, 4 percent of the occupants had worked in the building since 1975, while there was only one such respondent in WTC 2.*

Finding 2.4: *About 6 percent of the surviving occupants reported a pre-existing limitation to their mobility. These limitations included obesity, heart condition, needing assistance to walk, pregnancy, asthma, being elderly, chronic condition, recent surgery or injury, and other.*

Finding 2.5: *Overall, 7 percent of the surviving occupants reported having special knowledge about the building. These included fire safety staff, floor wardens, searchers, building maintenance, and security staff. Searchers assist the floor wardens in facilitating evacuation.*

Finding 2.6: *Approximately 87 percent of the WTC tower occupants, including more than 99 percent of those below the floors of impact, were able to evacuate successfully. Two-thousand one- hundred fifty-nine building occupants (1,560 in WTC 1 and 599 in WTC 2) and an additional 433 first responders, including security guards, were reported to have lost their lives that day. This does not include aircraft passengers and crew or bystanders.*

Rough initial estimates suggest that about 20 percent or more of those who were in the WTC towers and lost their lives may have been alive in the buildings just prior to their collapse. This estimate—which will be refined as analysis of the data is completed—assumes that nearly all of the first responders and 76 building occupants below the floors of impact but none of the people at or above the floors of impact who may have been alive. Below the floors of impact, there were 72 fatalities reported in WTC 1 and four fatalities reported in WTC 2, not including first responders. It is estimated that were a total of 2,592 building occupants and first responders who were in the WTC towers and lost their lives.

Finding 2.7: *Two-thirds of the surviving occupants reported having participated in a fire drill in the 12 months prior to September 11, 2001, while 17 percent reported that they received no training during that same period. Of those participating in fire drills, 93 percent were instructed about the location of the nearest stairwell. Overall, slightly over half of the survivors, however, had never used a stairwell at the WTC prior to September 11, 2001.*

Finding 2.8: *Overall, about 7,900 surviving occupants evacuated WTC 2 in 73 min (i.e., from the instant the WTC 1 was struck by aircraft until WTC 2 collapsed) while about 7,500 survivors evacuated WTC 1 in 103 min. Thus, the overall evacuation rate in WTC 2 (108 survivors per min) was about 50 percent faster than that in WTC 1 (73 survivors per min). Functioning elevators allowed many survivors to evacuate WTC 2 prior to aircraft impact.*

- *After the first airplane struck WTC 1 and before the second airplane struck WTC 2, the survivors in WTC 2 were twice as likely as those in WTC 1 to have already exited the building (41 percent versus 21 percent). The rate of evacuation completion in WTC 2 was twice the rate in WTC 1 during that same period. The elevators in WTC 2 were functioning at this time, while most of those in WTC 1 were not and survivors could only use the stairways. The stairwells, with partition wall enclosures that provided a 2 h fire-rating but little structural integrity, were damaged in the region of the aircraft impacted floors.*

- *Soon after WTC 2 was struck by the airplane until about 20 min before each building collapsed, the survivors in WTC 2 and WTC 1 had exited at about the same rate (the prior evacuation rate of WTC 1). Most of the elevators in both towers were not functioning at this time, and survivors could only use the undamaged stairways.*

- *During the last 20 min before each building collapsed, the evacuation rate in both buildings had slowed considerably to about one-fifth the immediately prior evacuation rate. This suggests that* for those seeking and able to reach and use undamaged exits and stairways, *the egress* capacity *(number and width of exits and stairways) was adequate to accommodate survivors.*

NIST has utilized existing computer egress models to better understand the evacuation experience on September 11, 2001. While these models were developed using data not indicative of the WTC buildings or events, they can provide some perspective into the relative magnitudes of evacuation times for phased evacuation (as the buildings are designed) and full evacuation of occupants. Three full evacuation scenarios are considered: a typical full capacity building evacuation assuming the WTC tower is fully occupied—with one case considering only tenants and another case considering both tenants and visitors; a full capacity building evacuation of each WTC tower with aircraft impact damage; and a September 11, 2001, capacity evacuation from a WTC tower.

NIST is using two classes of egress models in order to frame the evacuation questions: (1) partial behavior: simulates occupant movement and limited behavioral rules by including delay times, smoke effects, and occupant characteristics; and (2) behavioral: simulates movement and more comprehensive evacuation decisions and activities.

Finding 2.9: *Preliminary results from application of existing computer egress models for a full capacity evacuation of a single WTC tower with 25,000 occupants and visitors indicate a movement time of 2 h* *and 15 min. This is a minimum time estimate since the simulation assumed that there was no survivor delay, continual movement on the stairs, and no damage to the egress system. It was also assumed that elevators were not available. The egress model estimate for a September 11, 2001 capacity evacuation under the same assumptions is about 50 min, which is 2.5 times less than the time estimate for evacuating 25,000 people.*

Finding 2.10: *Given that the actual evacuation time on September 11, 2001 was about 100 min without elevator use, a full capacity evacuation of each WTC tower with 25,000 people would have required about 4 h (or 2.5 times 100 min). To achieve a significantly faster total evacuation at full capacity would have required increases in egress capacity (number and width of exits and stairways).*

Finding 2.11: *Ingress/egress was a tremendous physical challenge for first responders and many occupants; inadequate footwear presented a mobility challenge, particularly for many women. Many people were left shoeless, and their discarded shoes often littered the stairwells.*

NIST also has studied the possibility of roof evacuations from the WTC towers.

Finding 2.12: *A preliminary evaluation indicates that the PANYNJ's evacuation procedures did not include a plan to provide roof rescue for occupants trapped in a building incident at the WTC site. The standard policy was to keep the doors to the roof locked with a key being required to gain roof access. No fire safety procedures explicitly called for opening these doors, including anyone on a "key run." Instead, the standard occupant evacuation procedures and drills required the use of stairwells to exit at the bottom of the WTC towers. The PANYNJ reports that it never advised tenants to evacuate upward.*

Finding 2.13: *There were at least two instances reported on September 11, 2001, where roof access was found to be locked in both WTC towers. In the case of WTC 1, a decedent had called and informed a parent that they had tried to get to the roof and found the door locked. In the case of WTC 2, a decedent had called and informed a spouse that he had tried to get to the roof and found the door locked.*

Finding 2.14: *At least one case was reported on September 11, 2001, where a PANYNJ employee, trapped on Floor 105 of WTC 2, was instructed on the radio (PANYNJ Channel Y) by another PANYNJ employee to go to the roof of the building. The trapped occupant was unable to walk down the stairs, or go to the roof as instructed.*

Finding 2.15: *The NYPD aviation unit arrived at the WTC site soon after WTC 1 was attacked. Despite repeated attempts to examine the possibility of roof rescue, smoke and heat conditions at the top of the WTC towers prevented the conduct of safe roof evacuation operations. A helicopter, attempting to inspect the roof condition and determine if occupants were on the roof, experienced engine temperature increase as it approached WTC 1.*

Finding 2.16: *NYPD has an aviation-training manual to guide roof rescue in high-rise emergencies. The manual is not specific to the WTC. Considering the capacity of typical helicopters and travel times, it is not clear what fraction of the large number of occupants could have been evacuated from the WTC towers prior to their collapse had roof rescue been possible on September 11, 2001.*

The analysis of the first-person accounts collected from occupants by NIST and the evacuation modeling work is ongoing, and NIST will report its additional findings on occupant behavior and evacuation at a later date. That report will incorporate results from the analysis of previously published first-person accounts provided to the media by survivors and information released to the public by the 9-11 Commission.

Emergency Response and Communications

NIST's investigation of fire service technologies and guidelines, and more broadly the emergency response related to firefighting and evacuation on September 11, 2001, seeks to:

1. Document what happened during the emergency response to the attacks on the WTC up until the collapse of WTC 7;

2. Identify issues that need to be addressed in practices, standards, and codes;

3. Identify alternative practices and/or technologies that may address these issues; and

4. Identify technologies and guidelines to advance the safety of first responders in tall building emergencies.

Three FDNY suitcase-based, magnetic Command Boards were set up at the incident site. The unit identification and assignment for each unit that arrives at the scene is written on a magnetic chip and placed on the board. Information related to the location and activities of the units once they are on site are also recorded. One Command Board was set up at the original Incident Command Post in the lobby of WTC 1. The WTC 1 lobby Command Post became an Operations Post when the Incident Command Post moved outside. However, the original Command Board remained in place inside WTC 1 when the Incident Command Post was moved outside. The second Command Board was set up at the fire department's Operations Post in the lobby of WTC 2, and the third Command Board was set up at the new Incident Command Post established by the Chief of Department on West Street in front of the World Financial Center 2 building.

Finding 2.17: *The FDNY suitcase-based, magnetic Command Board system that was generally adequate for normal fire and rescue operations was not adequate for handling the massive operations that were necessary as a result of the terrorist attacks on the WTC. Interviews with FDNY personnel indicated that some FDNY personnel and others entered the towers and were not recorded on the Command Boards. This resulted in the lack of inportant command information. In addition, each of these Command Boards was damaged, and all were lost with the collapse WTC 2. There was no back-up capability for the Command Boards, and all information related to command, control, and accountability was lost.*

NIST has completed a partial analysis of emergency responder communications including:

- Digital copies of the audio communications tapes recorded by the PANYNJ, including communications from emergency response personnel, maintenance personnel, PAPD personnel, and a recording of the FDNY's city-wide high-rise Channel 7 (PAPD's Channel 30) radio repeater that was located at the WTC; and

- Audio tapes copied from original NYPD communications tapes, including NYPD internal department operations.

FDNY communications recordings from the WTC location on September 11, 2001, are not available because the primary field communication truck was in the shop for repairs, and a backup field communications van was used in its place. The backup van did not have the capability to record the on-scene incident command or tactical communications and was destroyed when the WTC towers collapsed.

The best record of radio communications reflecting fire department operations available to NIST came from the FDNY Channel 7/PAPD Channel 30 tape and first person accounts provided by FDNY personnel during their interviews. The tape provides limited information on FDNY communications and operations at the incident, but it does provide insight into FDNY operations inside WTC 2. FDNY Channel 7/PAPD Channel 30 was a city-wide channel designated by FDNY for use in high-rise building operations. The PANYNJ installed the radio repeater system at the WTC for use by FDNY after the 1993 bombing.

Finding 2.18: *The following findings have been drawn from the first-person interviews with emergency responders regarding telephone communications:*

- *Before the attack occurred, both the landline and cellular systems appeared to be working normally.*
- *Only moments after the first aircraft impacted WTC 1, the landline and cellular telephone systems were stressed by increased caller volume that made it difficult to get messages through. This condition continued for many hours following the attack.*
- *Telephone calls from the WTC to the 911 emergency operators, and statements from various individuals interviewed, show that even though WTC 1 and WTC 2 were severely damaged by aircraft impact and fires, many of the landline telephones in the buildings continued to work up until the collapse of WTC 2.*
- *After the collapse of WTC 2, a number of cellular phone systems were not functional in the area of lower Manhattan.*
- *After the collapse of WTC 2, there were still some landline telephones working within the city block areas adjacent to the WTC site.*

NIST has developed a preliminary chronology, based on analysis of selected communications messages, to provide information concerning (1) dispatch and arrival of emergency response units, (2) evacuation, (3) emergency response operations, (4) emergency response communications, and (5) observations of building conditions.

Finding 2.19: *The following findings have been drawn from the analysis of the emergency responder communication tapes:*

- *After the first aircraft struck WTC 1, there was an approximate factor of 5 peak increase in traffic level over the normal level of emergency responder radio communications, followed by an approximate factor of 3 steady increase in the level of subsequent traffic.*

- *A surge in communications traffic volume made it more difficult to handle the flow of communications and delivery of information.*

- *Roughly a third to a half of the radio messages transmitted during these radio traffic surge conditions were not complete messages or understandable.*

- *Preliminary analysis of the FDNY city-wide high-rise Channel 7 (PAPD Channel 30) recording indicates that the WTC site repeater was operating.*

- *Communications records and interviews with aviation unit personnel indicate that smoke and heat conditions on the top of the WTC towers prevented NYPD helicopters from conducting safe roof evacuation operations.*

- *NYPD aviation unit personnel reported critical information about the impending collapse of the WTC towers several minutes prior to their collapse. No evidence has been found to suggest that the information was communicated to all emergency responders at the scene.*

Finding 2.20: *Several FDNY personnel at the incident site did not think that the high-rise radio repeater was working. This is based on radio communications tests that were conducted by two chief officers working inside WTC 1 when the first command post was being set up in that lobby. This radio communications test was recorded on the FDNY Channel 7/PAPD Channel 30 tape. Following this radio test, a chief officer involved in the test chose to use different channels for command and tactical communications during the disaster. However, as FDNY operations increased in WTC 2, it was determined by FDNY members that the high-rise repeater was functioning, and use of the channel developed.*

Finding 2.21: *While the preliminary NIST analysis indicates that the repeater was operating, there also appears to have been some type of malfunction with the communications equipment that was detected, but not identified, by FDNY officers during the initial test. Three hypotheses are being investigated related to this malfunction: (1) damage to the repeater antenna system located in WTC 5, e.g., changing its direction, (2) failure of the radio handset located at the fire command desk in the lobby of WTC 1, and (3) the volume of the radio hand set not being turned up.*

NIST continues to evaluate the repeater system and its operations, as well as the handheld radios, which were used on September 11, 2001. The findings listed above will be updated and additional findings will be documented when the investigation is complete.

NIST has completed its review of the NYC 9-1-1 tapes and logs and the transcripts of about 500 interviews with FDNY employees involved in WTC emergency response activities. Analysis of this and other information is ongoing.

Finding 2.22: *Based on face-to-face interviews, NIST has determined that first responders— including key incident commanders—did not have adequate information (voice, video, and data) on and an overall perspective of the conditions in the WTC buildings and what was happening elsewhere at the WTC site; interagency information sharing was inadequate.*

NIST continues to analyze all of the data sources (documents, visual images, first-person accounts, and communications records) related to the emergency response activities at the WTC site, including deployment, evacuation, operations, and communication systems and protocols. A future report will document the findings from that analysis.

Fire History of the WTC Towers

NIST has completed a review of the history of post-occupancy fire incidents and identified significant fire incidents—those that exercised the fire suppression systems, specifically multiple sprinklers or one or more standpipes (with or without activation of at least one sprinkler).

The FDNY fire reports and fire investigation records indicate that in areas protected by automatic sprinklers, no fire activated more than three sprinklers. The design area for three sprinklers is a floor area of 63 m^2 (675 ft^2) in light hazard occupancy, such as a high-rise office building as specified in the National Fire Protection Association Standard for the Installation of Sprinkler Systems (NFPA 13).

Many of the fires that occurred were recorded as suspicious or unknown in cause, occurred during off-peak work hours, and involved materials such as trash or paper-based supplies. In cases where sprinklers were activated, the fire department records indicated that the sprinklers either extinguished the fire completely or aided in controlling the spread. In summary:

- 16 significant fires occurred in WTC 1, 2, and 7, with 12 in WTC 1, three in WTC 2, and one in WTC 7. Twelve of the 16 fires occurred between 6 p.m. and 4 a.m. when the number of occupants in the buildings was likely to be small.
- Of the 16 fires and their causes, five were labeled as unlisted or unclassified, six as suspicious or incendiary, two as discarded material, and three as an electrical failure or mechanical failure.
- Of the 16 fires, four were concentrated above the 100th floors and six fires were located in the basements. The other six were distributed throughout the rest of the buildings.
- 31 additional fires occurred in WTC 1 and WTC 2, which involved the use of one standpipe, with 23 in WTC 1 and eight in WTC 2.
- There is no known loss of life as a result of any of these fires (not including the 1993 bombing incident and September 11, 2001, terrorist attacks).

The following significant fires (not including the 1993 bombing incident and September 11, 2001, terrorist attacks) are noteworthy:

- February 14, 1975: Fire started on the 11th floor of WTC 1. Fire damage occurred on the 10th through the 19th floors. Approximately 9,000 ft^2 of 11th floor contents on the southeast corner was destroyed or damaged.
- April 19, 1980: Fire started on the 106th floor of WTC 1. Approximately 300 occupants from the Windows on the World restaurant on the 107th floor were evacuated.

- April 17, 1981: Fire started on the 7th floor of WTC 1. Approximately 1,500 occupants were evacuated from Floors 9 through 23.

Active Fire Protection Systems – Sprinkler Systems

Finding 2.23: *In WTC 1, 2, and 7, primary and secondary water supplies, fire pump size and locations, water storage tanks, and fire department connections provided multiple points of water supply redundancy. The potential for single point failure of the water supply to the fire sprinklers existed at each floor due to lack of redundancy in the sprinkler riser system that provided only one supply connection on each floor. As a result, the water supply to the sprinkler systems or a standpipe serving pre-connected hoses could be interrupted by routine maintenance needs (i.e., shutdown of the riser or standpipe) or by impairment due to deliberate acts to damage the sprinkler riser or standpipe systems. While this lack of redundancy may not have had an impact on September 11, 2001 because the sprinkler system was damaged by aircraft impact, it could have made a difference in other building emergencies.*

Finding 2.24: *Aided by the results of hydraulic modeling of a sprinkler system in WTC 1 and WTC 2—undamaged by aircraft impact and fully operational—the delivered water flow rate available from the automatic sprinkler systems was found to generally exceed the minimum requirements (by a considerable margin) for a high-rise office hazard classification in accordance with NFPA 13. In a number of cases, the amount of available water flow from sprinklers on specific floors was capable of protecting higher fire hazard classes than those associated with light hazard office buildings.*

Active Fire Protection Systems—Fire Alarm Systems

Finding 2.25: *The fire alarm system that was monitoring WTC 7 sent to the monitoring company only one signal (at 10:00:52 a.m. shortly after the collapse of WTC 2) indicating a fire condition in the building on September 11, 2001. This signal did not contain any specific information about the location of the fire within the building. From the alarm system monitor service view, the building had only one zone, "AREA 1." The building fire alarm system was placed on TEST for a period of 8 h beginning at 6:47:03 a.m. on September 11, 2001. Ordinarily, this is requested when maintenance or other testing is being performed on the system, so that any alarms that are received from the system are considered the result of the maintenance or testing and are ignored. NIST was told by the monitoring company that for systems placed in the TEST condition, alarm signals are not shown on the operator's display, but records of the alarm are recorded into the history file.*

Finding 2.26: *The resistance to failure of the fire alarm system communications paths between the fire command station and occupied WTC tower floors could have been enhanced if fiber optic communications cable had been used instead of copper lines. Extensive damage to the towers upon aircraft impact is likely to have cut and short-circuited the wiring of the alarm system network cables. If that occurred, communications between the distributed fire alarm panels, which are components of the integrated fire alarm system, would have been degraded and lost to certain panels depending on the location of those panels. Fiber optic cable is not susceptible to electric short-circuits and would have provided full communications with fire alarm system components, including voice communications systems, to the point where the cable was severed. Electric shorts in the voice communications disable that communication system over the entire cable length affected by the electric short-circuit. During initial engineering design for the fire alarm system in WTC 1 and WTC 2, the PANYNJ requested, but did* *not receive, approval of the City of New York for use of fiber optic communications cable in the system. The NYC code required copper wiring. As a result, ordinary copper wire communication cable was specified.*

A dedicated communications system for emergency responders, known as the "standpipe telephone" system, was installed in the stairwells of WTC 1 and WTC 2. To use the system, a compatible telephone handset was needed. Some firefighters that received handsets at the command post in the lobby of WTC 1 were interviewed as part of the Investigation. Every one of the firefighters interviewed indicated that they did not use the standpipe telephone communication system on September 11, 2001. Due to the loss of firefighters in WTC 2, there is no information about the use of the system in WTC 2.

Active Fire Protection Systems—Smoke Management System

The smoke management system in the WTC towers as designed and documented in the operation manuals consisted of a smoke purge mode using the components of the main HVAC (heating, ventilation, and air-conditioning) system. This system was intended to remove smoke and other gaseous combustion products from the fire area after a fire had been extinguished. This system was to be activated "manually" at the direction of FDNY.

Finding 2.27: *Based on the information reviewed, the smoke management systems were not activated during the fires on September 11, 2001. It was determined that the likelihood of these systems being functional in WTC 1 and WTC 2 was very low due to the damage inflicted by the aircraft impacts. In addition to the significant openings created in the building envelopes, the aircraft impacts are likely to have severed major vertical shafts through which ran electrical power supply and duct risers of the HVAC system, thereby causing the loss of power to the smoke management system air handlers and damage to the vertical HVAC duct risers used to provide smoke management (smoke purge).*

Finding 2.28: *The analysis of smoke flow in WTC 1 and WTC 2 on September 11, 2001, shows that HVAC ductwork was a major path for vertical smoke spread in the buildings. Fire dampers were installed in the systems, but not smoke dampers. Operational combined fire/smoke dampers in the HVAC ductwork on each floor would have provided a barrier to hot gas and smoke penetration into the vertical HVAC shafts in WTC 1 and WTC 2. However, smoke dampers were not available when the towers were built.*

Finding 2.29: *Modeling results show that in WTC 1 and WTC 2 stair pressurization systems would have provided minimal resistance to the passage of smoke had they been installed on September 11, 2001. While the existence of such systems was known when the WTC towers were built, the alternative smoke purge system used in the WTC towers was considered to be equivalent. Multiple stair doors being open for substantial periods of time due to occupant egress and stairway walls damaged by aircraft impact would have resulted in an inability to prevent smoke from entering stairwells.*

1.5 PROCEDURES AND PRACTICES

The 110-story WTC towers were among the world's tallest buildings, while the 47-story WTC 7 represented a more typical tall building. These buildings provide case studies to document, review, and, if needed, improve the procedures and practices used in the design, construction, operation, and maintenance of tall buildings. This investigation objective is independent of other objectives which are focused specifically on the consequences of the attack on September 11, 2001, viz., the building collapses, evacuation, and emergency response. While some findings under this objective are directly relevant to the events of September 11, 2001, others are concerned with general building and fire safety procedures and practices.

NIST seeks to determine the building and fire safety procedures and practices that were used over the life of the WTC buildings and how well those procedures and practices conformed to accepted national building and fire safety practices, standards, and codes. The procedures and practices of interest to the investigation include those related to:

- Design and construction,
- New and innovative design features,
- New and innovative technologies and materials,
- Passive and active fire safety systems,
- Emergency access and egress systems, and
- Structural modifications, inspection, and maintenance.

To provide context for studying the specifications and criteria used for the WTC buildings, NIST has completed a preliminary comparison of building regulatory and code requirements. For the structural system, this comparison included the following building codes:

- New York City Building Code - 1968 edition
- New York State Building Code - 1964 edition
- Chicago Building Code - 1967 edition
- BOCA Basic Building Code - 1965 edition (a national model building code)
- New York City Building Code - 2001 edition

For the fire protection and egress system, the comparison included the five codes listed above plus the 1966 edition of the National Fire Protection Association Life Safety Code (NFPA 101).

Applicable Building Codes

Finding 3.1: *Although not required to conform to NYC codes, the PANYNJ adopted the provisions of the proposed 1968 edition of the NYC Building Code, more than three years before it went into effect. The 1968 edition allowed the PANYNJ to take economic advantage of less restrictive provisions compared* *with the 1938 edition that was in effect when design began for the WTC towers in 1962. The 1968 code:*

- Eliminated a fire tower[5] as a required means of egress;
- Reduced the number of required stairwells from 6 to 3 and the size of doors leading to the stairs from 44 in. to 36 in.;
- Reduced the fire rating of the shaft walls in the building core from 3 h to 2 h;
- Changed partition loads from 20 psf to one based on weight of partitions per unit length (that reduced such loads for many buildings including the WTC buildings); and
- Permitted a 1 h reduction in fire rating for all structural components (columns from 4 h to 3 h and floor framing members from 3 h to 2 h) by allowing the owner/architect to select Class 1B construction for business occupancy and unlimited building height.

Many of these newer requirements, instituted in the 1968 NYC Building Code, are contained in current codes.

Finding 3.2: *The NYC Department of Buildings reviewed the WTC tower drawings in 1968 and provided comments to the PANYNJ concerning the plans in relation to the 1938 NYC Building Code. The architect-of-record submitted to the PANYNJ responses to those comments, noting how the drawings conformed to the 1968 NYC Building Code. NIST continues reviewing documents to determine the level of review conducted by the NYC Department of Buildings and the six specific items identified in that review.*

Finding 3.3: *In 1993, the PANYNJ and the NYC Department of Buildings entered into a memorandum of understanding that restated the PANYNJ's longstanding policy to assure that its facilities in the City of New York meet and, where appropriate, exceed the requirements of the New York City Building Code. The agreement also provided specific commitments to the NYC Department of Buildings regarding procedures to be undertaken by the PANYNJ to assure that buildings owned or operated by the PANYNJ are in conformance with the Building Standards contained in the NYC Building Code. Some salient points included in this agreement and the 1995 enhancement to the agreement are:*

- *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;*
- *The PANYNJ 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; and*

[5] A fire tower (also called a smoke-proof stair) is a stairway that is accessed through an enclosed vestibule that is open to the outside or to an open ventilation shaft providing natural ventilation that prevents any accumulation of smoke without the need for mechanical pressurization.

- *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.*

- *Variances from the Code, acceptable to the PANYNJ, would be submitted to the NYC Department of Buildings for review and concurrence.*

Finding 3.4: *In 1993, the PANYNJ adopted a policy providing for implementation of fire safety recommendations made by local government fire departments after a fire safety inspection of a PANYNJ facility and for the prior review by local fire safety agencies of fire safety systems to be introduced or added to a facility. Later that year, the PANYNJ entered into an agreement with FDNY which reiterated the policy adopted by the PANYNJ, recognized the right of FDNY to conduct fire safety inspections of PANYNJ properties in the City of New York, provided guidelines for FDNY to communicate needed corrective actions to the PANYNJ, assured that new or modified fire safety systems are in compliance with local codes and regulations, and required third-party review of such systems by a New York State licensed architect or engineer.*

Standard Fire-Resistance Tests

Finding 3.5: *Availability of code provisions with detailed procedures to analyze and evaluate data from fire resistance tests of other building components and assemblies to qualify an untested building element. Based on available data and records, no technical basis has been found for selecting the spray-applied fire resistive material (SFRM) used (two competing materials were under evaluation) or its thickness for the large-span open-web floor trusses of the WTC towers. The assessment of the fireproofing thickness needed to meet the 2 h fire rating requirement for the untested WTC floor system evolved over time:*

- *In October 1969, the PANYNJ directed the fireproofing contractor to apply 1/2 in. of fireproofing to the floor trusses.*

- *In 1999, the PANYNJ issued guidelines requiring that fireproofing be upgraded to 1-1/2 in. for full floors undergoing alterations.*

- *Unrelated to the WTC buildings, an International Conference of Building Officials (ICBO) Evaluation Service report (ER-1244), re-issued June 1, 2001, using the same SFRM recommends a minimum thickness of 2 in. for "unrestrained steel joists" with "lightweight concrete" slab.*

Finding 3.6: *Availability of code provisions that require the conduct of a fire resistance test if adequate data do not exist from other building components and assemblies to qualify an untested building element. Instead, several alternate methods based on other fire-resistance designs or calculations or alternative protection methods are permitted with limited guidance on detailed procedures to be followed. Both the architect-of-record (in 1966) and the structural-engineer-of-record (in 1975) stated that the fire rating of the floor system of the WTC towers could not be determined without testing. NIST has not found evidence indicating that such a test was conducted to determine the fire rating of the WTC floor system. The PANYNJ has informed NIST that there are no such test records in its files.*

NIST has awarded a contract to Underwriters Laboratories (UL) to determine the fire resistance rating of the WTC floor system under both as-specified and as-built conditions. The tests, which are expected to be conducted in August 2004, will provide the fire endurance ratings of typical WTC floor construction to evaluate three primary factors: (1) test scale, (2) fireproofing thickness, and (3) thermal restraint. The four tests will be performed as follows:

- 17 ft span assembly, thermally restrained, SFRM thickness of 1/2 in.
- 17 ft span assembly, thermally restrained, SFRM thickness of 3/4 in.
- 35 ft span assembly, thermally restrained, SFRM thickness of 3/4 in.
- 35 ft span assembly, thermally unrestrained, SFRM thickness of 3/4 in.

The first test represents current U.S. practice for establishing a fire endurance rating of a building assembly. The test assembly, fabricated to meet the design of the WTC steel joist-supported floor system, has a span of 17 ft. This span is typical of the floor assembly test furnaces used by the U.S. testing laboratories that routinely conduct the ASTM E119 test for the construction industry. As is common practice, the floor assembly will be tested in the thermally restrained condition. This test will be conducted at UL's Northbrook, Illinois, fire test facility. A second test will be identical except for the thickness of SFRM. The third and forth tests will be at twice the scale of the first two tests, with a span of 35 ft. This span represents a full-scale assembly of the 35 ft floor panel of the WTC floor system. The floor assembly for the third test will be thermally restrained as in the first two tests thereby allowing direct comparison for the determination of the effect of test scale on fire endurance rating. The fourth test will be conducted in the thermally unrestrained support condition which will allow direct comparison of the effect of thermal restraint on the fire endurance rating. The third and fourth tests will be conducted at the UL Canada fire test facility near Toronto.

Building Classification and Fire Rating

Finding 3.7: *Use of the "structural frame" approach, in conjunction with the prescriptive fire rating, would have required the floor trusses, the core floor framing, and perimeter spandrels in the WTC towers to be 3 h fire-rated, like the columns for Class 1B construction in the 1968 NYC Building Code. Neither the 1968 edition of the NYC Building Code which was used in the design of the WTC towers, nor the 2001 edition of the code, adopted the "structural frame" requirement. The "structural frame" approach to fire resistance ratings requires structural members, other than columns, that are essential to the stability of the building as a whole to be fire protected to the same rating as columns. This approach, which appeared in the Uniform Building Code (a model building code) as early as 1953, was carried into the 2000 International Building Code (one of two current model codes) 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 WTC floor system was essential to the stability of the building as a whole since it provided lateral stability to the perimeter columns and diaphragm action to distribute wind loads to the perimeter columns.*

Finding 3.8: *Availability of technical basis to establish whether the construction classification and fire rating requirements in modern building codes are risk-consistent with respect to the design-basis hazard and the consequences of that hazard. The fire rating requirements, which were originally developed* *based on experience with buildings less than about 20 stories in height, have generally decreased over the past 80 years since historical fire data for buildings suggested considerable conservatism in those requirements. However, for tall buildings, the likely consequences of a given threat to an occupant on the upper floors are more severe than the consequences to an occupant, say, on the first floor. It is not apparent how the current height and area tables in building codes consider the technical basis for the progressively increasing risk to an occupant on the upper floors of tall buildings that are much greater than 200 ft in height. The maximum required fire rating in current codes applies to any building more than about 12 stories in height. There are no additional categories for buildings above, for example, 40 stories and 80 stories, where different building classification and fire ratings requirements may be appropriate, recognizing factors such as the time required for stairwell evacuation without functioning elevators (e.g., due to power failure or major water leakage), the time required for first responder access without functioning elevators, the presence of sky lobbies and/or refuge floors, and limitations on the height of elevator shafts. The 110-story WTC towers, initially classified as Class IA based on the 1938 NYC Building Code, were classified as Class 1B before being built to take advantage of the provisions in the 1968 edition of the code. This re-classification permitted a reduction of 1 h in the fire rating of the components (columns from 4 h to 3 h and floor framing members from 3 h to 2 h).*

Fire Performance of Structures

Finding 3.9: *Structural design does not consider fire as a design condition, as it does the effects of dead loads, live loads, wind loads, and earthquake loads. Current prescriptive code provisions for determining fire resistance of structures—used in the design of the WTC towers and WTC 7— are based on tests using a standard fire that may be adequate for many simple structures and for comparing the relative performance of structural components in more complex structures. A building system with 3 h rated columns and 2 h rated girders and floors could last longer than 3 h or shorter than 2 h depending upon the performance of the structure as a 3-dimensional system in a real fire. The standard tests cannot be used to evaluate the actual performance (i.e., load carrying capacity) in a real fire of the structural component, or the structure as a whole system, including the connections between components. Performance-based code provisions and standards are not available for use by engineers, as an alternative to the current prescriptive fire rating approach, to (1) evaluate the system performance of tall-building structures under real fire scenarios, and (2) enable risk consistent design with appropriate thickness of passive protection being provided where it is needed on the structure. Standards development organizations, including the American Institute of Steel Construction, have initiated development of performance-based provisions to consider fire effects in structural design.*

Finding 3.10: *Availability of detailed procedures to select appropriate design-basis fire scenarios to be considered in the performance-based design of the sprinkler system, compartmentation, and passive protection of the structure. The standard fire in current prescriptive fire resistance tests is not adequate for use in performance-based design. While the NFPA 5000 model building code contains general guidance on design fire scenarios (the IBC Performance Code contains no such guidance), the details of the scenarios are left to the fire engineer and regulatory official. The three major scenarios that are not considered adequately are: frequent but low severity events (for design of sprinkler system), moderate but less frequent events (for design of compartmentation), and a maximum credible fire (for design of passive fire protection on the structure). The maximum credible fire scenario for passive protection of structures would assume that the sprinkler system is compromised or overwhelmed and that there is no active firefighting. These building-specific representative fire scenarios are similar in concept, though not* *identical, to the approach used in building design where the performance objectives and design-basis of the hazard are better defined (e.g., a two-level design that includes an operational event with a 10 percent probability of occurrence in 50 years and a life safety event with a 2 percent probability of occurrence in 50 years). The design-basis fire hazards for the WTC towers and WTC 7 are unknown, and it is difficult to evaluate the performance of the fire protection systems in these buildings under specific fire scenarios.*

Finding 3.11: *Availability of code provisions to ensure that structural connections are provided the same degree of fire protection as the more restrictive protection of the connected elements. The provisions that were used for the WTC towers and WTC 7 did not require specification of a fire-rating requirement for connections separate from those for the connected elements. It is not clear what the fire rating of the connections were when the connecting elements had different fire ratings.*

Finding 3.12: *Availability of technical basis to establish whether the minimum mechanical and durability related properties of SFRM are sufficient to ensure acceptable in-service performance in buildings. While minimum bond strength requirements exist, there are no serviceability requirements for such materials to withstand typical shock, impact, vibration, or abrasion effects over the life of a building. There are existing testing standards for determining many of these properties, but the technical basis is insufficient to establish serviceability requirements. Knowledge of such serviceability requirements is relevant to determine the post-impact fireproofing condition of the WTC towers.*

Finding 3.13: *Availability of validated and verified tools for use in performance-based design practice to analyze the dynamics of building fires and their effects on the structural system that would allow engineers to evaluate structural performance under alternative fire scenarios and fire protection strategies. Existing tools are either too simplified to adequately capture the performance of interest or too complex and computationally demanding, and lack adequate validation. While considerable progress has been made in recent years, significant work remains to be done before adequate tools are available for use in routine practice. NIST has had to further develop and validate existing tools to investigate the fire performance of the WTC towers and WTC 7.*

Structural Integrity

Finding 3.14: *Availability of explicit structural integrity provisions to mitigate progressive collapse. Federal agencies have developed guidelines to mitigate progressive collapse and routinely incorporate such requirements in the construction of new federal buildings. The United Kingdom incorporates such code requirements for all buildings. New York City adopted by rule in 1973 a requirement for buildings to resist progressive collapse under extreme local loads. The rules, which were adopted after the WTC towers were built but before WTC 7 was built, applied specifically to buildings that used precast concrete wall panels and not to other types of buildings. As stated in Finding 1b.1, the current working hypothesis for the collapse of the 47-story WTC 7, if it remains viable upon further analysis, would suggest that it was a classic progressive collapse.*

Finding 3.15: *Availability of minimum structural integrity provisions for the means of egress (stairwells and elevator shafts) in the building core that are critical to life safety. In most tall buildings the core is designed to be part of the vertical gravity load carrying system of the structure. However, in many of those buildings, especially in regions where earthquakes are not dominant, the core may not be part of* *the lateral load carrying system of the structure. Thus, the core may be designed to carry only vertical gravity loads with no capacity to resist lateral loads, i.e., overturning moment and shear loads. In such situations, the structural designer may prefer the use of partition walls over structural walls in the core area to reduce building weight. The decision to have the core carry a specified fraction of the lateral design loads or be made part of a dual system to carry lateral loads, each of which would enhance the structural integrity of the core if structural walls were used, is left to the discretion of the structural engineer. Alternatively, stairway/elevator cores built with concrete or reinforced concrete block, which are not part of the lateral load carrying system, may be able to provide sufficient structural integrity if they meet, for example, the hose-stream impact test already required by ASTM E 119, or other more appropriate test. In the case of the WTC towers, the core had 2 h fire-rated partition walls with little structural integrity and the core framing was required to carry only gravity loads. Had there been a minimum structural integrity requirement to satisfy normal building and fire safety considerations, it is conceivable that the damage to stairways, especially above the floors of impact, may have been less extensive.*

Finding 3.16: *Availability of standards and code provisions for conducting wind tunnel tests and for the methods used in practice to estimate design wind loads from test results. Building codes allow the determination of wind pressures from wind tunnel tests for use in design. Such tests are frequently used in the design of tall buildings. Results of two sets of wind tunnel tests conducted for the WTC towers in 2002 by independent commercial laboratories as part of insurance litigation, and voluntarily provided to NIST by the parties to the litigation, show large differences, of as much as about 40 percent, in resultant forces on the structures, i.e., overturning moments and base shears. Independent reviews by a NIST expert on wind effects on structures and a leading engineering design firm contracted by NIST indicated that the documentation of the test results did not provide sufficient basis to reconcile the differences. In addition, the wind loads estimated from these tests are about 20 percent to 60 percent higher than those apparently used in the original design of the WTC towers, also obtained from wind tunnel testing. NIST is conducting an independent analysis to establish the baseline performance of the WTC towers under the original design wind loads and will compare those wind load estimates with then-prevailing code requirements. Wind loads were a major governing factor in the design of structural components that made up the frame-tube steel framing system.*

Compartmentation and Sprinklers

Building fire protection is based on a four-level hierarchical strategy comprising detection, suppression (sprinklers and firefighting), compartmentation, and passive protection of the structure.

- Detectors are typically used to activate fire alarms and notify building occupants and emergency services.
- Sprinklers are designed to control small and medium fires and to prevent fire spread beyond the typical water supply design area of about 1,500 ft^2.
- Compartmentation mitigates the horizontal spread of more severe but less frequent fires and typically requires fire-rated partitions for areas of about 7,500 ft^2. Active firefighting also covers up to about 5,000 ft^2 to 7,500 ft^2.

- Passive protection of the structure seeks to ensure that a maximum credible fire scenario, with sprinklers compromised or overwhelmed and no active firefighting, results in burnout, not overall building collapse. The intent of building codes is also for the building to withstand local structural collapse until occupants can escape and the fire service can complete search and rescue operations.

Compartmentation of spaces has long been a cornerstone to building fire safety to limit fire spread. The WTC towers initially had 1 h fire-rated partitions separating tenants (demising walls) that extended from the floor to the suspended ceiling, not the floor above (the ceiling tiles were not fire rated). Over the years, these partitions were replaced with partitions that were continuous from floor to floor (separation wall) as required by the 1968 NYC Building Code. Some partitions had not been upgraded by 1997, and a consultant recommended to the PANYNJ that it develop and implement a survey program to assure that the remediation process occurred as quickly as possible. It appears that with few exceptions, nearly all of the floors not upgraded were occupied by a single tenant, and it is not clear whether separation walls would have mattered in terms of meeting the 1968 code. The PANYNJ adopted guidelines in 1998 that required such partitions to provide a continuous fire barrier from top of floor to underside of slab.

Finding 3.17: *Building codes typically require 1 h fire-rated tenant separations but do not impose minimum compartmentation requirements (e.g., 7,500 ft²) for buildings with large open floor plans to mitigate the horizontal spread of fire. This is the case with both the 1968 NYC Building Code, which did not require above-ground sprinklers, and the 2001 NYC Building Code, which requires sprinklers. The sprinkler option was chosen for the WTC towers in preference to the compartmentation option in meeting the subsequent requirements of Local Law 5 adopted by New York City in 1973. Thus, if there was only one tenant on a WTC floor there would be no horizontal compartmentation requirement. Conversely, if there were a large number of tenants on a WTC floor, it would be highly compartmented with separation walls. The affected floors in the WTC towers were mostly open—with a modest number of perimeter offices and conference rooms and an occasional special purpose area. Some floors had two tenants and those spaces, like the core areas, were partitioned (slab to slab). Photographic and videographic evidence confirms that even non-tenant space partitions (such as those that divided spaces to provide corner conference rooms) provided substantial resistance to fire spread in the affected floors. For the duration of about 50 to 100 min prior to collapse of the WTC towers that the fires were active, the presence of undamaged 1 h fire-rated compartments may have assisted in mitigating fire spread and consequent thermal weakening of structural components.*

Finding 3.18: *Availability of state and local building regulations for early installation of sprinklers in existing buildings, not as an option in lieu of compartmentation. Functioning sprinklers can provide significant improvement in safety for most common building fires and prevent them from becoming large fires. NYC promulgated local laws in 1973 and 1984 to encourage installation of sprinklers in new buildings, and is now considering a law to require sprinklers in existing buildings. The WTC towers were fully sprinklered by 2001, about 30 years after their construction. Sprinklering of the tenant floors in the WTC towers was completed by October 1999, while sprinklering of the sky lobbies was still underway at that time. The sprinkler system was installed in three phases. Phase 1 was completed during initial building construction and included the sub-grade areas. Phase 2 was done in 1976, in compliance with Local Law 5, and included sprinklering the corridors, storage rooms, lobbies, and certain tenant spaces. Phase 3 was begun in 1983 and completed in 2001 and resulted in fully sprinklering the complex.*

Finding 3.19: *Modern building codes allow a lower fire rating for structural elements when a building is sprinklered. This trade-off provides an economic incentive to encourage installation of sprinklers. Sprinklers provide better intervention against small and medium fires, fires which are more likely to occur than a WTC disaster, as long as the water supply is not compromised and there is redundant technology in place. The required technical basis is not available to establish whether the "sprinkler trade-off" in current codes adequately considers fire safety risk factors such as: (1) the complementary functions of sprinklers and fire-protected structural elements, (2) the different fire scenarios for which each system is designed to provide protection, and (3) the need for redundancy should one system fail. It is noteworthy that the British Standards Institution (BSI) has established a group to review all the sprinkler trade-offs contained in their standards. While the classification and fire rating of the WTC towers did not take advantage of the sprinkler-tradeoff since such provisions were not contained in the 1968 NYC Building Code, had such provisions existed, they would have required a lower fire rating for many WTC building elements.*

Occupant Behavior and Evacuation

The capacity of egress systems in very tall buildings is based on the phased evacuation concept, where occupants are evacuated first from the three floors closest to the emergency (e.g., fire), while others wait their turn. Such systems require a voice communication system to manage the process from a fire command center and, e.g., in New York City, fire wardens on each floor directing the flow. These systems are not designed to accommodate a total or full emergency evacuation of the building.

