NIST Response to the World Trade Center Disaster

U.S. Federal Building and Fire Safety Investigation of the World Trade Center Disaster

WTC Technical Conference

September 13, 2005

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U.S. Department of Commerce

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National Context for WTC Investigation

- The collapse of the World Trade Center structures following the terrorist attacks of September 11, 2001 was among the worst-ever building disasters in recorded history – killing 2749 people.
- More than 400 emergency responders were among those killed, the largest loss of life for this group in a single incident.
- Strong private sector, public, and Congressional demand for a comprehensive response to the World Trade Center disaster.
- Congress passed and the President signed into law on October 1, 2002, the National Construction Safety Team (NCST) Act.
    - Gives NIST authorities to investigate building failures.
    - Modeled after the NTSB, with some differences.

Stakeholders and Partners

Construction Industry
CII, IAI, CERF, FIATECH, NIBS, AGC

Fire & Emergency Service
IAFC, NASFM, IAFF, FDNY, NYPD,…

Other Government Agencies
FEMA, ATF, FBI, DOD, USACE, DOE, DTRA, NIOSH, CDC, GSA, State, NSTB, NRC, IRC/NRCC, NCSBCS,...

Public/Groups
Skyscraper Safety,..
Occupants/Witnesses
Entrepreneurs/Inventors
Small Businesses,
Students,...

Codes and Standards Organizations
ASCE, AISC, ACI, ICC, NFPA, ASHRAE, ASTM, ANSI, ISO,

Public-Private Response Plan

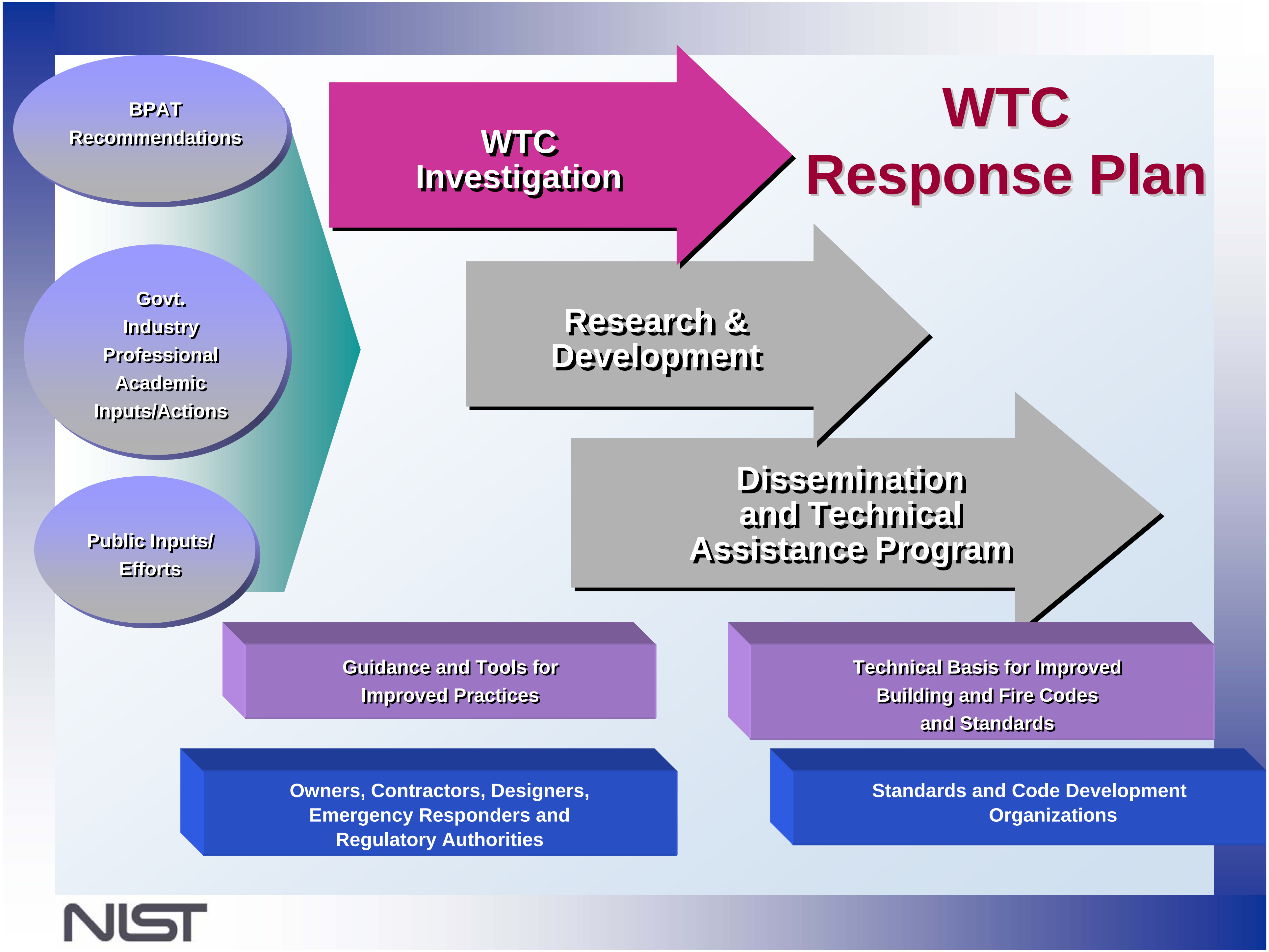
Academics
IAFSS, ASME, LANL, MIT, Princeton, Northwestern, UT Austin, Georgia Tech, Penn State, Drexel, Wharton, Columbia, Lehigh, UMd, WPI,…