There were at least three instances where a full evacuation of the WTC towers was ordered; a 1977 terrorist threat associated with bombings in two midtown Manhattan buildings, during the 1993 bombing, and on September 11, 2001. During the 1977 event, a full evacuation of the WTC complex was ordered at 11:45 a.m., and fire safety teams searched and evacuated 35,000 occupants. The evacuation was orderly, and no one was injured. The WTC complex was reopened to the public at 3:00 p.m. In addition, about 1,500 people were evacuated from 15 floors of WTC 1 during a fire on the morning of April 17, 1981.

Sufficient data do not exist on the frequency with which full evacuations are conducted in buildings not at risk for terrorist attacks and whether this frequency has increased since September 11, 2001. In one of the three instances, the WTC towers had to be fully evacuated even though the terrorist threat was to other remote buildings in the city. Based on NIST interviews of WTC survivors and anecdotal data reported to the 9-11 Commission, it appears that since September 11, 2001, building occupants may be more likely to evacuate even when the safety risk at their location may not be sufficient to require them to evacuate. It is not clear how widespread this sentiment is among the general population that did not experience the events of September 11, 2001 directly.

Finding 3.20: *Availability of technical basis for the design of egress systems. Current prescriptive methods (e.g., unit width or inches per person) for minimum stair width or number of stairs do not provide information on the target performance to be achieved. For example, what would be the evacuation rate or time, for a given occupant population, considering travel distance, remoteness requirements, and human factors such as occupant size (reflecting current population data), stairwell environmental conditions, visibility, and congestion. Also, the technical basis for the "sprinkler trade-off") in egress specifications (generally a doubling of allowed travel distance is not available).*

Further, proposals for increases in stair width do not consider the effect of doors in limiting the flow. Also, proposals for increases in the number of stairs do not balance the need to meet remoteness requirements (physical separation of stairways that are located in separate enclosures) while possibly permitting scissor stairs (two separate stairways within the same enclosure and separated by a fire rated partition). Scissor stairs are credited as a single stair but provide additional capacity and additional doors that achieve real increases in evacuation rate with only minor impact on leasable space. The egress capacity in the WTC towers was based on the unit-width method contained in the 1968 NYC Building Code; it is not possible to assess the adequacy of the resulting egress capacity to achieve a target performance (e.g., evacuation rate or time) under a design-basis evacuation event. Further, although the NYC code permitted scissor stairs—which are prohibited in most other codes—none were used in the WTC towers or WTC 7.

Finding 3.21: *Consideration of counterflow, e.g., due to first responder emergency access, in the design of egress systems. For typical short height buildings, the occupants are evacuated from the affected floors within a matter of several minutes, before first responders arrive and climb up the stairs. While such evacuation still would be ongoing after arrival of first responders in taller buildings, NIST interviews with WTC occupants suggest that on September 11, 2001, with about one-third of building occupants present, there were only occasional encounters with first responders, and counterflow was not a significant issue. This finding is consistent with the Finding 2.8—based on occupant first-person interviews—related to adequacy of the egress capacity in the WTC towers on September 11, 2001.*

Use of Elevators in Emergencies

Finding 3.22: *With a few special exceptions, building codes in the United States do not permit the use of fire-protected elevators for routine emergency access by first responders or as a secondary method (after stairwells) for emergency evacuation of building occupants. The use of elevators by first responders would additionally mitigate counterflow problems in stairwells. While the United States conducted research on specially protected elevators in the late 1970s, the United Kingdom has required such "firefighter lifts," located in protected shafts, for a number of years. Without functioning elevators (e.g., due to a power failure or major water leakage), first responders carrying gear typically require about a minute per floor to reach an incident using the stairs. While it is difficult to maintain this pace for more than about the first 20 stories, it would take a first responder about an hour to reach, for example, the 60th floor of a tall building if that pace could be maintained. Such a delay, combined with the resulting fatigue and physical effects on first responders that were reported on September 11, 2001, would make firefighting and rescue efforts difficult even in tall building emergencies not involving a terrorist attack. Each of the WTC towers had 100 elevators, and WTC 7 had 38 elevators. By code, the elevators could not be used for fire service access or occupant egress during an emergency since they were not fire-protected, nor were they located in protected shafts. The elevators were equipped through normal modernization with fire service recall. Most were damaged by the aircraft impacts; though prior to the impact in WTC 2 the elevators were functioning and contributed greatly to the much faster initial evacuation rate in WTC 2 as stated in Finding 2.8.*

Building Practices

Finding 3.33: *While the PANYNJ entered into agreements with the NYC Department of Buildings in the 1990s (with regard to conformance of PANYNJ buildings constructed in New York City to the NYC*

Building Code), the PANYNJ did not yield jurisdictional authority for regulatory and enforcement oversight to the New York City Department of Buildings. The PANYNJ was created as an interstate entity, under a clause of the U.S. Constitution permitting compacts between states, and is not bound by the authority of any local, state, or federal jurisdiction.

Finding 3.34: *Availability of rigorous field application and inspection provisions and regulatory requirements to assure that the as-built condition of the passive fire protection, such as SFRM, conforms to conditions found in fire resistance tests of building components and assemblies. For example, provisions are not available to ensure that the as-applied average fireproofing thickness and variability (reflecting the quality of application) is thermally equivalent to the specified minimum fire proofing thickness. In addition, requirements are not available for in-service inspections of passive fire protection during the life of the building. The adequacy of the fireproofing of the WTC towers posed an issue of some concern to the PANYNJ over the life of the buildings, and the availability of accepted requirements and procedures for conducting in-service inspections would have provided useful guidance.*

Finding 3.35: *State and local jurisdictions do not require retention of documents related to the design, construction, operation, maintenance, and modifications of buildings, with few exceptions. These documents are in the possession of building owners, contractors, architects, engineers, and consultants. Such documents are not archived for more than about 6 to 7 years and there are no requirements that they be kept in safe custody physically remote from the building throughout its service life. In the case of the WTC towers, the PANYNJ and its contractors and consultants maintained an unusually comprehensive set of documents, a significant portion of which had not been destroyed in the collapse of the buildings but could be assembled and provided to the investigation. In the case of WTC 7, the situation was more typical of current practice, and a significant portion of the documents could not be assembled since they were lost in the collapse of the building. However, NIST has adequate information for its investigation. Neither the original general contractor nor the architects was able to supply more than a few documents.*

Finding 3.36: *The architect is responsible for specifying the fire protection and designing the evacuation system in current building practice. The structural engineer is not required to evaluate and certify that the passive fire protection is adequate to protect the structural system. In accordance with established practice, the structural engineer was not responsible for the passive fire protection in the design of the WTC tower structures. In addition, there is no requirement for a fire protection engineer to be part of the team designing the overall fire protection (including detection, suppression, compartmentation, and passive fire protection) and evacuation systems for the building. A change in this respect is already underway for signature/iconic buildings, where it is becoming more common for a fire protection engineer to be included in the design team. In the case of the WTC towers, the building owner played a significant role in specifying the fire protection and evacuation systems; a fire protection engineer was not part of the original design team. There are only a few academic degree programs or continuing education programs that qualify engineers (or architects) to evaluate the fire performance of structures. The current state-of-practice is not sufficiently advanced for engineers to routinely analyze the performance of a whole structural system under a prescribed design-basis fire scenario.*

1.6 APPROACH TO RECOMMENDATIONS

In the United States, state and local governments are responsible for promulgating and enforcing building and fire regulations. While states are increasingly adopting a single, uniform set of statewide regulations, in many instances major cities and counties adopt their own regulations. The national organization representing state building officials is the National Conference of States on Building Codes and Standards (NCSBCS)—a body of the National Governors Association—and that representing building officials of major local jurisdictions is the Association of Major City/County Building Officials (AMCBO).

With some exceptions, the state and local regulations are based on national model building and fire codes developed by private sector organizations, the International Code Council (ICC) and the NFPA. The model codes, in turn, reference voluntary consensus standards developed by a large number of private sector standards development organizations (SDOs). They include organizations such as NFPA, ASTM International, the American Society of Civil Engineers (ASCE), the American Institute of Steel Construction (AISC), and the American Concrete Institute (ACI). The SDOs are accredited by the American National Standards Institute (ANSI).

Other key stakeholder groups involved in the design, construction, operation, and maintenance of buildings include organizations representing building owners and managers, real estate developers, contractors, architects, engineers, suppliers, and insurers.

NIST is a non-regulatory agency of the U.S. Department of Commerce. NIST does not set building codes and standards, but provides technical support to the private sector and other government agencies in the development of U.S. building and fire practices, standards, and codes. NIST recommendations are given serious consideration by private sector organizations that develop national standards and model codes – which provide minimum requirements for public welfare and safety. The model codes become regulation when adopted by state and local governments.

The NIST building and fire safety investigation of the WTC disaster has not yet formulated recommendations under this objective. However, in formulating its recommendations, NIST will consider the following:

- Findings from the first three independent investigation objectives related to building performance, evacuation and emergency response, and procedures and practices.
- Whether findings relate to the unique circumstances surrounding the terrorist attacks of September 11, 2001, or to normal building and fire safety considerations, including evacuation and emergency response?
- What technical solutions are needed, if any, to address potential risks to buildings, occupants, and first responders, considering both identifiable hazards and the consequences of those hazards?
- Whether the risk is in all buildings or limited to certain building types (e.g., height and area, structural system), buildings that contain specific design features, iconic/signature buildings, or buildings that house critical functions?

NIST urges organizations responsible for building and fire safety at all levels to carefully consider the interim findings contained in this report. NIST welcomes comments from technical experts and the public on the interim findings presented herein. Comments can be sent by e-mail to wtc@nist.gov, facsimile to 301-975-6122, or regular mail to WTC Technical Information Repository, Stop 8610, 100 Bureau Drive, Gaithersburg, MD 20899-8610.

In its final report, a draft which is expected to be released in December 2004, NIST will recommend appropriate improvements in the way buildings are designed, constructed, maintained and used. It will be important for those recommendations to be thoroughly and promptly considered by the many organizations responsible for building and fire safety. As a part of NIST's overall WTC response plan, the Institute has begun to reach out to those organizations to pave the way for a timely, expedited consideration of recommendations stemming from this investigation. NIST also already has expanded its research in areas of high priority need.

Chapter 2
PROGRESS ON THE WORLD TRADE CENTER INVESTIGATION

2.1 STATUS OF DATA COLLECTION EFFORTS

The National Institute of Standards and Technology (NIST) is basing its review, analysis, modeling, and testing work for the World Trade Center (WTC) Investigation on a solid foundation of technical evidence. This requires access to critical data such as building documents, videographic 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, tenants, first responders, contractors, insurers, news media, survivors, and families of victims. In addition, NIST has received and is grateful for cooperation from The National Commission on Terrorist Attacks Upon the United States (9-11 Commission). The documents and other information relate to the design, construction, operation, inspection, maintenance, repair, alterations, emergency response, and evacuation of the WTC complex.

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

NIST also has received information from Silverstein Properties and its consultants and contractors; the group of companies that insured the WTC towers and its technical experts; Nippon Steel; Laclede Steel; U.S. Mineral Products Co. and Isolatek International; Morse Zehntner Associates; W.R. Grace & Co.; Citigroup, formerly Salomon Smith Barney; United Airlines; American Airlines; and Boeing. NIST also received information on floor plans, furnishings, and contents from tenants of all three buildings.

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

NIST has received all of the essential information it needs for the WTC investigation. That information includes NYC 9-1-1 tapes, the transcripts of approximately 500 interviews of employees of the FDNY who were involved in WTC emergency response activities, and supporting documents for McKinsey & Company's FDNY study.

The following is the list of documentary information received or inspected by NIST.

December 2002

- The original design drawings (structural, architectural, mechanical, electrical, plumbing) and the original fabrication and construction drawings for the WTC towers
- Tenant alteration application reports, including drawings and specifications, for the WTC towers and WTC 7, and associated construction audit reports
- Tenant design standards manuals for structural; architectural; heating, ventilating, and air-conditioning (HVAC); fire protection; plumbing; electrical; fire alarm; and construction review
- Emergency evacuation procedures manuals, including fire safety guide
- Operations manuals for the fire protection system, including sprinklers, standpipes, alarm system and communication protocols, and water and power supply
- Operations manuals for the HVAC systems
- Reports on facility condition surveys and structural integrity inspections for the WTC towers and WTC 7
- Recent inspection and maintenance reports for the elevators and escalators in the WTC towers; elevator numbering system
- Reports on pre-design tests of structural components, including dampers for the WTC towers
- Reports on wind tunnel tests of the WTC towers and wind speed measurements near the WTC site
- Reports on the 1993 bombing damage assessment and repairs, and documentation of changes made to the evacuation system after 1993
- Documents related to the location, approval, and inspection of fuel tanks in WTC 7
- Documents related to fire rating and fireproofing of structural steel members in the WTC towers
- Documents related to PANYNJ building and fire code requirements and practices
- Correspondence sent to the Occupational Safety and Health Administration regarding the evacuation experience of WTC occupants on September 11, 2001
- Documents related to the lease of the WTC towers by Silverstein Properties
- Reports prepared by McKinsey & Company for FDNY and NYPD

- Basic FDNY dispatch data, including time of dispatch and unit identification
- Firefighter fatality and injury data from FDNY

May 2003

- More than 1,000 hours of recordings made by PANYNJ on September 11, 2001 (from 0705 through 1900 hours) of telephone calls, as well as police, fire, operations, maintenance, security, and other radio transmissions from four distinct locations
- Personal injury data from FDNY and Port Authority of New York and New Jersey Police Department (PAPD)
- Handwritten notes on the events of September 11, 2001, by PAPD staff
- Emergency responder fatality data for FDNY, NYPD, and PAPD
- WTC list of tenants with contact information from PANYNJ and Silverstein
- WTC list of occupants issued security badges by PANYNJ
- Report on WTC smoke management system by Hughes Associates, Inc.
- Phase I and final reports on fire engineering of WTC steelwork by Buro Happold
- Transcripts of depositions by two PANYNJ staff in the WTC insurance litigation
- Documents, videos, and photographs related to the fireproofing of the WTC tower structures
- WTC floor plan for the fire alarm system and drawings of WTC subgrade plumbing and city water main
- Information regarding building contents such as partitions and furnishings from a key WTC tower tenant, to characterize the types of combustibles and estimates of the mass loading in the region of the fires
- FDNY WTC incident summary, September 20, 2001
- FDNY reports on the fire history of WTC 1, 2, and 7 from 1970 to 2001
- FDNY reports related to inspections of WTC 1, 2, and 7 from 1999 to 2001
- FDNY policies and practices on operations specific to the WTC buildings and on accountability of firefighters at incidents
- FDNY information on dispatched units, apparatus, command posts, and staging areas
- FDNY information on number of command and company officers and firefighters operating in and around WTC 1, 2, and 7 with number of surviving personnel

- Detailed briefing on the NYPD communications system, including 9-1-1 system and radio networks

August 2003

- Design and structural calculations from Leslie E. Robertson Associates (LERA) for the WTC towers, including TV antenna, beams, and beam girders, as well as wind analysis and calculations
- Correspondence from LERA during the time of construction
- Laclede floor truss shop drawings (1,364 sheets) and other documents on steel and joints
- Information on steel from Nippon
- List of WTC drawings in possession of Yamasaki and Associates
- Information on the flammable contents of the American Airlines B-767 aircraft
- Information regarding building contents and floor layouts from some WTC tower and WTC 7 tenants
- Mechanical and electrical specifications for WTC 7
- Asbestos litigation documents from PANYNJ
- Underwriters' Laboratories, Inc. (UL) test reports regarding spray-on fireproofing from supplier (Isolatek)
- Correspondence on the selection of WR Grace fireproofing products, test data, and UL design listings (WR Grace)
- Data on the WTC internal radio system and FDNY radio repeater from PANYNJ
- Some FDNY training practices for operations in high-rise buildings
- Global positioning system coordinates and map where human remains and equipment were located from FDNY
- Information on FDNY personnel killed on September 11, 2001, and map of fire and Emergency Management Services Command Post Locations
- NYPD internal communications concerning the terrorist attacks on WTC (43 cassette tapes)
- Disaster Response Plan, Patrol Guide Procedures, and other guides and manuals from NYPD, including the Unusual Occurrence Report on the 1993 WTC bombing
- A large portion of NYPD and FDNY extensive photographic and videographic collection

- Updated badge list of WTC occupants maintained by PANYNJ
- WTC fire safety and PA/FDNY WTC training videos and pre-September 11, 2001 WTC photographs

September 2003

- Information on the flammable contents of the United Airlines B-767 aircraft
- Documents from PANYNJ on accessibility for disabled persons, active fire protection systems, and adoption of revisions to NYC Building Code
- Elevator and escalator contract information from PANYNJ
- Status of changes to WTC towers (March 1973) from PANYNJ
- Transcripts from September 11 PAPD audiotapes, police reports, and PAPD special awards ceremony documents for September 11, 2001
- Additional documents from PANYNJ on asbestos litigation

October 2003

- Supporting documents for McKinsey & Company's FDNY and NYPD studies
- Review of UL test reports regarding spray-on fireproofing from supplier (W.R. Grace)
- Information from Boeing on flammable contents of aircraft that contributed to fires

May 2004

- Review of NYC 9-1-1 tapes and logs, transcripts of about 500 first responder interviews with employees of the FDNY who were involved in WTC emergency response activities
- General description of WTC building systems and capital program
- WTC documents presented as exhibits in asbestos litigation
- Additional documents on WTC maintenance services, accessibility, elevators, code compliance, fire rating, fire detection system, fire alarm system, etc.
- Photographs of WTC 7 construction project
- Architectural and HVAC drawings for WTC 7, including modifications
- Well in excess of 6,000 photographs representing more than 185 professional and amateur photographers. Organizations that have provided materials include FDNY, NYPD, Associated Press, Corbis, Reuters, *The New York Times*, *The New York Daily News*, and the

Star Ledger. Many organizations have provided both published and unpublished photographs.

- In excess of 150 hours of videotapes from news media (NBC, CBS, ABC, CNN, and local New York stations WABC, WCBS, WNBC, WPIX, WNYW, and New York One), FDNY, NYPD, and more than 20 individuals. In many cases, the videos provide not only broadcast material (known as air checks), but also material that was recorded but not broadcast (known as outtakes).

The few NIST requests for materials that are lost, currently pending, or not yet located include:

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

NIST is making efforts to assemble this information from various sources because much of it was lost when the buildings collapsed. NIST continues to pursue other materials that can further clarify some aspects of the Investigation.

2.2 ANALYSIS OF BUILDING AND FIRE CODES AND PRACTICES (PROJECT 1)

2.2.1 Project Objective

One of the four primary objectives of the NIST Investigation of the WTC disaster is to determine the procedures and practices that 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.

For most buildings constructed in the United States, building codes adopted by local jurisdictions establish minimum requirements for design and construction. However, because PANYNJ is an interstate agency, its construction projects are not required to comply with any local or national model building code. Thus, to determine the criteria, procedures, and practices that were used in the design, construction, operation, and maintenance of WTC 1, 2, and 7, Project 1, Analysis of Building and Fire Codes and Practices, has the following objectives:

- Document the requirements that governed the design and construction of WTC 1, 2, and 7

- Document any differences between the Port Authority requirements used for design and the then current building code requirements of other jurisdictions and the appropriate model building code
- Document the procedures used by the Port Authority to accept new and innovative design features that deviated from the Port Authority building design requirements
- Document the procedures used to accept new technologies and materials that were not recognized by then-current standards
- Document passive and active fire safety, emergency access and egress provisions that were incorporated in the original design and subsequent modifications during occupancy
- Document major modifications made to structural, fire protection, and egress systems of WTC 1, 2, and 7
- Document the inspection and maintenance procedures used for WTC 1, 2, and 7.

2.2.2 Project Approach

The design and construction documents of the WTC buildings that were kept centrally at the Port Authority office in WTC 1 were destroyed when the tower collapsed. Thus, existing copies of design and construction documents of WTC 1, 2, and 7 had to be assembled from various sources that were associated with these projects. Documents were obtained principally from:

- The Port Authority, and
- Architectural and engineering firms who designed and inspected the WTC buildings.

In addition, information was obtained from others who were associated with WTC 1, 2, and 7 construction projects.

The information collected will enable the NIST investigators to accomplish the five tasks of Project 1:

- **Task 1**. Document the design and construction of structural systems to determine:
  - Provisions used to design and construct the buildings. This will include the Port Authority building design and construction requirements, the building code used, standards referenced, and Port Authority policies and agreements with the NYC Department of Buildings regarding building code requirements.
  - Tests performed to support the design, such as wind tunnel tests and tests of structural assemblies.
  - Criteria used to proportion structural members and other components of the buildings including structural connections.

- Innovative systems, technologies, and materials that were used, and the acceptance procedures used by the Port Authority.
- Variances granted by the Port Authority, including the justification for those variances.
- Special fabrication and inspection requirements.
- Inspection protocols used during construction.
- Technical problems that occurred during construction of the buildings and their resolution.

- **Task 2.** Document the design and construction of the fire protection and egress systems to determine:
  - Provisions used to design and construct the fire protection (passive and active) and egress systems of the buildings. This will include the Port Authority building and fire regulatory requirements, the building and fire code used, and standards referenced.
  - Building regulations adopted after the issuance of the certificates of occupancy, or equivalent, that were applied to the buildings through retroactivity (including any provisions of NYC Local Laws), and any permits issued or special inspections required resulting from the installation of special hazards or equipment in the buildings.
- **Task 3.** Document the fuel system for emergency power in WTC 7 to determine:
  - Locations of emergency power generating systems;
  - Size and locations of the fuel storage tanks and distribution systems;
  - Specific fire protection systems used for the fuel storage and distribution systems;
  - Normal and emergency operating procedures; and
  - Maintenance history.
- **Task 4.** Compare building regulatory and code requirements to document:
  - Port Authority building regulatory requirements.
  - Differences among the Port Authority building regulatory requirements and the then-current NYC, New York State, Chicago, and Building Officials Conference of America (now known as the Building Officials and Code Administrators [BOCA]) building code provisions.
  - Differences between the Port Authority building regulatory requirements and the current (2001) NYC Building Code provisions.

   - Evolution of the life safety provisions in the NYC Building Code since the design of WTC 1 and WTC 2.

- **Task 5.** Document maintenance of and modifications to the structural, fire protection, and egress systems to determine:
   - Guidelines used by the Port Authority for inspection, repair, and modifications to structural, fire protection, and egress systems.
   - Structural integrity inspection programs during the occupancy of the buildings.
   - Any significant modifications and/or repairs of the original structural framing system by the owner or tenants during original construction and occupancy.
   - Any repairs and modifications made to the passive and active fire protection systems from initial occupancy to September 11, 2001.

2.2.3 Status of Tasks

Except for the task of comparing building regulatory and code requirements (Task 4), the tasks depend upon the availability of design, construction, and maintenance documentation related to WTC 1, 2, and 7. Efforts by NIST to obtain needed documents are described briefly, and the current status of each of the five tasks is stated below.

Sections 2.2.4 and 2.2.5 present salient points related to Tasks 1 and 2, particularly how changes in NYC Building Code provisions from the 1938 edition to the 1968 edition, and subsequent promulgation of NYC Local Laws, affected the design, construction and maintenance of WTC 1, 2, and 7. Section 2.2.6 describes the fuel system that powered the emergency generators in WTC 7 (Task 3). Comparison of the requirements of several building codes (Task 4) pertaining to structural and fire safety is presented in Appendix A, Interim Report on the Analysis of Building and Fire Codes and Practices, of this report. Task 5, which deals with maintenance and modifications to the structural, fire protection, and egress systems of WTC 1, 2 and 7, is near completion.

Collection of Design and Construction Data

NIST requested that the Port Authority and the design and construction firms for WTC 1, 2, and 7 provide design, construction, and maintenance documents. NIST obtained a considerable amount of information (design drawings, shop drawings, specifications, project correspondence, and inspection reports) related to WTC 1 and WTC 2 from the structural engineers who were involved in the original design and subsequent modifications to the towers. The Port Authority provided construction related files for WTC 1, 2, and 7, mostly pertaining to tenant alteration projects, wherein tenants modified parts of the buildings to meet their needs. No document was obtained from the general contractor of WTC 1, 2, and 7. The general contractor retains construction documents for about 7 years. As a result, few records are available related to changes to the structural and fire safety systems that were made during construction of these buildings. However, documents obtained from the structural engineer included revisions to structural modifications for tenant renovations.

It should be pointed out that there is no mandated requirement by NYC for design and construction firms to retain their documents for a specific duration. Currently, no municipalities in the United States have document retention policies that require design and construction firms to retain their documents.

Collected documents have been examined by NIST, and pertinent documents have been organized into a searchable database. Using keywords, the user of the database can retrieve relevant documents. NIST has engaged a contractor to assist in reviewing the vast amount of documentation that has been collected.

Task Status and Report Preparation

Under NIST guidance and direction, a team of NIST contractors, led by Rolf Jensen and Associates, Inc., has made an in-depth review of the relevant documents and is in the process of preparing draft reports that address the Project 1 tasks. Independent examination of documents by NIST engineers together with the contractor's reports will be the basis for the final report of this project. Table 2–1 indicates the status of each of the tasks.

Table 2–1. Status of Project 1 tasks.

Task	Status
1	Documented code provisions used to design and construct WTC 1, 2 and 7. Documented criteria used to design WTC 1 and WTC 2. Contractor submitted final draft report to NIST.
2	Documented code provisions used to design and construct the passive and active fire protection systems for WTC 1, 2, and 7. Documented adoption of Local Laws that modified and/or amended the fire safety provisions of the 1968 NYC Building Code. Contractor submitted second draft report to NIST.
3	Documented all emergency power generating systems and the size and locations of the fuel storage tanks and distribution system in WTC 7. Contractor submitted final draft report to NIST.
4	Documented line-by-line comparison of structural and life safety provisions of the 1968 NYC Building Code vs. three other contemporaneous building codes and the 2001 NYC Building Code. Contractor submitted final draft report to NIST.
5	Documented repairs, modifications to the structural and fire protection systems, and emergency access and egress systems. Contractor submitted final draft to NIST.

2.2.4 Building Codes

As discussed in Appendix A, the Port Authority adopted the 1968 NYC Building Code (NYCBC 1968) for the final design of the WTC buildings. Therefore, this code served as the basis for the code comparison. NIST examined the structural and fire safety provisions in several contemporaneous codes, including the 1964 New York State Building Construction Code (NYSBC 1964), the 1965 BOCA model building code (Basic Building Code), the 1967 Municipal Code of Chicago (MCC 1967), and the 1966 National Fire Protection Association (NFPA) 101 Life Safety Code (NFPA 1966) egress requirements. A comparison was also made between the 1968 NYC Building Code and the current (2001) NYC Building

Code. The current NYC Building Code (NYCBC 2001) is basically the document adopted in 1968 with modifications made over the years by adoption of Local Laws and rules.

Because fire protection and fire safety provisions are of major importance to this Investigation, this section provides background information on building codes, focusing on matters related to fire protection. Appendix A provides additional background information and provides a summary of the code comparison.

Code Provisions on Fire Safety

The fire safety provisions in building codes can be confusing to those who are not familiar with the code provisions that have evolved over the past century. The following provides basic concepts related to fire protection and fire safety.

Fire Rating

This is a time expressed in hours or minutes. It represents fire resistance assigned to a building element on the basis of a test. Fire rating is the time that a test assembly is able to withstand the furnace temperature exposure specified in American Society for Testing and Materials (ASTM) E 119 (ASTM 2003) without exceeding one of the "failure conditions." Thus, a fire rating of 2 h for a structural member indicates that when the member was tested in accordance with ASTM E 119, it performed successfully for at least 2 h. It is not necessary to conduct a test for all materials to be used in a building if data are available from past standard tests showing acceptable performance, and the same materials and application methods will be used. The fire rating of a member or assembly does not indicate for how long a similar member or assembly in the building would perform under a real fire because the actual fire exposure and structural configuration are never the same as during the ASTM E 119 test.

Occupancy Group

Buildings and spaces are classified according to how the buildings and spaces will be used. The concept of "occupancy group" is used to define different types of occupancy or use such as storage, industrial buildings, general assembly, business, and so forth. A given occupancy group is associated with a different level of fire risk. Factors such as amount of combustible material, ignition sources, and characteristics of the occupants are considered in developing these groupings. In some codes, such as the 1968 NYC Building Code, occupancy groups are listed in a hierarchal sequence (highest to lowest hazard) and assigned an overall "fire index" rating in hours. For example, "high hazard" occupancy is assigned a fire index of 4 h, while "business" occupancy is assigned a fire index of 2 h.

Construction Classification

The nature of the materials used in constructing exterior walls and interior building elements define the construction type. In general, building codes characterize construction materials as "combustible" and "noncombustible" materials. For example, the 1968 NYC Building Code uses the designations "Group I" and "Group II" for noncombustible and combustible construction materials, respectively. Other codes, however, also consider whether these types of materials are used in exterior walls, or interior elements, or both. For example, International Building Code (IBC) 2000 (ICC 2000) lists Type I through Type V. These types, or groups, are further divided into different subclasses that are designated with letters, such as Class IA, Class IB, Class IIA, Class IIB, or in some codes as Type IA, Type IB, Type IIA, Type IIIA, and so forth. Building codes typically include tables that specify fire ratings for different structural elements (columns, walls, beams) and for different construction classifications (Type IA, Type IB, and so forth).

Height and Area Limits

Tall buildings and buildings with large floor areas pose greater risks in the event of fire. Building codes, therefore, place limitations on the heights and floor areas of buildings based on the construction classification, the occupancy group, and whether or not the building has sprinklers.

Partitions

Partitions, in general, are walls that provide separations between spaces within the story of a building. Partitions may or may not require minimum fire ratings, depending on the spaces being separated. In general, three types of partitions require fire ratings:

- Walls that provide separations between different occupancy groups
- Walls that provide separations between tenants (often called demising partitions)
- Walls that separate large floor areas into smaller compartments

Buildings codes specify different minimum fire ratings based on the type of partition and the types of occupancies in the spaces being separated.

Variances

All building codes make allowances for obtaining approval of materials and methods not strictly in compliance with code provisions, but which are judged to be equivalent. Normally, the regulatory authority makes this equivalence determination during the plan approval process, and a variance is issued. Compliance with building code provisions is verified by controlled inspections by building (and fire) inspectors at specified points in the construction process using sets of approved plans showing all such variances.

Evolution of Fire Safety Provisions in Model Building Codes

Model building codes are documents prepared by qualified nongovernmental organizations. When adopted by local jurisdictions, the code provisions become law. The following provides a short review of the evolution of provisions in model codes related to types of construction and fire resistance requirements of structural elements.[6]

The 1927 edition of the Uniform Building Code (ICBO 1928) placed office occupancies in Group F Division 1 and allowed only Type 1 construction for such buildings. This required a 4 h fire rating for

[6] This historical summary was provided by Joseph Messersmith of the Portland Cement Association with a letter of July 31, 2002. See also Messersmith (2002).

columns, beams, and girders and a 3 h rating for floors for buildings (steel and reinforced concrete) over eight stories or 85 ft in height.

The 1934 (5th) edition of the National Building Code (NBFU 1934) required business buildings over 75 ft in height to be "fireproof" construction, defined as having a 4 h fire rating for bearing walls, firewalls, party walls, piers and columns, and a 3 h rating for other walls, girders, beams, and floors.

The 1946-1947 edition of the Southern Standard Building Code (SBCC 1946) required Type 1 construction for business occupancies over 80 ft in height. Type 1 was defined as a 4 h fire rating for columns, bearing walls, trusses or girders supporting masonry or bearing walls, columns or girders, and beams, and a 2 1/2 h rating for floors. There is, however, a note under Type 2 construction that allows residential and business occupancies of unlimited height with a rating of 3 h for columns and a rating of at least 2 h for other structural members including floors.

The 1950 Basic Building Code (BOCA 1950) permits Group E business occupancies of unlimited height to be Type 1A or 1B. Type 1A requires a 4 h fire rating for bearing walls and for columns supporting more than one floor, and 3 h rating for floors including beams. Type 1B reduces those to 3 h and 2 h, respectively. Because this is the model code used in the Northeastern United States, this may have provided the basis for the changes from the 1938 to the 1968 NYC Building Code (see next section). However, because records of technical substantiations for code changes were not kept in this era, conclusive evidence does not exist.

Evolution of the NYC Building Code

Historically, NYC has developed and promulgated its own building code, in contrast to most jurisdictions that adopt (locally modified) versions of one of the model building codes. At the time the WTC project was begun (early 1960s), the 1938 NYC Building Code, which was first adopted January 1, 1938, was in effect and enforced throughout the five boroughs.

In the late 1950s, it was noted that "great changes have occurred in all facets of the building industry" and that "As a result of these developments, and the failure in many instances, of the Code to keep pace, there had been a growing dissatisfaction with it" (Schaffner 1964). Thus in 1960, the Building Commissioner requested the New York Building Congress to form a working committee to study the problem. The committee recommended that the Code should not be rewritten by a group of volunteers and that a local educational institution should conduct a study to develop an approach to solve the problem. The Polytechnic Institute of Brooklyn conducted the study, and in July 1961, the Institute made the following recommendations (Schaffner 1964):

1. The NYC Building Code be completely rewritten. The new Code should provide for frequent periodic revision through a committee or board appointed solely for this purpose.

2. The new Code be a combination of performance and specification types with heavy emphasis on performance, wherever possible, and with liberal reference to accepted national standards.

3. The BOCA Basic Building Code be used as a guide for the development of the NYC Building Code.

4. The Code be rewritten by a private professional group such as an engineering company, architectural firm, educational institution, or any combination of the three. Those rewriting the Code should work closely with the NYC Building Department. They should be supported, for review purposes, by volunteer committees composed of representatives of professional, trade, and industry associations."

In April 1962, NYC signed an agreement with the Polytechnic Institute of Brooklyn for the writing of a new Code to be completed in 3 years. The first draft was completed in 1964. A public relations document highlighted the "major advantages to be gained from recommendations in the proposed new Building Code" (Bell and Stanton 1964). One of these related to the "area and height limitations," and it was stated that:

> Area and height limitations will be liberalized and present unrealistically high construction requirements for fire protection in structures of low combustible content such as auditorium, halls, schools, institutions and residences will be significantly reduced and considerable economy will result.

On December 6, 1968, Local Law 76 repealed the 1938 code and replaced it with the 1968 code, which itself was subsequently amended by Local Laws. As is the general custom with changes to building codes, the new provisions generally are not applied to existing buildings (those approved under the prior code) provided they do not represent a danger to public safety and welfare.

There were 79 Local Laws adopted between 1969 and 2002 that modified the 1968 code. Of particular importance with regard to fire protection and life safety are Local Law 5, adopted in 1973, and Local Law 16, adopted in 1984. Local Law 5, among other things, added requirements on compartmentation of large floor areas, and Local Law 16 added requirements for sprinklers in high-rise buildings (greater than 100 ft). Local Law 5 is particularly significant because its provisions, which are reviewed in a subsequent section, applied retroactively to existing office buildings. Local Law 84, which was passed in 1979, revised the compliance dates of Local Law 5 so that full compliance was required by February 7, 1988.

As discussed in Appendix A, the 1968 NYC Building Code contained a number of provisions not addressed in the other codes of the time, but which were added to these other codes at later times.

Selection of Construction Type for WTC Towers

The 1938 NYC Building Code recognized one construction type for buildings of unlimited height and area, namely Class 1—Fireproof Structures, which required a 4 h fire rating for columns and a 3 h rating for floors. In the 1968 code, Group I (Noncombustible) construction was subdivided into "Class 1A—4-hr protected" and "Class 1B—3-hr protected" construction. Class 1A specifies similar protection as the previous Class 1, and Class 1B specifies a 3 h rating for columns and girders supporting more than one floor and a 2 h rating for floors including beams. Both Class 1A and Class 1B construction permit unlimited height and area for unsprinklered business occupancy.

If a building qualifies for more than one construction classification, such as Class 1A or Class 1B, codes are silent on which classification should be used. In such situations, the classification selected for construction is at the discretion of the owner/architect. To date, no contemporaneous documentation has been found that provides the rationale for the decision to select Class 1B for the WTC towers. This decision, however, appears to have been made by the architect-of-record on the basis of economics. In a 1987 memorandum on the subject of fire rating of the WTC buildings, the following statement was included (Feld 1987):

> For office buildings there is no economic advantage in using Class 1A Construction, and ER&S [architect-of-record] used Class 1B Construction for the WTC Towers and Plaza Buildings which are Occupancy Group "E" (Business) with a fire index of 2 hours.

An interoffice memorandum between staff of the general contractor written in 1969 is the only contemporaneous document found to date that refers to the classification of the WTC towers (Bracco 1969). The following statement is included in that memorandum:

> The WTC towers would be classified, by our interpretation of the code, as occupancy Group E, Business; Construction Group 1, Non-combustible; and Construction Classification 1-B, (since there are no area or height limitations applicable).

2.2.5 The 1968 New York City Building Code

Applicability to Port Authority Properties

Established in 1921, the Port Authority is a self-supporting, public interstate agency and is not subject to the local laws of jurisdictions where its properties are constructed. This means that for the construction of the WTC buildings, the Port Authority was not bound by the NYC Building Code or any regulations requiring inspection or approval of the building construction or operation. The Port Authority could establish its own requirements, conduct its own inspections, and enforce its own rules without independent oversight.

According to a joint report written by the Fire Commissioner and Commissioner of Buildings on March 15, 1993 (after the 1993 bombing), in 1975 the NYC Council submitted a resolution to the New York State Legislature to require the Port Authority to comply with the NYC Building Code when building within the City (Rivera and Rinaldi 1993). The 1993 report includes the following statements with respect to jurisdiction over the WTC complex:

> After several major fires in the 1970s, the Fire Department in 1975 testified at the City Council for the need to have jurisdiction over this complex as well as other buildings owned by public benefit corporations, again particularly for Local Law 5 compliance. As a result, the City Council forwarded a Resolution dated August 29, 1975, to the State legislature. ... Proposed legislation which would have granted City agencies jurisdiction was introduced in the State legislature over the years; the State has not enacted such legislation.

It appears that there was friction between the FDNY and the Port Authority as evidenced by the following statements in the same joint report (Rivera and Rinaldi 1993):

> Prior to the February 26, 1993, explosion, the Fire Department acted pursuant to the joint protocol for inspectional activity at the WTC which was signed in 1986. The Port Authority's policy was to voluntarily cooperate with the Fire Department 'to the fullest extent practicable.' Fire Department representatives met continually with Port Authority officials to discuss problems with the WTC's emergency procedures and fire safety equipment. Generally, the Port Authority was cooperative and verbally informed the Fire Department that it was their intent to fully comply with Local Law 5. However, since its compliance with fire code requirements was dependent upon economic and design feasibility, the PA agreed to comply with selected provisions of the code, but has not fully done so. Moreover, it was difficult for the Fire Department to monitor code compliance by the WTC because the WTC consistently asserted its legal exemption from local law. Fire officials relied on persuasion and negotiation to gain compliance. The extent of these negotiations is reflected in the voluminous WTC files maintained at the Fire Department. Code compliance at the WTC has been dealt with by every Fire Commissioner and Chief of the Department over the last twenty-five years.

It was not until 1993 that a formal agreement was reached between the Port Authority and the NYC Department of Buildings with regard to code conformance for Port Authority buildings constructed in NYC (PANYNJ and NYCDOB 1993). The introduction of the memorandum of understanding contained the following statements:

> While the facilities of the Port Authority, an agency of the States of New York and New Jersey, are not technically subject to the requirements of local building codes, the long-standing policy of the Port Authority has been to assure that its facilities meet and, where appropriate, exceed Code requirements.
>
> The purpose of this Memorandum is not only to restate that longstanding policy as part of an understanding with the City but to provide specific commitments to the Department, as the agency of the City responsible for assuring compliance with the Code, regarding procedures to be undertaken by the Port Authority for any Project at its facilities in the City to assure that the buildings owned or operated by the Port Authority within the City are in conformance with the Building Standards contained in the Code.

Some salient points included in this agreement are:

- 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.

This agreement was enhanced in 1995 by the approval of a supplement to the 1993 memorandum of understanding (PANYNJ and NYCDOB 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, the Port Authority entered also into an agreement with the FDNY related to fire safety inspections (PANYNJ and FDNY 1993). The introduction to the memorandum of understanding contains the following statements:

> On April 15, 1993, the Port Authority, in order to maintain and enhance the safety of Port Authority facilities, 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 and for the prior review by local fire safety agencies of fire safety systems to be introduced or added to a facility.
>
> The purpose of this Memorandum of Understanding is to reiterate the Port Authority's commitment to this policy and to set forth certain procedures to facilitate the implementation of this policy for buildings at Port Authority facilities located in New York City.

The agreement recognized the right of the FDNY to conduct fire safety inspections of Port Authority properties in NYC and provided guidelines related to corrective actions.

Port Authority's Transition from the 1938 to the 1968 Code

As discussed in Appendix A, in 1963 the Port Authority instructed the designers of the WTC to follow the then current 1938 NYC Building Code. During this time, the code was in the process of being revised (as noted above), and in 1965, the Port Authority directed its designers to adopt the draft version of the new code for their final designs. Some of the advantages of the new draft code were noted to be the following (Levy 1965):

- Fire towers[7] could be eliminated;
- Provisions for exit stairs were more "lenient;" and
- Criteria for partition weights were more "realistic."

It was not certain whether all the changes being proposed to the 1938 code would be incorporated into the final version of the new code. Thus in 1966, the Chief Engineer of the Port Authority suggested that the

[7] A "fire tower" is a stair tower enclosed within a 4 h fire rated shaft that is entered through a naturally ventilated vestibule. The 1938 Code stipulated that one of the required exits in most buildings over 75 ft in height be a fire tower.

"architect/engineers prepare a listing of the elements of the design which do not conform to old code requirements, but are acceptable under the new. With this list in hand, we could initiate discussions, at top level in the Building Department, to see if we can secure agreement to go along with our design (Kyle 1966)."

A one-page document,[8] dated "2/15/67", with the initials "CKP" listed the following items:

1. Fire tower corridors [sic] eliminated.
2. Number of stairs reduced from 6 to 3. (Old plans had 5 stairs at 3'-8" and 1 stair at 4'-8" for a total population of 390. New plans have 2 stairs at 3'-8" and 1 stair at 4'-8" allowing a population of 390.)
3. The size of doors leading to the stairs are [sic] changed from 3'-8" to 3'-0".
4. All stairs exit through a lobby. Old plans had fire tower stair exiting through a fire enclosed corridor.
5. Shaft walls are changed from a 3-hour rating to a 2-hour rating.
6. Corridors are limited to a 100' dead end and with a 2-hour rating.
7. Additional [word(s) missing] changed from 20 pounds per square foot to 6 pounds per square foot (based on partition weight of 50 pounds to 100 pounds per linear foot).

Apparently, the above list represents elements of the WTC design that would not have satisfied the 1938 code, but did satisfy the then-current draft version of the new code.

A letter dated February 18, 1975, from the architect-of-record to the Port Authority discusses compliance with the 1968 NYC Building Code (Solomon 1975). This letter begins with the following paragraph:

> In accordance with the instructions issued by the Port Authority at the start of the project, construction drawings for the World Trade Center were to conform with requirements of the Building Code of New York City, and any variations therefrom were to be called to the attention of the Port Authority for final decision and authorization. This procedure has been followed in the production of the contract drawings and, with the exceptions authorized by the Port Authority noted below, the drawings are in accordance with the new Building Code adopted in December, 1968. The Building Department reviewed the tower drawings in 1968 and made six comments concerning the plans in relation to the old code. Specific answers noting how the drawings conformed to the new code with regard to these points were submitted to the Port Authority on March 21, 1968.

[8] "Changes to Building to Conform to New New York City Building Code," dated 2/15/67.

The same letter continues with a list of four items that the architect was "instructed by the Port Authority to deviate from code (Solomon 1975)." The four items are:

- Omission of vents from closed shafts.
- Demising partitions to stop at suspended ceiling or bottom of truss instead of running from slab to slab.
- Omission of fire protected openings on exterior walls with separation of less than 30 ft.
- Treatment of the concourse level as Underground Street.

Section C26-504.3(a) of the 1968 NYC Building Code required that tenant spaces be separated "by fire separations having at least the fire resistance rating prescribed in table 5-1, but in no case less than 1 hr, and shall continue through any concealed spaces of the floor or roof construction above." The Port Authority chose to stop tenant (demising) partitions at the bottom of the suspended ceiling and use 10 ft strips of 1 h rated ceiling on either side of the partition (Solomon 1969). The general contractor stated in a letter to the Port Authority "…we have been unable to find any precedent for the fire rated ceiling 10' on either side of the demising partitions beyond the one you described from your construction experience on Port Authority hangers [sic] (Endler 1969)."

In a code compliance evaluation report written in 1997, it was stated "Tenant demising partitions, including separations from the public corridor, do not in all cases meet the requirement of being built to the slab above (Coty 1997)." The author of the report recommended that: "Generally, this condition has been and will continue to be remediated as a requirement of new tenant alterations. However, it is recommended that the Port Authority develop and implement a survey program to assure that this remediation process occurs as quickly as possible."

The tenant alteration guidelines issued in 1998 require that tenant partitions have a 1 h fire rating, and the standard details for fire rated partitions indicate a continuous fire barrier from top of floor to bottom of slab (PANYNJ 1998).

Compartmentation and Sprinklers

Neither the 1968 NYC Building Code nor any of the other contemporaneous codes that were examined required sprinklers in tall buildings except for underground spaces. Thus, only the parking garage under WTC 1 and WTC 2 was originally sprinklered. Although Local Law 16, adopted in 1984, required sprinklers in new office occupancies, it was not retroactive. The incentive to retrofit for sprinklers (as explained below) was the passage of Local Law 5 in 1973, which was retroactive.

In the 1968 NYC Building Code, Class 1B construction for business occupancies had no limit on floor area. Local Law 5 required compartmentation of large floor areas in existing business occupancies over 100 ft in height by the installation of fire rated partitions in accordance with the following:

- Compartmentation to 7,500 ft^2 with 1 h partitions; or
- Compartmentation to 10,000 ft^2 with 2 h partitions; or

- Compartmentation to 15,000 ft^2 with 2 h partitions and smoke detectors.

Compartmentation was not required, however, if "complete sprinkler protection" were provided. Compliance dates for these provisions were revised in 1979 by Local Law 84 so that one-third of the total area of buildings had to be in compliance by December 13, 1981, two-third of the total area had to comply by August 7, 1984, and full compliance was required by February 7, 1988.

Following the February 13, 1975, fire in the lower stories of WTC 1 (Powers 1975), an independent consultant was retained to review WTC life-safety provisions, including response to Local Law 5. It is reported that the "consultant concluded that the existing structural fire retardants of the building are sufficient to make the probability of serious structural damage extremely remote and the degree of vertical compartmentation provided sufficiently limits the spread of fire in the structures but that the spread of smoke requires attention from a life safety standpoint (PONYA 1976)." The consultant reported that "...either of the two fire protection options provided for under Local Law 5 would provide a good level of occupant life safety within the World Trade Center complex, provided that whichever is selected is supplemented by certain additional measures." The consultant provided a series of recommendations to supplement either the compartmentation option or the sprinklering option.

The Port Authority initially decided to adopt the compartmentation option in response to Local Law 5. The summary of the January 1976 report on the *Fire Safety of the World Trade Center* lists the following actions to be implemented to enhance the fire safety of the WTC towers (PONYA 1976):

1. The openings between floors of telephone closets, which was a source of fire spread during the February 13, 1975, fire should be closed. This work has been accomplished to prevent any reoccurrences of a similar condition.

2. In addition, the Port Authority will proceed with the compartmentation option of Local Law 5, including all of its requirements for fire alarm, communications, and stairway pressurization.

3. Sprinklering of all storage rooms, janitor closets, mail rooms and file rooms in the central core of each floor.

4. Building additional sprinkler capacity and provisions for extension of a sprinkler system to any area of such usage requiring it in the event of an occupancy change.

5. Equipping those doors which are normally kept open to the corridor system, such as doors at consumer service areas, with electromagnetic 'hold open' devices which would be activated by smoke detectors to close the doors.

6. Providing fail-safe automatic door closers, arranged to close upon activation by smoke detectors, for the overhead rolling fire doors separating the below-grade truck dock from the elevator lobby.

7. Developing an optimum mode of operation of the building air-conditioning system to remove smoke from the central core compartments without contaminating adjacent areas.

Thus, while the Port Authority initially chose to implement the compartmentation option, it also chose to provide "for extension of sprinkler system to any area of such usage requiring it." According to the 1993 joint report written by the NYC Fire Commissioner and Commissioner of Buildings, in the 1980s the Port Authority began "a program to fully sprinkler the Tower buildings (Rivera and Rinaldi 1993)." The report goes on to state that by March 1993 sprinklering was " nearly complete in Tower 2 and 85 percent complete in Tower 1." The report also included a table that summarized "the major system requirements of Local Laws 5/73 and 16/84 with conditions in place when the1993 explosion occurred." The content of that table is reproduced here as Table 2–2.

The tenant alteration guidelines issued in 1998, contained the following requirement and information (PANYNJ 1998):

> All tenant spaces shall be sprinklered. Except for a few areas, most tenant floors in The World Trade Center are provided with wet-pipe sprinkler systems. New tenants normally require a new sprinkler system. For renovations of existing spaces, modifications to the existing system are normally needed to comply with any new partition configuration.

Because Local Law 16 required that business occupancies taller than 100 ft be sprinklered, WTC 7 was sprinklered during the original construction.

Emergency Egress

The 1968 NYC Building Code has requirements for the number and capacity of stairs and for the assumed occupant load that are similar to requirements in the other contemporaneous codes (see Appendix A). Codes of the time required that multiple stairs be located "as remote from each other as practicable." NYC permits scissor stairs,[9] and the code requires the exit doors to be at least 15 ft apart. Local Law 16 (1984) first imposed a remoteness requirement of 30 ft or one-third the maximum travel distance of the floor (whichever is greater), which was not retroactive, so it did not apply to WTC 1 and WTC 2 but did apply to WTC 7.

The 1968 NYC Building Code also has a requirement that, " …vertical exits should extend in a continuous enclosure to discharge directly to an exterior space or at a yard, court, exit passageway or street floor lobby …" (C26-602.4). Similar requirements are found in the 1965 BOCA Basic Building Code and in 1966 NFPA 101, but not in the 1964 New York State Building Construction Code or the 1966 Municipal Code of Chicago. Current code language (2003 IBC, section 1003.6) defines continuous as: not " … interrupted by any building element other than a means of egress component."

This requirement was the subject of ongoing discussion with respect to the stairs in WTC 1 and WTC 2 discharging onto the mezzanine level, which was not at street level but rather at the Plaza level. It was the

[9] Scissor stairs refers to two separate interior stairways contained within the same enclosure and separated by a fire rated partition.

position of the Port Authority that the Plaza was like a street, and the arrangement met the intent of the Code.

Table 2–2. Summary of compliance with Local Laws 5/73 and 16/84 provided in March 1993 report by Fire Commissioner and Commissioner of Buildings (Rivera and Rinaldi 1993).

	Type of Work {Code Section}	Compliance
1	Compartmentation {504.1(c)}	Not required in sprinklered buildings
2	Smoke shaft of stair pressurization {504.15(c)}	Not required in sprinklered buildings. However, smoke purge and pressurization of corridors with 100% fresh air is provided.
3	Emergency power exit lights {605.2(b)}	Exceeds requirement. Required — On separate circuit ahead of main switch Provided — Separate feeders and emergency generators (NOTE A)
4	Emergency power exit signs {606.2(b)}	Exceeds requirement. Required — On separate circuit ahead of main switch Provided — Separate feeders and emergency generators (NOTE A)
5	Stair and elevator signs {608.0}	Yes
6	Emergency power {610.0}	Exceeds requirement. Required — None Provided — See NOTE A above
7	Sprinklers {1703.1}	Yes 95% completed for one tower [WTC 2] 85% completed for other tower [WTC 1]
8	Class "E" fire alarm signal system {1704.5(f)}	Yes — But air supply and exhaust air to fire floor are not closed off when sprinklers are activated. Note: equivalent system provided by item #2 above and smoke detectors at fans, which stop fans.
9	Fire command and communication {1704.8}	Yes — except that each building does not have its own fire command station
10	Elevator in readiness {1800.8(b)}	Yes — See NOTE A above
11	Removal of locks on elevators and hoistway doors {1801.4}	Yes
12	Firemen's service operation {1801.5}	Yes — See NOTE A above

Fire Alarm Systems

Consistent with practice at the time, the original fire alarm system in WTC 1 and WTC 2 was a manual system with four smoke detectors on each tenant floor, positioned to monitor for smoke entering the HVAC returns and arranged to stop the fans to prevent smoke circulation to non-fire areas. Local Law 5 (1973) included retroactive requirements for fire alarm systems and emergency voice communication systems in business occupancies over 100 ft in height. Subsequently, such systems were installed in WTC 1 and WTC 2 with the required fire command center located in the underground parking garage. Following the 1993 bombing, the fire command stations were relocated to the tower building lobbies with a third monitoring location in the Port Authority offices. There are no code requirements for off-site monitoring of fire alarm systems in this occupancy.

Elevators

Local Law 5 requires that elevators be provided with an emergency recall system. This requirement was incorporated subsequently into the American Society of Mechanical Engineers (ASME) A17.1, Safety Code for Elevators and Escalators, that governs elevator design and operation in all the building codes. The ASME Code requires that:

- All passenger elevators be marked with signs stating that they cannot be used during a fire;
- Fire detectors installed in every elevator lobby and machine room be arranged to initiate a recall of the elevators to the ground floor where the doors open and the elevator is taken out of service; and
- Fire service personnel can use a special key to operate any individual car in a manual mode as long as they feel it is safe to do so.

The elevator and building codes require that at least one elevator serving every floor be connected to emergency power. Refer to Table 2–2 for elevator status in WTC 1 and WTC 2 in 1993.

Structural Stability

As discussed in Appendix A, provisions related to structural stability in the 1968 NYC Building Code were in general agreement with those of the contemporaneous codes that were compared. There were, however, a number of provisions in the NYC code that were not included in the other codes such as uniform partition dead loads based on the weight of the partitions, consideration of loads due to thermal expansion/contraction and shrinkage of concrete, minimum strength requirements for bracing of compression members, and allowance for design wind loads based on wind tunnel tests. The NYC code, however, does not provide a standard protocol for wind tunnel testing to establish design wind loads.

2.2.6 WTC 7 Fuel System

WTC 7 was constructed and owned by Silverstein Properties on land owned by the Port Authority. It was built and operated by Silverstein as a Port Authority tenant alteration (see Appendix A.1). Many of the tenants conducted critical business operations in the building and required uninterruptible power to prevent the loss of information or operational continuity in the event of a power failure. This backup power was provided by diesel generators located in the mechanical spaces of the building. These generators were designed to start automatically in the event of an interruption of the utility supply. The total generator capacity and quantity of fuel stored in the building was sized to tenant needs.

Code Requirements

Design and installation of the WTC 7 emergency power and associated fuel systems were to follow the NYC Building Code. The base system was installed in 1987 with modifications occurring in 1990, 1994, and 1999. Over the period 1987 to 1999, the NYC Building Code provisions discussed below were not changed, so all systems were installed to the same requirements. Some of the key code provisions for the construction and location of fuel storage tanks, piping, and controls are discussed here, and additional details will be published in a separate report.

Tanks [27-828 and 27-829] [10]

All tanks must be fabricated of steel and coated to prevent corrosion. Minimum thicknesses are specified by tank diameter for storage tanks and for so-called "day tanks" (60 gal or 275 gal). Large storage tanks (up to 20,000 gal) may be buried inside or outside the building or on the lowers floor of the building with protection related to the tank capacity. For example, tanks from 550 gal to 1,100 gal must be enclosed in 2 h fire rated, noncombustible construction and tanks larger than 1,100 gal in 3 h construction.

Tanks on floors above the lowest floor are limited to 275 gal and one such tank per story. These "day tanks" must be surrounded by a concrete curb or steel pan with the capacity to hold twice the volume of the tank in the event of a leak. The curb or pan must be provided with a float switch to sound an alarm and shut off the transfer pump in case of tank failure. Appropriate controls (generally a float switch in the day tank) are provided to transfer fuel from the storage tanks to the day tank through a transfer pump and piping, with only one such transfer pump and piping network per day tank.

Piping [27-830]

Piping from transfer pumps to day tanks is required to be enclosed in a shaft of 4 in. thick concrete or masonry with a 4 in. clearance to the fuel pipe. Horizontal offsets may be enclosed in a steel sleeve two (pipe) sizes larger and enclosed in 2 h fire rated construction. The spaces between the fuel pipe and sleeve or shaft must lead to an open sight drain or an open sump so leaks can be detected.

Power Systems Designs

NIST located and reviewed specifications and drawings for each of the emergency power systems. It was noted that some of the fuel risers were installed in existing shafts containing other utilities. The NYC Building Code requires that pipe shafts containing piping from the transfer pump to storage tanks above the lower floors not be penetrated by or contain other piping or ducts [27-830(f)(5)]. Correspondence relating to the system for the Mayor's Office of Emergency Management shows that this system was

[10] Sections of the New York City Building Code in which these requirements are found. These provisions are found in the subchapter on "Heating and Combustion Equipment."

reviewed and inspected by the FDNY, a list of needed corrections was produced, and each item was initialed as the corrections were verified.

Base Building System

The initial base emergency power system was installed in 1987, and consisted of two 900 kW generators and a 275 gal day tank located on floor 5. Main fuel storage was in two 12,000 gal tanks buried under the loading dock on the south side of the building. The tanks were double wall fiberglass[11] with leak detectors between the walls.

Fuel was transferred by one of the two pumps through a 2 in. supply line in an existing shaft containing other utilities, near the west bank of passenger elevators. The transfer pump was controlled by a float switch in the day tank with a low (pump on) and high (pump off) position. An alarm would be sounded if the fuel level in the day tank fell below the low level or went above the high level. The day tank was located within a 550 gal pan fitted with an alarm and another pump cutoff. The vent for the day tank terminated outside the south wall.

The 2 in. fuel lines were encased in a second pipe covered with 2 in. of calcium silicate to provide the required 2 h fire rating. Pipe supports were located approximately 10 ft apart, and inspection plugs were provided approximately 50 ft apart. Mechanical equipment rooms were sprinklered (ordinary hazard group I), and the fuel pump room was sprinklered (ordinary hazard group III). The generator area on floor 5 was not sprinklered.

Modifications to System

From 1990 to 1999, four major modifications (additions) were made to the base emergency power system. These modifications are summarized in Table 2–3. Of significance are the 1990 modification (Salomon Brothers) that required a pressurized fuel supply system, because a day tank already existed on floor 5, and the 1999 modification (Mayors' Office of Emergency Management) that required a separate 6,000 gal tank on the first floor. Figure 2–1 is a schematic of the locations of the various components of the base system and the four major modifications.

For the Salomon Brothers system, the transfer pumps were powered from the output of the generators. In the event of a failure of utility power, all nine generators were started automatically to ensure that if any of the nine did not start there would be enough power. Once the generators were up to speed, the control system would shut down those that were not needed, but these could be restarted later if power demand increased. There was enough fuel and residual pressure in the lines to start the generators and to run them for a few minutes, but once running, the fuel pumps were powered to supply fuel. As long as any one generator was running, the pumps ran at full capacity.

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[11] While the NYCBC requires steel tanks, effective in November of 1985 the U.S. Environmental Protection Agency required (40CFR280) that all new underground fuel storage tanks be double wall fiberglass and that any steel tanks older than 20 years be replaced by double wall fiberglass.

Table 2–3. Summary of modifications to base emergency power system in WTC 7.

Year	Day Tank/Generator	Storage Tank	Piping	Comments
1990	No day tank permitted since base design included one on floor 5/9 generators on floor 5, 1750 kW combined capacity	Two 6,000 gal next to base tanks.	Two 2 1/2 in. pipes in separate rated shaft	50 psi pressurized fuel system
1994	50 gal/125 kW on floor 9; generator room sprinklered	Used existing base tanks	1 1/4 in. in new 2 h rated dedicated shaft	New transfer pump connected to existing storage tanks
1994	275 gal/350 kW on floor 8; generator room sprinklered	Used existing base tanks	2 in. in same dedicated shaft as above	New transfer pump connected to existing storage tanks
1999	275 gal/three 500 kW on floor 7; smoke detectors in generator room	6,000 gal on floor 1, in 4 h rated enclosure; gaseous (clean) fire suppression system; space below tank sprinklered	10 gauge conduit in 2 h rated enclosure	Storage tank kept filled from base storage tanks.

2.2.7 Preliminary Findings

The following preliminary findings are based on (1) review of the design and construction documents of WTC 1, 2, and 7; (2) review of the 1968 NYC Building Code, the 1964 New York State Building Code, the 1967 Municipal Code of Chicago, the 1965 BOCA Basic Building Code, and the 2001 NYC Building Code; and (3) correspondence of the Port Authority, design consultants, and general contractor.

1. Building code used for design of WTC 1, 2, and 7

   When the design of WTC 1 and WTC 2 began in 1962, the governing building code in NYC was the 1938 edition. In September 1965, the Port Authority instructed its consultants to revise their design for WTC 1 and WTC 2 to comply with the second and third drafts of the new building code of NYC that was under development (Levy 1965). The new building code was adopted on December 6, 1968.

   The Port Authority took advantage of some of the less restrictive provisions of the 1968 Code compared with the outdated 1938 Code. Some of these new provisions included:

   a. Elimination of a fire tower as a required means of egress;

   b. Reduction in the number of required stairs;

   c. Reduction in fire rating of shaft walls from 3 h to 2 h;

   d. Use of uniform partition load that depends on weight of partition per unit length; and

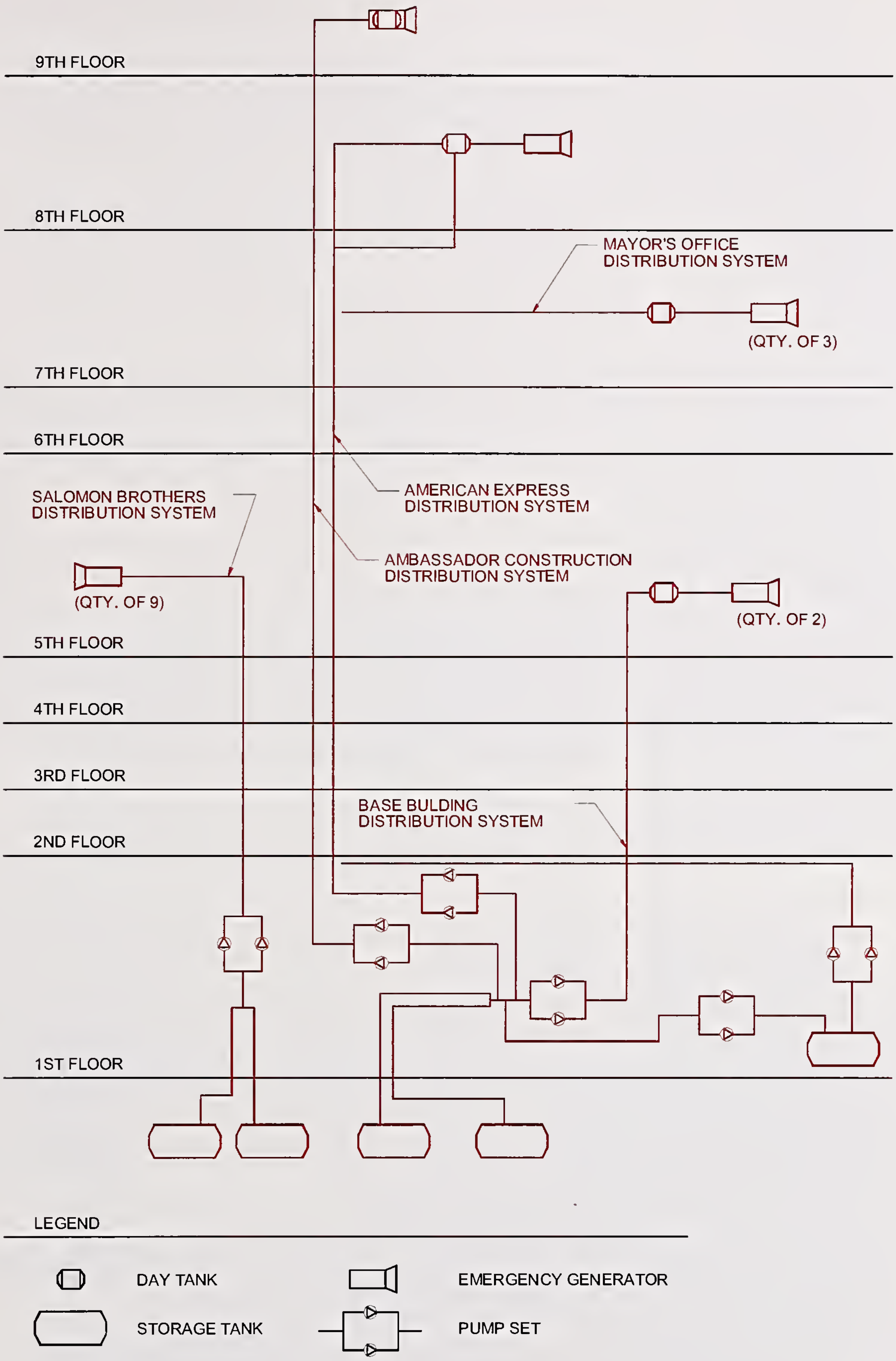


Figure 2–1. Locations of emergency generators and fuel tanks in WTC 7.

e. Allowance of Class 1B construction for business occupancy and unlimited building height.

One of the reviewed documents noted that "For office buildings there is no economic advantage in using Class 1A Construction, and ER&S [architect-of-record] used Class 1B Construction for the WTC Towers and Plaza Buildings…." (Feld 1987).

The design of WTC 7 followed the 1968 code as amended by Local Laws, which includes Local Law 16, requiring sprinklers in buildings taller than 100 ft.

2. Review of design documents by the Department of Buildings of NYC

   In 1963, the Port Authority instructed its consultants that the design of the WTC should comply with NYC Building Code. The Port Authority also stated that: "When preliminary designs have been completed, the Chief Engineer will review all design concepts with the appropriate municipal agencies before the consultants proceed with the final design (Levy 1963)." This implies that the NYC Department of Buildings would be involved in reviews of the design. A letter in 1975 from the architect-of-record to the Port Authority indicates that in 1968 the NYC Department of Buildings reviewed the tower drawings and "made six comments concerning the plans in relation to the old code (Solomon 1975)." It was stated further that on March 21, 1968, the architect submitted to the Port Authority responses to these comments "noting how the drawings conformed to the new code." NIST is attempting to locate a copy of this correspondence to determine, if possible, the level of review conducted by the Department of Buildings and the specific six items identified in that review.

3. The 1968 NYC Building Code compared with contemporaneous codes

   The 1968 NYC Building Code was more comprehensive in the coverage of provisions in certain areas compared with the other contemporaneous codes that were reviewed. For example, the 1968 NYC Building Code requires special design consideration for expansion and contraction due to temperature and shrinkage of concrete, and it permits determination of design wind loads from tests. In general, except for permitted construction classifications, provisions for structural stability, fire safety and egress were similar among the four contemporaneous codes that were compared (see Appendix A.5.1 and A.5.2 for details). There were, however, differences in permitted live load reduction, design wind pressures, and the treatment of partition loads. Table A–8 in Appendix A provides a summary of fire safety provisions for high-rise buildings used for business.

   In the 1993 joint report, the Fire Commissioner and Commissioner of Buildings made this comment about the NYC Building Code (Rivera and Rinaldi 1993):

   > We pride ourselves that our codes are among the most stringent in the nation, and we have been in the forefront in applying technological advances to assure fire and structural safety in buildings.

4. Permitted construction classification for high-rise buildings

   The 1938 NYC Building Code permitted only Class 1 (fireproof) construction for unsprinklered office buildings of unlimited height and area, which required a 4 h fire rating for columns and a 3 h rating for floor framing members (4-3 rated construction). The 1968 New York Building Code subdivided Group 1 (noncombustible) construction into Class 1A and 1B. Class 1B required a 3 h fire rating for columns and a 2 h rating for floor framing members (3-2 rated construction). There was precedence in earlier model building codes for permitting 3-2 fire rated construction for unsprinklered high-rise office buildings (BOCA 1950 and SBCC 1946). Of the contemporaneous codes that were reviewed, the 1964 New York State Building Code and the 1965 BOCA Basic Building Code permitted 3-2 rated construction for unsprinklered office buildings of unlimited height and area. The 1967 Chicago Municipal Building Code permitted only 4-3 rated construction for high-rise office occupancy. (See Appendix A.4.4 for more detail.)

5. Deviations from NYC Building Code

   In 1975, the architect-of-record wrote a letter to the Port Authority pointing out that the Port Authority had provided instructions to deviate from the NYC Building Code with respect to four items (Solomon 1975). One of these was a deviation from the requirement that tenant fire-rated partitions be continuous from floor to floor. Over the years, these partitions were replaced with partitions that were continuous as required by the 1968 Code. In the 1997 report on code compliance, it was noted that some partitions did not meet the requirement (Coty 1997). The 1998 tenant alteration guidelines require that core walls have a 2 h fire rating and walls separating tenants (demising walls) have a 1 h rating (PANYNJ 1998). The standard details for 2 h and 1 h rated partitions show that the partitions provide a continuous fire barrier from top of floor to underside of slab.

6. Compartmentation and sprinklering

   Following the passage of Local Law 5 in 1973, the Port Authority implemented a program to proceed with the compartmentation option of Local Law 5 and to provide for the extension of the sprinklering system beyond the below grade spaces installed during original construction. In addition, sprinklers were installed in storage rooms, janitor closets, mailrooms and other spaces in the core area of each floor, and outside the core for tenants not selecting the compartmentation option. In the 1980s, the Port Authority began a program to sprinkler the remaining tenant spaces, initially as tenants changed, and later on negotiated schedules. According to Local Law 86, passed in 1979, full compliance with Local Law 5 was required by February 7, 1988. A report in 1997 states that there were four floors and the sky lobbies (all in WTC 1) that remained to be sprinklered, and that installation of sprinklers on these floors was in progress (Coty 1997). In the October 1999 report on code compliance, it is stated that sprinklering of the tenant floors was completed and sprinklering of the sky lobbies was "currently under way" (PANYNJ 1999). The tenant design guidelines in 1998 require that all tenant spaces be sprinklered (PANYNJ 1998).

7. Fuel system for emergency generators in WTC 7

   The generators and associated fuel distribution system installed in WTC 7 followed the requirements of the NYC Building Code with two exceptions. First, the underground storage tanks were fiberglass and not steel, but this is consistent with federal requirements promulgated by the U.S. Environmental Protection Agency, which preempt the City requirements. The second deviation was the installation of the fuel risers for the base system in an existing shaft with other utilities. All of the subsequent sets of fuel risers were installed in a separate 4 h rated shaft.

   The modification in 1990 included a pressurized fuel system, and the generators powered the fuel pumps. As long as one generator was running, the pumps ran at full capacity.

2.3 BASELINE STRUCTURAL PERFORMANCE AND AIRCRAFT IMPACT DAMAGE ANALYSIS (PROJECT 2)

2.3.1 Project Objective

Project 2 of the NIST investigation into the collapse of the WTC towers focuses on (1) establishing the baseline structural performance of each of the two towers under design gravity and wind loads and (2) analyzing the aircraft impacts into each of the two towers to estimate the damage to the towers and establish the initial conditions for the fire dynamics modeling in Project 5 and thermal-structural response and collapse initiation analysis in Project 6. The objective of the project is to evaluate the role of the structural system and the abnormal loads from aircraft impact on the collapse of the WTC towers by (1) developing reference structural models of the WTC towers that serve as reference for more detailed models to be developed for Projects 2 and 6, (2) using these models to establish the baseline performance of each of the towers under design loading conditions, (3) estimating probable damage to the structural, mechanical, and architectural systems of the towers due to aircraft impacts, (4) evaluating the role of floor diaphragms and hat trusses on the structural integrity of the towers, and (5) estimating the structural reserve capacities of the towers under service loading conditions after losing a number of exterior and core columns and floor segments due to aircraft impact.

2.3.2 Project Approach

This project is divided into two primary focus areas. The first, related to establishing the baseline performance of the towers under design loading conditions, is divided into the following tasks:

- **Develop Structural Databases of the Primary Components of WTC 1 and WTC 2.** To develop electronic databases for the major structural components of the WTC towers from original computer printouts of the structural design documents and modifications made after construction. This task will also estimate all cross-sectional properties and link the databases into a format suitable for the development of the reference structural models of the towers.

- **Develop Reference Structural Analysis Models of WTC 1 and WTC 2.** To use the structural databases to develop finite element structural models of WTC 1 and WTC 2 that capture the intended behavior of the towers. The models include typical floor models and global models of the towers. The models are used to establish the baseline performance of each of the towers under gravity and wind loads and serve as reference for more detailed structural models to be used for other phases of the investigation.

- **Estimate Wind Loading Criteria on the WTC Towers Based on the State of the Art.** To develop wind loads on the towers based on currently available aerodynamic information (from two wind tunnel tests conducted recently by parties to an insurance litigation concerning the towers) and on extreme climatological information from available data and applicable standards.

- **Establish the Baseline Performance of WTC 1 and WTC 2 Under Design Loading Conditions.** To use the reference structural models to analyze the two towers to estimate stresses, deflections, and member utilization ratios under the following loads:

  - Gravity loads considering the following cases: (1) dead loads, (2) live loads used in the original design of the towers, and (3) live loads according to the current American Society of Civil Engineers (ASCE) 7 Standard.

  - Lateral wind loads considering the following cases: (1) wind loads used in the original design of the towers, and (2) wind loads based on the state of the art.

The second focus area, related to analyzing the aircraft impacts into each of the two towers, is divided into the following tasks:

- **Analyze the Aircraft Impacts into WTC 1 and WTC 2.** To analyze the aircraft impact into each of the two towers to provide the following: (1) estimates of the damage to structural systems due to aircraft impact – including exterior walls, floor systems, and interior core columns; (2) estimates of the aircraft fuel dispersal during the impact; (3) estimates of accelerations and deformations in each of the two towers due to aircraft impact to be used for estimating damage to fire proofing; and (4) a database of the major fragments of the aircraft and destroyed structural components of the towers to be used for estimating damage to the mechanical and architectural systems inside the towers. The impact analyses are conducted at various levels including: (1) the component level, (2) the subassembly level, and (3) the global level to estimate the probable damage to the towers due to aircraft impact. The analyses also include simplified and approximate methods. This task will include the development of detailed models of the aircraft and the towers at the impact zone.

- **Analyze the Post-Impact Stability of WTC 1 and WTC 2.** To examine the stability of each of the two towers and determine the reserve capacity after losing columns and floor segments due to aircraft impact and show that the towers did not collapse immediately after impact. The analyses will help understand the mechanism by which the towers remained standing after impact, including the load redistribution provided by the hat truss system, and determine how close to collapse were each of the towers immediately after impact.

- **Perform Sensitivity and Probabilistic Analysis of Aircraft Impact.** To (1) conduct a sensitivity analysis to assess the effects of variability associated with various input parameters and identify the most influential parameters that affect the damage estimates and

(2) perform probabilistic analysis to determine the probabilities associated with different damage estimates.

Work completed to date on the above tasks is summarized in the following sections.

2.3.3 Development of Structural Databases for WTC 1 and WTC 2

The development of structural databases of the primary components of the towers has been completed under a contract from NIST by the firm of LERA, the firm responsible for the structural engineering of the WTC towers. The work included digitization of the original drawing books with tabulated information, a quality control procedure to ensure consistency of the generated databases with original design documents, cross sectional property calculations, and developing relational databases to link the database files into a format suitable for models development. The developed databases include modifications made after construction.

NIST has implemented a rigorous review procedure to mitigate potential conflicts of interest and to ensure the integrity and objectivity of the deliverables. The review procedure includes an in-house NIST review and a third-party review by the firm of Skidmore, Owings, & Merrill (SOM) also under a contract from NIST. The third-party review by SOM included random checks of the digitized structural databases and cross section property calculations. The review indicated no discrepancies between the developed databases and the original drawing books. The in-house NIST review included: (1) line-by-line review of all database files, (2) random checks on the developed databases by project leader, and (3) calculation of all cross section properties and comparing with those in the developed databases. The review indicated minor discrepancies between the developed databases and the original drawing books. These discrepancies were reported to LERA, who implemented the changes and modified the databases accordingly. Consequently, the structural databases have been approved by NIST and are being made available for other phases of the NIST investigation.

Additional details on the development of the structural databases appear in Appendix B.

2.3.4 Development of Reference Structural Models for WTC 1 and WTC 2

The development of the reference structural models for the towers has been completed by LERA. These are three-dimensional, linear, finite element models (FEMs) of the towers developed using SAP2000 software. The models include:

- Typical truss-framed floor model (floor 96 of WTC 1): The model contains all primary structural members of the floor system, including primary and bridging trusses, beams in the core, strap anchors, viscoelastic dampers, exterior and core columns above and below floor level, spandrel beams, and concrete slabs. Initial verification of the model has also been performed.

- Typical beam-framed (mechanical) floor model (floor 75 of WTC 2): The model contains all primary structural members of the floor system, including composite beams, horizontal trusses, viscoelastic dampers, exterior and core columns above and below floor level, spandrel beams, and concrete slabs. Initial verification of the model has also been performed.

- Global models of each of the two towers: These are models of the 110-story above grade and 6-story below grade structure for each of the two towers and include the following six main parts: core columns, exterior wall (foundation to floor 7), exterior wall trees (floors 7 to 9), exterior wall (floors 9 to 106), exterior wall (floors 107 to 110), and hat trusses. These models were developed separately and then assembled into a unified model. Rigid and flexible diaphragms representing the floor systems, core bracing, and loads were then added to the unified model. Parametric studies were undertaken to establish the idealizations used in the global models. These studies included detailed shell element and simplified beam element models for typical exterior wall panels and exterior corner panels. The parametric studies also included development of a simplified flexible floor diaphragms calibrated against the detailed floor models. Initial verification of the global models has also been performed.

Similar to the structural databases, the developed reference models were thoroughly reviewed. As part of the review process, NIST conducted a workshop for NIST investigators, outside experts, and contractors to review the reference structural models developed by LERA. The purpose of the workshop was to discuss the methodology, assumptions, and details of the developed reference models. The feedback from individual workshop participants was included in the final review of the models.

The in-house NIST review and the third-party review by SOM included: (1) checks on the consistency of the developed reference models with the original structural drawings and drawing books, and (2) verification and validation of the models, including reviewing assumptions and level of detail and performing analyses using various loading conditions to assess the accuracy of the models. The reviews indicated minor discrepancies between the developed reference models and the original design documents. The reviews also indicated that, in general, the modeling assumptions and level of detail in the models were accurate and suitable for the purpose of the project. The reviews identified two areas where the models need to be modified. The first is the effect of additional vertical stiffness of the exterior wall panels due to the presence of the spandrel beams. The second area is the modeling of the connections of the floor slab to the exterior columns of the typical beam-framed floor model, where this connection appeared to be fixed while the connection should be modeled as pinned. The minor discrepancies and the areas identified for modification were reported to LERA, who implemented the changes and modified the models accordingly. Consequently, the reference structural models have been approved by NIST and are being made available for other phases of the NIST investigation.

More details on the development of the reference structural models appear in Appendix B.

2.3.5 Estimates of Wind Loads on the WTC Towers

The development of estimates of wind loads on the WTC towers has been completed by NIST on the basis of the current state of the art in wind engineering. The estimates make use of wind tunnel test results and extreme wind climatological estimates obtained by Rowan Williams Davis and Irwin, Inc. (RWDI) and by Cermak Peterka Peterson, Inc. (CPP) as part of insurance litigation concerning the WTC towers. In addition, the estimates of wind-induced forces and moments on the WTC towers make use of independent extreme wind climatological estimates performed by NIST, based on airport wind speed data obtained from the National Climatic Data Center, National Oceanic and Atmospheric Administration, and on the NIST hurricane wind speed database.

A comparison of estimates by CPP and RWDI of wind-induced maximum base moments on WTC 2 indicates a difference of about 40 percent between the two estimates. NIST studied the two wind tunnel reports and attempted to identify the sources of disagreement between them in order to develop the wind loading on the towers. The NIST study included: estimates of the wind speeds for the direction that corresponds in the CPP and RWDI reports to the peak wind-induced base moment, and a critique of wind profiles used in estimation of wind loads by RWDI and methods used to integrate aerodynamic and extreme wind climatological data (the sector-by-sector approach in the CPP report and the up-crossing method in the RWDI report).

The wind load estimates are currently being reviewed by SOM. Upon completion of the third-party review, the loads will be applied to the global models of the towers as part of the baseline analysis.

2.3.6 Baseline Performance Analysis of the Towers

Work is under way to complete this portion of the study. Significant progress has been made in using the reference models subject to gravity loads (dead loads and live loads used in the original design and according to ASCE 7-02 Standard) and wind loads used in the original design of the towers. Upon completion of loads application into the models, the models will be analyzed to establish the baseline performance of the towers. The results of the analysis will be reported at a later date.

2.3.7 Analysis of Aircraft Impacts into WTC 1 and WTC 2

The objective of the analysis of aircraft impacts into the WTC towers is to estimate the impact response of the towers, including damage to structural systems, acceleration environment, and fuel and debris dispersion. The analysis is being conducted at various levels including: (1) the component level, (2) the subassembly level, and (3) the global level to estimate the probable damage to the towers due to aircraft impact. The analyses also include simplified and approximate methods. NIST is working with experts from Applied Research Associates, Inc. (ARA) under a contract from NIST to conduct these analyses. The commercially available finite element analysis (FEA) software, LS-DYNA is being used for most impact analyses in this project.

The development of constitutive models describing the actual behavior of the structure under the dynamic impact conditions of the aircraft is an important step prior to conducting the impact analyses. Significant progress has been made to identify the proper constitutive relationships, including high strain-rate effects and failure criteria for the various materials included in the analysis of aircraft impacts into the WTC towers. These materials include the various grades of steels used in the exterior walls and core columns of the towers, weldment, bolts, reinforced concrete, and aircraft materials. Details on the development of the materials constitutive models appear in Appendix C.

Another important step prior to conducting the various impact analyses is the development of an aircraft model to be used in the component, subassembly, and global analyses. The model is developed based on information gathered from documentary aircraft structural information, and data from measurements on a Boeing 767 aircraft. The development of the Boeing 767 aircraft model for impact analysis is nearing completion. The engine and wing models have been completed and are being used in the component and subassembly analyses. Also completed is the empennage and landing gears. Work is under way to finalize the model of the fuselage, nose, and nonstructural components of the aircraft. Details on the development of the aircraft model appear in Appendix C.

The WTC towers and Boeing 767 aircraft are complex structural systems, and a large database of detailed structural information has been collected on them. In the model development process, the objective was to include all of the primary structural components and details of both the aircraft and towers. This approach, however, results in very large models. The component and subassembly analyses were used to determine model simplifications that can reduce the overall model size while maintaining fidelity in the analysis. Therefore, a series of component impact analyses were performed. The primary objectives of component modeling are to (1) develop understanding of the interactive failure phenomenon of the aircraft and tower components and (2) develop the simulation techniques required for the global analysis of the aircraft impacts into the WTC towers, including variations in mesh density and numerical tools for modeling fluid-structure interaction for fuel impact and dispersion. The approach taken for component modeling is to start with finely meshed, brick element models of key components of the tower structure and progress to relatively coarsely meshed beam and shell element representations that will be used for the global models. Much progress has been made on the component level analyses using models of tower exterior and core columns with column end bolted connections and spandrel bolted connections, as well as floor segments impacted separately with an engine or a wing section with and without fuel. This analysis is nearing completion, and details on the analysis methodology and results appear in Appendix C.

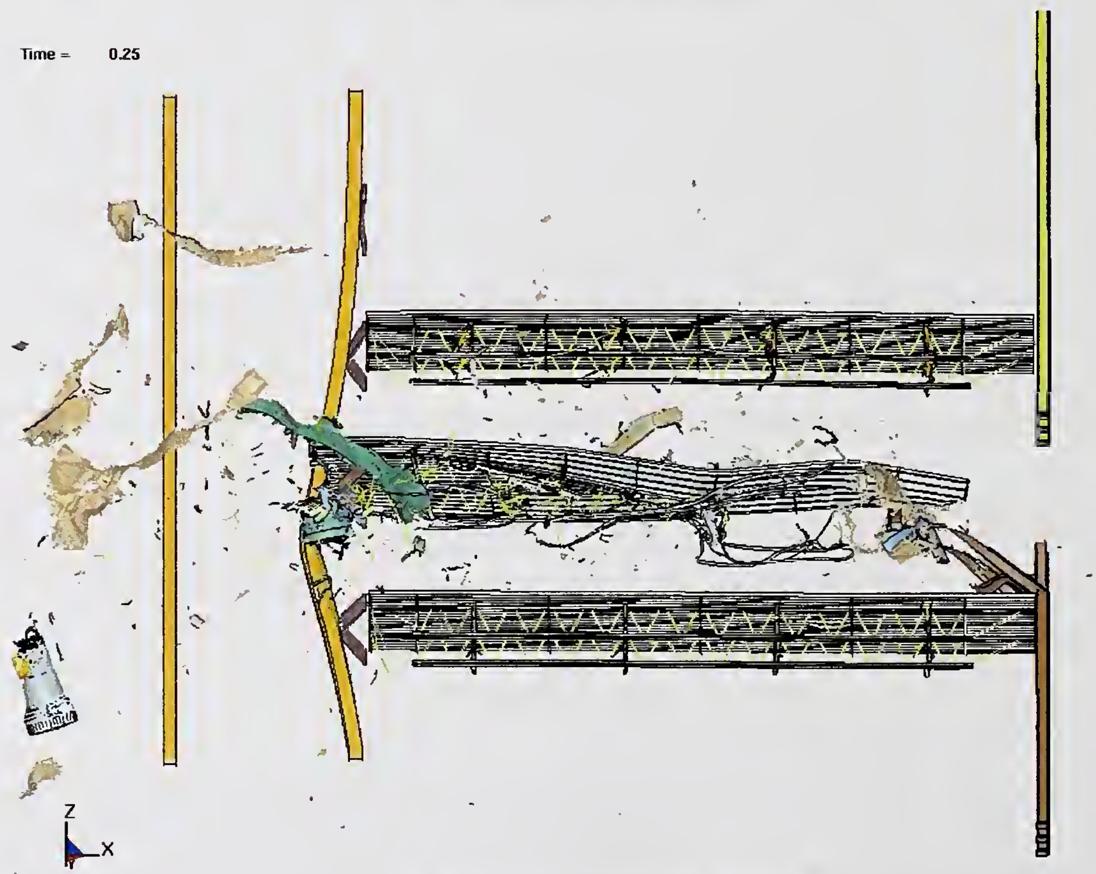
Not reported in Appendix C is progress made on the subassembly analysis. This work is under way. Preliminary subassembly engine impact analyses into a strip from the exterior wall to the core of WTC 1 have been performed. An example analysis, shown in Fig. 2–2, is for a 500 mph engine impact centered on the spandrel for exterior panel 121A at floor 96 and includes core columns 503A and 603A between floors 94 and 98. This model includes a single width exterior panel and floor assembly of the same width. The concrete slab is modeled with brick elements, and the diagonal round bar members in the floor trusses are modeled with beam elements. The remainder of the structures, including the columns, metal decking, and truss upper and lower chord components, are modeled with shell elements. An alternate view of the impact damage at 0.25 s is shown in Fig. 2–3. Current work focuses on expanding the size of the model in width (larger number of exterior panels), height (larger number of floors), and depth (extension all the way through the core) to minimize the effect of boundary conditions on the model response. Details of further work on the subassembly analysis will be reported at a later date.

Also not reported in Appendix C is progress made on the development of the models of the towers in the impact zone to be used for the global impact analysis. This work is ongoing. Examples include single floor models in the core (Fig. 2–4), multiple floor models (Fig. 2–5), and exterior wall models (Fig. 2–6). Details of further work on the development of the global models will be reported at a later date.

2.3.8 Preliminary Stability Analysis of the WTC Towers

Preliminary system stability analyses of the WTC towers have been performed to: (1) examine the overall stability of the undamaged tower upon removal of floors, (2) study possible load redistribution mechanisms upon losing columns in the core due to aircraft impact, and (3) study the response of WTC 1 when columns in the exterior walls and the core are assumed destroyed due to aircraft impact and columns in the exterior are damaged due to subsequent fire effects.

(a) Initial configuration



(b) Impact response at 0.25 s

Figure 2–2. Example engine impact subassembly analysis.

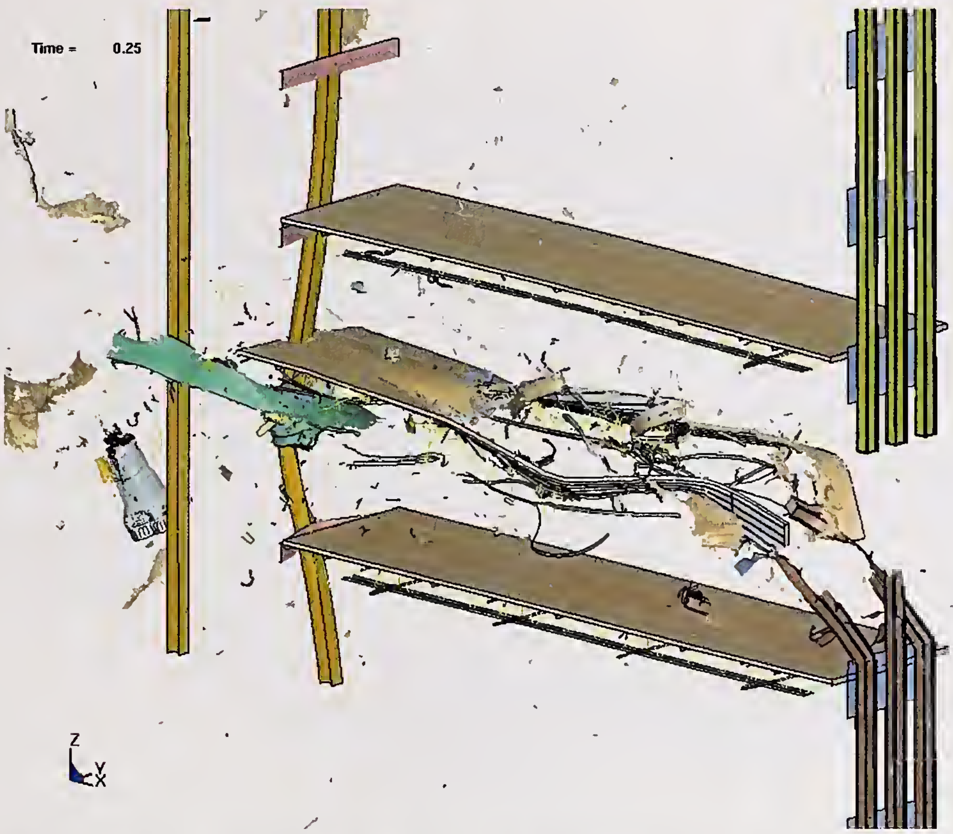


Figure 2–3. Oblique view of the subassembly engine impact damage.

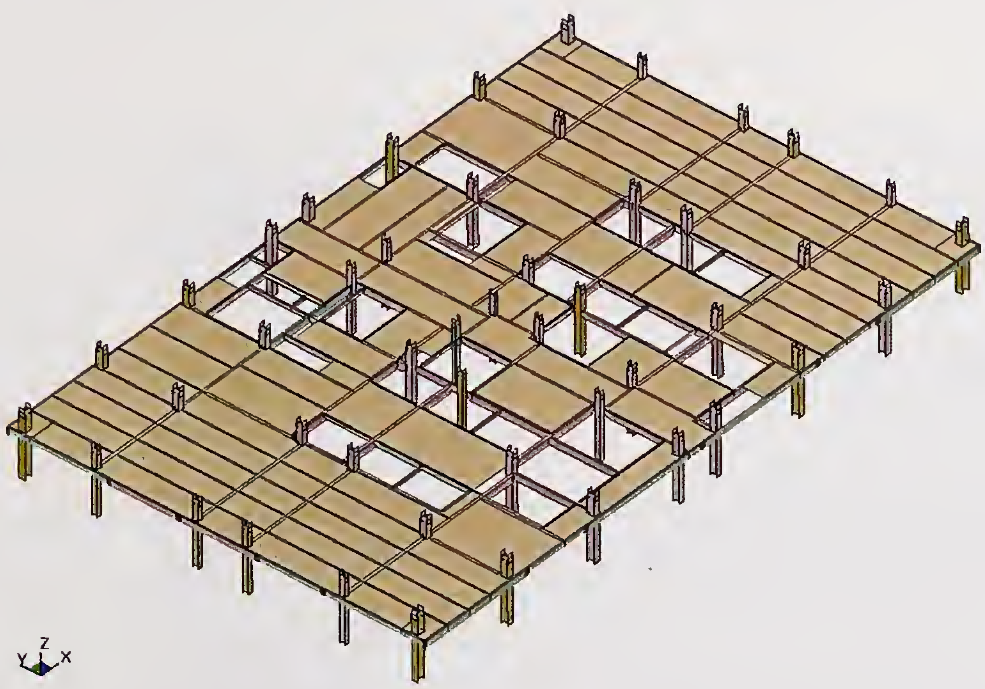


Figure 2–4. Model of the 96th floor and columns of WTC 1.

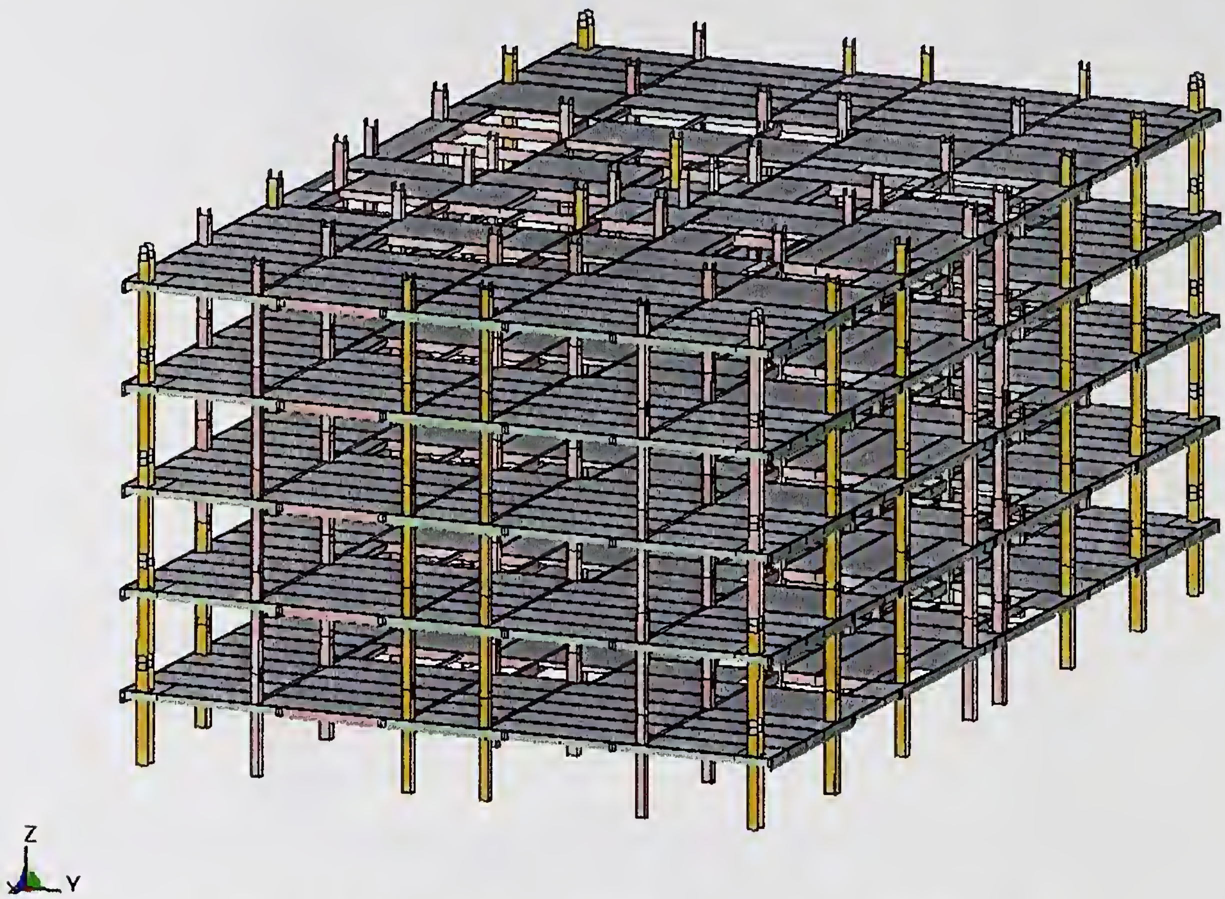


Figure 2–5. Model of the core of WTC 1, floors 94–98.

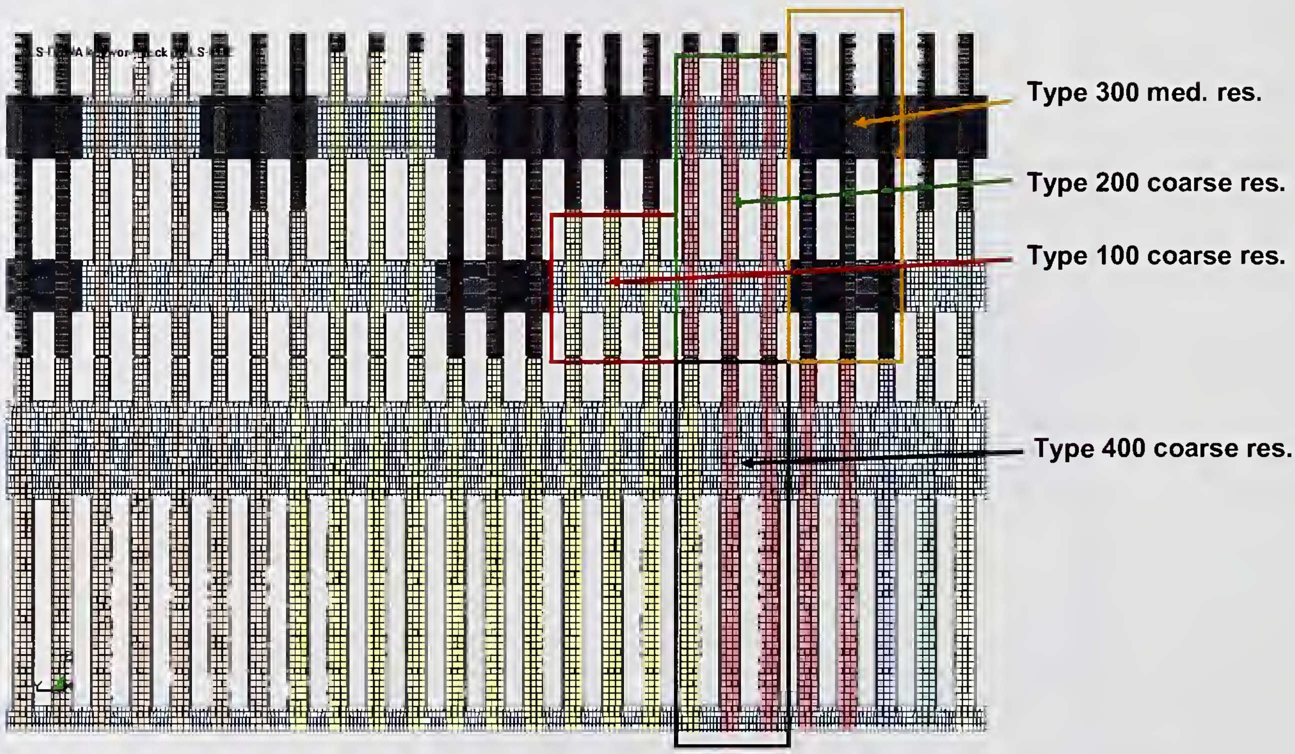


Figure 2–6. Detail of the WTC 2 impact zone exterior column panels.

The analyses used the typical truss-framed floor model and a reduced version of the global reference model of WTC 1 (see Section 2.3.4) with proper modifications. Modifications included adding vertical springs at the bottom of the reduced models to account for the removed lower portion of the towers, and using actual steel properties and actual loads on the towers. The analyses used staged construction technique to account for the sequential construction of the towers, especially in the zone of the hat trusses. Linear buckling analysis and nonlinear analysis with plastic hinges were used to study the effects of removal of floors and loss of exterior and core columns, respectively. In addition, analysis of the floor system, where severed core columns were replaced by equivalent springs representing the stiffness of the hat trusses and columns between the floors and hat trusses, was conducted to study the mechanism by which the floor loads were redistributed when the core columns were severed by aircraft impact.

Details on the preliminary stability analyses appear in Appendix D.

2.3.9 Summary and Preliminary Findings

Significant progress has been made on the first focus area of this project dealing with the baseline performance of the WTC towers. This includes the completion, review, and, final approval by NIST of the structural databases and reference structural models of the towers. Also completed are the NIST estimates of the wind loading on the towers based on the state-of-the-art, which is currently under review. Progress has been made on performing the baseline analysis.

For the second focus area, dealing with aircraft impact into the towers, work is nearing completion on the development of materials constitutive modeling, aircraft model, and component level analyses. Progress has been made on the subassembly and global models development. In addition, preliminary stability analyses of the towers under damage from aircraft impact have been performed.

The following presents some preliminary findings obtained from the component impact analyses (see Appendix C):

- A 500 mph engine impact against an exterior wall panel results in a penetration of the exterior wall and failure of impacted exterior columns. If the engine does not impact a floor slab, the majority of the engine core will remain intact through the exterior wall penetration with a reduction in velocity of about 10 percent and 20 percent. The residual velocity and mass of the engine after penetration of the exterior wall is sufficient to fail a core column in a direct impact condition. Interaction with additional interior building contents prior to impact or a misaligned impact against the core column could change this result.

- A normal impact of the exterior wall by an empty wing segment from the wing tip region will produce significant damage to the exterior columns, but not necessarily complete failure. A fuel-filled wing section impact results in extensive damage to the exterior wall, including complete failure of the exterior columns. This is consistent with photographs showing the exterior damage to the towers due to impact.

- Three different numerical techniques were investigated for modeling impact effects and dispersion of fuel: (1) standard Lagrangian FEA with erosion, (2) Smoothed Particle Hydrodynamics (SPH) analysis, and (3) Arbitrary-Lagrangian-Eulerian (ALE) analysis. Of these approaches, SPH analyses appear to offer the greatest potential for modeling fuel in the global impact analysis due to the combination of both computational efficiency and modeling fidelity.

The following presents some preliminary findings obtained from the preliminary stability analyses under service live loads and subject to the assumptions and the limitations of these models (see Appendix D):

- Linear stability analysis was used to examine the stability of the undamaged WTC 1 under service loads through increased unbraced column lengths (floor removal). The tower was stable when two floors were removed. Two core columns buckled when three floors were removed, but the tower maintained its overall stability. The tower also maintained its stability when four columns buckled with four floors removed. The analysis suggested that global instability of the tower occurred when five floors were removed from the model. Assuming that all columns at the region of the removed floors reached a temperature of 600 °C (reduced modulus of elasticity), the analysis indicates that removal of four floors would induce global instability.

- Analysis of the typical truss-framed floor model with fifteen severed core columns indicated that, under service loads, the floors first attempted to redistribute their loads to the hat trusses through tension in the columns above the damage. The load followed this path due to the relatively large stiffness of the hat trusses-column system compared to the flexural stiffness of the floors. At a certain floor level, column splices fail due to the large tensile forces and the floors below the failed splices must redistribute their loads directly to neighboring undamaged core columns. When only eight core columns were assumed severed, the analysis indicated that the tensile forces in the columns were smaller, due to the relatively larger stiffness of the floor. These forces may still have failed the columns at the splices.

- Nonlinear analysis that included geometric nonlinearities and material nonlinearities using plastic hinges was conducted on the reduced global model of WTC 1. The model assumed the following damage to the tower: (1) due to aircraft impact, loss of columns and spandrels in the north face, and an exterior panel in the south face of the tower, as well as eight columns in the core; and (2) due to fire, loss of columns in the south face, which were shown in videos to be bowing inward a few minutes prior to collapse. The analysis indicated that after aircraft impact, the tower maintained its stability, where the highest stressed elements were the exterior columns next to the damaged area on the north face of the tower. The tower also maintained its stability after losing columns in the south wall due to fire effects with some reserve capacity left, indicating that additional loss or weakening of columns in the core, weakening of additional columns in the exterior, or additional loss of floors is needed to collapse the tower. More detailed models will account for local bucking of columns, and the failure and role of the floor system in redistributing the loads; factors that are not considered in this analysis.

2.4 METALLURGICAL AND MECHANICAL ANALYSIS OF STRUCTURAL STEEL (PROJECT 3)

2.4.1 Project Objective

Structural steel recovered from the WTC site provides information essential to understanding the events of September 11, 2001. Important data available from analysis of the steel include failure modes of the steel that provide clues to the interaction of the aircraft with the buildings and mechanical properties of the steel that assist in modeling of the buildings during impact and under the high temperatures concomitant with the fires. The steel may provide additional clues, such as information on the extent of high temperature exposure of the steel in the fires.

Thus, the objective of Project 3 is to analyze structural steel available from WTC 1, 2, and 7 for determining the metallurgical and mechanical properties and quality of the metal, weldments, and connections, and providing essential data to other investigation projects.

2.4.2 Project Approach

This project is divided into five substantive tasks as follows:

- **Task 1–Physical Evidence.** Collect and catalog the physical evidence (structural steel components and connections) and other available data, such as specifications for the steel, the location of the steel pieces within the buildings, and the specified steel properties.

- **Task 2–Visual Observations.** Document failure mechanisms and damage based on visual observations of recovered steel, especially for available columns, connections, and floor trusses. Photographs taken before collapse will be used to determine damage occurring to the recovered steel before collapse.

- **Task 3–Mechanical Properties.** Determine the metallurgical and mechanical properties of the steel, weldments, and connections, including temperature dependence of properties. The grades of steel will be identified in the columns, welds, spandrels, trusses, truss seats, and fasteners. The identification will include composition, microstructure, mechanical, and impact properties. This task will provide steel property data, including models of elevated temperature behavior for relevant steels, to estimate damage to the structural steel members from aircraft impact, evaluate structural fire response, and study the initiation of structural collapse in Project 6, Structural Fire Response and Collapse Analysis.

- **Task 4–Correlation with Engineering Drawings.** Correlate determined steel properties with the specified properties for construction of the buildings. The quality of the steel used in the buildings will be compared with that specified.

- **Task 5–High Temperature Excursions.** Analyze the steel metallographically to estimate maximum temperatures reached. It is recognized that high temperature exposure before the collapse may be difficult to distinguish from exposure during post-collapse fires.

2.4.3 Physical Evidence

NIST has studied steel elements from the WTC buildings and collected and analyzed documents on steel and welding specifications from the 1960s applicable to the WTC towers. This analysis has resulted in the documents described below.

Catalog of Structural Steel

NIST has catalogued the 236 structural steel elements from the WTC buildings recovered for the investigation. These pieces represent a small fraction of the enormous amount of steel examined at the various recovery yards where the debris was sent as the WTC site was cleared. Components include full exterior column panels, core columns, portions of the floor truss members, channels used to attach the floor trusses to the interior columns, and other smaller structural components (e.g., bolts, diagonal bracing straps, aluminum facade).

NIST catalogued and documented the steel pieces, and when possible, identified markings on the steel which pinpoint the intended as-built location within the buildings. Roughly 0.25 percent to 0.5 percent of the 200,000 tons of steel used in the construction of the two towers was recovered. The recovered steel includes portions of:

- 90 exterior column panels; the as-built location of 41 distinct sections has been unambiguously identified within WTC 1 and WTC 2:
  - 26 panels from WTC 1: 22 from near the impact floors, 4 hit directly by the airplane
  - 15 panels from WTC 2: 4 from near the impact floors.
- 55 wide flange sections and built-up box sections; 12 core columns have been positively identified from WTC 1 and WTC 2, including 1 column from the impact zone of WTC 1 and 2 columns from the impact zone of WTC 2.
- 23 pieces of floor truss material from WTC 1 and WTC 2; however, the as-built location of the trusses within the buildings could not be identified.
- 25 pieces of channel sections that connected the floor trusses to the core columns in WTC 1 and WTC 2; however, the as-built location of the channels could not be identified.

The design drawings for WTC 1 and WTC 2 designate 14 different grades (or strengths) of steel for the exterior panels, four grades for the core columns, and two grades for the floor trusses. Stampings on identified perimeter and core columns indicate that the steel supplied was the appropriate strength as indicated on the design drawings, with the exception that 100 ksi plate was used for the 85 ksi and 90 ksi material called for in the design, leading to a total of 12 grades of steel in the buildings. The recovered structural elements have yielded representative samples of the following:

- All 12 grades of exterior panel material;

- Two grades of core column steel (representing 99 percent, by total number, of the columns); and
- Both grades for the floor truss material.

The collection of steel from the WTC towers is adequate for purposes of NIST's investigation (i.e., chemical, metallurgical, and mechanical property analyses as well as a substantial damage assessment and failure mode examination) to examine why and how WTC 1 and WTC 2 collapsed following the impact of the aircraft and ensuing fires.

More detail on the recovered steel appears in Appendix F, Inventory and Identification of Steels Recovered from WTC Buildings.

Contemporaneous Specifications and Other Documents

As part of an analysis of contemporaneous (1960s era) documents, NIST has studied the building drawings to ascertain the major structural elements and grades of steel in the towers relevant to the investigation. Also, 1960s era steel and welding specifications used to construct the WTC towers have been located and analyzed. The many steels (combinations of strengths and manufacturers) that were used have been characterized based on structural engineering specifications for the buildings and manufacturer documents of the era. Appendix E, Contemporaneous Structural Steel Specifications, also describes the major structural elements in the towers relevant to the investigation.

Ten steel companies fabricated structural elements for the two towers. The floors involved in the aircraft impact and major fires contained steel from four of these companies. Laclede Steel (St. Louis, Missouri) fabricated the trusses for the floor panels that spanned the opening between the core and the perimeter columns. They used steels conforming to ASTM A36 and A242, which they made and rolled in their own mill. NIST chemical analyses and strength tests, as well as contemporaneous mill reports indicate that many of the floor truss components specified as ASTM A36 were actually fabricated with a micro-alloyed steel of considerably higher yield strength.

Pacific Car and Foundry (Seattle, Washington) fabricated the perimeter box column panels (generally 3 columns wide by 3 stories tall) above Floor 9. Although 14 grades of steel (36 ksi to 100 ksi yield strength) were specified in the structural steel drawings, only 12 grades were supplied due to an upgrading of two of the specified steels. Most of the steel came from Yawata Iron and Steel (now Nippon Steel) and Kawasaki Steel, although about 10 percent of the plate was produced domestically, primarily by Bethlehem Steel. Many of these steels were relatively new proprietary steels and were not covered by ASTM standards of the time. In the impact zones of the towers, the perimeter columns damaged by the aircraft were largely of three specified grades: 55 ksi, 60 ksi, and 65 ksi steels.

Stanray Pacific (Los Angeles, California) fabricated the welded core box columns (rectangular columns assembled from four steel plates) above Floor 7, primarily using steels conforming to ASTM A36. The thicker plates came from Colvilles, Ltd. (Motherwell, Scotland, now Corus Steel), while the thinner plates came from Fuji Steel (now Nippon Steel).

Montague-Betts (Lynchburg, Virginia) fabricated the rolled wide-flange core columns and beams above the Floor 9. Much of the steel for the wide-flange columns came from Yawata Iron and Steel. The rest

Montague-Betts purchased from numerous domestic suppliers. For WTC 1, the core columns damaged by impact and fire were mostly wide-flange shapes, since the highest floors of the buildings contained few box columns. In WTC 2, the damaged columns were a roughly equal mix of welded box columns and wide-flange shapes.

Details on the 1960s era documents appear in Appendix E.

2.4.4 Visual Observations

Visual analysis includes analysis of both photographic evidence just before the collapse and analysis of the recovered steel for clues to the performance of the steel structure throughout the event. Airplane impact damage to the towers has been characterized from enhanced precollapse photographs (Fig. 2–7). Such analyses provide input for validation of airplane impact models. In addition, these images allow investigators to determine whether damage observed in the recovered steel occurred before or after the collapse, greatly aiding the failure analyses of these pieces.

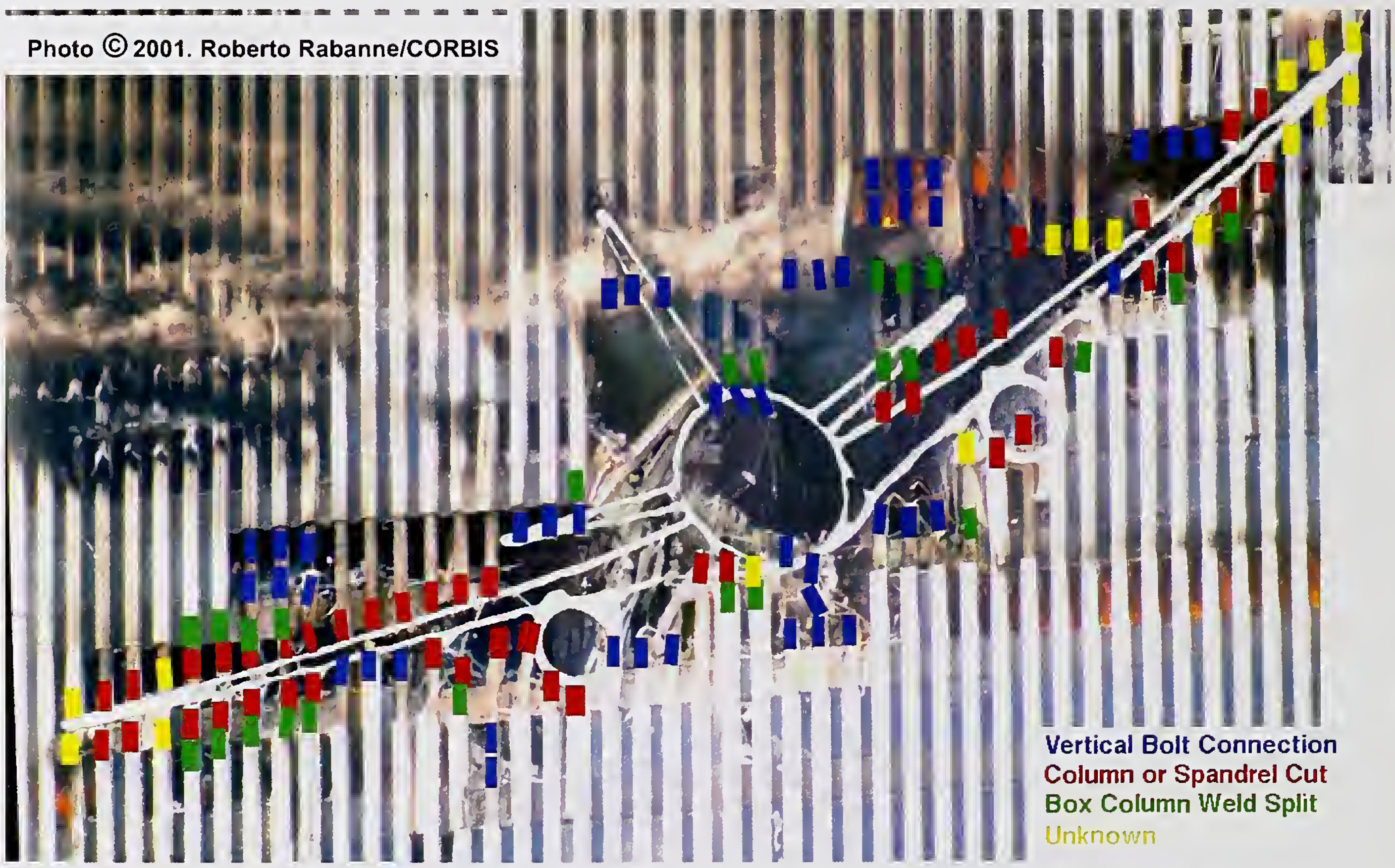


Figure 2–7. Enhanced precollapse image of the north face of WTC 1 with superimposed outline of the Boeing 767. Likely failure modes of damaged columns are indicated.

The recovered steel has been studied to determine failure modes of the various components and connections. In addition, a NIST contractor, Wiss, Janney, Elstner, has surveyed the recovered steel to characterize failure behavior.

2.4.5 Mechanical Properties

Mechanical tests of steel at room temperature (for baseline performance), high temperature (for strength and deformation behavior in fire conditions) and high rates of deformation (to calibrate strength enhancements occurring during airplane impact) are completed and are being analyzed. Preliminary analysis of the perimeter column and truss steel indicates that the quality and strength (relative to required minimum values) of the steel is as expected for steel of the period. Results for the core columns and connections are still being analyzed. Data are being provided to the impact damage and fire modeling teams.

Mathematical models of the stress-strain behavior of 21 steels (various grades and manufacturers) in the WTC towers have been developed and provided to contractors for use in computer models of the behavior of the buildings. The models of the steel behavior are based on the conventional room temperature tests, high strain rate tests, and high temperature characterization.

2.4.6 Correlation with Engineering Drawings

In order to determine if the great variety of steels were in the proper positions in the buildings, NIST has correlated stamped yield strength values (generally stamped on each plate in the perimeter panels) and the measured mechanical properties with the yield strengths on the design drawings. This correlation is largely complete, and there are no indications that any inappropriate steel was in place in the buildings.

2.4.7 High-Temperature Excursions

The structural steel from the impact area of the towers is being characterized to determine maximum exposure temperatures for input to Project 5. After surveying a number of possibilities, NIST developed a technique to map thermal exposure of the relevant pieces by characterization of paint condition. By this means, sections with no damage (i.e., no "mud-crack" patterns) to the paint are known to have remained below approximately 250 °C, and paint with mud-cracks, but remaining relatively intact, remained below approximately 750 °C. Above 750 °C the paint becomes powdery and flakes off. Mapping of the steel is nearly complete, and data will be supplied to Project 5.

2.4.8 Significant Interim Results

1. NIST has cataloged the 236 pieces of recovered steel (Appendix F).

2. Material and construction specifications of the construction period, as well as steel fabrication documents, have been located, analyzed, and documented (Appendix E).

3. Mechanical tests at room temperature (for baseline performance), high temperature (for strength and deformation behavior in fire conditions) and high rates of deformation (to calibrate strength enhancements occurring during airplane impact) are completed and are being analyzed.

4. Mathematical models of the stress-strain behavior of 29 steels (various grades and manufacturers) in the WTC towers have been developed for use in computer models of the behavior of the building during the airplane impact and during the resulting fires. The models of the steel

behavior are based on the conventional room temperature tests, high strain rate tests, high temperature characterization and literature on properties of steel produced in the era in which the WTC towers were constructed.

5. Airplane impact damage has been characterized from enhanced precollapse photographs and correlated with recovered steel.

6. Ten different steel companies fabricated structural elements for the towers, using steel supplied from at least eight different suppliers; four fabricators supplied the major structural elements of floors 9 to 107.

7. Documents from the era of WTC tower construction, from the steel suppliers and others, were used to estimate average yield strengths for each of the supplied steels. These strengths typically exceed the specified minimum strengths given in the engineering drawings by 5 percent to 10 percent.

8. In contrast to the above, extensive studies of steel from the construction period show that due to statistical variation expected in steel products, a fraction of mechanical tests would be expected to fall below specified minimums.

9. Although ASTM structural steel standards have evolved since the construction of the towers, changes have been minor and do not represent changes to the basic mechanical properties of the steels.

2.4.9 Preliminary Findings

1. Analysis of recovered samples of the many grades of steel in the towers indicates that, based on stampings on the steel and mechanical tests, the correct specified grades of steel were provided for the specific fabricated elements. Furthermore, when this data is combined with pre-collapse photographic images of the five recovered WTC 1 panels in NIST's possession that were damaged by the aircraft impact, it has been shown that these particular elements contained proper steel in the precise locations as specified in the design drawings.

2. Metallography and mechanical property tests indicate that the strength and quality of steel in the towers was adequate, typical of the era, and likely met all qualifying test requirements.

2.5 INVESTIGATION OF ACTIVE FIRE PROTECTION SYSTEMS (PROJECT 4)

2.5.1 Project Objectives

The active fire protection systems studied in this investigation are the automatic fire sprinklers, fire detection and alarms, smoke purging, and preconnected hose lines. The automatic fire sprinkler system is the first line of defense against fires in these buildings. Water stored in the building, from public sources and even pumped from fire apparatus can be supplied through dedicated piping to the area of the fire. Also present in the buildings were preconnected hose lines connected to a water supply through standpipes located in the stairwells and other utility shafts. The standpipes provided hose connections at each floor for the FDNY. In addition, standpipe preconnected hoses were installed for trained occupants to manually suppress fires. The heart of the fire detection system is the automatic fire alarm and emergency notification system. Occupants in the building depend on this system to detect fires and provide information for emergency evacuation. Capabilities were also designed for the ventilation system to operate in a way to purge smoke produced by fires from the building. Smoke purge was intended to be used for post-fire clean-up, but could be used during a fire event at the discretion of the FDNY.

All of the active fire protection systems provide capabilities that are important for fire control, providing information for occupants and first responders, and limiting the effects of the fire on the building and its occupants. Therefore, this project has the objectives of documenting and evaluating the performance of the installed active fire protection systems in WTC 1, 2, and 7 and assessing their role in fire control, emergency response, and the fate of occupants and responders.

2.5.2 Project Approach

The tasks of this project are to (1) document fire protection systems design and installation, and (2) evaluate performance without the benefit of any physical evidence from the collapsed buildings. The need to document facts associated with the installed fire protection systems was made difficult because many of the relevant documents for WTC 1, 2, and 7 were lost in the collapse of those buildings.

With the cooperation of the PANYNJ and Silverstein Properties Inc., information was obtained from other locations and from contractors, consultants, and operators. As an example, some information was obtained from the engineering offices of PANYNJ in Newark. Other written materials describing the design and operation of active fire protection systems were obtained through files maintained by contractors. Lastly, information from engineers and system operators was helpful in clarifying details of the installation and operation.

NIST investigators led three groups of fire protection systems contract experts. Each group specialized in one of the fire protection systems being investigated – fire sprinkler, fire alarm, and smoke management. The group examining the sprinkler system was also tasked with investigation of the other water-based fire suppression systems—the standpipe and preconnected hoses.

Technical assistance to NIST in the investigation of the sprinklers, standpipes and preconnected hoses was provided by Hughes Associates Inc. of Baltimore, Maryland. This group was tasked with:

1. Documenting the design and installation of the systems;
2. Documenting the design and capacity of the water supply including provisions for redundancy;
3. Identifying differences in the designs used in WTC 1, 2, and 7;
4. Documenting the normal operation and effect of the fully functional systems for fire control;
5. Assessing the probable performance of the systems in WTC 1 and WTC 2 on September 11, 2001; and
6. Assessing the installed systems with respect to present best practices.

The amount of water that the water supply and sprinkler systems were capable of delivering for a series of fire scenarios was determined using a hydraulic model of the sprinkler system and the associated water supply.

Technical assistance to NIST in the investigation of the fire alarms was provided by Rolf Jensen and Associates, Inc., of Fairfax, Virginia. This group was tasked with:

- Documenting the design and installation of the system;
- Documenting the normal operation and effect of the fully functional systems, including provisions for redundancy;
- Documenting modifications made to the fire alarm systems in WTC 1 and WTC 2 after the 1993 bombing;
- Assessing the probable performance of the systems in WTC 1 and WTC 2 on September 11, 2001; and
- Assessing the installed systems with respect to present best practices

Technical assistance to NIST in the investigation of the smoke management systems was provided by Hughes Associates, Inc., of Baltimore, Maryland. This group was tasked with:

- Documenting the design and installation of the systems;
- Describing the normal operation in fire emergencies;
- Assessing the probable performance of the systems in WTC 1 and WTC 2 on September 11, 2001; and
- Assessing the installed systems with respect to present best practices.

The NIST building airflow and contamination dispersal computer model, CONTAM, was used to evaluate the performance of several smoke management system configurations in WTC 1 and WTC 2 under specific fire scenarios.

Significant fires in WTC 1, 2, and 7 prior to September 11, 2001, were of interest to understand, in particular, how the fires were suppressed. Information was sought on all fires that activated multiple sprinklers or where hose lines were used to suppress the fires. Because the records of fire events in the buildings maintained by the PANYNJ were destroyed in the fire and collapse of WTC 1, information was collected from FDNY fire reports.

2.5.3 Fire History of WTC 1, 2, and 7

Fires occurred in WTC 1, 2, and 7 prior to September 11, 2001. The facts related to the performance of automatic sprinkler, manual suppression, fire detection and smoke purge systems during significant fires in the buildings after first occupancy were documented.

Extensive records of fire incidents kept in the WTC 1 offices of the PANYNJ were lost in the collapse of the building; however, FDNY maintains records of the responses to all fires. These records consist of standardized forms on which fire events are described using codes from a predefined list of descriptive phrases and categories.

The FDNY provided 397 Bureau of Operations Fire Reports and 112 Bureau of Fire Investigation Records (Fire Marshals' Reports) that served as the basis for this summary of the fire history in the WTC 1, 2, and 7. NIST reviewed these reports of fires for the period of 1970 to 2001 and fire investigation records between 1977 and 2001 for WTC 1, 2, and 7. All of these records consist of standardized forms that may be supplemented with other materials. Many were for minor fire events, such as fires that were extinguished by occupants before FDNY arrival. These were not of interest for this investigation. The records of significant fires were identified. Significant fire incidents were those involving the discharge of multiple sprinklers, use of a standpipe connected hose, or the combination of a single sprinkler discharge and a hose. As an aside, the majority of fire records for significant fires documented the performance of the detectors and sprinkler systems, but almost all reports lacked information about the performance of the smoke purge system.

Table 2–4 contains the categorization of all structural fire incidents contained in the FDNY records for WTC 1, 2, and 7 available to this Investigation. This information was obtained from 345 of the 397 Bureau of Operations Fire Reports that reported structural fire incidents. The table contains information on the category of fire incident, the time period over which the fire occurred, the number of records in that category, and a descriptive statement about the category.

Forty-seven of these cases were considered significant fires based on information about the number of sprinklers activated, and/or hose lines used to suppress the fire. Sixteen fire incidents exercised multiple sprinklers or multiple standpipes (with or without the activation of at least one sprinkler). Thirty-one fires involved the use of one standpipe line or one standpipe line and discharge of one sprinkler. These incidents are documented further in Appendix G. In addition, the appendix contains information from publicly available investigation reports of the 1975 office fire in WTC 1 and the 1993 bombing incident.

The FDNY fire reports and fire investigation records indicate that in areas protected by automatic sprinklers, no fire activated more than three sprinklers. The design area for three sprinklers is a floor area of 63 m^2 (675 ft^2) in a light hazard occupancy, such as a high-rise office building as specified in the NFPA Standard for the Installation of Sprinkler Systems (NFPA 13).

Many of the fires that occurred were recorded as suspicious or unknown in cause, occurred during off-peak work hours, and involved materials such as trash or paper-based supplies. In cases where sprinklers were activated, the FDNY records indicated that the sprinklers either extinguished the fire completely or aided in controlling the spread.

Table 2–4. Summary of historical fires in WTC 1, 2, and 7.

WTC 1			
Category	**Dates**	**Number**	**Generalization of Incidents**
No detection, no sprinkler	1980–2001	66	Unattended food/appliances, overheated elevator equipment, discarded material, welding operations, electrical failure and suspicious fires
No detection information and no sprinklers	1970–1979	79	Trash can fires, discarded material, food on stove, electrical failure, overheated equipment
Detection, no sprinklers	1980–2000	57	Unattended food/appliances, overheated elevator equipment, discarded material, welding operations, electrical failure
Detection and sprinklers	1977–1999	18	Suspicious, electrical failure, discarded material
WTC 2			
Category	**Dates**	**Number**	**Generalization of Incidents**
No detection, no sprinkler	1980–1999	37	Discarded material, welding too close, overheated equipment, suspicious, elevator motor
No detection information and no sprinklers	1975–1979	40	Discarded material, fire in office furniture, trash can fires
Detection, no sprinklers	1981–1999	40	Food on stove, small elevator fire, electrical failure, suspicious, overheated equipment
Detection and sprinklers	1977–2000	5	Mechanical failure, suspicious
WTC 7			
Category	**Dates**	**Number**	**Generalization of Incidents**
No detection, no sprinkler	2000	1	Trash can fire/discarded material
Detection, no sprinklers	1990	1	Electrical switch on floor – explosion
Detection and sprinklers	1988	1	Suspicious

2.5.4 Fire Sprinkler, Standpipe, and Preconnected Hoses

Resources used in the investigation of the sprinkler, standpipe, and preconnected hoses in WTC 1, 2, and 7 are being documented by NIST investigators and subject experts at Hughes Associates, Inc. This information will be included in the final report

The design and installation of the fire sprinkler, standpipe, and preconnected hoses are described in a report being prepared for NIST by Hughes Associates, Inc. This report will provide an analysis of the performance capabilities of the suppression systems based on hydraulic modeling of the water supply and sprinkler distribution system.

Preliminary Findings

1. **Sprinkler Risers and Standpipes**. In WTC 1, 2, and 7, primary and secondary water supplies, fire pump size and locations, water storage tanks, and FDNY connections provided multiple

points of water supply redundancy. The potential for single point failure of the water supply to the fire sprinklers existed at each floor due to lack of redundancy in the sprinkler riser system that provided only one supply connection on each floor. As a result, the water supply to the sprinkler systems or a standpipe serving preconnected hoses could be interrupted by routine maintenance needs (i.e., shutdown of the riser or standpipe) or by impairment due to deliberate acts to damage the sprinkler riser or standpipe systems. While this lack of redundancy may not have had an impact on September 11, 2001 because the sprinkler system was damaged by aircraft impact, it could have made a difference in other building emergencies.

2. **Water Flow Rate to Sprinklers**. Aided by the results of hydraulic modeling of the sprinkler system in WTC 1 and WTC 2—undamaged by aircraft impact and fully operational—the delivered water flow rate available from the automatic sprinkler systems was found to generally exceed the minimum requirements (by a considerable margin) for a high-rise office hazard classification in accordance with NFPA 13. In a number of cases, the amount of available water flow from sprinklers on specific floors was capable of protecting higher fire hazard classes than those associated with light hazard office buildings.

2.5.5 Fire Alarm Systems

The WTC 7 fire alarm system was monitored by AFA Protective Systems, Inc., at a location remote from the WTC site. AFA Protective Systems furnished the record from the fire alarm system history tape to NIST for use in the Investigation.

Other resources used in the investigation of the fire alarm systems in WTC 1, 2, and 7 are being documented by NIST investigators and subject experts at Rolf Jensen and Associates, Inc. This information will be included in the final report.

The design and installation of the fire alarm systems will be described in a report being prepared for NIST by Rolf Jensen and Associates, Inc. This report will provide the analysis of performance based on the design and programming of the systems.

WTC 7 Alarm System Monitoring Record

Although a great amount of information is normally collected and stored by any fire alarm system from fire detectors installed throughout a building, typically, and in the case of WTC 7, no specific fire information is sent to the monitoring site beyond the fact that a fire condition has been detected.

The information from the WTC 7 alarm system monitoring record for September 11, 2001, is shown in Fig. 2–8.

09/11/01	14:48:22	DYJ	4612	**** FULL CLEAR ****		
09/11/01	14:47:22	LATE	3923	SYSTEM TEST OVER		
09/11/01	14:47:22	COMMENT:		TEST: ALL		
09/11/01	14:47:21	COMMENT:		LAST SET: 091101 64742		
09/11/01	10:00:52	1	1510	CO TO CLASS E	AREA:1	*T
09/11/01	06;47:43	COMMENT:		RIC: WILLIAMS		
09/11/01	06:47:03	RIC	4210	PLACE ON TEST	CAT:11	
09/11/01	06:47:03	COMMENT:		091101 647 091101 1447		
09/11/01	06:47:02	COMMENT:		TEST: ALL		
09/11/01	06:05:01	RP		20 TIMER TEST		

Figure 2–8. Monitoring station history tape record for the WTC 7 fire alarm system on September 11, 2001.

The fire alarm history tape record is read from the bottom to the top. Some entries occur as the result of normal operations, and others are the result of actions taken by operators. The bottom line of the record shows that at 6:05:01 a.m. on September 11, 2001, the fire alarm system completed a normal communications check with the central monitoring station. This check is made every day.

At 6:47:02 a.m., AFA placed WTC 7 in a “TEST: ALL” condition. This is normally done in response to a request from the building manager. Ordinarily, it is requested when maintenance or other testing is being performed on the system, so that any alarms that are received from the system are considered the result of the maintenance or testing and are ignored. NIST was told by AFA that for systems placed in the TEST condition, alarm signals are not shown on the operator’s display, but records of the alarm are recorded into the history file.

At 6:47:03 a.m., the record includes an explanation of the request to put the system in the TEST condition. Continuing to read from bottom to top, the date and time the system was placed in TEST is recorded. In this case it is 091101 647 (6:47 a.m., September 11, 2001), and the system will automatically go back to normal monitoring after 8 hr, a system default value, at 091101 1447 (2:47 p.m., September 11, 2001). On the next line above, “RIC” identifies the AFA operator; 4210 is a code number for the “PLACE ON TEST” message. CAT:11 indicates the authority of the person requesting the action. On the next line above, the comment entered by RIC identifies that the person who requested that the system be placed on TEST was Williams. This action appears to be common for the building alarm system. Records show that the system was placed on test condition every morning for the 7 days preceding September 11, 2001.

At 10:00:52 a.m., a fire condition [1 1510 CO TO CLASS E] was indicated in WTC 7 by sensing performed by the fire alarm system. The *T at the right end of that record indicates that the system was in TEST at the time. The alarm record also shows that the fire condition is in AREA 1. NIST has been told by AFA that AREA 1 is not a specific area within the building, but a reference to a zone consisting of the entire building. That is to say, fires detected in any fire alarm zone in the building by the fire alarm system would result in the same AREA 1 identification at the monitoring station. The time 10:00:52 a.m.

is shortly after the collapse of WTC 2. It is unknown if this fire alarm was triggered by smoke from a fire or dust entering smoke detectors.

At 2:47:21 p.m. and 2:47:22 p.m. (14:47:21 hr and 14:47:22 hr), at the time the 8 hour "TEST: ALL" condition was set to expire, additional actions are recorded that end in an operator (DYJ) entry to "FULL CLEAR."

Alarm System Network Communications Paths

During initial engineering design for the fire alarm system in WTC 1 and WTC 2, PANYNJ requested approval of the City of New York for use of fiber optic communications cable in the system. NYC Building Authorities denied the use of fiber optic cable. As a result, ordinary copper wire communication cable was specified. The copper communications cable is susceptible to electrical shorts that can prevent any communication between all of the distributed control units of the system. Fiber optic cable is not susceptible to electrical shorts. If fiber optic communications cable had been used, communications between panels where the fiber optic cable had not been severed would continue to be able to communicate with each other.

Severing either type of data communications cabling without electrical shorts would have produced the same effect on the system. The system was designed with redundant communication paths to provide Class A signaling circuits. If one communication path is served without electrical shorts, a trouble condition would be annunciated, but communications would not be impaired.

"Standpipe Telephone" System

A dedicated communications system for emergency responders was installed in the stairwells of WTC 1 and WTC 2. To use the system, a compatible telephone handset was needed. This system was known as the "standpipe telephone" system.

Preliminary Findings

1. **Fire Alarm Monitoring System.** The fire alarm system monitoring WTC 7 sent to the monitoring company only one signal indicating a fire condition in the building on September 11, 2001. This signal did not contain any specific information about the location of the fire within the building. From the alarm system monitor service view, the building had only one zone, "AREA 1."

2. **Alarm System Communications Paths.** The resistance to failure of the fire alarm system communications paths between the fire command station and occupied floors may have been enhanced if fiber optic communications cable had been used instead of copper lines. Extensive damage to the towers upon aircraft impact is likely to have cut and shorted the wiring of the alarm system network cables. If that occurred, communications between the distributed fire alarm panels, which are components of the integrated fire alarm system, would have been degraded and lost to certain panels depending on the location of those panels. Fiber optic cable is not susceptible to electric short-circuits and would have provided full communications with fire alarm system components, including voice communications systems, to the point where the cable was

severed. Electric shorts in the voice communications disable that communication system over the entire cable length affected by the electric short-circuit. During initial engineering design for the fire alarm system in WTC 1 and WTC 2, the PANYNJ requested, but did not receive, approval of the City of New York for use of fiber optic communications cable in the system. The NYC code required copper wiring. As a result, ordinary copper wire communication cable was specified.

3. **"Standpipe Telephone" System.** Some firefighters that received handsets at the command post in the lobby at WTC 1 were interviewed as part of the investigation. Every one of the firefighters interviewed indicated that they did not use the standpipe telephone communication system on September 11, 2001. Due to the loss of firefighters in WTC 2, there is no information about the use of the system in WTC 2.

2.5.6 Smoke Management

Resources used in the investigation of the fire alarm systems in WTC 1, 2, and 7 are being documented by NIST investigators and subject experts at NIST contractor, Hughes Associates, Inc. This information will be included in the final report.

The design and installation of the smoke management systems will be described in a report being prepared for NIST by Hughes Associates, Inc. This report will provide the analysis of performance based on the design and programming of the systems.

The smoke management systems as designed and documented in the operation manuals consisted of a smoke purge mode using the components of the main HVAC systems. The systems were intended to remove smoke and other gaseous combustion products from the fire area after a fire was extinguished. This system was to be activated "manually" at the direction of FDNY.

Preliminary Findings

1. **Smoke Management Systems Performance on September 11, 2001.** Based on the information reviewed, the smoke management systems were not activated during the fires on September 11, 2001. It was determined that the likelihood of these systems being functional in WTC 1 and WTC 2 was very low due to the damage inflicted by the aircraft impacts. In addition to the significant openings created in the building envelopes, the aircraft impacts are likely to have severed major vertical shafts through which ran electrical power supply and HVAC system duct risers, thereby causing the loss of power to the smoke management system air handlers and damage to the vertical HVAC duct risers used to provide smoke management (smoke purge).

2. **Fire/Smoke Dampers.** The analysis of smoke flow in WTC 1 and WTC 2 on September 11, 2001, shows that HVAC ductwork was a major path for vertical smoke spread in the buildings. Fire dampers were installed in the systems, but not smoke dampers. Operational combined fire/smoke dampers in the HVAC ductwork on each floor would have provided a barrier to hot gas and smoke penetration into the vertical HVAC shafts in WTC 1 and WTC 2. However, smoke dampers were not available when the towers were built.

3. **Stair Pressurization Systems.** Modeling results showed that in WTC 1 and WTC 2 stair pressurization systems would have provided minimal resistance to the passage of smoke had they been installed on September 11, 2001. While the existence of such systems was known when the WTC towers were built, the alternative smoke purge system used in the WTC towers was considered to be equivalent. Multiple stair doors being open for substantial periods of time due to occupant egress, and stairway walls damaged by aircraft impact, would result in an inability to prevent smoke from entering stairwells.

2.6 RECONSTRUCTION OF THERMAL AND TENABILITY ENVIRONMENTS (PROJECT 5)

2.6.1 Project Objective

The collapse of the WTC towers resulted from a combination of aircraft impact damage and the ensuing fires. However, both the relative importance of these two factors and their interaction leading to the observed total collapse is at present unclear. It is also unresolved:

- Which structural features of the buildings were affected, and thus what location, magnitude, and duration of fire brought about the collapse, and
- Whether the nature of the fires is typical of what might be expected in common occupancies, or whether there were special features that made these fires especially severe.

These facets are even more pivotal for WTC 7, where the fires that led to the unexpected collapse followed an unknown ignition in an unknown location.

In addition to the flames and heat, the smoke from the fires plays multiple roles, for example:

- It serves as a telltale for the locating of fires, although the determination of location also requires a knowledge of smoke movement within the buildings.
- Its visual obscuration and perhaps its toxicity may have affected choices made by people as they decided direction of movement, whether to wait for rescue, etc.

Thus, Project 5 has as its objective to reconstruct, with assessed uncertainty limits, the time-evolving temperature, thermal radiation, and smoke fields in WTC 1, 2, and 7 for use in understanding the behavior and fate of occupants and responders and the structural performance of the buildings.

2.6.2 Project Approach

Due to the near absence of physical evidence, the recreation of the fires depends on computer modeling. NIST is redefining the state-of-the-art in fire and thermostructural modeling, since this type of reconstruction has never been done before. Fire experiments are being used to guide adaptation of existing models and develop new algorithms for them; additional experiments form the basis for validating the models.

The models will then be exercised for a range of possible initial conditions. Those simulations that agree with the photographic evidence and the eyewitness information will be accorded a higher likelihood of being correct. To the extent that simulations contradict the evidence, they will be deemed less plausible.

There is essential input that will arise from other projects, for example:

- Specifications of the liquid fuel storage systems in WTC 7 – Project 1
- Degree and nature of aircraft impact damage – Project 2
- Maximum temperatures experienced by the structural steel – Project 3
- Performance specifications for the smoke handling system – Project 4
- Extent and location of structural weakening needed for collapse to be initiated – Project 6
- Eyewitness accounts of building damage and fire locations – Projects 7 and 8

The interdependence with Projects 2, 6, and 7 is particularly broad, with Project 5 providing, for example:

- Establishment of the nature and precision of the information needed from the aircraft input modeling – Project 2
- Descriptions of the duration and intensity of likely fires for use in assessing the possible locations of collapse initiation – Project 6
- Description of fire and damage information to be requested of survivors – Project 7

Project 5 is divided into the following eight tasks:

- **Visual Collection and Time Line Development for WTC 1, 2, and 7.** To acquire and use photographs, videos, and other relevant information to develop detailed time lines for the spread and growth of fires at the peripheries of WTC 1, 2, and 7 and to organize the information such that it can be utilized by other investigation team members. The cataloging and analysis will provide guidance on the initial conditions for modeling the fires, the rates of spread of the fires, the floors on which the structural collapses appear to have begun, etc.
- **Characterization of Combustibles.** To gather data on and characterize the types, mass and distribution of combustibles in the pertinent floors of WTC 1, 2, and 7 at the time of the September 11, 2001, disaster. The results are to serve as input to the overall Project 5 effort to reconstruct the thermal and tenability environment within the three buildings.
- **Characterization of Partitions.** To identify the location of and characterize the fire endurance properties of the internal partitions (floors, walls, and ceilings) in the pertinent floors of WTC 1, 2, and 7 at the time of the September 11, 2001, disaster. This entails obtaining existing data on the fire performance of floor, wall, ceiling systems, and complementing this with additional measurements as needed. The results will help in

determining the potential and rates of intercompartment fire spread and also the degree to which the interior of a building was visible in the photographs and videos.

- **Characterization of Structural Insulation.** To determine the effective thermal properties of the structural fireproofing systems, the effect of vibration, impact, and shock on their thermal insulation performance, and whether chemical interaction between the fireproofing materials and the steel at elevated temperatures could degrade the steel and fireproofing performance during thermal insult. This will enable simulation of the temperature rise within the structural elements as a result of the changing thermal environment.

- **Model Development.** To upgrade the NIST computational fluid dynamic (CFD) Fire Dynamics Simulator (FDS) for its application to the reconstruction of the fires in WTC 1, 2, and 7. This will affect a pragmatic fire growth routine and also improve the efficiency of the model, enabling more extensive simulations during the timeframe of the Investigation. In addition, this task will develop a computational method for relating the turbulent fire environment to the transport of heat to and through the insulating layer to the underlying structural steel. This will enable simulation of the temperature rise and resulting loss of structural capability of the steel.

- **Experiments for Model Development.** To provide input parameters and guidance for the FDS combustion submodel.

- **Fire Reconstruction.** To reconstruct the gaseous thermal environment (radiation and temperature fields) surrounding the structural elements and in the inhabitable spaces within WTC 1, 2, and 7. Using such input information as the estimated aircraft damage from Project 2, the contents and layout of the building from the above tasks, NIST will use FDS to simulate fully involved fires in the three buildings, with and without the initial damage from the aircraft or incident debris, enabling addressing the extent to which that damage affected the thermal environment felt by the structure. Parameters in the re-creation of the fires will enable estimating the roles of jet fuel and building contents, ventilation system, compartment damage, pressurized core, and fire protection system on the growth and spread of fire. The use of statistical design for the sets of simulations will lead to identification of those input conditions to which the results are the most sensitive and those combinations of input conditions that lead to the best agreement with the photographic evidence.

- **Reconstruction Validation.** To generate and use experimental data for assessing the accuracy of the fire model prediction of thermal insult on structural members such as columns, trusses, beams and other support structures like those in WTC 1, 2, and 7. Comparison of the data from large-compartment tests of fire growth and heat transfer to steel specimens will establish the accuracy of FDS in simulating heat transfer and complex burning at a realistic scale.

2.6.3 Collection of Photographic Evidence

NIST has compiled an extraordinary collection of still and video images of the three buildings. These have been digitized and organized into a searchable database. The user can organize a search to view each of the two towers from all four sides from the time of the airplane strike to the time of collapse, although there are still significant gaps in time and vantage point. The collection is less definitive for WTC 7, due mainly to the high hazard level in the vicinity following the collapses of the two towers and to obscuration of the building by other structures and the smoke cloud from the tower collapses.

To facilitate comparison of the predictions of the fire modeling (see below) with the photographic evidence, NIST has created animations of the building facades that depict the evolving breaking of windows, the emanation of smoke from the windows, the appearance of fire through the windows, and the emanation of flames out the windows.

More detail on the collection appears as Appendix H.

2.6.4 Data on the Building Interiors

The solicitation of information on the tenant spaces was focused on those floors of the three buildings in which physical damage was observed and those floors where fires were observed or might have existed unobserved (as shown in Table 2–5).

Table 2–5. Floors of visible damage.

Building	Aircraft Impact Damage	Observed Fires
1	93–99	92–99, 100, 104
2	77–85	78–83
7	–	7, 8, 9, 11, 12, 13, 22, 29, 30

Floor Plans

Examination of documents combined with discussions with architects, product manufacturers, occupants, and building managers indicate a general picture of the building interior. The floor slab was generally carpeted; there are some cases of raised floors and of wood- or stone-covered areas. There were glass walls at the entrances to some of the suites. For multi-tenant floors, the demising walls between the tenants were of gypsum board over steel studs and ran from the floor slab to the bottom of the slab above. Tenant space interior walls were of similar construction, but ran from the floor slab to just above the drop ceiling. Thus, the joist space was often open across a whole story or large fractions of a story. The drop ceiling systems, one for the tenant spaces and one for the core areas, were designed for the WTC.

NIST requested that tenant companies provide architectural drawings of the most recent renovation of their space. The following features are of particular importance:

- Location of walls.
  - These can act as a barrier to fire spread. In the towers, the fire resistance time of the demising and interior walls may have been comparable to the time between aircraft impact and building collapse. Even though the overall duration of the fires in WTC 7 was much longer, the walls could have limited the rate of fire spread.

  - When there were walled offices at the perimeter of a floor, the interior walls block the view of the interior from the exterior. Thus, the nonobservation of fire through a particular window could indicate either the absence of a fire on that floor or the presence of a vision-obstructing wall.

- Air flow between floors. Fires need both fuel and air. To the extent that the flow of air to the fire is limited, so is the size of the fire. The direction of air access will also determine the direction(s) of fire spread. Thus, it is important to know where there were perforations, e.g., interior stairwells, air ducts, to have the most realistic sets of input conditions for the fire simulations.

NIST has obtained floor plans for a large fraction of the floors of interest in the three buildings. For the few that are missing, NIST is working with the design drawings and is estimating their similarity to the layouts on September 11, 2001, from eyewitness, tenant, and manager accounts.

Combustibles

While much of the public attention has been focused on the jet fuel, this was fully combusted in only a few minutes. By contrast, typical office furnishings can sustain intense fires of at least an hour's duration on a given floor. NIST has obtained generic information about the furnishings in many of the suites and specific details for a few. This information has already been of use in the design of workstation fire tests (see below). NIST is checking to identify the location and size of any unusual fuel loads, such as file rooms, film storage, etc.

In addition, NIST has obtained descriptions from the airlines of the combustible contents of the airplanes on that day. This includes the cabin materials (both installed and carried on by the passengers), aircraft components (e.g., wire insulation, flammable fluids other than the jet fuel), and the cargo bay contents. A preliminary estimate indicates that the combined mass of aircraft-borne combustibles is a considerable fraction of the building combustibles in the impact zone.

For WTC 7, NIST is aware of two special sources of combustible fluids. Rolf Jensen and Associates, Inc., a NIST contractor, is gathering data on the fuel tanks and distribution lines for the emergency generators in WTC 7. NIST has obtained information on the magnitude of the volume of the transformer fluids located in the power substation in WTC 7.

2.6.5 Insulation of Structural Members

The required fire resistance ratings of the structural members in the three buildings were obtained by gypsum framing of some columns or the use of spray-applied fireproofing on other columns and web joists. The architectural drawings provide definition of the former. Working from documents and discussions with engineers, NIST has identified the various spray-applied fireproofing materials and where each was used, as shown in Table 2–6. For the exterior columns in the towers, both Vermiculite plaster and BlazeShield DC/F were used. NIST is still investigating the specific locations for each.

Table 2–6. Types and locations of spray-applied fireproofing on fire floors.

Building	Fireproofing Material	Locations		
		Interior Columns	Floor Systems	Exterior Columns
WTC 1	BlazeShield II		Floors 92 to 100, 102	
	BlazeShield DC/F	Yes	Remaining floors	
	Vermiculite plaster and BlazeShield DC/F			Yes
WTC 2	Vermiculite plaster and BlazeShield DC/F	Yes	Yes	Yes
WTC 7	Monokote ML-5	Yes	Yes	Yes

The ability of the fireproofing to delay the rise of temperature in the protected structural steel depends on:

- **The thermophysical properties of the insulation material.** NIST has obtained samples of the three types of spray-applied insulation and four types of gypsum wallboard and has sent them to testing laboratories for determination of their thermal conductivity, density, and heat capacity, all as a function of temperature from ambient. The spray-applied material data will be from 25 °C to 1,200 °C; the wallboard data will be from 25 °C to 600 °C.

- **The thickness of the insulation**. The gypsum wallboard thickness is described in the architectural drawings. As documented in the May 2003 Progress Report, NIST has traced the evolution of the intended thickness of the spray-applied material. NIST has evaluated the variation in the actual thickness of the fireproofing in the WTC towers. Appendix I presents the results of that evaluation.

- **Any damage to the layer during construction or refitting of the building.Damage from the impact or shock of the incident airplane (WTC 1 and WTC 2).** NIST will obtain estimates of the impact intensity from ARA, which is the NIST contractor modeling the aircraft impact under Project 2. Using both standard and custom measurement methods, NIST is determining the cohesive properties (shear strength and tensile strength) to steel of the two types of spray-applied insulation used in WTC 1 and WTC 2. NIST is also developing models to predict dislodgement of the insulation.

- **Damage from distortion of the WTC 1 and WTC 2 structures from the impact or the fires.**

- **Damage to the insulation in WTC 7 from incident debris from the collapse of the towers.**

Prior to this Investigation, there was no computational method for modeling in three dimensions the effect of a fire on structural assemblies, that is, modeling the absorbance of incident heat from a turbulent fire by an insulating surface, the transport of heat through the insulating layer, and the distribution of heat throughout the steel structure. This is in large part because the turbulent fire is characterized by short time steps and large computational cell size, while the structural member is characterized by longer time steps (slower changes in temperature) and smaller computational cell size.

NIST has developed a tool to do just this, the Fire-Structure Interface (FSI), for the first time linking FDS with ANSYS (a finite element, FE, thermostructural model). Of particular importance is the relationship between the thickness of the insulation and the time for the underlying steel to reach a temperature at which the steel strength is compromised. Variations in thickness could be random in nature or as stark as bare spots.

The first computational runs were for a column as heavy as the thickest core column on the floors of impact in WTC 1. For each of three cases, a sequence of portraits of the temperature distribution in the steel was generated throughout an exposure to a uniform external temperature of 1,100 °C. From these depictions, the following times were determined for when the steel temperature reached 600 °C, a temperature near which significant compromising of the steel's structural properties would ensue:

- Insulation with the (estimated) properties of BlazeShield applied to a thickness of 13 mm. The time to reach 600 °C was over 10 h.
- A 20 percent reduction in the total mass of insulation, with the loss of thickness being varied randomly. The time to reach 600 °C was about 6 h.
- All insulation removed from one face of the column. The time to reach 600 °C was about 12 min.

In a second set of calculations, the same material was applied to a bar 25 mm × 25 mm × 1,500 mm. A 25 mm notch (to bare metal) of insulation was removed from the midpoint of the bar. Upon exposure to the same thermal environment, the temperature of the steel reached 600 °C along its full length in a matter of minutes.

A further description of the interface and sample calculations appears in Appendix J. The preliminary indications are that, in the future predictions of the impact of the WTC fires on structural members, NIST should expect the results to be sensitive to small gaps in the thickness of the insulation. In other words, small areas of thin or missing insulation can lead to accelerated heating, and this effect could be felt well away from the susceptible sites.

2.6.6 Modeling the Fires

In simulating the fires, NIST will be examining the effects of uncertainty in knowing the initial conditions of the fire and the building. Thus, it is critical that the accuracy of the fire model itself be established so that the uncertainty in the model's predictions is small compared to the effects caused by the differences in the initial conditions.

As a first step, certain enhancements to FDS were implemented:

- Realistic state relation curves for underventilated fire scenarios. The prior computational code used ideal state relations for its combustion routine, i.e., user-prescribed values for the combustion efficiency that did not change as the ventilation within the fire compartments evolved.

- The combustion module was enhanced to enable the inclusion of charring materials, such as those that comprise much of the office furniture.

- Computational code enhancements to enable time-efficient computations. Multiblock gridding now enables needed dimensional resolution in the vicinity of the structural components. The FDS code was also re-written for parallel processing.

- Fire spread. Each combustible is characterized by a heat of gasification, with the surface irradiance calculated from the thermal radiation field generated by existing fire. When the mixture fractions in two adjacent computational cells straddle the stoichiometric value, the flame then extends to the interface between the cells.

- Enhanced visualization. Smokeview has been modified to handle the extremely large data sets that will be generated in these simulations.

A first set of experiments was conducted in the NIST Large-scale Fire Laboratory to assess the accuracy with which FDS predicts the thermal environment in a burning compartment and to establish a data set to validate the prediction of the temperature rise of structural steel elements using FSI. Within a large test compartment, assorted steel members were exposed to controlled fires of varying heat release rate and radiative intensity. The steel members were bare or coated with spray-applied fireproofing of two thicknesses. The thermal profile of the fire was measured at multiple locations within the compartment. Temperatures were also recorded at multiple locations on the surfaces of the steel, the insulation, and the compartment. Prior to each test, a prediction of the thermal environment in the compartment was determined using FDS. Following the tests, the prediction and experimental results were compared.

Much of the combustible material on the fire floors of the WTC buildings consisted of employee workstations. Each such space was a combination of desk space, generally made of fiberboard with a laminated finish; file cabinets; carpet; chair; computer; paper; etc. NIST conducted a set of fire tests of a generic workstation in our Large Fire Laboratory. A single unit was burned under a large hood with a soffitted ceiling. Ignition was by a 2 MW spray burner, simulating an already burning adjacent workstation. Test variables included the combustible mass, the presence of jet fuel, and the presence of inert material (simulating fallen ceiling tiles or wall fragments). Gasification data for the combustible was generated using a Cone Calorimeter. These data plus the geometry of the workstation were used as input to the fire model. The intent was to use the experiments to identify any needed changes in the combustion algorithms. In fact, little adjustment was needed. These tests and their analyses are detailed in Appendix J.

A third set of tests was conducted to determine the accuracy of the FDS under conditions simulating a portion of a representative floor of the WTC towers. Thus, the predictions of the outcome of the tests were performed prior to the experiments. Three workstations were situated in a large compartment. Two were contiguous, the third was across an aisle. The open end of the compartment had windows of aspect ratio similar to those in the towers. The test variables included the presence of jet fuel, the presence of inert material, the location of the ignition burner (at or away from the windows), and the extent to which the workstations had been reduced to rubble. The analysis of the results is under way, but preliminary indications are that the model predictions closely resembled the test results.

Additional information on the three sets of experiments appears in Appendix J. Full reports on the first two sets of experiments are expected in the coming months.

2.6.7 Preliminary Findings

To date, the calculations and analyses have led to several interim findings that will guide the reconstruction of the fires in the three WTC buildings:

Observed Fires

1. Despite the airplane striking the center of the north face of WTC 1, the resulting fires are not symmetric about the centerline of the building. After the initial fireballs, the flames damped considerably. The early fire growth was on the north face, the center of the east face and the west side of the south face. On some floors, there was continuous spread; in some instances sudden, noncontiguous fires appeared.

2. The damage and initial fires in WTC 2 were highly asymmetric, as the airplane struck off center to the east. Burning debris piles of long duration were observed at the northeast corner of some floors. In general, the fires spread less actively than in WTC 1, but there were sudden fires here as well. There was visual evidence of collapsed floors.

Building Interiors

1. The view through many windows was blocked by interior walls.

2. The mass of aircraft solid combustibles was significant relative to the mass of the building combustibles in the impact zone.

3. In laboratory experiments, impulses like those estimated from the aircraft caused serious damage to the ceilings. This is consistent with the accounts of survivors from floors below the impact zone. This damage enabled "unabated" heat transport over the walls and to the joists.Small areas of thin or missing insulation can lead to accelerated heating over much larger lengths of steel.

Combustion Modeling

1. FDS is a useful tool to recreate the burning of the complex arrays of combustibles that existed in the WTC buildings, provided that the initial damage conditions and combustible descriptions are accurate.

2. FSI is a tractable construct for linking the output of a computational fluid dynamic model of the fire-generated thermal environment in the building compartments to a FEM of the building structure.

2.7 STRUCTURAL FIRE RESPONSE AND COLLAPSE ANALYSIS (PROJECT 6)

2.7.1 Project Objective

Both the north and south towers, WTC 1 and WTC 2, were severely damaged by the impact of Boeing 767 aircraft, yet they remained standing for some time. The ensuing fires were observed to move through both buildings until their eventual collapse. The extent and relative importance of the structural damage caused by the aircraft impact, and subsequent weakening due to the fires, is still being investigated. WTC 7 was reported to be damaged by falling debris from the collapse of WTC 1. The fires in WTC 7 that burned for much of the day appeared to play a key role in the building collapse. Project 6 addresses the first primary objective of the NIST-led technical investigation of the WTC disaster: to determine why and how WTC 1 and WTC 2 collapsed following the initial impacts of the aircraft and why and how WTC 7 collapsed. Specifically, the objective of this Project is to determine the response of structural components and systems to the impact damage and fire environment in WTC 1, 2, and 7, and to identify probable structural collapse mechanisms.

2.7.2 Project Approach

Three steps are required to determine the response of structural components and systems to fire conditions. First, the thermal environment (radiation flux and temperature fields) for the floors involved in fire are determined using computational fluid dynamics calculations. The predicted upper layer gas temperatures vary both spatially and temporally. Next, transient thermal analysis is used to predict the time-temperature relationship for the structural components and systems for bare and fireproofed steel conditions. Finally, the time-dependent structural response of the components and systems to the estimated service loads and elevated temperatures is computed using thermal-mechanical FEA.

Project 6 relies heavily on information provided by other projects, specifically:

- Reference structural models of typical floor and exterior wall subsystems of each WTC 1 and WTC 2 tower (Project 2)
- Extent of aircraft damage to WTC 1 and WTC 2 (Project 2)
- Mechanical properties of the steels, welds, and bolts used in the construction of the towers, including elastic, plastic, and creep properties from 20 °C to 700 °C (Project 3)
- Thermal properties of spray-on fire resistant materials (SFRM) (Project 5)
- Temperature time-histories for various components, sub-systems and systems for both standard fires (e.g., ASTM E 119) and real fires based on fire dynamics simulations (Project 5).

This project is divided into several tasks as follows:

- Evaluate the structural response of floor and column subsystems under fire conditions.

- Evaluate the response of the WTC towers under fire conditions, both with and without aircraft impact damage.
- Identify and evaluate candidate hypotheses for initiation and propagation of collapse, and estimate the uncertainty for probable collapse initiation and propagation mechanisms.
- Conduct tests of structural components and systems under fire conditions.
- Report on the performance of open-web steel trussed joist systems in fire.
- Analyze the response of WTC Building 7 under fire conditions.

Work completed to date on the above tasks is summarized in the following sections.

2.7.3 Fireproofing of WTC Towers

In May 2003, NIST issued an interim report on the Procedures and Practices Used for Passive Fire Protection of the Floor System of the World Trade Center Tower Structures as Section 3.3 of the May 2003 Progress Report. The report summarized factual data contained in documents provided to NIST by the PANYNJ and its contractors and consultants; by Laclede Steel Company, the firm that supplied the floor trusses for the WTC towers; and by United States Mineral Products Co. (USM) doing business as Isolatek International, the manufacturer of the fireproofing material.

The report discusses the applicable building codes and building classification system, which dictates the fire rating required for structural members and assemblies. The structural system for the WTC towers was constructed predominantly with steel, which, in general, requires protection from fire to maintain its strength and stiffness. Available information on the spray-on fireproofing and the procedures and practices used in its selection and application is presented. 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.

In May 1963, the Port Authority instructed its consulting engineers and architects to comply with the NYC Building Code for the design and construction of the WTC towers. Because the NYC Building Code was being revised during this period, the plans for fire protection of the structural steel underwent concurrent modification. While available records 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.

A few of the more significant interim findings are:

- The WTC towers were identified as Occupancy Group E – Business, and classified as Construction Class IB in accordance with the 1968 NYC Building Code. This classification required that the columns and floor systems of the towers have a 3 h and 2 h fire endurance, respectively.

- The steel trusses that supported the floors of WTC 1 and WTC 2 were fireproofed with specified 1/2 in. of spray-on fire-protection although the technical basis for the selection of fireproofing material and its thickness are not known.
- In 1999, a decision was made to begin upgrading the fireproofing to a specified 1 1/2 in. thickness as tenant spaces became unoccupied. In general, the floor systems in WTC 1 subject to impact and fire conditions had been upgraded; the floors in WTC 2 subject to impact and fire conditions had not been upgraded.
- The fire protection of a truss-supported floor system by directly applying spray-on fireproofing to the steel trusses was innovative at the time the WTC towers were designed and constructed and, while the benefits of conducting a full-scale fire endurance test were recognized by the building designers, no tests were conducted on the floor system used in the WTC towers to establish a fire endurance rating.

The specified material and thickness of SFRM at the time of construction are as given in Table 2–7.

Table 2–7. Specified passive fire protection.

Structural Component	Member Size	Location	Material	Thickness (in.)
Floor trusses	All	All	Cafco DC/F	1/2
Interior columns	< 14WF228	All	Cafco DC/F	2 3/16
	≥ 14WF228	All	Cafco DC/F	1 3/16
Exterior columns	"Heavy"	Exterior faces	Cafco DC/F	1 3/16
	"Heavy"	Interior faces	Vermiculite aggregate	7/8
Spandrel beams	All	Exterior face	Cafco DC/F	1/2
	All	Interior face	Vermiculite aggregate	1/2

2.7.4 Response of WTC 1 and WTC 2 Floor and Column Systems under Fire Conditions

The detailed component and subsystem models will provide guidance for the analysis of the larger, global analysis of each WTC tower under damage and fire conditions. To determine the structural response of components and subsystems under fire conditions requires the development of nonlinear structural models that account for gravity (service) and thermal loads, temperature dependent material properties, and nonlinear structural behavior, such as plastification and large deflection effects, including instability. These nonlinear structural models are then subjected to thermal-mechanical analysis to determine the time-dependent structural response to the estimated service and fire loads. The commercially available FEA code, ANSYS (version 8.0), is being used for the thermal and mechanical analyses.

The analytical work is being conducted with the assistance of Simpson Gumpertz & Heger Inc. under a contract from NIST and includes the following tasks:

- **Task 1**. Component, Connection, and Subsystem Structural Analysis
- **Task 2**. Global Analysis of the WTC Towers Response to Fire Without Impact Damage
- **Task 3**. Global Analysis of the WTC Towers Response to Fire With Impact Damage

The scope of work under Task 1 includes: (1) the development and validation of ANSYS models of the full floor and exterior wall subsystems, (2) evaluation of structural responses under dead and live loads and elevated structural temperatures, (3) identification of failure modes and failure sequences, and the associated temperatures and times-to-failure, and (4) identification of simplifications for the global models and analyses.

Selected technical results and findings for the typical floor system and its components are presented in the following sections. More detailed coverage is given in Appendix K, Interim Report on Structural Fire Response and Collapse Analysis. A simplified approach to the analysis of the WTC truss-framed floor system response to fire is presented in Appendix M, Interim Report on 2-D Analysis of WTC Towers Under Gravity Load and Fire.

Structural Models and Analyses

Structural FEMs of components and subsystems have been developed for the following:

- Shear connector between the truss and concrete slab, referred to as a knuckle, shown in Figure 2–9
- Truss-to-column bearing seats
- Truss section, including composite floor slab, knuckles, and truss seat connections to columns
- Single-story exterior column for a 9-story height
- Exterior wall subsystem consisting of a 3-by-3 panel section of the exterior wall, where a panel is 3 columns wide and 3 stories long
- Full floor subsystem including the concrete slab, truss seat connections to columns, and core floor area

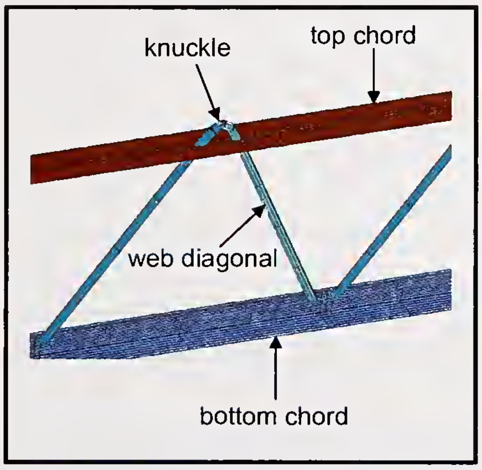


Figure 2–9. Features of truss model.

The truss section model (see Figs. 2–9 and 2–10) includes the following:

- Temperature-dependent elastic material properties for both steel and concrete
- Temperature-dependent steel plasticity

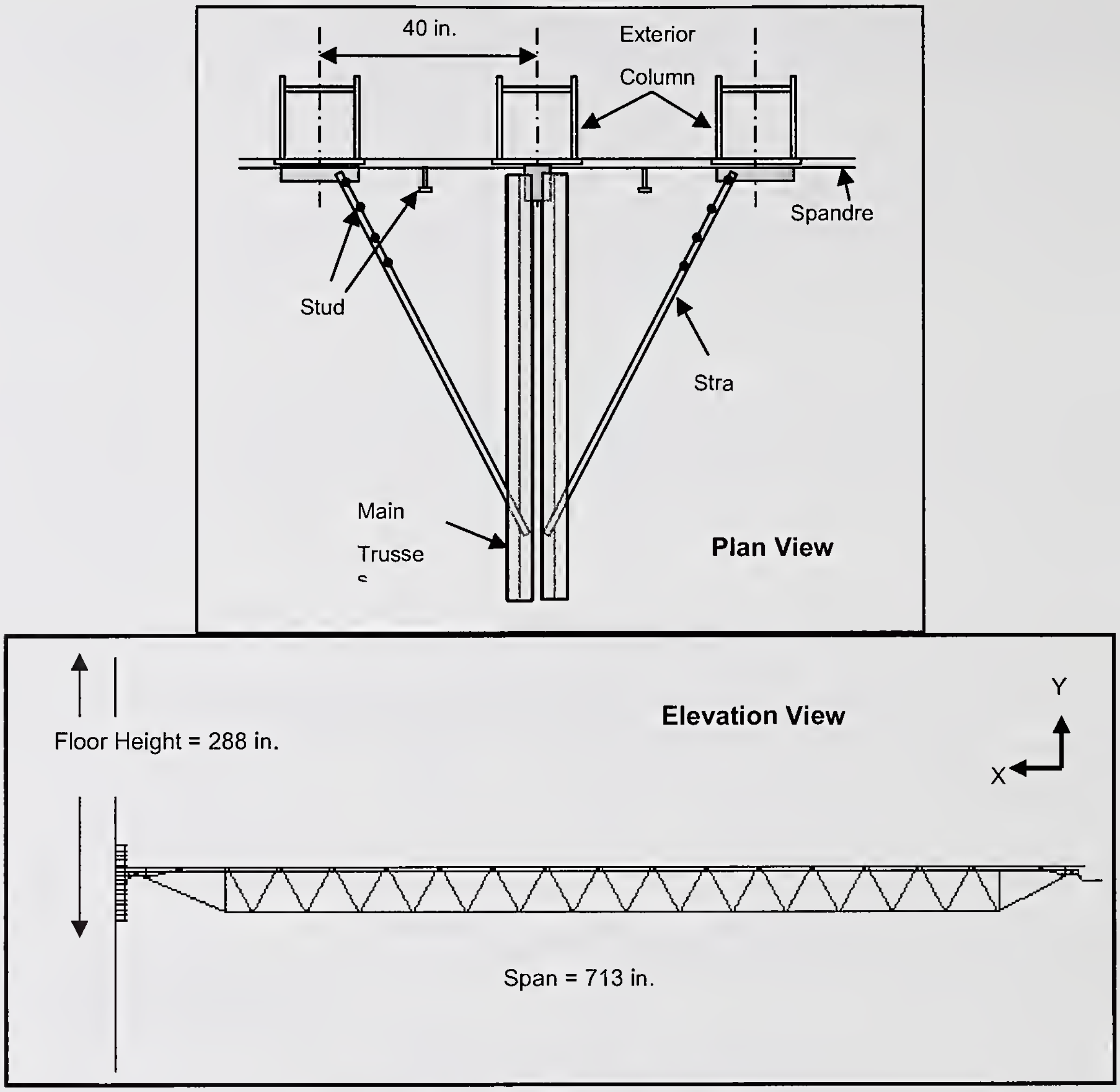


Figure 2–10. Truss model.

- Buckling of truss members
- Failure of knuckle leading to loss of composite action
- Failure of studs on the strap
- Failure of stud between the spandrel and the concrete slab
- Failure of truss resistance welds between the web diagonals and the chords
- Failure of the exterior and interior truss seats

The full floor subsystem model includes the following:

- The main trusses and bridging trusses
- Concrete slab with metal deck
- Strap and seated connections to columns

- Restraint provided by interior and exterior columns

The model was developed by translating a SAP2000 full floor model developed under Project 2 into ANSYS format and validating the analysis results against the SAP2000 model for design loads. A corner of the full floor model is shown in Fig. 2–11.

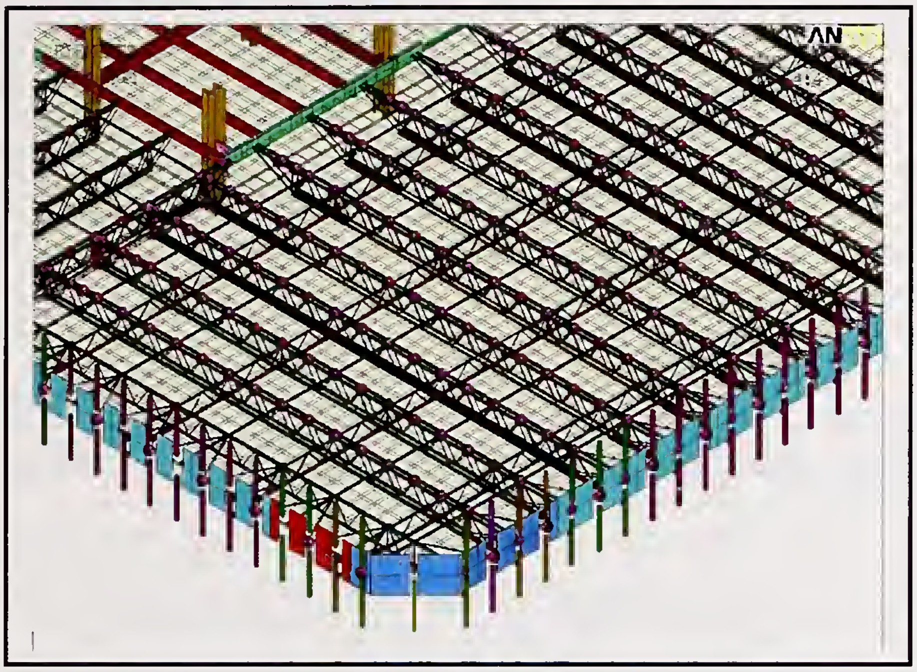


Figure 2–11. Converted ANSYS model of floor 96.

Summary of Technical Results

Capacity of Truss-to-Column Connections

The horizontal and vertical load capacities of the twelve truss-to-column connection configurations on floor 96 have been calculated. These calculated capacities were used to develop simplified models of the connection behavior for use in the floor and exterior wall subsystem analyses. As an illustration, Fig. 2–12 shows a seated connection of the floor truss to the exterior wall of the tower (spandrel plate). The connection is designed to carry vertical floor loads and horizontal loads that are at least 2 percent of the column design load. These connections may be subjected to large horizontal forces, and the capacity of the exterior truss connection under such circumstances must be ascertained.

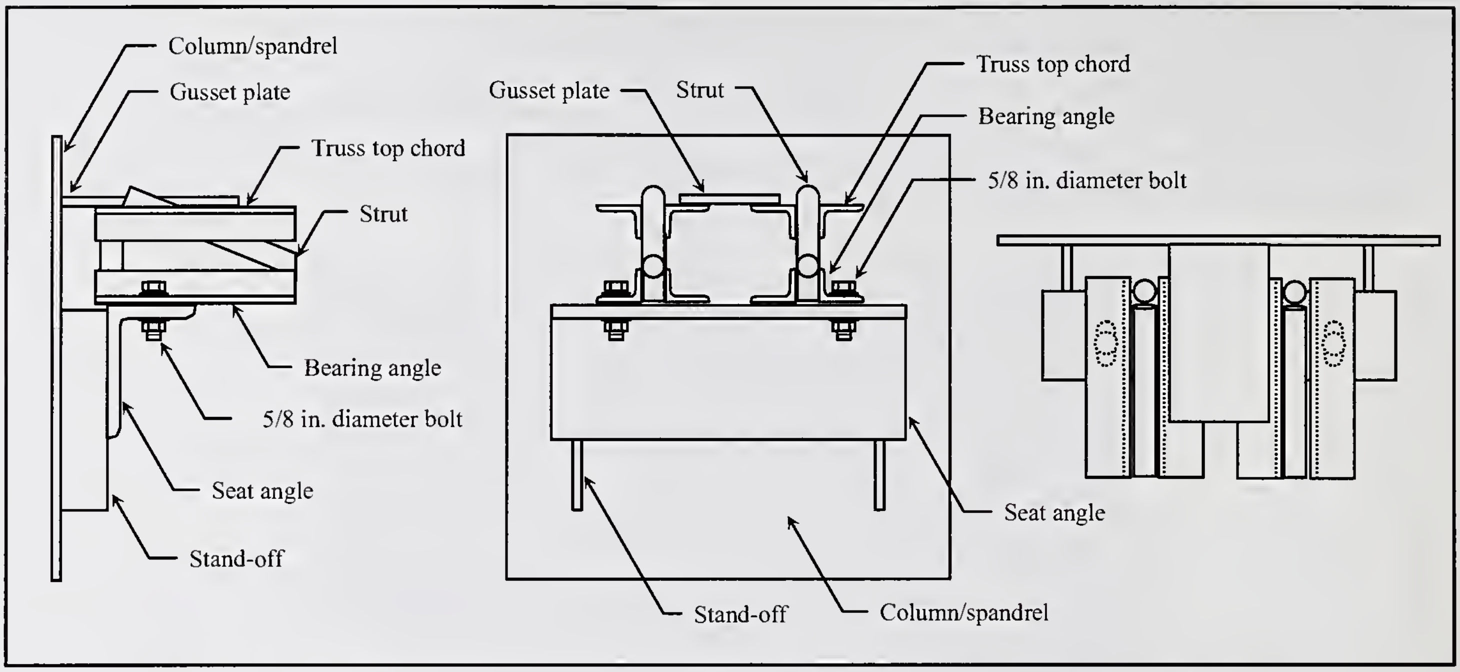


Figure 2–12. Exterior connection of the floor truss to the spandrel plate.

The failure modes considered for the truss-to-column connections are: (1) failure of the groove weld between gusset plate and spandrel, (2) failure of the fillet weld between the gusset plate and the truss top chord, (3) tensile failure of the gusset plate, (4) bolt shearing off, (5) bolt bearing, (6) bolt tear-out, and (7) block shear failure. Possible failure sequences are illustrated in Fig. 2–13. Of the seven exterior connections types that were analyzed, path A is the failure sequence most frequently followed, which is described as follows: first the gusset plate yields across its section and then fractures, followed by truss sagging and deformation and the bolts slipping until they bear against the edge of the slotted hole, then the bolt shears off, and finally the truss walks off the seat. The travel distance for the truss to walk-off of the seat is 4 5/8 in. Sequence (A) and typical tensile force resistance for an exterior seat is shown in Fig. 2–14.

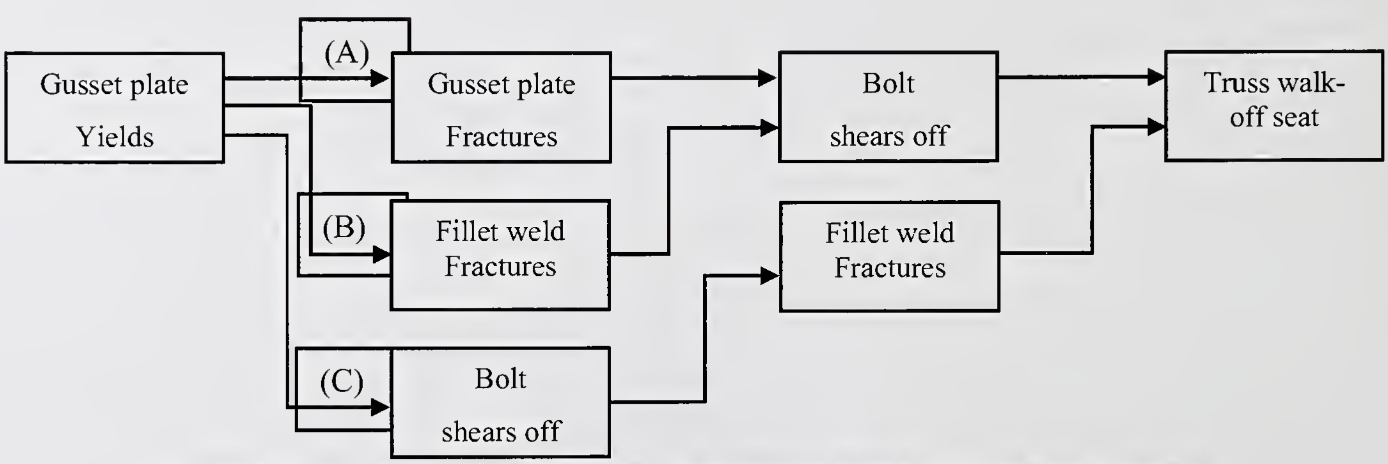


Figure 2–13. Failure sequence of exterior seats for tensile forces.

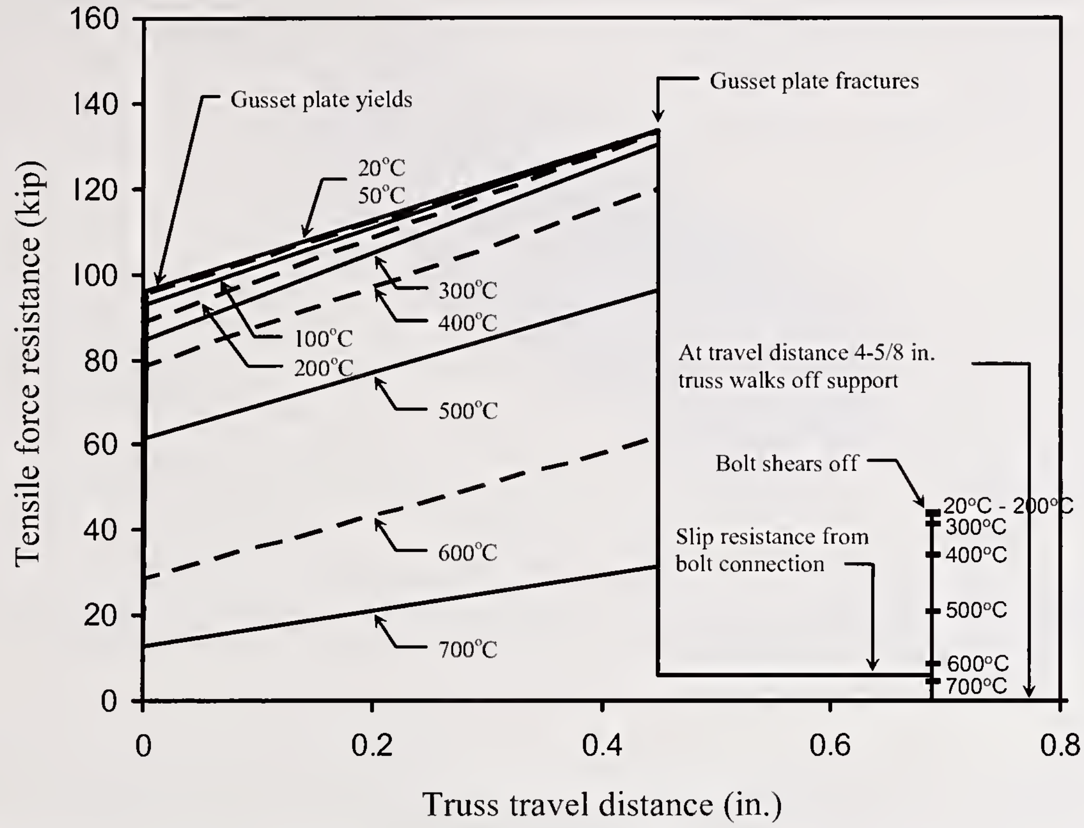


Figure 2–14. Typical tensile force resistance of exterior seat connection.

Knuckle Analysis

The knuckle is a shear connector formed by the extension of the truss diagonals into the concrete slab. Composite action is developed due to the shear transfer between the knuckle and the concrete slab in both the longitudinal and transverse truss directions. The objective of the knuckle analysis is to predict its shear capacity when the truss and concrete deck act compositely and to develop a simplified model of the knuckle behavior for the full floor subsystem model. FEAs have been conducted and calibrated against tests of both longitudinal and transverse loading conditions that were conducted by Laclede Steel in 1967.

Figure 2–15 shows the FEM of the longitudinally loaded knuckle, representing one quarter of the knuckle test specimen. The ANSYS LS-DYNA program, which is part of the ANSYS software package for explicit nonlinear structural analysis, was used for the analysis of the knuckle tests as it had a concrete material model for nonlinear behavior. Solid steel elements were used for the knuckle and channel members and the Psuedo Tensor material model in LS-DYNA was used for the concrete. The knuckle-to-concrete interface was modeled as a bonded or no-friction contact. The finite-element analysis results of the knuckle capacity depended on the steel-concrete interface assumption of bonded or no-friction contact.

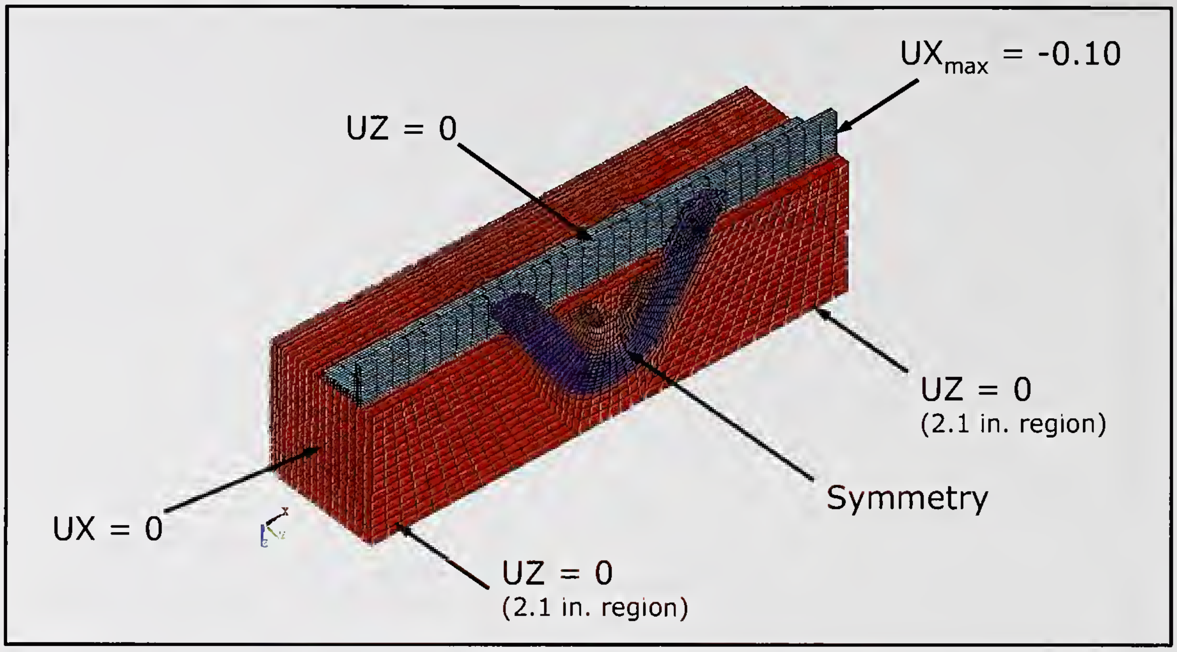


Figure 2–15. Finite element model of transversely loaded knuckle.

Truss Analysis

A typical long-span truss, designated as C32T1, is modeled to study its response to failure when subjected to dead and live loads and thermal loads. The model includes the following:

- One truss of the pair of trusses at column line 143 in floor 96 of WTC1,
- Two exterior columns (columns 143 and 144) with half the area and bending properties (see plan view of Fig. 2–10) , and a length of 24 ft (12 ft above and below the floor level),
- The portion of the spandrel between the two exterior columns,
- The portion of the slab (40 in. wide) between the two exterior columns,
- One strap anchor that is attached to the truss top chord, concrete slab and the adjacent exterior column (Column 144), and
- Exterior and interior seats, and the top plate at the exterior end.

A typical slab section consists of 4 in. thick lightweight concrete on 22 gauge metal deck and has two layers of welded wire fabric. An equivalent thickness of 4.35 in. is used as the slab thickness to account for the fluted metal deck profile. The metal deck and the welded wire fabric are not included in the truss model. Steel bar joist trusses support the concrete slab and act compositely with it. The chords of the trusses consist of double angles while the web members are round bars.

The truss and the columns are modeled with temperature-dependent elastic and plastic material properties. The concrete slab is modeled with shell elements. The nodes of the concrete slab are located at the neutral plane of the concrete slab with an offset relative to the nodes of the top chords. A low tensile yield stress is used to simulate concrete cracking. At knuckle locations, the top chord elements and the elements representing the concrete slab are connected by control elements with capacities determined from the knuckle analysis. Studs on the strap between the top chord and column are also modeled by control elements that connect the strap to the slab. The exterior and core truss seats are modeled by a combination of control elements and link elements, which can have temperature-dependent capacities determined from the truss seat analysis. The interior column is modeled as a fixed support for the interior truss connection, allowing no lateral displacements at the floor level, as the column was braced by the core framing.

Loading consists of gravity dead and live loads and temperature time-histories for all steel members, including the truss seats. The gravity loads include weight of the structure, superimposed dead load (including nonstructural dead loads due to architectural items and fixed service equipment), and a service live load equal to 25 percent of design live load. The steel and concrete temperatures were subjected to a uniform heating condition by ramping to a maximum temperature over 1,800 s and then holding the maximum temperatures for another 1,800 s. The steel temperature increased from 20 °C to 700 °C; the bottom surface of the slab increased from 20 °C to 700 °C, and the top surface of the slab increased from 20 °C to 300 °C. This thermal load creates a linear temperature gradient through the slab from 300 °C at the top surface to 700 °C at the bottom surface of the slab. Elevated temperatures are not applied to the columns.

The truss model can capture the following:

- Temperature-dependent elastic material properties for both steel and concrete
- Temperature-dependent steel plasticity
- Buckling of truss members
- Failure of knuckle – loss of composite action
- Failure of knuckle causing loss of composite action
- Failure of studs on the strap
- Failure of stud between the spandrel and the concrete slab
- Failure of the exterior and interior truss seats

Figure 2–16 shows that the top chords of the truss yield in compression beyond 300 °C (for clarity, the concrete floor slab is not shown). This is due to a significant difference of coefficients of thermal expansion (CTE) between concrete and steel. At 500 °C, the CTE of steel is twice that of light-weight concrete. Bottom chords remain in the elastic range throughout the thermal loading. Web diagonal buckling starts around 350 °C and, as seen in the figure, some diagonals are bent significantly in the plane of the truss by high axial force and end moments.

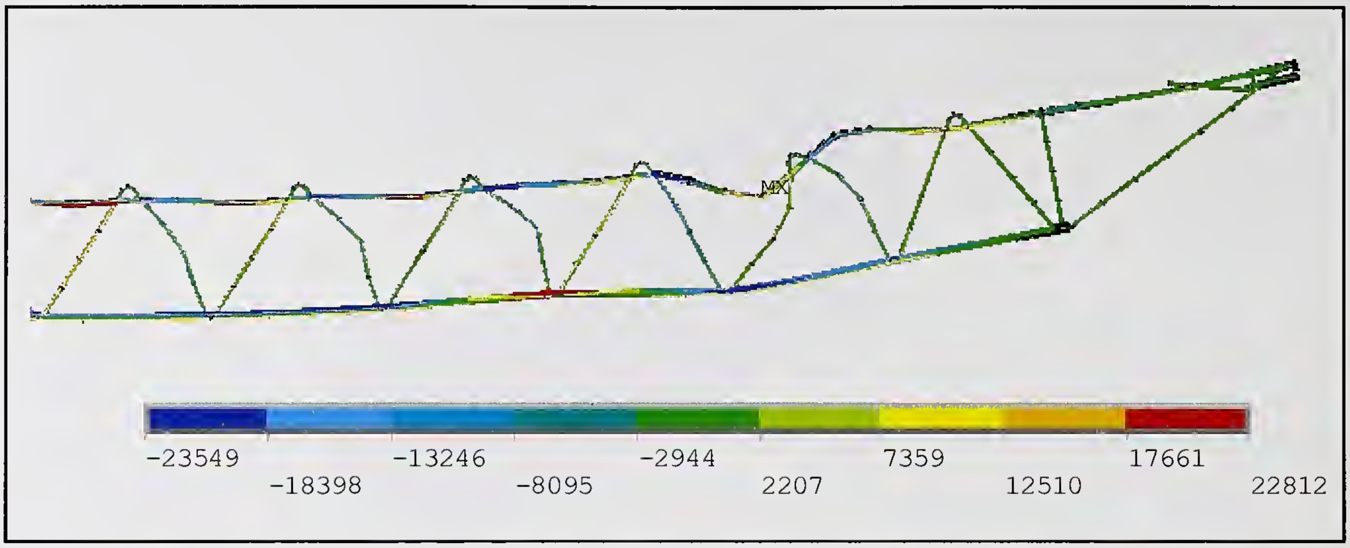


Figure 2–16. Finite element solution for floor truss under gravity and temperature loads.

Preliminary Findings

Preliminary findings are described here for floor truss connection capacities, knuckle capacities, and floor truss response to the uniform heating condition.

Floor Truss Connection Capacities

Capacities of the interior and exterior floor truss connections, for both vertical (gravity) and horizontal forces (tension and compression), have been computed for the variety of connection types found on floor 96 of WTC 1. In all cases, the sequences of failures of the connection components have been taken into account, as illustrated in Fig. 2–13, for the exterior seated connection under horizontal (tension) force. Capacities have been computed as a function of temperature for the applicable plate, weld, or bolt properties. It should be noted that while the computed vertical and horizontal capacities are primarily due to the loads they must support, construction-related decisions may have increased the capacity. For example, an available bolt or steel section size or a minimum allowable weld thickness may provide greater capacity than that required for design loads.

Failure mode of the interior truss seat for vertical force is the fracture of the fillet welds at the seat-to-channel beam connection. Failure mode of the exterior truss seat for vertical force is fracture of the fillet welds at the stand-off-to-spandrel connection. Preliminary findings of connection capacities for vertical bearing forces at room temperature (20 °C), 400 °C, 600 °C, and 700 °C are summarized in Fig. 2–17.

Similarly, connection capacities for horizontal tensile forces at the same temperatures are shown in Fig. 2–18. For interior truss seat connections, the shear strength of the two bolts controls the horizontal tensile capacity. The connection capacity of exterior truss seats that follow failure sequence (A), as shown in Fig. 2–13, equals the failure load for the tensile capacity of the gusset plate. Note that the strength of the truss seat #1013 increases by approximately 38 percent at a temperature of 100 °C. For temperatures less than 100 °C, the horizontal capacity is controlled by the gusset fillet weld strength, and for temperatures above 100 °C, the bolt bears against the edge of the slotted hole and increases the capacity of the connection.

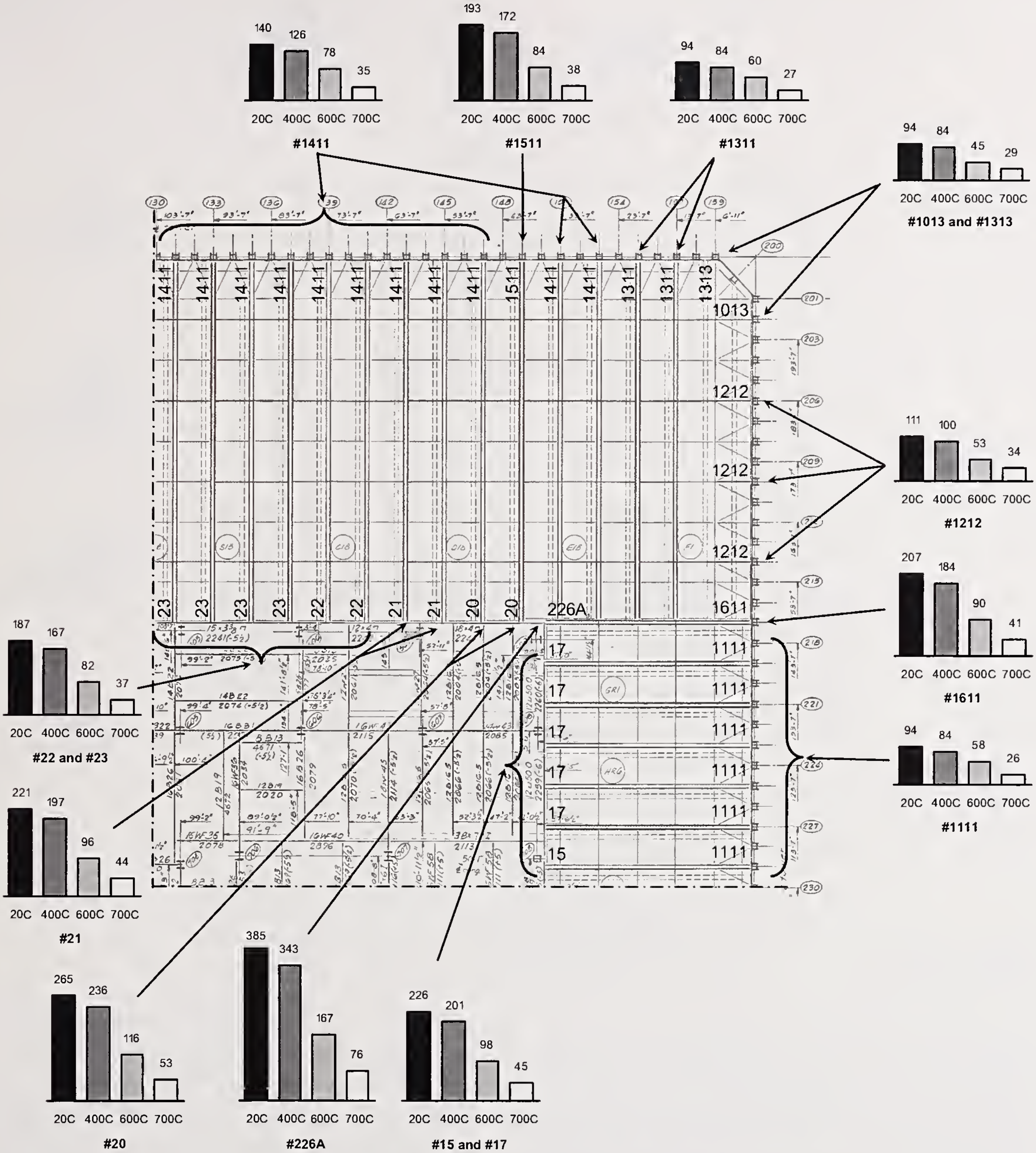


Figure 2–17. Truss seat capacity for vertical forces.

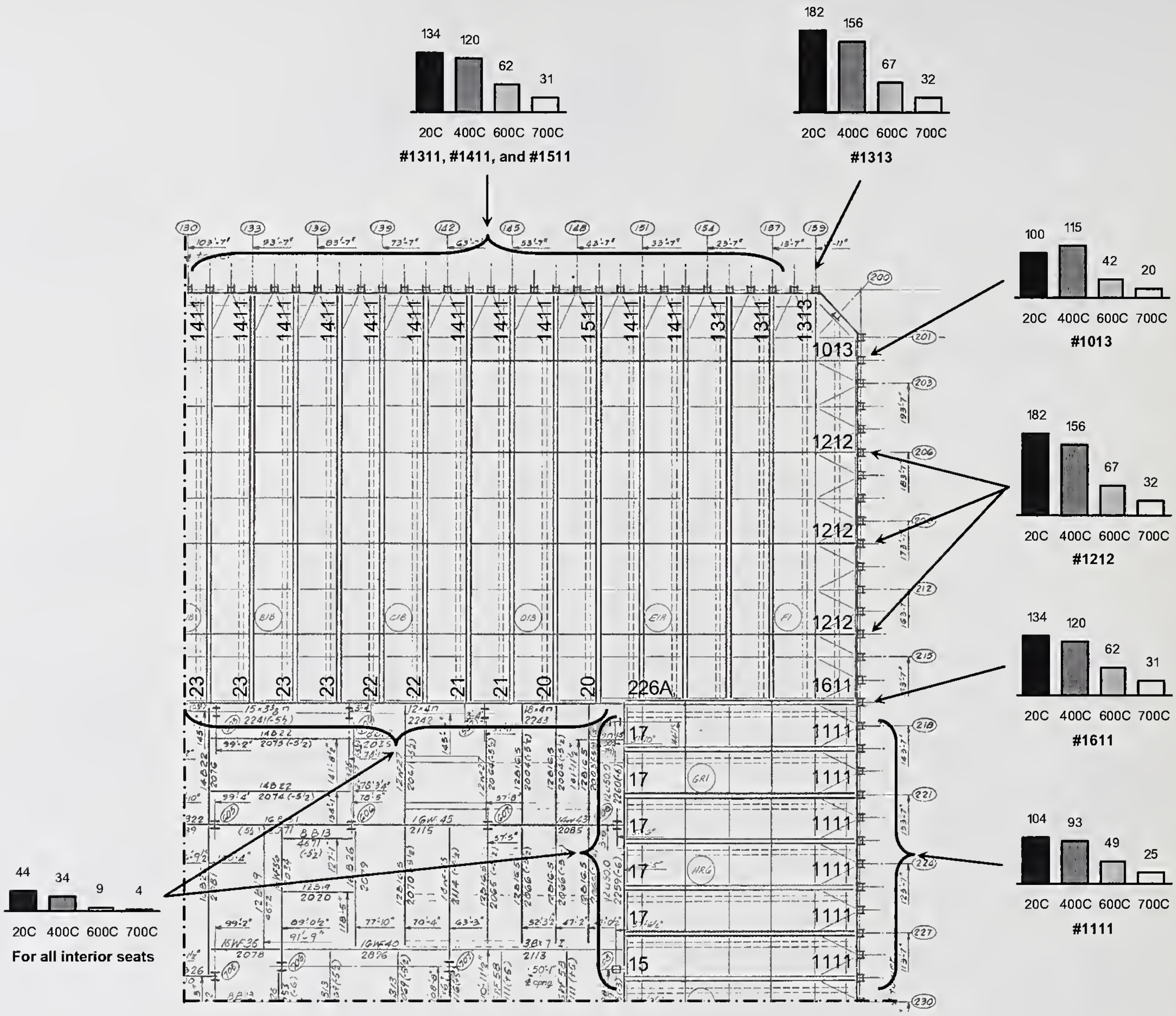


Figure 2–18. Truss seat capacity for horizontal forces.

Knuckle Analysis

FEA results of the knuckle under longitudinal loading are shown in Fig. 2–19. Displacement results shown in Fig. 2–20 indicate a significant dependence on the characteristic of the interface between the steel and concrete. Results show that each knuckle has a capacity in the range of 15 klb to 35 klb, depending on the steel-to-concrete interface assumption. Results of longitudinal shear tests conducted by Laclede Steel in 1967, using normal weight concrete with an average compressive strength of 3,707 psi, indicate an average shear capacity of approximately 28.3 klb per knuckle. After adjusting for the strength of in-place light-weight concrete of 4,100 psi (i.e., multiplying 28.3 klb by the ratio of 4,100 to 3,707 psi), the longitudinal shear capacity of the knuckle is approximately 31 klb per knuckle. This is consistent with the finite element solution for the fully bonded case shown in Figure 2–21 (note results are for two knuckles). A shear capacity of approximately 30 klb per knuckle is used for subsequent analyses of the floor truss.

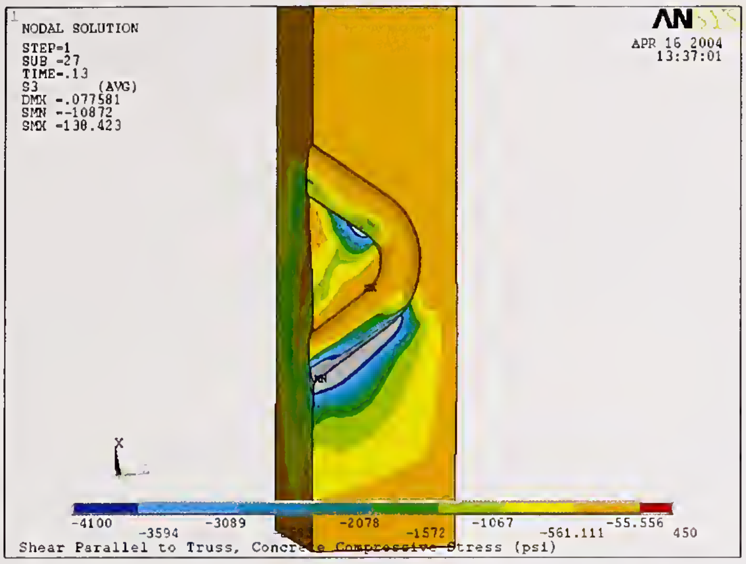


Figure 2–19. Compressive stress in longitudinal shear.

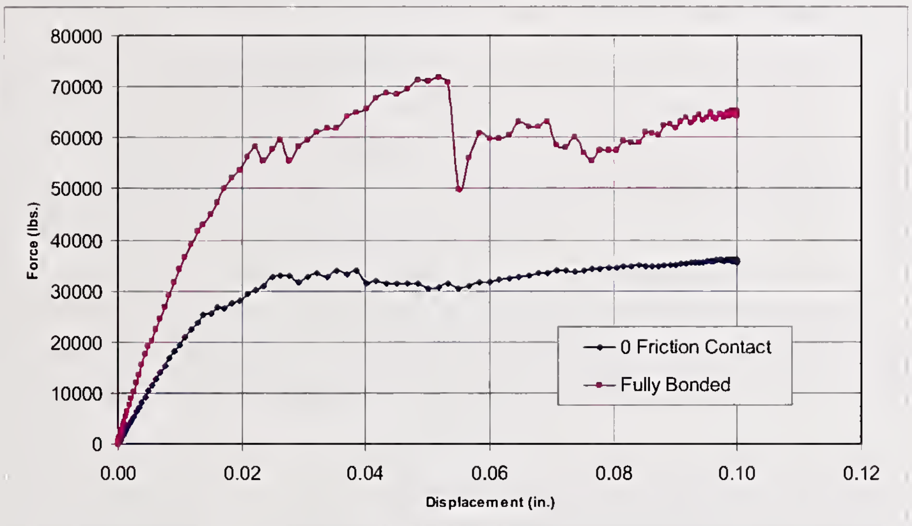
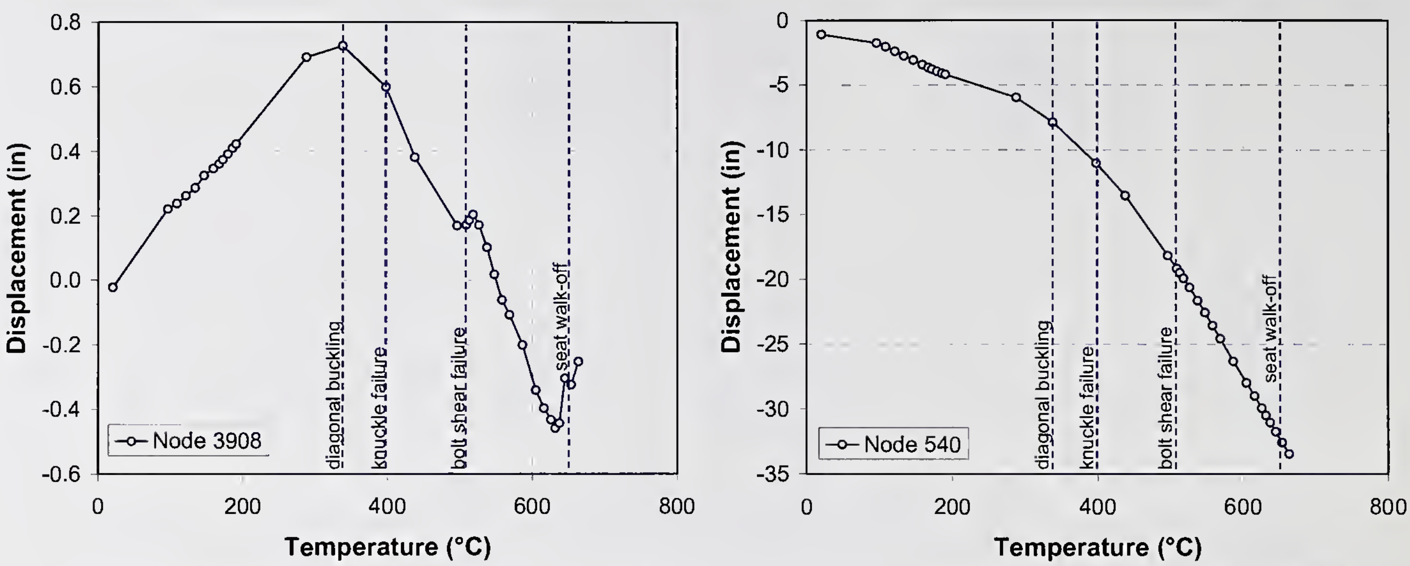


Figure 2–20. Shear force versus displacement for two knuckles under longitudinal shear.

Truss Analysis

The floor truss analysis was carried out dynamically with 5 percent Rayleigh damping and a temperature ramp set to 1.0 s. The floor slab had only gravity loads applied; no other loads related to floor diaphragm action were included. The analysis of truss behavior under the gravity plus thermal loading proceeded to a temperature of T=663 °C. Figure 2–20 shows the horizontal displacement of the column and the vertical midspan displacement of the truss. A positive horizontal displacement indicates that the exterior columns are pushed out, and a negative vertical displacement indicates that the truss is deflected downward.



(a) Horizontal displacement at Column 143 (b) Vertical displacement at midspan

Figure 2–21. Floor truss response due to gravity load and uniform heating.

As the truss and floor slab heat up, the column is pushed outward by thermal expansion. The trust top chord begins to yield in compression around 300 °C due to the difference in coefficient of thermal expansion between steel and lightweight concrete. At approximately 340 °C, web diagonals begin to buckle and the horizontal displacement at the exterior column reverses and begins to decrease. At 400 °C, knuckles start to fail sequentially from both interior and exterior supports toward the center. With the loss of composite action, the floor begins to sag at an increasing rate. Eventually, at about 500 °C, with the truss sagging almost 20 in., the bolts at the interior connection are found to shear. At 560 °C, the exterior columns begin to displace inward, and the truss begins to act as a catenary. At 650 °C, the truss walks off the interior seat while the interior end of slab remains intact and continues to carry vertical load. For the truss to walk off the interior seat, the truss must shorten by 4 in. This shortening is caused mainly by the significant plastic deformation of the top chord of the truss (Fig. 2–14), resulting from differences in the thermal expansion of the top chord relative to the slab and the failure of the first two knuckles near the interior seat. At roughly 660 °C, the gusset plate fracture at the exterior end which precipitates vertical failure of the exterior seated connection.

The results for the additional debris weight show that the knuckles start failing when 2.4 times dead load is applied. Most knuckles fail before 3.0 times dead load. After the knuckle failure, the truss loses composite action between the truss and the concrete slab, and the vertical displacement increases significantly. As a result, the horizontal reaction force increases.

Models of the truss, including knuckles with temperature-dependent capacities, diagonal weld failure, steel creep strains, and concrete cracking and crushing, are under study.

Summary of Preliminary Findings

Preliminary findings for a single truss and its seat connections and knuckles subject to service load conditions, uniformly increasing elevated temperatures in the steel, and an increasing temperature gradient in the concrete slab, can be summarized as follows:

- The floor truss first experiences increasing vertical deflections at midspan as it pushes outward and exerts a compressive lateral load on the exterior column. The exterior column begins to displace outward at the floor connection.

- As web diagonals begin to buckle at 340 °C, the midspan deflection continue to increase but the horizontal displacement of the exterior column begins to decrease. The maximum horizontal displacement of the exterior column is approximately 0.7 in. when the diagonals begin to buckle. The interior column is assumed to have no lateral displacements at the floor level, as it was braced by the core framing.

- Knuckles at each end of the truss begin to fail as the steel and bottom surface of the slab temperatures reach 400 °C, with knuckle failures moving progressively inward from the truss ends. The failure of web diagonals and knuckles at the ends of the truss reduce the flexural rigidity of the floor truss at the ends, further increasing the floor sag and decreasing the lateral outward force exerted on the columns.

- The truss bearing angle slips until the bolt is bearing against the edge of the slotted hole. The bolt shears off at the interior seat connection at approximately 500 °C. The floor truss sag increases to 20 in. when the bolt fails.

- The interior end of the reinforced slab continues to carry vertical loads as the truss bearing angle continues to slip. At 560 °C, the exterior column begins to be displaced inward as the floor truss continues to sag and exert vertical and horizontal tensile loads.

- At 650 °C, the truss begins to walk off the interior seat, followed by fracture of the gusset plate at the exterior connection at 660 °C. Fracture of the gusset plate precipitates weld failure of the exterior seat connection resulting in complete loss of vertical support of the truss.

- The truss model, with knuckle and seat connections, includes all potential failure modes that may occur under loading and thermal conditions, though the actual sequence of failure may differ under other loading and fire conditions.

2.7.5 Standard Fire Endurance Tests of Floor System

Standard Fire Tests of the steel truss-supported concrete slab floor system used in the WTC towers are being conducted by UL. The results of the testing will provide the fire endurance ratings of typical floor construction to evaluate three primary factors: (1) test scale, (2) fireproofing thickness, and (3) thermal restraint. Four ASTM E 119 Standard Fire Tests of the WTC floor construction will be performed as follows:

- 17 ft span assembly, thermally restrained, SFRM thickness of 1/2 in.

- 17 ft span assembly, thermally restrained, SFRM thickness of 3/4 in.

- 35 ft span assembly, thermally restrained, SFRM thickness of 3/4 in.

- 35 ft span assembly, thermally unrestrained, SFRM thickness of 3/4 in.

The first test represents current U.S. practice for establishing a fire endurance rating of a building construction. The test assembly, fabricated to meet the design of the World Trade Center steel joist-supported floor system, has a span of 17 ft. This span is typical of the floor assembly test furnaces used by the U.S. testing laboratories that routinely conduct the ASTM E 119 test for the construction industry. As is common practice, the floor assembly will be tested in the thermally restrained condition. This test will be conducted at UL's Northbrook, Illinois, fire test facility. A second test will be identical except for the thickness of SFRM.

The third and forth tests will be at twice the scale of the first two tests, with a span of 35 ft. This span represents a full-scale assembly of the 35 ft floor panel of the WTC floor system. The floor assembly for the third test will be thermally restrained as in the first two tests, thereby allowing direct comparison for the determination of the effect of test scale on fire endurance rating. The fourth test will be conducted in the thermally unrestrained support condition, which will allow direct comparison of the effect of thermal restraint on the fire endurance rating. The third and fourth tests will be conducted at the UL Canada fire test facility near Toronto.

In all tests, individual structural members of the steel trusses with varying thickness of SFRM will be exposed to the standard fire environment, and temperatures will be recorded. This will allow comparison of results for various amounts of fireproofing based on the end point criteria for steel temperatures.

The test specimens have been designed and fabricated to duplicate as closely as possible the actual floor system in the WTC towers. Laclede Steel shop drawings were used to ensure the specimens were dimensionally accurate. Properties of the constituent materials and components have been duplicated as closely as possible, including the steel angles and rods that make up the floor trusses, concrete (lightweight aggregate, air entrainment, etc.), metal deck, welded wire fabric, reinforcing steel, shop primer, and Cafco DC/F SFRM. NIST has overseen fabrication of the steel trusses, assembly of test specimens, and casting of the concrete slab and test cylinders. NIST will continue oversight of the installation of instrumentation and application of SFRM.

The test assemblies have been fabricated as shown in Fig. 2–22, and at this time, the concrete floor slabs are drying to the ASTM E 119 specified moisture condition under controlled conditions to obtain concrete design strength. The specimens are currently drying in a temperature/humidity controlled environment to achieve the ASTM E 119 prescribed moisture equilibrium.

Figure 2–22. Fabrication of 35 ft span ASTM E 119 test assembly.

2.7.6 WTC 7

The structural response of WTC 7 to damage from debris and fires is being evaluated to identify possible collapse sequences and critical components that are consistent with the videographic and photographic records, interview accounts by individuals that were in or around WTC 7, and other available data.

The analytical work is being conducted with the assistance of Gilsanz Murray Steficek LLP under a contract from NIST and includes the following tasks:

- **Task 1**. Structural response analysis to identify critical components
- **Task 2**. Structural analysis of possible collapse initiation hypotheses

The scope of work under Task 1 includes (a) develop a nonlinear global structural model of WTC 7 and evaluate its performance under design gravity loads, (b) identify credible failure sequences for the structural model with service loads and initial structural damage by analyzing the effect of component failures (that may have occurred directly or indirectly from fires) on the structural system stability, (c) identify dominant failure modes for critical components and subsystems determined in (b) for service loads and elevated structural temperatures, (d) conduct parametric studies of critical subsystems to identify influential parameters, and (e) develop approaches to simplify structural analyses for global modeling and analyses.

Selected technical results and finding for progress on Task 1 (a), (b), and (c), data collection of building conditions, working collapse hypotheses, and supporting analyses are presented in the following sections. Appendix L presents more detailed information about the WTC 7 structural design, observations about damage and fires, a timeline and description of the collapse sequence from videographic records, and working collapse hypotheses developed to date. Detailed thermal-structural analyses of selected collapse sequences are planned to refine the working hypotheses presented here and identify probable collapse hypotheses.

Summary of Data Collection for Building Conditions

Data that have been obtained about building conditions from photographic and videographic records and interview accounts include:

- Structural damage to the south face and to the southwest corner from WTC 1 debris was reported by witnesses. A multi-story gash that extended across approximately a quarter to a third of the south face, in the lower portion of the face, was reported by a number of individuals, though details vary. This damage extended to the core area as two elevator cars were reported to be ejected from the elevator shaft at floor 8 or 9. Reported damage to the southwest corner was also seen in photographic records, which show approximately 2 columns and related floor areas missing from floors 8 to 18. Multiple photographic and videographic records also appear to show damage on the south face that started at the roof level and severed the spandrels between exterior columns near the southwest corner for at least 5 to 10 floors. However, the extent and details of this damage have not yet been discerned, as smoke is present.

- The south face was covered by smoke the entire day, following the collapse of WTC 1. This smoke appeared to be emanating from fires in WTC 5, 6, and 7, though the contribution from each building cannot be discerned. The smoke was dense enough that no information about structural damage to the south face has been seen in photographic or videographic records.

- No fires were observed in WTC 7 after WTC 2 collapsed, but fires were observed after WTC 1 collapsed. Fires, or evidence of fires, were observed initially on the south face and near the southwest corner. Many of these fires appeared to burn out before noon to 2 p.m. Around 2 p.m., fires were observed in photographic and videographic records to be burning across floors 11 and 12 on the east face, from the south to the north. Around 3 p.m., fires were observed on floors 7 and 12 along the north face. The fire on floor 12 appeared to bypass the northeast corner and was first observed at a point approximately one third of the width from the northeast corner, and then spread both east and west across the north face. Some time later, fires were observed on floors 8 and 13, with the fire on floor 8 moving from west to east and the fire on floor 13 moving from east to west. At this time, the fire on floor 7 appeared to have stopped progressing near the middle of the north face. The fire on floor 8 continued to move east on the north face, eventually reaching the northeast corner and moving to the east face. Around 4:45 p.m., a photograph showed fires floors 7, 8, 9, and 11 near the middle; floor 12 was burned out by this time.

- Floor 5 did not have any exterior windows, and any fires that may have burned on this floor would not have been visible in photographic or videographic records. However, there was a fuel distribution system on the south, west and north floor areas. Given the variability of damage descriptions for the south face from WTC 1 debris impact, fires on floor 5 will be considered as a possible fire location, subject to further data and/or analysis on building conditions that improve knowledge of fire conditions in this area.

- The first exterior sign of structural failure in WTC 7 was the sinking of the east penthouse roof structure into the building. Photographic and videographic records taken from the north have provided information about the sequence of failure events and their relative times.

Other key observations include window breakage along the east side of the north face, occurring almost simultaneously with the sinking of the east penthouse structure, an approximate 5 s delay before the other roof structures also sink into the building core, a second set of window breakage along the west side of the north face occurring simultaneously with the other roof structure movements, and the appearance of the entire north façade above floor 13 appearing to drop as an intact unit 8 s after the east penthouse movement was first detected.

Structural Models and Analysis

Analyses have been conducted to assess proposed collapse hypotheses that are based upon available information about the building conditions and sequence of events prior to the global collapse. Models and analyses to date have included the following:

- Structural analysis of WTC 7, as built in 1985, for design gravity and wind loads on a global structural model. Development of a reference model for understanding global behavior of the structure, and providing a foundation for other models.

- The global structural model was modified for reported structural damage and estimated service loads for analysis of the structural system response to building condition after debris impact.

- A kinematic structural analysis assisted with identifying possible failure sequences following an initiating event, such as a column or group of columns becoming unstable as steel temperatures reach critical levels.

- Typical tenant floors were analyzed to identify the sequence of floor system load redistribution and component failure for initiating events, such as failure of a support column.

- The global structural model was used to develop a submodel of the lower 10 floors of WTC 7 to evaluate the effect of component failure and load redistribution within this portion of the structural system.

- Thermal-structural analysis of critical columns to fire scenarios for proposed collapse hypotheses have been conducted to evaluate the effect of component response to fires, including time to reach critical uniform elevated temperatures and temperature gradients across component cross-section and length.

- These models were used to consider a range of possible failure scenarios, based upon knowledge of the reported damage, observed or possible fire scenarios, and the exterior failure sequence recorded on videos.

Summary of Technical Results

Some of the more important technical results developed to date, based upon known building conditions and analyses, include the following:

- The perimeter moment frame was highly redundant and was able to redistribute the loads around the reported damage areas without over-stressing or failing surrounding members.

- The working hypothesis has been developed around four phases of the collapse that were observed in photographic and video records: the initiating event, a vertical progression at the northeast corner of the building, and horizontal progression from the east to west side of the building, and global collapse.

- The first exterior sign of failure in WTC 7 was the displacement at the center of the east penthouse roofline, which appeared to be a kink in the roof line. This kink aligns with columns 79, 80, and 81. This observation has led to postulating initiating event failure sequences that lead to the failure of one of these columns.

- Thermal-structural analyses have been used to evaluate components in postulated initiating event failure sequences. Analyses to date have included single and multi-story columns subject to severe fires (gas temperatures of 1,100 °C), intact and damaged fireproofing, intact and missing lateral support conditions, and temperature-dependent material properties (yield strength, ultimate tensile strength, thermal expansion, and creep strains) to evaluate the structural response to thermal softening, axial expansion, and bowing from thermal gradients. These types of analyses continue to be developed and refined. Simpler initiating events that have been analyzed appear unlikely as initiating events, such as the direct failure of columns 79, 80, or 81 in the lower portion of the building for intact fireproofing and the fires observed in the photographic and videographic records. Other initiating event sequences continue to be postulated and analyzed. Possible initiating events include consideration of interior columns 69, 72, 75, 78, and 78A, the east transfer girder (which supports column 78A and frames into transfer truss #2), and adjacent framing and floor systems and their response to possible structural and fireproofing damage from debris impact and subsequent fire growth and progression. See Appendix L for component locations.

- Interior columns 79, 80, and 81, were located directly below the east penthouse on the roof and supported large tributary areas. The tenant floor areas on the east side of the building had spans of approximately 50 ft between columns. Their failure would likely result in failure of the tributary floor system, as analysis indicates that the floors would not be able to redistribute their loads. This failure mechanism would progress vertically upward within the failed bay to the roof level, and would not be visible from the exterior until the east penthouse lost support, as shown in Fig. 2–23. Available information on the floor-to-column connections indicate that the connections would fail under this scenario without significantly damaging the perimeter or interior columns.

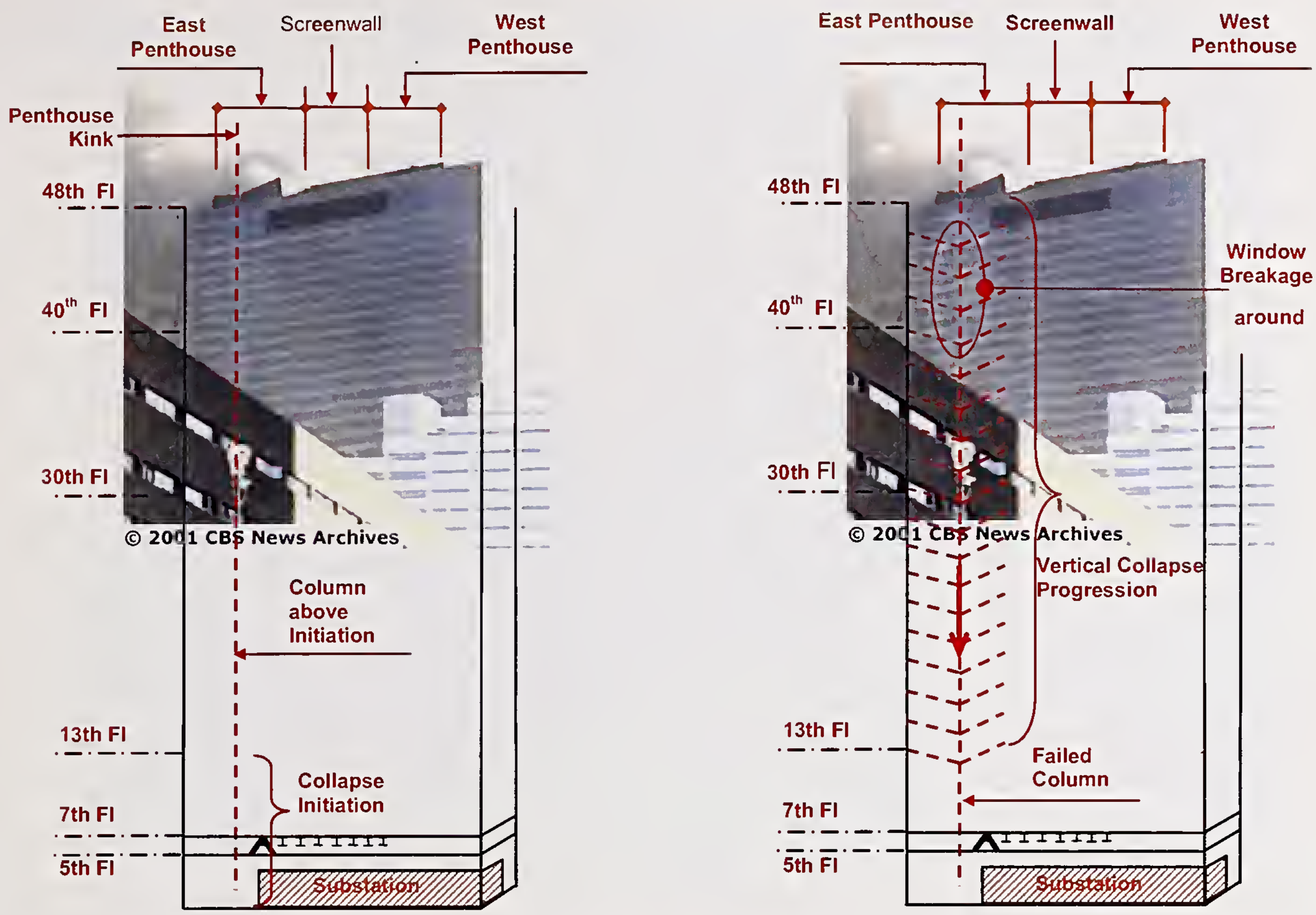


Figure 2–23. Collapse initiation and vertical progression on the east side of WTC 7.

- The debris pile from a vertical failure progression on the east side of the building would damage or sever transfer girders and trusses between the fifth and seventh floors, shown in Fig. 2–24. Two system responses to this secondary damage have been postulated and are being further investigated. (1) The columns supported by these transfer components would become unstable, and their loads would transfer to adjacent core columns. If the columns could not support the transferred loads, the column instability would progress sequentially to adjacent core columns. (2) The floor-to-column connections in the fifth and seventh floors are strong enough to impose lateral displacements upon the other core columns, particularly in the center of core where there were elevator areas without reinforced concrete slab. Such a horizontal pull would fail the columns at their connection near the seventh floor, as shown in Figs. 2–25 and 2–26.

- The core columns failed sequentially and redistributed loads until the building loads could no longer be supported, and the global collapse occurred with few external signs prior to the system failure, as illustrated in Fig. 2–26.

This working hypothesis has been developed to date for the data and analyses described. Continued analyses and evaluation continue toward determining probable collapse sequences.

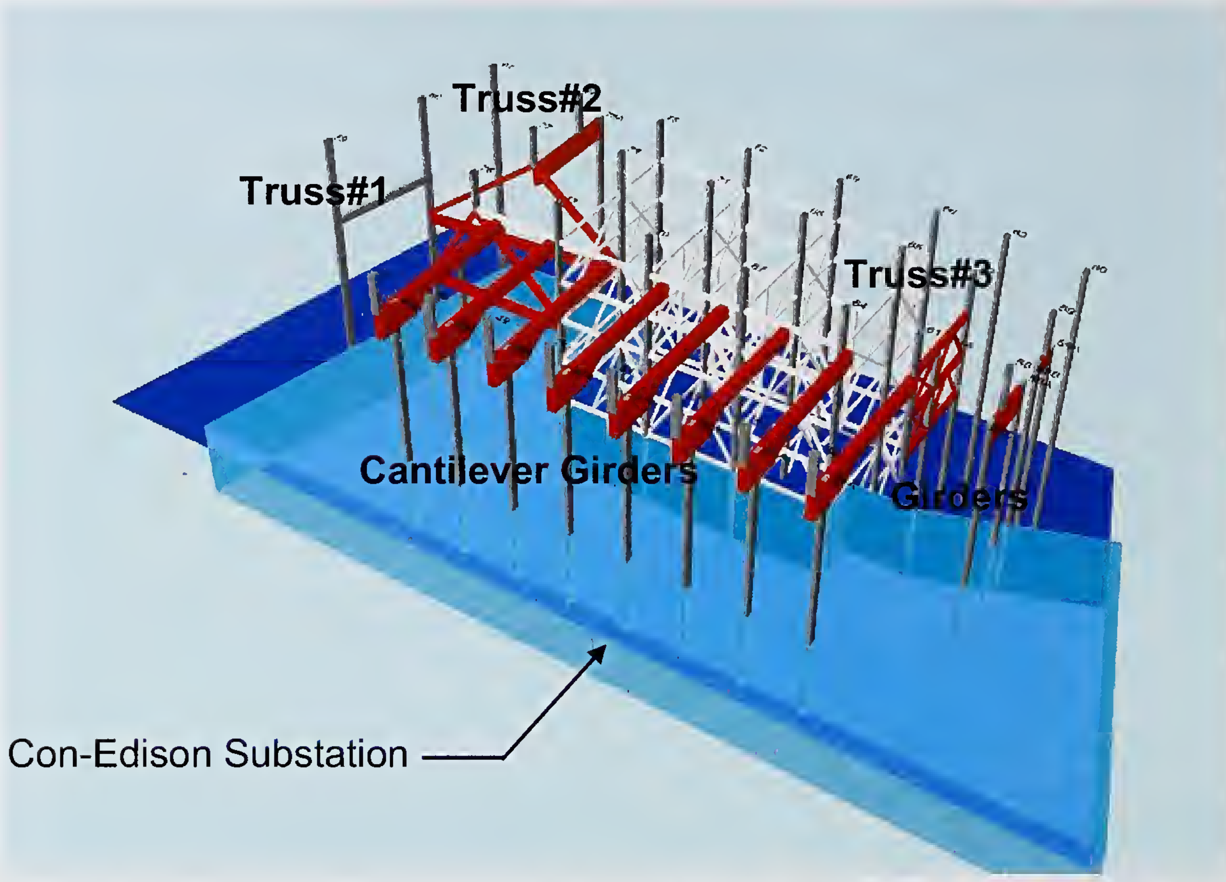


Figure 2–24. Transfer trusses and girders between the fifth and seventh floors.

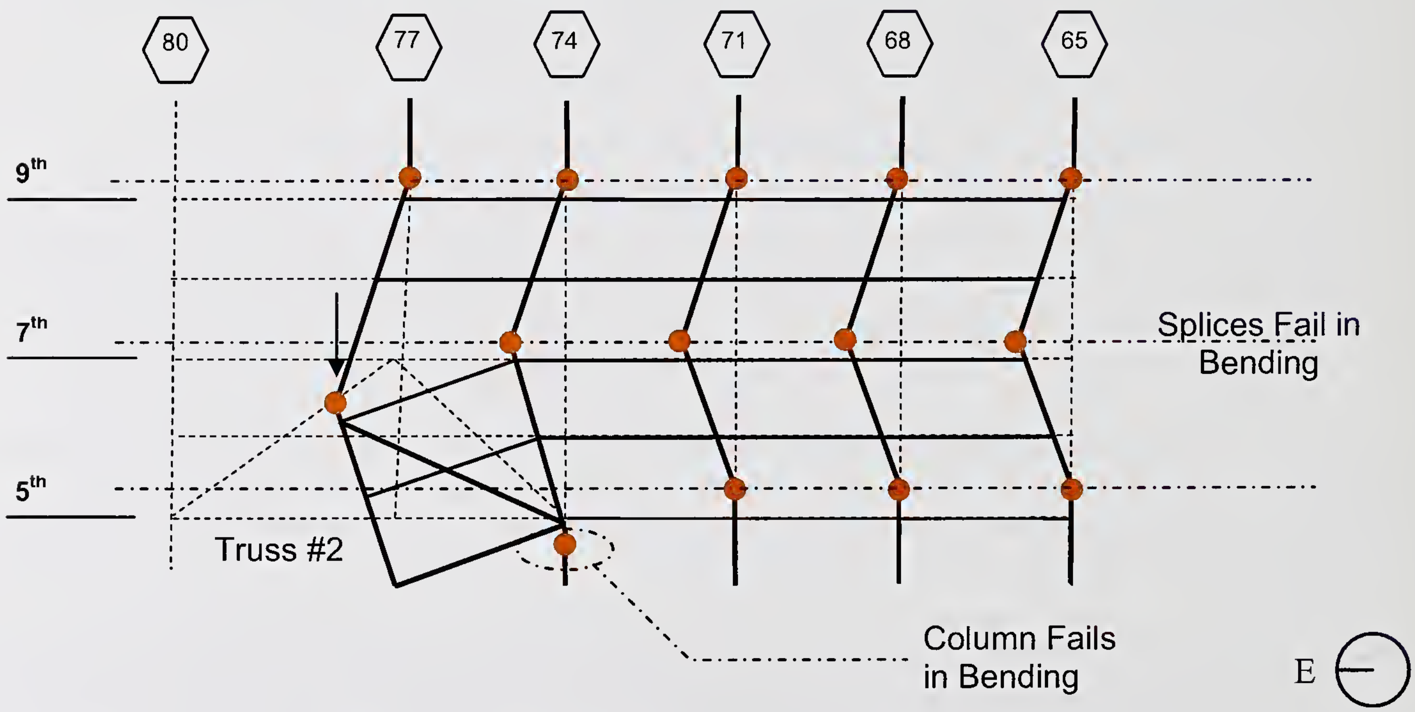


Figure 2–25. Example of horizontal progression of failure in core columns following damage to transfer components on the east side of the building.

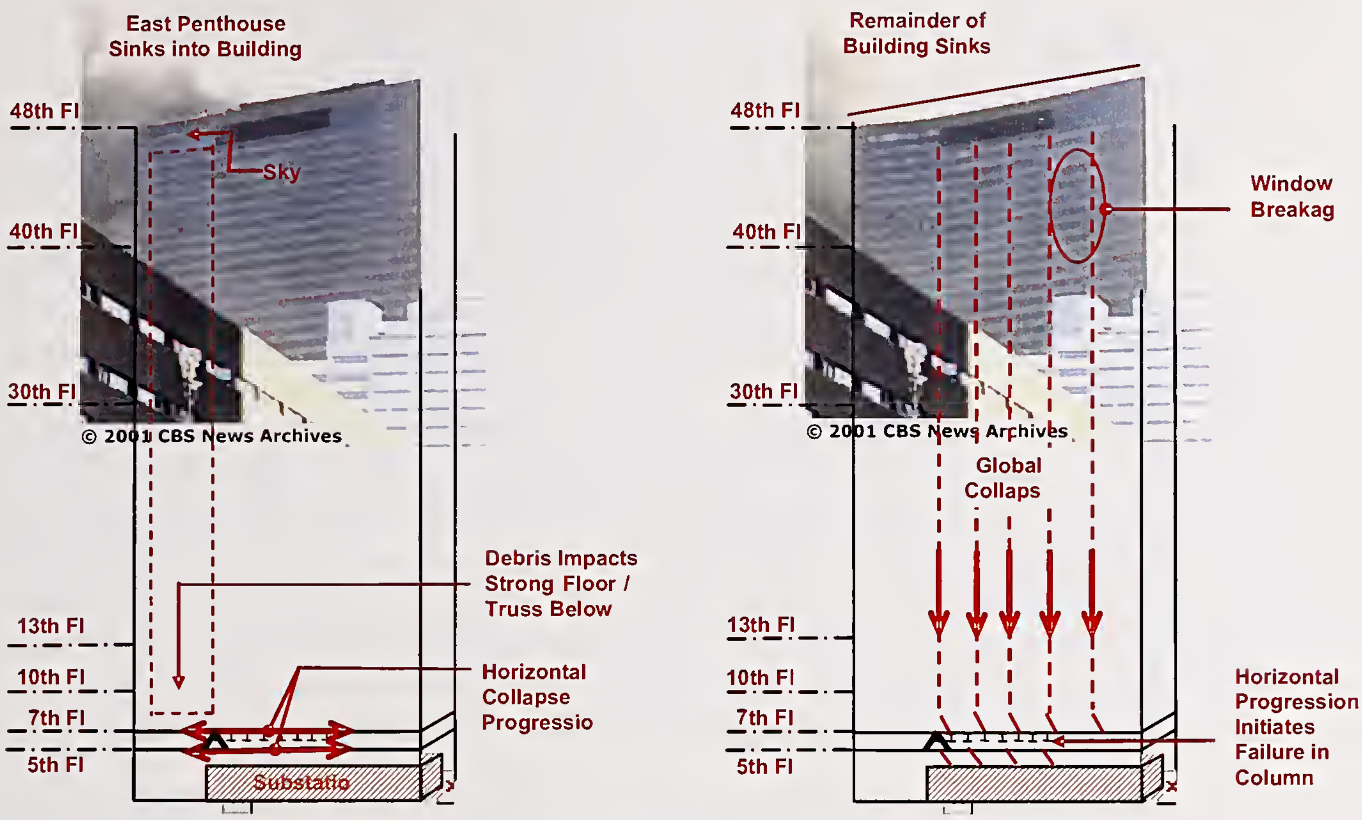


Figure 2–26. Horizontal progression to the west side of WTC 7.

2.8 OCCUPANT BEHAVIOR, EGRESS, AND EMERGENCY COMMUNICATIONS (PROJECT 7)

The purpose of this project is to determine the behavior and fate of occupants and responders - both those who survived and those who did not - by collecting and analyzing information on occupant behavior, human factors, egress, and emergency communications in WTC 1, 2, and 7, and evaluating the performance of the evacuation system on September 11, 2001.

2.8.1 Project Objectives

This project is divided into six tasks as follows:

- **Task 1.** Gather baseline information on the evacuation of the WTC buildings on September 11, 2001 through a comprehensive, systems-oriented, and interdisciplinary data collection effort focused on occupant behavior, human factors, egress, and emergency communications (including instructions given, interpretation of instructions, and response to instructions). This involves the collection of new data from people affected by the WTC attacks (e.g., building occupants, building operators, and first responders via direct accounts from survivors and families of victims), especially those who had to evacuate the buildings. Experts in human behavior and statistical sampling were used develop a data acquisition strategy that considers various data collection methods such as interviews and questionnaires. Inputs and suggestions were obtained from organizations with an interest in the content of the data collection effort. Additionally, written accounts, transcripts of (emergency) communications, published accounts, and other sources of egress related information were obtained, in coordination with other data collection efforts for the investigation.

- **Task 2.** Collect archival records from prior WTC evacuation incidents (e.g., 1975 fire, 1977 blackout, 1980 bomb scare, 1990 power outage, and 1993 bombing) and practice evacuations, including oral history data from floor wardens and fire safety directors. These records are compared and contrasted with the September 11, 2001, incident evacuation. Changes made to the evacuation procedures following the earlier incidents and in recent years will be evaluated in the context of the experience on September 11, 2001.

- **Task 3.** Document pre-event data for WTC Buildings 1, 2, and 7. This information includes, but is not limited to, physical aspects of building egress components, such as stairs (width, number, location, vertical continuity), evacuation lighting, back-up power, elevators (number, operational before and after impact, role in evacuation), and active fire protection systems (sprinklers, manual suppression, fire alarms, smoke control). Building plans, emergency plans, type and frequency of evacuation drills, occupancy level and distribution on the morning of September 11, 2001, and communications also constitute pre-event data. This information provides a baseline for evaluating the performance of the egress system.

- **Task 4.** Store the information collected in Task 1 in a database. Additionally, information from third-party sources, such as television interviews and newspaper articles, as well as other relevant published material, will be analyzed, examined, and assembled in the database.

- **Task 5.** Analyze the data to study the movement of people during the evacuations, decision-making and situation awareness, and issues concerning persons with disabilities. A timeline of the evacuation will be developed using the results of these analyses together with other data sources. This timeline will be compared with the timeline of the structural response, the development of the interior conditions (fire and smoke), as well as activation of the active fire protection systems. The characteristics of the WTC evacuation designs and protocols will be evaluated, including the performance of stairs and elevators, emergency communications, and the temperature and smoke conditions. The designs will also be compared with building code requirements and practices for tall buildings in other major cities worldwide. The observed evacuation data will be compared with results obtained using alternate egress models to better understand occupant behavior and identify needed improvements to existing egress models. In addition, the evacuation experience will be compared with previous evacuation incidents in these buildings. The results of the analyses will be reviewed in the context of occupant protection practices for tall buildings, including the consideration of full evacuation and phased evacuation strategies.

- **Task 6.** Report preparation. The results of this project will be synthesized into a chapter to describe the occupant behavior, egress, and emergency communications in WTC 1, 2, and 7, and the performance of the evacuation system. The project staff will contribute to drafting the final investigation report for review by the National Construction Safety Team (NCST) Advisory Committee.

2.8.2 Project Status

Project 7 has made significant progress since the last interim report. Data collection is substantially complete, including interviews and focus groups with survivors and family members. Significant portions of the data analysis are complete, and egress modeling is under way.

Face-to-Face Interviews, Telephone Interviews, and Focus Groups

Over 220 face-to-face interviews have been completed with occupants of WTC 1, 2, and 7, and family members of victims. These numbers do not reflect interviews conducted with first responders or other key building personnel. A preliminary analysis of the interview data indicates that the topic areas of interest and physical building locations of the occupants have resulted in an adequate number of interviews to support analysis. While additional face-to-face interviews may occur in the near future should conditions necessitate, no further interviews are scheduled. Face-to-face interviews typically required two hours, with some requiring significantly more or less depending upon the particular experiences of the respondent. Data were collected using a cooperative, electronic format, previously described as the cue-action-reason technique. The technique formalized a logical, chronological data collection, enabling detailed recall, and diminishing gaps in continuity of actions.

Egress Simulation

The purpose of the modeling project is to obtain evacuation times for two different evacuation procedures for the WTC towers, phased evacuation and total evacuation of the occupants from the buildings. The first objective is to simulate a phased evacuation of WTC 1 or WTC 2, which involves the evacuation of the occupants on the fire floor, the floor above, and the floor below to a specific floor of the building. For this simulation, a representative fire floor was chosen within one of the towers, and the simulation consisted of occupants from the fire floor, the floor below, and the floor above evacuated to two floors below the fire floor. The purpose of the phased evacuation simulation is to obtain evacuation results (time) on how the evacuation from a fire emergency was supposed to work.

The second objective is to simulate total evacuation of the building, and involves three different scenarios. The first total evacuation scenario is the simulation of a full capacity building evacuation (without damage) involving all occupied floors of a WTC tower. The second scenario involves a full capacity building evacuation of WTC 1 with plane damage blocking floors 91 to 110 and a full capacity building evacuation of WTC 2 with plane damage blocking floors 78 to 110. The second scenario will be used to show how long it would have taken occupants in a scenario resembling the September 11, 2001, emergency to evacuate if each tower was fully occupied. Finally, the third scenario is a simulation of a September 11, 2001, capacity building evacuation from a WTC tower. The results from the simulation of the third full evacuation scenario will be compared with evacuation time results obtained from the telephone interviews in an attempt to verify the accuracy of the model. None of the simulations run for this project involves the simulation of the fire environment.

Three evacuation models will be used to perform the modeling objectives outlined in the previous paragraphs. These models are Simulex (IES 2000 and IES 2001), EXIT89 (Fahy 1999), and buildingEXODUS (Galea et al. 2001). Simulex will be used in a limited capacity to simulate the phased evacuation and observe occupant movement on specific floors. EXIT89 and buildingEXODUS will be used in all of the objectives stated above.

Other September 11, 2001, Data Collection

A systematic review of all 9-1-1 emergency calls related to the WTC attacks between 8:46 a.m. and 10:28 a.m. was completed. Occupants from inside the WTC called 9-1-1, sometimes repeatedly, in order to report where they were trapped, the conditions on the floor, and how many other people they were with. The callers often requested advice, guidance, information about the attack, and the progress of the rescue efforts. The information relayed to the 9-1-1 system was unique and invaluable in specificity and timing. Information related to building damage, fire and smoke spread, and occupant mobility has been integrated with other aspects of the NIST investigation.

Seven-hundred forty-five media accounts from were compiled and analyzed. Finally, information about significant previous building fires and evacuations has been compiled as background. An overview of the preliminary results of both analyses is included in the next section, while more detailed analyses are contained in Appendix N and Appendix O. The database can be obtained electronically at http://wtc.nist.gov.

Collection of documents related to the design and maintenance of the egress and emergency communication systems is complete. This collection was coordinated with Project 1, Analysis of Codes, Standards, and Practices.

Data Analysis

Every data channel is being analyzed and synthesized to form a complete understanding of the evacuation of WTC 1, 2, and 7 on September 11, 2001. There are two primary analysis modes, proceeding in parallel: quantitative and qualitative. Quantitative analysis techniques are being implemented with the telephone interview data. An example of the quantitative data analysis can be found in Appendix N. The SPSS 12.0 data analysis package is being used to analyze the telephone interview data. The qualitative analysis is being consolidated with the ATLAS.ti 4.2 program. All face-to-face interviews, 9-1-1 emergency call records, focus group notes, emergency communications, and formal complaints will be simultaneously analyzed using over 100 coding variables. The coding variables encompass the entire scope of Project 7 objectives and are coordinated with the analyses conducted by other projects within the investigation, particularly Project 8, First Responder Technologies and Guidelines.

2.8.3 Interim Findings and Key Issues

Significant Historical Building Incidents

Although historically the WTC attack, subsequent fires, and building collapses are arguably the most significant fire event where building egress played a critical role, concern for fires in large buildings is hardly new. In many cases, provisions in current building codes evolved as a result of high-rise fires as early as 1911 where egress or collapse was an important issue. These provisions include remoteness and protection of egress stairways, the need for control of combustible contents of buildings, the need to provide sprinklers or other alternatives for high-rise buildings, and concern that sprayed-on fireproofing may not adhere properly to surfaces or may be dislodged.

Analysis of Published Accounts

NIST contracted with the NFPA to collect first-person accounts from newspapers, radio and television programs, e-mail exchanges, and a variety of websites. Over a period of 18 months, a total of 745 first-person accounts were collected. These accounts had been published up to 14 months after the event. Although media accounts do not provide the scientific rigor of a proper study, they do present important insights into the events of the day. The objectives of the analysis of the first-person accounts were to gain insight into the variability of human behavior and response time displayed during the evacuation, with the findings to be used as a guide for additional investigation. It should be acknowledged that content analysis of first-person accounts has important limitations: the questions asked by journalists are usually unknown, and, some details might be left unreported and the most dramatic stories over represented. Consequently, the results cannot be generalized to the overall population of the WTC towers.

To analyze the content of the first-person accounts, a questionnaire tool was developed and used to "interview" each account. The questionnaire had 33 questions such as: "On what floor was the person?," "What was the first cue of the event?," "Was the person injured?," or "What were the conditions in the stairs?" Not every account provided answers for all 33 questions, since some accounts lacked certain details, but this is similar to a respondent who did not answer some questions in a survey. Once the 745 first-person accounts were summarized, multiple accounts from the same person were merged into one, which provided accounts for 465 individuals. (Some survivors provided multiple accounts through different sources.) Before any analysis began, the database was further limited to the 435 civilian building occupants who were in either WTC 1 or WTC 2 on that day.

In summary, the accounts analyzed were from 435 individuals; 251 occupants of WTC 1 and 184 occupants of WTC 2. They represented the three different floor strata of the two towers. The accounts were mainly from men (314 versus 118) and from people varying in age from 20 to 89 years old. Among the interesting results found was the means of egress used that morning. Out of 158 people who mentioned their means of egress in WTC 2, 18 used the elevators, and 26 used a combination of stairs and elevators to leave the tower. It was found that the higher the person was located in the tower initially, the more likely it was that this person used an elevator to evacuate. In WTC 1, out of 202 people who mentioned their means of egress, 198 used the stairs, 1 used an elevator, and 3 used a combination of stairs and elevator. This does not include the 22 people who were stuck in elevators when WTC 1 was hit. The most common adverse floor condition mentioned by people in WTC 1 was the presence of smoke (mentioned by 74 people), debris or collapsed walls, ceilings, or floors (72 people), and fires (41 people). In WTC 2, 37 people reported debris or collapsed walls, ceilings or floors on their floor, and 25 people saw smoke.

The most prevalent condition reported for the stairwell was that it was crowded and hot (mentioned by 106 people). A particular condition mentioned for the stairs in both towers was the presence of smoke, mentioned by 78 people in WTC 1 and 29 in WTC 2. The presence of water, usually on the lower stairwell floors, was mentioned by 49 people in WTC 1 and four people in WTC 2. Jammed or locked doors were mentioned by 20 people in WTC 1 and two people in WTC 2.

In WTC 2, 96 people mentioned hearing a message over the communication system to “stay in or return to their office.” The majority of them, 69 people, decided to disregard the instructions and continued their evacuation. The 16 people who decided to remain in their offices or decided to turn back didn’t have time to travel very far before the second plane hit; at that point they all resumed their evacuation downward.

Among the accounts analyzed, 27 people reported having a disability, and 47 were injured that morning. All these people were supported in their evacuation by coworkers. Half of them stated that they started their evacuation immediately, and one-third mentioned some delay to get organized and seek first-aid. Several people who were disabled or injured evacuated the towers swiftly as occupants formed a single line to let them through rapidly down the stairwell. Many people (143 in WTC 1 and 26 in WTC 2) mentioned being reassured and feeling safe when meeting firefighters in the building. Although the emergency crews disrupted the evacuation in the stairwell by going against traffic, the people appreciatively cheered them on. Phone calls were made by 151 survivors to family and friends to give and obtain information; 20 people called their bosses or colleagues; and another 12 people made calls to authorities. Another 14 people used e-mail wireless technology and pagers to exchange information, which seems to be the only reliable devices used from inside the stairwells.

Telephone Interviews

The survey objectives of the telephone interviews called for collecting 800 computer-assisted telephone interviews (CATI) of persons occupying either of the two WTC towers at the time of the terrorist attacks on September 11, 2001. Attempts were made to equally divide the respondents among WTC 1 and WTC 2 occupants (i.e., n = 400 occupant interviews from each tower). Within each of the WTC buildings, independent, proportionate, stratified samples of survivors were drawn. Eight-hundred three telephone interviews were completed, with 440 from WTC 1 and 363 from WTC 2. Additional discussion of the sampling methodology and disposition can be found in Appendix O.

A response rate analysis indicated differential nonresponse, more noticeably near the impact floors in WTC 1. In other words, respondents were less likely to complete a telephone interview if they had been near the impact floor than respondents who had been lower in the building. Thus, percentages presented in this summary are weighted, unless otherwise indicated. Weighting preserves the ability to accurately generalize the results.

Population of WTC 1 and WTC 2 on September 11, 2001

The total building population is the sum of survivors and decedents. At the time of this report, the City of New York has officially determined that 2,749 people were killed at the WTC on September 11, 2001; no official breakdown of where people were killed presently exists. While an analysis of this issue by Dennis Cauchon, a reporter for *USA Today*, in the months immediately following September 11, 2001, was remarkably complete (Cauchon 2001), differences exist between his projections and the official numbers from the City of New York and other official sources. These differences are shown in Table 2–8. For example, the number of first responders depends on the definition of first responder. The City of New York published an occupational analysis of WTC decedents based on a Census of Fatal Occupational Injuries (U.S. Department of Labor, Bureau of Labor Statistics, in cooperation with the NYC Department of Health and Mental Hygiene and State and Federal agencies). Four hundred and thirty-three decedents’ occupations were listed as firefighting, police, or security. This number exceeds by 30 the number of FDNY, NYPD, and PAPD reported killed. This may be attributable to private security forces present inside the towers on September 11 and/or first responders not employed by New York City or PANYNJ. NIST is attempting to resolve these differences in order to fully understand the initial building population.

Table 2–8. Reports of WTC decedents.

Decedent	Official Numbers		USA Today[a]
WTC 1 occupants			1,434
At or above impact			1,360
Below impact			72
WTC 2 occupants			599
At or above impact			595
Below impact			4
First responders (total)	433[b,c]		479
FDNY	403[d]	343[e]	
NYPD		23[f]	
PAPD		37[g]	
UA 175 and AA 11	157[d]		157
Uncertain location in towers			147
Bystanders			10
Total number of decedents	**2,749[b,h]**		**2,826**

a. Cauchon, Dennis. 'For many on September, 11, 2001, survival was no accident.' USA Today, December 20, 2001.
b. Summary of Vital Statistics 2002: The City of New York. Bureau of Vital Statistics, NYC Department of Health and Mental Hygiene. December 2003.
c. Table WTC 8: Occupation of Decedents. All decedents classified as 'protective service' occupations, which includes firefighting, police, and guards.
d. World Trade Center Building Performance Study. FEMA 403. May 2002. Includes 10 hijackers as passengers.
e. Increasing FDNY's Preparedness (McKinsey Report). Available at: http://www.ci.nyc.ny.us/html/fdny/html/mck_report/index.shtml
f. Available at http://www.ci.nyc.ny.us/html/nypd/html/memorial_01.html
g. Available at http://www.panynj.gov/AbouttheP ortAuthority/PortAuthorityPolice/InMemorium/
h. Does not include 10 airplane hijackers for whom the City has not issued death certificates.

Using the known eligibility rates allows for a projection of the survivors of WTC 1 and WTC 2 present in the building at 8:46 a.m. on September 11, 2001. The analysis indicates that WTC 1 had approximately 7,500 ± 750 surviving occupants, while WTC 2 had approximately 7,900 ± 900 surviving occupants. Thus, the total population of survivors from both towers was 15,400 ± 1,200. Table 2–9 summarizes the projection of population of WTC 1 and WTC 2 on September 11, 2001. Pending resolution of decedent locations, the total building population at the time of the first airplane impact was 17,400 ± 1,200, calculated using the building decedent locations reported by Cauchon.

Table 2–9. Occupancy estimates on September 11, 2001, by tower.

	WTC 1	WTC 2	Total
Estimated total population of survivors	7,500	7,900	15,400
Statistical Precision Calculations			
Sample n	427	376	803
Standard error (p)	1.90 %	1.92 %	1.36 %
Standard error (total)	750	900	1,200
Confidence limits at 5%	±1,470	±1,790	±2,320
Number of Occupant Decedents			
Decedents	1,434[a]	599[a]	2,033[a] – 2,236[b]
Total Building Population			
Total population	8,900	8,500	17,400

a. Calculated as 2,749 – 343 FDNY – 23 NYPD – 147 airplane passengers (not including hijackers).
b. Calculated as 2,749 – 403 First Responders – 157 airline passengers (not including hijackers).

Previous Evacuation Experience

Whether an occupant had a previous evacuation experience may have affected the decisions an individual made during the September 11, 2001, evacuation. NIST will conduct further analysis to develop this hypothesis. Of the WTC 1 occupants present on September 11, 2001, 16 percent (n = 64) were also present during the 1993 bombing. Sixty percent (n = 38) of WTC 1 evacuees in 1993 reported that they evacuated immediately, 30 percent (n = 20) reported that they waited to evacuate, and 9 percent (n = 6) did not recall. Most (95 percent [n = 53]) who were able to recall their evacuation decision felt that they made the right decision, while 5 percent (n = 3) did not believe they made the right decision.

Similarly, 16 percent (n = 59) of WTC 2 evacuees on September 11, 2001, also evacuated in 1993. In WTC 2, however, only 75 percent (n = 42) felt that they made the right decision in 1993, possibly due to the fact that many more waited to evacuate in 1993 in WTC 2 (69 percent [n = 39]) than did so in WTC 1. Only 31 percent (n = 17) who reported their decision evacuated immediately from WTC 2 in 1993, keeping in mind that the bomb had a more significant impact on WTC 1 in 1993.

Preparedness and Training

Long a cornerstone of public policy on the emergency preparedness of office workers around the country, the Port Authority required tenants to conduct fire drills every 6 months and appoint employee floor wardens and searchers. Sixty-six percent (n = 529) of WTC 1 and WTC 2 occupants reported participation in at least one fire drill in the 12 months immediately prior to September 11, 2001. Seventeen percent (n = 139) reported that they did not participate in any fire drills in the 12 months prior to September 11, and 17 percent (n = 135) did not know. Fire drill participation rates were similar between the two towers (as shown in Table 2–10).

Table 2–10. WTC fire drills in 12 months prior to September 11, 2001.[a]

Number of Drills	WTC 1	WTC 2
None	18 % (n = 78)	17 % (n = 61)
1	13 % (n = 57)	8 % (n = 29)
2	21 % (n = 90)	24 % (n = 88)
3	11 % (n = 47)	15 % (n = 53)
4	10 % (n = 44)	9 % (n = 32)
5–11	7 % (n = 31)	9 % (n = 32)
12 or more	3 % (n = 13)	4 % (n = 13)
Unknown	18 % (n = 80)	15 % (n = 55)

a. Percentages are weighted, n values unweighted.

One of the primary goals of fire drill training is to make occupants aware of the location of the emergency exits. Ninety-three percent (n = 490) of respondents who reported participation in a fire drill were instructed about the location of the nearest stairwell as part of the drill. However, of the respondents who reported being shown a stairwell, 82 percent (n = 432) did not enter or use the stairwell. Seventeen percent (n = 92) reported that they did use the stairs during a drill, while approximately 1 percent (n = 5) reported not knowing. Overall, more than half (51 percent [n = 415]) of the occupants had never used a stairwell in WTC 1 or WTC 2 prior to September 11, while 48 percent (n = 386) had used a stairwell. Two persons reported not knowing whether they had used the stairs previously.

Another goal of the fire drills was to introduce the floor warden system and evacuation procedures. Eighty-two percent (n = 528) of the occupants with fire drill training were aware that there was a floor warden for their floor. Approximately 70 percent (n = 557) of all occupants reported that they were aware of the evacuation procedures. When asked what those evacuation procedures comprised, however, answers varied significantly, including: wait in hallway for further instructions; do not use elevators, use stairs; meet at a designated site outside the building for a head count; or proceed down (varied number of) flights of stairs and wait. Further analysis of the understanding and implementation of the emergency procedures is under way.

Future Work

Significant additional analysis is presently under way. It is particularly important that results of questions related to the events, observations, and activities within the towers on September 11, 2001, be analyzed within the context of the findings coming from face-to-face interviews, focus groups, and other data collection activities. As with the work presented in this appendix, ongoing analysis of the telephone interviews will form the statistical basis for many significant recommendations, and there will be continued analysis of the information collected during the face-to-face interviews and focus groups.

NIST is utilizing existing computer egress models to better understand the evacuation experience on September 11, 2001. Three full evacuation scenarios are being considered: a typical full capacity building evacuation assuming the WTC tower is fully occupied—with one case considering only tenants and another case considering both tenants and visitors; a full capacity building evacuation of each WTC tower with aircraft impact damage; and a September 11, 2001, capacity evacuation from a WTC tower. NIST is using two classes of egress models in order to frame the evacuation questions: (1) partial behavior: simulates occupant movement and limited behavioral rules by including delay times, smoke effects, and occupant characteristics; and (2) behavioral: simulates movement and more comprehensive evacuation decisions and activities.

2.9 FIRE SERVICE TECHNOLOGIES AND GUIDELINES (PROJECT 8)

The purpose of this project is to build on work already done by the FDNY and McKinsey & Company by (1) fully documenting what happened during the response by the fire services to the attacks on the WTC up to the time of collapse of WTC 7; (2) identifying issues that need to be addressed in changes to practices, standards, and codes; (3) identifying alternative practices and/or technologies that may address these issues; and (4) identifying research and development (R&D) needs that advance the safety of the fire service in responding to massive fires in tall buildings.

2.9.1 Project Objectives

Project 8, Fire Service Technologies and Guidelines, has four tasks:

- **Task 1.** Collect emergency response data in cooperation with FDNY to document first responder fatalities, command and control procedures, and equipment performance. Records of interest include dispatch logs, recorded radio communications, run logs from surviving responding units, 9-1-1 records, data recorded by the FDNY, PANYNJ operations, and the NYPD, and fireground positioning of emergency apparatus. Information will also be sought on operations and function of communications systems, on-site emergency information systems, fire alarm panels, elevator control panels, standpipes and fire hoses, and other pre-positioned emergency equipment. In coordination with Project 7, Occupant Behavior, Egress, and Emergency Communications, oral history data will be collected from witnesses, those in control of emergency operations, and surviving first responders to the extent their oral history has not already been documented. Technical experts will review and conduct a fact-based analysis of the data.

- **Task 2**. Interpret the factual analysis to determine the effect on responder successes of factors such as:

  - The influence of building design (e.g., height, stairways, elevators, smoke control systems) on fire service command and control procedures, life saving operations, and safety of rescue personnel;

  - The influence of aircraft impact damage and fuel run-off on fire service command and control procedures, life saving operations, and safety of rescue personnel;

  - The impact of systems failures (e.g., communications systems, water supply, sprinklers, standpipes) on fire service command and control procedures, life saving operations, and safety of rescue personnel;

- Building occupant egress as related to fire service operations;
- The ability to fight large fires on the upper floors of tall buildings;
- The impact that the 1993 bombing of the WTC had on codes, standards, and procedures that affected first responders in tall buildings;
- Preplanning, training, and standard operating procedures (including command and control) at the time of the incident;
- Firefighter accountability, location, and tracking;
- Fire and emergency response protocols for tall buildings;
- The resources available for initial situation assessment and incident management, and practices for determining the possibility of structural collapse; and
- Communications and coordination of response activities with other authorities at the incident.

- **Task 3**. Identify alternative emergency response practices and technologies that may advance the safety and effectiveness of first responders, such as: knowledge/information systems for command and control decisions; elevator use by firefighters; firefighter tracking systems; interoperability of communication systems (occupants, firefighters, police, emergency management services); fire growth and smoke hazard prediction; structural safety monitoring, assessment and prediction; and simulation tools for training.

- **Task 4**. Report preparation. The results of this project will be synthesized into a report to describe the actions of the fire service and performance of their equipment; identify available alternatives related to fire service technology, training, and operational procedures; and identify R&D needs in support of their capability to protect the public, themselves, and vital physical infrastructure during extreme events.

2.9.2 Project Status

Task 1, Data Collection

Project 8 has collected or reviewed a large volume of data from the three primary departments that sent first responders to the WTC, FDNY, NYPD, and PANYNJ. NYÇ submitted data directly to NIST for analysis and also provided NIST with the opportunity to review other data related to the incident in their offices. The data collection and review process is largely completed. Data collected and review includes: documentary data, electronic data, and first-person face-to-face interviews.

Documentary data collected or reviewed included the following:

- Official lists of first responder fatalities
- FDNY and NYPD McKinsey & Company reports

- FDNY dispatch logs
- FDNY run logs of surviving units (CD12/CD15)
- FDNY standard operating procedures and policies
- Documents describing radio communications equipment and operations
- Review of approximately 500 interviews conducted by FDNY

The following electronic data have been collected or reviewed:

- Approximately 1,000 hours of radio and telephone communications for PAPD and other departments within the Port Authority
- NYPD Special Operations Division and Division 1 tape recordings
- NYC 9-1-1 Emergency Telephone Operator tapes
- FDNY Fire Dispatcher tapes

First-person interviews—To date, 108 face-to-face emergency responder interviews have been completed:

- 68 FDNY personnel including Commissioners, Chief Officers, Company Officers, Firefighters, and Emergency Medical Service personnel
- 24 NYPD personnel including Commissioners, Chief Officers, Aviation Officers, Emergency Service Unit personnel, and Police Officers
- 13 PANYNJ personnel including managers, directors, communications personnel, vertical transportation personnel, fire safety personnel, security personnel, PAPD Chief Officers, and Police Officers
- 3 other emergency responders including security personnel, fire safety personnel, and communications personnel

Task 2, Factual Analysis of the Collected Data

As documentary data were collected they were reviewed for information critical to understanding the emergency response at the WTC. This information has been filed relative to the source of information and the type of information. The documentary data are being compared with other data gained through communications records and recordings and first-person face-to-face interviews. The data are in the process of being coded for analysis using Atlas.ti software.

In addition, Appendix P contains results from a preliminary analysis of emergency responder communications. The objective of this analysis is to develop a better understanding of the role that emergency communications played during the WTC attack, and to quantify information related to communications effectiveness. Although there have been numerous reports of radio equipment failures during the emergency response at the WTC, and these are all being examined as part of the overall project, the only radio equipment system examined in this preliminary report is that of the FDNY WTC site high-rise repeater that was installed by the Port Authority. Many factors are associated with the ability of emergency communications to be successful. The following objectives were set in this report:

- To document radio and telephone communications operations
- To document radio communications readability or understandability
- To quantify radio communications traffic volume
- To understand the impact of traffic volume on communications readability and the transfer of information
- To identify communications associated with dispatch and arrival of responders
- To identify communications related to evacuation and emergency response operations
- To identify communications related to building conditions at the WTC and the impact of this information on the emergency response.

Results from this analysis are presented in Sections 2.9.3, Preliminary Results on Emergency Responder Communications; 2.9.4, Preliminary Findings; and Appendix P, Interim Report on Emergency Communications.

Appendix P also contains a detailed description of methods used for documenting and analyzing the communications data obtained from the various sources.

Task 3, Alternative Emergency Response Practices and Technologies

As the data analysis has progressed, issues critical to emergency responder operations are being identified. Most of the critical practices and technologies identified relate to Command and Control, Communications, and significant issues related to emergency responder high-rise building operations. This work is still in progress, and details concerning alternative practices and technologies will be addressed in the final report.

Task 4, Report Preparation

The efforts described above in Tasks 1, 2, and 3 continue. Data analysis necessary for final report preparations is ongoing. The final report outline has been drafted, and report preparation has been initiated.

2.9.3 Preliminary Results on Emergency Responder Communications

A more detailed analysis of radio equipment and systems operations is in progress, and it will be addressed in the final report. However, the following preliminary results on emergency communications provide some insight into the challenges associated with communications systems following the attack on the WTC.

All radio systems analyzed appeared to work well during the normal operations period just before the attack on the WTC. It was noted that Channel W of the PAPD was experiencing some difficulty with a handie-talkie radio transmitting a carrier wave from an open or keyed microphone. This disrupted communications on that channel. PAPD personnel were trying to correct the problem just before the first aircraft struck WTC 1. The problem continued after the attack occurred. NYPD also had a problem with an open microphone after the incident began. This occurred on the Special Operations Division (SOD) channel. Efforts made by NYPD personnel corrected the problem.

All radio communications evaluated experienced traffic volume surge load conditions as a result of the attack. Coupled with the increase of traffic load was a significant increase in a process known as "Doubling" or "Crossing" of radio signals. This condition occurs when more that one person attempts to transmit a message at the same time on the same radio frequency. Doubling results in the mixing of radio signals that seriously degrades the signal readability. This condition will often block all clear communications from getting through, except possibly from a high power base station.

2.9.4 Preliminary Findings

The following are preliminary findings based on the current status of emergency responder communications analysis:

- After the first aircraft struck WTC 1, there was an approximate factor of 5 peak increase in traffic level over the normal level of emergency responder radio communications, followed by an approximate factor of 3 steady increase in the level of subsequent traffic.
- A surge in communications traffic volume made it more difficult to handle the flow of communications and delivery of information.
- Analysis of the radio communications records received by NIST indicates that roughly one-third to one-half of the radio messages transmitted during these radio traffic surge conditions were not complete messages nor understandable.
- Preliminary analysis of the FDNY City-wide, high-rise Channel 7 (PAPD Channel 30) recording indicates that the WTC site repeater was operating.
- Communications records and interviews indicate that smoke and heat conditions on the top of the two WTC buildings prevented the NYPD helicopters from conducting safe roof evacuation operations.
- NYPD aviation unit personnel reported critical information about the impending collapse of the WTC towers several minutes prior to their collapse. No evidence has been found to suggest that the information was further communicated to all emergency responders at the scene.

Analysis of communications records and face-to-face interviews with emergency responders indicate that radio and telephone communications were a critical part of the emergency response operations. It is also clear from the evaluation that communications technology was not operating at a performance level adequate for handling emergency responder requirements at the incident.

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Chapter 3
Update on Safety of Threatened Buildings (WTC R&D) Program

3.1 OBJECTIVES OF SAFETY OF THREATENED BUILDINGS (WTC R&D) PROGRAM

This program is designed to (1) facilitate the implementation of recommendations resulting from the World Trade Center (WTC) investigation, and (2) provide the technical basis for cost-effective improvements to national building and fire codes, standards, and practices. Under the program National Institute of Standards and Technology (NIST) will develop guidance and tools to assess and reduce building vulnerabilities and will support private sector organizations that develop building and fire codes and standards in the United States. Implementation of the results will better protect building occupants and property in the future, will enhance the safety of fire and emergency responders, and will increase confidence in the safety of commercial and public buildings.

Four general areas of research are targeted to support near- and long-term improvements to reduce the vulnerability of the structure, building occupants, and first responders to potential threats:

- Increased Structural Integrity
- Enhanced Fire Resistance
- Improved Emergency Egress and Access
- Building and Emergency Equipment Standards and Guidelines

3.2 BACKGROUND AND DESIRED OUTCOMES OF SAFETY OF THREATENED BUILDINGS (WTC R&D) PROGRAM

Building and fire codes in the United States exist, among other reasons, to ensure the safety of occupants in the event of anticipated excessive loads due to wind, earthquake, and snow, and the potential for severe fires. The tragic collapse of the WTC buildings in 2001 (along with the terrorist attacks on the Pentagon, Hart Senate Office Building, and the Murrah Federal Building) has focused the general public, governments at all levels, and the construction and building products industries on the need to understand the possible impacts of terrorist acts on building operations, structural integrity, and emergency response procedures, and on the need to develop economically justifiable strategies to mitigate the potential loss of life from possible future threats.

The standard test methods and building practices upon which current building and fire codes are based rank the performance of one material, component, or system against alternative designs, with the expectation that some minimum rating translates into a sufficient level of safety of the material, component, or system when installed in a building. Safety factors are used to account for our ignorance abut the magnitude of actual loads, and of the uncertainty in response of the complex building frame to these loads.

The prediction of failure modes in a closely-coupled building system is beyond our current capability, and standard test methods provide little information on the expected performance of the building should the mechanical or thermal load exceed a prescribed value.

In addition, building designers, operators, occupants, and first responders are faced with chemical and biological threats unforeseen as little as two years ago. How should heating, ventilation, and air-conditioning (HVAC) systems be designed and operated to contain a poisonous aerosol or gas? How has the behavior of occupants changed since September 11, 2001, in responding to an emergency? Should the same emergency egress and fire service access techniques and strategies be used in the case of a biological threat as for a fire? Can new technologies be developed, or design practices adapted, to increase the safety of the building occupants without undue economic burden on the owners/operators?

Additional research and development is being conducted in this program to answer questions like these, to provide guidance and tools to assess and reduce future vulnerabilities, and to better prepare facility owners, contractors, designers, and emergency personnel to respond to future disasters, naturally or intentionally initiated.

Increasing Structural Integrity—Structural integrity will be increased through the development and implementation of performance criteria for codes and standards, tools and practical guidance for prevention of progressive structural collapse. System design concepts, retarded collapse mechanisms, built in redundancy, and hardening structures though retrofit are being considered. Performance criteria for fire safety design and retrofit of structures is being developed through examination of five key factors: the suitability of standard fire resistance test methods; the role of structural connections, diaphragms, and redundancy in enabling load transfer and maintaining overall structural integrity; the effectiveness of alternative retrofit, design and fire protection strategies to enhance structural fire endurance; the fire behavior of structures built with innovative materials; and models to predict the fire hazard to structures from internal and external fires. Guidance on methods to enhance fire resistance of steel and concrete structures based upon our current state of knowledge is being developed as well.

Enhancing Fire Resistance—Fire resistant steels exist and are in use elsewhere in the world. More efficient and accurate tests for performance of steels under building fire conditions are needed and are being developed to help industry incorporate fire resistant steels into U.S. construction practice. Fundamental mechanical and thermal properties of fire protective materials are being measured. This requires the development of new test methods and instrumentation, and a data base that spans the full range of expected temperatures and mechanical loads. These data will supplement, or may even supplant the need for, the ASTM E 119 test in certain situations, and in any case are essential to the implementation of meaningful performance codes and design criteria.

Facilities do not yet exist that are suitable for demonstrating in a quantitative manner the improved performance of new materials, systems, and processes in their end-use within a building under actual fire conditions. Hence, simulations are required to bridge the fundamental data and the results of bench- and pilot-scale tests to the environment in which they would be exposed during severe fire conditions. The severity of a fire is dependent upon many parameters that are beyond the control of the building designer, especially when one considers the range of terrorist threats that are possible. The performance in a fire of non-structural elements such as walls and ceilings is directly linked to the structural integrity of the building because a collapsed wall, ceiling, or floor exposes more areas of the building to the fire while providing additional fuel and air upon which the fire can feed. The technical basis for accurate measurement methodology and simulation tools for the inclusion of fire resistant properties of walls and ceilings in performance-based fire safety design is being developed under this program.

Improving Emergency Egress and Access—By working with the primary stakeholders (elevator and construction industries, fire services, professional societies, and code making bodies), the role of elevators in providing access by the fire service to a fire in a high rise building is being greatly enhanced over current practice. The development of hardened fire service elevators and new emergency operation procedures/controls will also lead to improved egress capabilities from tall buildings, especially for mobility-impaired or injured occupants. However, the behavior of people in an emergency situation has been altered in unpredictable ways by the events of 9/11. Current egress models may be inappropriate and/or insufficient for the design and placement of doors and stairways and the control of elevator movement. Behavioral and engineering studies are being conducted, drawing on experts in academia and elsewhere, to enable the development of simulation tools that better capture the movement of people within a building under fire and other emergency situations.

Developing Building and Emergency Equipment Standards and Guidelines—Partnering with other federal agencies and American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE), NIST-developed indoor air quality (IAQ) simulation tools are being extended to analyze and guide the assessment and subsequent reductions in the vulnerability of buildings to chemical, biological, and radiological aerosols. Standard building information models that facilitate the simulation of building system behavior during adverse events are being developed to allow communication among IAQ controls and other building controls associated with, for example, security, transportation, energy, and fire alarm systems. A user-friendly tool is being developed for building owners and managers to aid in the selection of cost-effective strategies for the management of terrorist and environmental risks. Also, facilities are being established for science-based exposures for measurement of firefighter equipment performance attributes essential to support informed fire service procurement decisions.

3.3 ACCOMPLISHMENTS OF WTC R&D PROGRAM

Prevention of Progressive Collapse

Buildings that are designed according to modern building codes are not expected to collapse during their service life period. They are designed typically to resist traditional governing vertical loads and lateral loads such as wind and earthquake. This situation is changing, however, due to an increase in deliberate terrorist attacks. In general, a terrorist attack may lead to failure of a small part of a building. When an initial local failure causes the loss of gravity load capacity in the structural frame, the failure spreads from story to story, which may lead to the total collapse of an entire building or a disproportionately large part of the building. This type of collapse is defined as "progressive collapse" (see Fig. 3–1). At present, U.S. building codes do not provide explicit provisions to enhance the resistance to progressive collapse. In terms of magnitude and probability of occurrence, the traditional vertical and lateral design loads are quantifiable. In contrast, terrorist loads are difficult to quantify as to size, location, and the nature of the loads. Terrorist attacks may include thermal, impact, or blast loads. Thus, in order to improve resistance to progressive collapse, U.S. building code developers have attempted to incorporate into the codes structural redundancies by introducing prescriptive requirements for "structural integrity." Changes are needed in the way buildings are designed and constructed so that resistance to progressive collapse is provided explicitly. Following the 2002 National Workshop, NIST is working jointly with the Multihazard Mitigation Council of the National Institute of Building Sciences and industry experts to produce a "Best Practices Guide" for mitigating progressive collapse of buildings for design professionals. This document will be published in FY2004. Subsequent research efforts will focus on the development of tools to assist design professionals in the design of new buildings against progressive collapse and methods to enhance the resistance of existing buildings to progressive collapse.

Figure 3–1. Ronan Point Collapse in 1968.

Fire Safety Design and Retrofit of Structures

Current building design practice does not consider fire as a design condition to predict and evaluate structural performance in the presence of an uncontrolled fire. Instead, fire endurance ratings of building members, derived from standard fire endurance tests, are specified in building codes. At the present time, there is no accepted science-based set of verified tools to evaluate the fire performance of entire structures under realistic fire conditions. Thus, there is an urgent and critical need to develop and implement verified and improved standards, technology, and practices that explicitly consider structural fire loads in the design of new structures and the retrofit of existing structures. A workshop was held recently in cooperation with the Society of Fire Protection Engineers to assess current fire safety practice and existing codes and standards, and to identify research gaps for an improved fire safety design and retrofit approach. The workshop was attended by national and international fire safety experts and provided the technical basis for the development of a national R&D roadmap for Fire Safety Design and Retrofit of Structures.

In addition, an evaluation has been performed of state-of-the-art numerical tools, including ANSYS and SAFIR, to assess their suitability for use in analyzing performance of structures under the combined fire and mechanical loadings. The evaluation process of these analytical platforms, which are rarely used in practice for fire safety design, is ongoing and necessary due to the complexity of structural systems, loading conditions, boundary conditions, and the highly nonlinear nature of material and structural behaviors. The effect of high thermal loading on structural performance of tested concrete columns, WTC steel connections, members, and subassemblies was examined. To better inform the modeling effort, a series of large-scale tests were conducted of steel components in a fire environment (see Fig. 3–2 and Fig. 3–3). The tested components included steel rods, columns, and open-web steel joists that were either left bare or had sprayed-on fire protective insulation material of varying thickness. Test fires were generated using liquid hydrocarbon fuels to produce medium-soot fires and high-soot fires, and the tests were continued until the temperature at any steel surface approached approximately 600 °C.

Figure 3–2. Insulated steel trusses, steel rod and steel column inside the NIST large-scale fire laboratory.

Figure 3–3. View of fire compartment from air exhaust outlet several minutes after the start of a fire test. Note: the flame impingement on the steel trusses and bar.

Fire Resistant Steel

Structural steel loses strength at building fire temperatures, leading to the need for fireproofing (see Fig. 3–4). Fireproofing adds costs and can be damaged or removed from the structure in a blast situation or unanticipated impact. In contrast, a new class of fire-resistant steels is specifically designed to retain more of the design strength at high temperature. These steels are being produced in Japan and Europe, and are now in use, either with or without additional fire protection. The use of fire-resistant steels leads to cost savings and schedule benefits during construction when application of fire protection can be avoided, and enhanced performance when protection is applied in the case of damage to the insulation. Unfortunately, the benefits of fire-resistant steel are not adequately tested under the standard U.S. structural fire standards (ASTM E 119), and thus, are not currently used in the U.S.

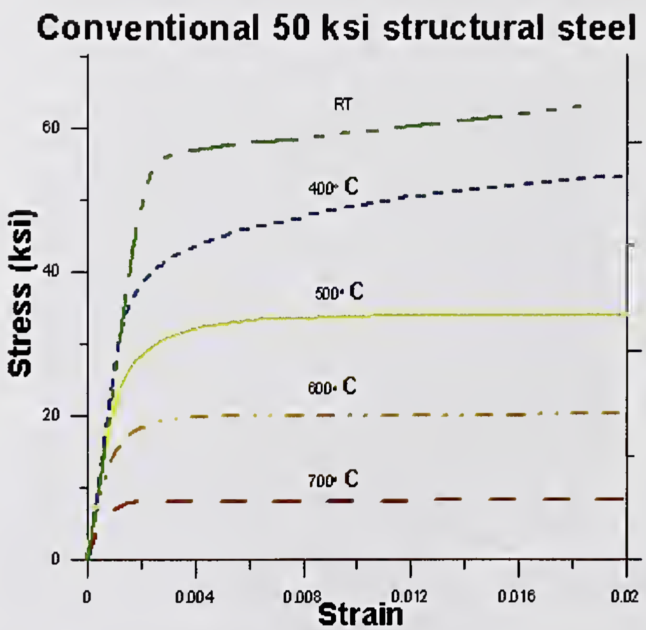

Figure 3–4. Stress-strain curves of a conventional structural steel, showing degradation of properties at high temperature.

A project has been initiated to ascertain which properties of steel are critical for efficient use of fire-resistant steels, such as high temperature strength and creep (see Fig. 3–5). Conventional steels and fire-resistant steels are being characterized to determine these critical properties. Our goals include both provision of accurate data on fire-resistant steels and development of quick and accurate tests for measuring relevant high temperature properties.

Figure 3–5. High temperature tensile tests to measure performance of structural steel at temperatures found in building fires.

Methodology for Fire Resistance Determination

Compartmentation is the cornerstone of limiting room-to-room and building-to-building fire spread. Standard fire resistance testing of wall/floor/ceiling assemblies provides an indicator of fire resistance and has proven valuable over time. However, these procedures have significant limitations that restrict their value for performance-based design and especially for high-risk occupancies. These limitations include: (a) standard time-temperature curves that may not be sufficient for all threats; (b) uniform heating, while many fires produce hot spots that may make the tests non-conservative; (c) single point thermal measurements; (d) pass/fail criteria, which make adaptation to other fire scenarios difficult; (e) documentation of the initial failure mode, but not the relative time to any successive modes, and (f) relative ratings, not absolute values.

Compartmentation is especially important in tall buildings, where the egress of numerous occupants can be a complex process, and barriers to the spread of flame keep the egress paths open, extend the time available for escape, and increase the safe time in places of refuge. For all these functions, it is necessary to know, in terms of real time, how long the interior partitions in a building will contain flames and smoke.

NIST has embarked on a course to provide such a methodology for inclusion in performance-based design of buildings. The research involves obtaining real-scale experimental data, modeling the behavior of partitions as they are driven to failure by fire, and developing recommendations for obtaining the input parameters from modifications of standard fire resistance tests such as ASTM E 119 and ISO 834. The initial work will focus on non-loadbearing walls of gypsum panels and steel studs, the most common interior construction in tall buildings. A continuing effort will extend the research to glass-panel walls.

The modeling effort will be done in three steps. First is a simple model for failure, beginning with crack initiation and propagation, continuing to the supporting structure, and finally to the fasteners and their failure points. This is now underway. The second component will be development of a detailed model of the partition materials to ascertain what additional data need to be obtained from the test method. The third component is development of a detailed model of a partition assembly for use by building design and engineering firms.

A series of real-scale compartment tests is providing information on the phenomenology of partition response and failure and also quantitative information to guide the model development (see Fig. 3–6). Various wall assemblies 2.44 m x 2.44 m were exposed to intense fires from the time of ignition to beyond flashover. Flux meters provided time histories of the energy incident on the walls. Thermocouples and infrared videos provided data on the transport of heat through the walls and on the progress toward perforation.

Figure 3–6. NIST measured the thermal behavior of gypsum/steel wall assemblies subjected to severe fire conditions.

Emergency Use of Elevators

This project is aimed at the development and implementation of protected elevators that can be used for fire department access and occupant egress during emergencies in tall buildings. The general strategy is to first incorporate into U.S. codes and standards a protected elevator system for fire department access. These are known in other countries as firefighter lifts, and there are existing requirements for these in at least 12 countries (as identified in a report by ISO TC178 on Elevators and Escalators). Once the U.S. fire services are satisfied that elevators are safe and reliable during fires, codes and standards would be changed to recognize protected elevators for occupant egress, secondary to, or integrated with, stairs.

The key technological advancement offered in the NIST strategy is the (new) concept of remote manual control. Here, the elevator system safety is monitored in real time by the fire alarm system and displayed on a standardized fire service interface developed jointly by NIST and the fire alarm industry, through the National Electrical Manufacturers Association (NEMA) and implemented in the 2002 edition of the

National Fire Alarm Code (NFPA72). This system addresses residual concerns held by the fire service and elevator industry even where such systems are utilized under existing codes and standards. The system might be further specified for accessible elevators required in U.S. and other building codes for access by people with disabilities but where the safety for use in egress during fires is still considered questionable.

Several technical papers have been written by NIST and presented at a recent international conference on Tall Buildings organized by International Council for Research and Innovation in Building and Construction (CIB) and Council on Tall Buildings and Urban Habitat (CTB&UH). NIST organized and chaired the speakers' session on emergency use of elevators, which included papers by two of the largest U.S. elevator companies (Otis and Kone). NIST also co-sponsored and presented papers at a workshop in March 2004, organized by American Society of Mechanical Engineers (ASME) and their A17 committee, who are responsible for the standard convening the safe use of elevators referenced in all U.S. building codes. NIST is working with the key representatives of the elevator industry and regulators represented on the A17 committee and with the product development engineers at Otis and Kone to implement the required technology and interfaces into their elevator controls, and on a novel approach to work out changes to the elevator control software for emergency operations protocols during fires. This approach would utilize NIST Virtual Cybernetic Building Testbed (VCBT) to allow numerous simulations of building fires to test the ability of the control software to adapt to conditions and to maintain safe operations.

Workshop on Building Occupant Movement During Fire Emergencies

NIST, in cooperation with the United Technologies Research Center, hosted a 2-day workshop focusing on the needed research on occupant behavior and movement during building emergencies. This workshop was motivated by a renewed interest in how buildings should be evacuated during fire emergencies and by the desire to provide a forum for the exchange of experiences among the fire and non-fire communities working on emergency egress. Sessions were held on codes and standards requirements for building evacuation, data needs for predictive building movement models, building movement strategies, and a roundtable discussion among selected government agencies. Participants included national and international experts in building occupant movement, representing the academic, consulting engineering, building products, and codes and standards communities. An outcome of the workshop will be the identification of areas where research is needed most to aid government agencies, industry and academic researchers in prioritization of their resource investments.

Guidelines and Technologies for Mitigation of Chemical, Biological and Radiological Aerosol Attacks

The increased attention to the potential vulnerability of buildings to airborne chemical, biological and radiological (CBR) agents has led to the need for better simulation tools to evaluate the transport and fate of such agents in buildings. NIST's longstanding expertise in airflow and contaminant transport modeling in buildings systems has been employed in many such analyses, and recently these capabilities have been extended via the release of version 2.1 of the CONTAM software. Among other enhancements, CONTAM is now able to use the output of exterior plume models as an input, such that outdoor contaminant concentrations from an exterior agent release can vary as a function of opening location on the building façade and time. This new capability allows users to link their exterior transport models to CONTAM and allow detailed analyses of the impact of an exterior release on indoor concentrations. In addition, CONTAM version 2.1 has improved models of particulate contaminants and has added fan and damper transients to the ability to simulate controls. The updated CONTAM model is now being used by an increasing number of researchers and practitioners in their evaluation of specific buildings and of technologies with the potential to increase building protection (see Fig. 3–7).

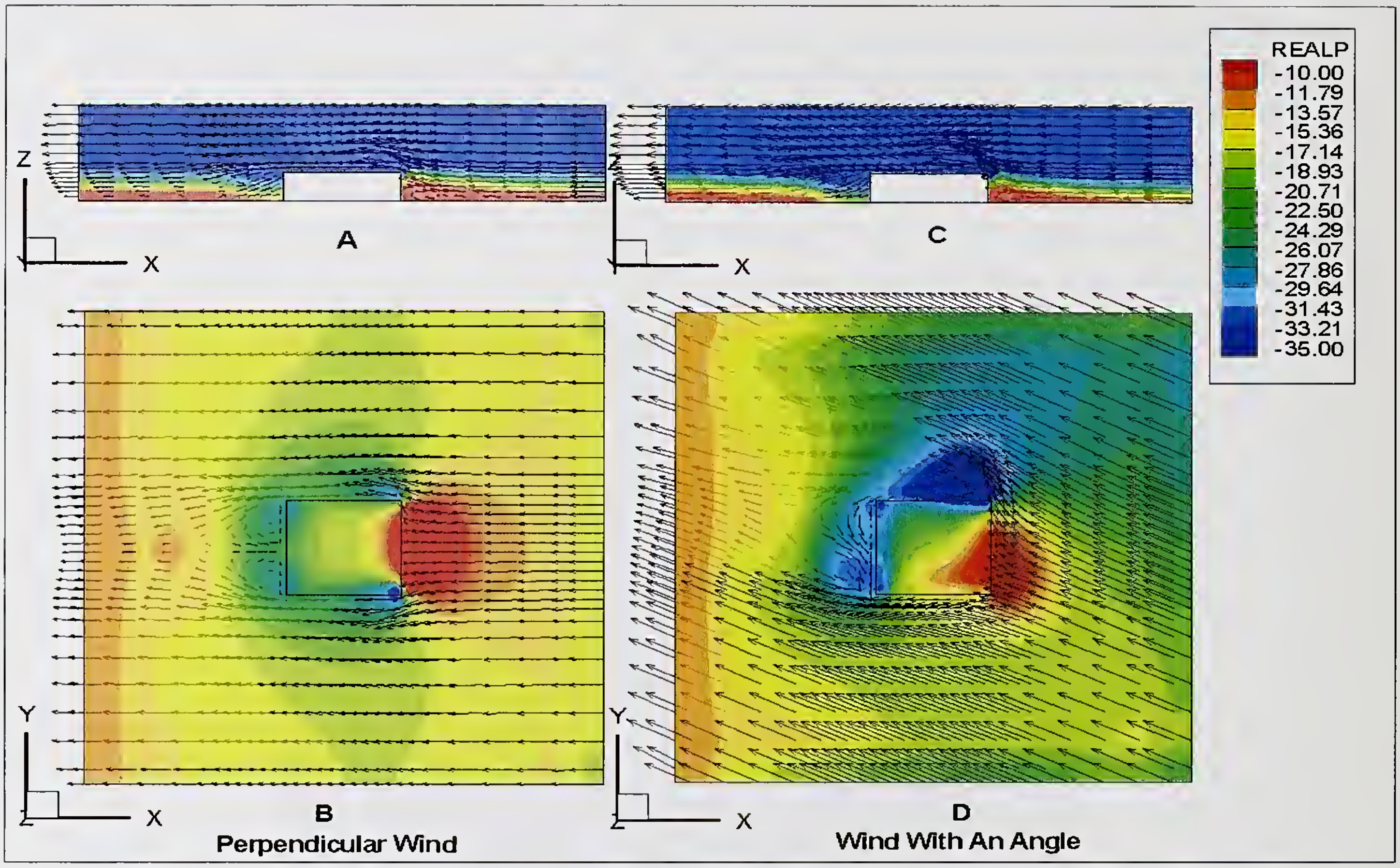

Figure 3–7. Exterior flow field as input to CONTAM model of building.

Cost-Effectiveness Tool for Managing Terrorist Risks in Constructed Facilities

Owners and managers of constructed facilities are faced with the task of responding to the potential for future terrorist attacks in a financially responsible manner. An economic tool is needed to direct limited resources to investments in mitigation strategies that will provide the most cost-effective reduction in personal injuries, financial losses, and damages to buildings, industrial facilities, and infrastructure.

The economic tool under development by NIST is a decision methodology, embedded in user-friendly, decision-support software, that helps building/facility owners and managers choose the most cost-effective mix of mitigation strategies. Three mitigation strategies are considered: (1) engineering alternatives; (2) management practices; and (3) financial mechanisms. The economic tool will provide decision makers with the basis for generating a risk mitigation plan that responds to the potential for future terrorist attacks in a financially responsible manner.

Early in 2002, NIST prepared a white paper outlining the tool development effort. NIST used the white paper to solicit stakeholder inputs, create opportunities for collaborative efforts, and form a technical working group of individual external subject matter experts. This has resulted in collaborative efforts with the Wharton Risk Management and Decision Processes Center, the Construction Industry Institute, ASTM International, and the U.S. Environmental Protection Agency. Safe Buildings Program. An expanded version of the white paper entitled "Economic Approaches to Homeland Security for Constructed Facilities" was delivered at the September 2002 CIB Meeting in Cincinnati as the invited Keynote Address.

Significant recent products include a prototype version of the software and a NIST Internal Report illustrating the methodology via a case study building. The prototype version of the software was completed and presented to the Steering Committee in September 2003. The prototype includes the software's graphical user interface and linkage to database files and key reports. The beta version of the software is planned for completion in 2004; it will facilitate a variety of user-specified analyses. All analyses employed in the software will be consistent with ASTM standard practices. A case study report illustrating how to apply the life-cycle cost method (ASTM E 917) to a prototypical commercial building renovation project was published in NIST IR 7025. A subsequent technical report documenting the decision methodology is planned for publication in 2004.

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Chapter 4
UPDATE ON THE WTC DISSEMINATION AND TECHNICAL ASSISTANCE PROGRAM

4.1 OBJECTIVES OF THE WTC DISSEMINATION AND TECHNICAL ASSISTANCE PROGRAM (DTAP)

An industry-led dissemination and technical assistance program (DTAP) is the third part of the National Institute of Standards and Technology (NIST) response plan. The 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 practical guidance and tools to better prepare facility owners, contractors, architects, engineers, emergency responders, and regulatory authorities to respond to future disasters. The DTAP is an important component of the World Trade Center (WTC) Response Plan because it will facilitate the timely adoption and widespread use of proposed changes to practice, standards, and codes resulting from the WTC Investigation and the research and development (R&D) program.

4.2 BACKGROUND AND DESIRED OUTCOME OF DTAP

NIST is working closely with other government agencies; with the engineering and architecture professions; with the construction and manufacturing industries; with authorities having jurisdiction over building and fire code enforcement; and with national code-making organizations to target building safety issues (including those identified in the Federal Emergency Management Agency (FEMA) Building Performance Study) that (1) could be addressed by expeditious revision to national building codes, standards, and practices based upon current knowledge, and (2) would benefit from additional research. The mechanism by which this is being done is through contracts to the private sector. About $1 M has been spent to date since the start of the WTC Investigation. The objectives of each contract are described in the following section. Note that these contracts are over and above those in direct support of the Investigation and that the DTAP will continue beyond the completion of the WTC Investigation.

4.3 ACCOMPLISHMENTS OF THE DTAP

Contracts have been issued to the following organizations: the Civil Engineering Research Foundation (CERF), the National Institute of Building Sciences (NIBS), the National Conference of States on Building Codes & Standards, Inc. (NCSBCS), the Construction Industry Institute (CII), Integrated Manufacturing Technology (IMTI), the Society of Fire Protection Engineering (SFPE), and the Wharton School of Business.

National Workshop on Progressive Collapse (NIBS)

The Multihazard Mitigation Council of NIBS conducted a workshop in February 2004 that brought together national experts who have an interest in mitigating the threat of progressive collapse. The two-day workshop included presentation of ten white papers to frame the issues associated with mitigation of progressive collapse with respect to guidelines, codes, design of new buildings, and retrofit of existing buildings. The workshop also included breakout sessions on the topics of development of codes and guidelines, structural systems and analytical methods, and existing buildings. The breakout sessions resulted in identification of research needs and included estimation of costs to address each of those needs. The workshop also provided an opportunity for industry to review and comment on draft guidelines for retrofit of existing buildings and design of new buildings to resist progressive collapse.

Information Technology in the Building Regulatory Process (NCSBCS)

The National Alliance for Building Regulatory Reform in the Digital Age, a public-private partnership, will continue action on its agenda to stimulate economic recovery, enhance public safety, and increase the security of buildings. The agenda 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. This effort includes support for the development and initial testing of a prototype secure database for first responders of as-built designs, evacuation plans, and other contact information.

National Alliance Interoperability Project (NCSBCS)

The objective of this project is to speed the development of technologies and requirements needed to advance the creation of a state-of-the-art integrated and interoperable building regulatory system by developing, in collaboration with New York City, an interoperability statement. This statement is to be included in their fall 2003 request for proposals for permitting software services and holding a national summit workshop with the software industry to identify common data requirements for currently available software component systems, common data/information formats, and recognized standards and best practices. The workshop will also identify actions that the industry and the National Alliance and state and local jurisdictions can take together to generate national standards for interoperable hardware and software for use in the building codes adoption, administration, and enforcement processes.

Strategies, Candidate Liaison Teams, and Actions to Conduct and Implement the NIST Response Plan (NIBS)

The NIST response plan and R&D program and the NIST outputs will be reviewed. Strategies will be suggested for achieving the private sector and state and local involvement needed to assure the likelihood of implementing each of the final products and for assessing their impacts in use. Synergistic benefits will be identified beyond those relevant to homeland security for which the outputs and strategies hold promise. The contractor will identify potential liaison teams and develop action plans for implementation of each product, or group of products. The liaison teams will include potential advocates, and those with serious concerns from public and private sector organizations most likely to be affected by the product.

Capital Projects Technology Roadmap (IMTI)

The baseline Capital Projects Technology Roadmap is being updated to address technological issues and solution paths related to homeland security and economic development. An outcome of this effort will be a detailed plan for the necessary R&D to support the deployment of technological solutions. Specific tasks include a workshop with FIATECH, follow-on meetings with technical experts, and review and teambuilding with top-level executives from the construction/capital facilities industry.

Benchmarking Homeland Security Construction Practices (CII)

The goal of this effort is to collect information on 9/11-driven security initiatives from industry leaders in the areas of chemical manufacturing, oil production and refining, natural gas processing and distribution, water treatment, and other critical industries needed to support the Nation's infrastructure. Information collected as part of a series of regional workshops and field site visits shall establish a basis for identifying best practices related to the security of capital facilities projects, and provide the basis for assessing the impacts of these practices on the key project outcomes of cost, schedule, and safety.

Best Practices Guidelines for the Mitigation of Progressive Collapse of Buildings (NIBS)

NIBS has begun to formulate a course of action that will increase the design and construction community's understanding of progressive collapse and provide practitioners with appropriate guidance. Draft guidelines have been completed and were reviewed by national experts during a February 2004 workshop. The draft is currently being revised, and a complete draft is planned for publication in September 2004. Following publication of the draft guidelines, a series of regional seminars is planned to educate practitioners and gather additional input that will be used to finalize the guidelines.

Workshop on Structural Fire Resistance (SFPE)

An international group of experts was convened in early October, 2003, to examine different technical aspects associated with structural fire resistance and to develop a detailed roadmap identifying research gaps to be filled to meet industry needs. Ten detailed white papers were presented by leading national and international experts on topics relevant to fire resistance of building structures. Workshop attendees supported the development of a best-practices manual for structural fire protection, including design and analysis tools, to add to the knowledge base and aid building officials in evaluating the adequacy of performance-based rather than “prescriptive” designs. The participants also developed a list of actions/research needs having the highest priority in developing best practices for fire design and retrofit of structures.

Accelerating Technologies/Systems for Fire Protection of Structural Steel in High Rise Buildings (CERF)

There are a number of objectives for this study. The first is to conduct a brief review of the types of materials and systems that are in use, in development or proposed for fire safety protection of structural steel in high-rise buildings. A second objective is to identify the performance requirements for such systems, including fire resistance, durability, impact and/or vibration resistance. A workshop was held in February 2004. In preparation for the workshop, white papers were developed on the topics cited above to frame the issues. Participants developed a prioritized set of recommendations to address technical and procedural/organizational issues.

Cost-Effective Risk Management (Wharton, CII)

The Wharton Risk Management and Decision Processes Center is expected to deliver in October 2004 a draft report covering (1) economic incentives for mitigation of consequences of extreme events (e.g., natural disasters and terrorism) and (2) procedures for estimating potential benefits and costs of alternative mitigation measures. The CII has developed a security rating index for industrial facilities. It is planned to be published by October 2004 in a report entitled *Best Practices for Project Security.*