Structural Engineering and Design
AIA, Council on Tall Buildings and Urban Habitat, SEAoNY, TMS, NCSEA, CASE, NYC/DDC, NYNJ Port Authority

Industry Suppliers
W.R. Grace,
United Technologies,
Sensors, Controls,…

Fire Safety Engineering
Private Consultants, SFPE,…

Insurance/ Testing labs
UL, FM Global, SwRI, IRI


WTC
Response Plan
BPAT
Recommendations
Govt.
Industry
Professional
Academic
Inputs/Actions
Public Inputs/
Efforts
WTC
Investigation
Research &
Development
Dissemination
and Technical
Assistance Program
Guidance and Tools for
Improved Practices
Technical Basis for Improved
Building and Fire Codes
and Standards
Owners, Contractors, Designers,
Emergency Responders and
Regulatory Authorities
Standards and Code Development
Organizations

Investigation Objectives

- Determine:
  - why and how the WTC Towers collapsed following the initial impact of the aircraft, and
  - why and how the 47-story WTC 7 collapsed
- Determine why the numbers of injuries and fatalities were so low or high depending on location, including technical aspects of fire protection, occupant behavior, evacuation, and emergency response
- Determine the procedures and practices that were used in the design, construction, operation, and maintenance of the WTC buildings
- **Identify, as specifically as possible, areas in current national building and fire model codes, standards, and practices that warrant revision**

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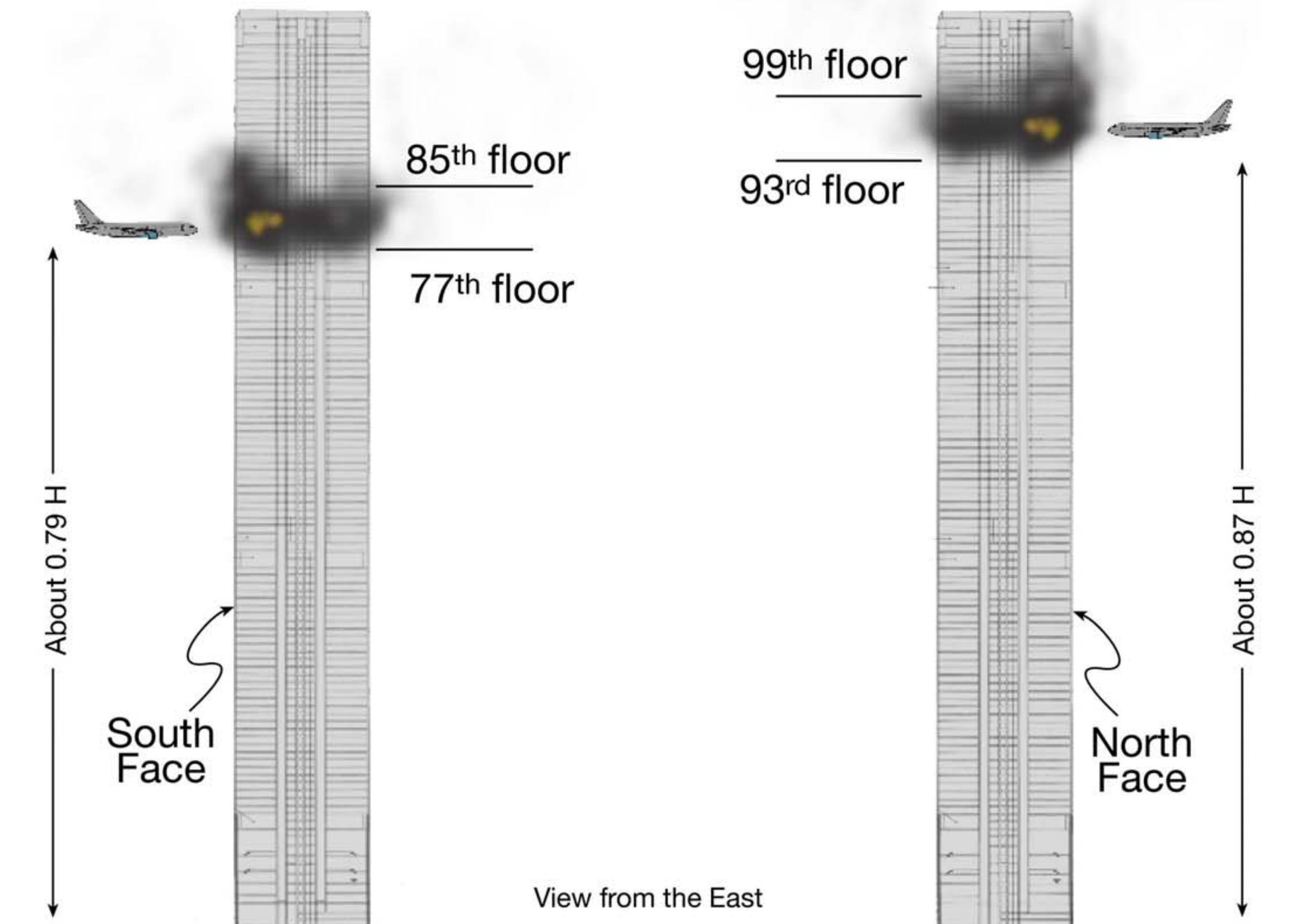
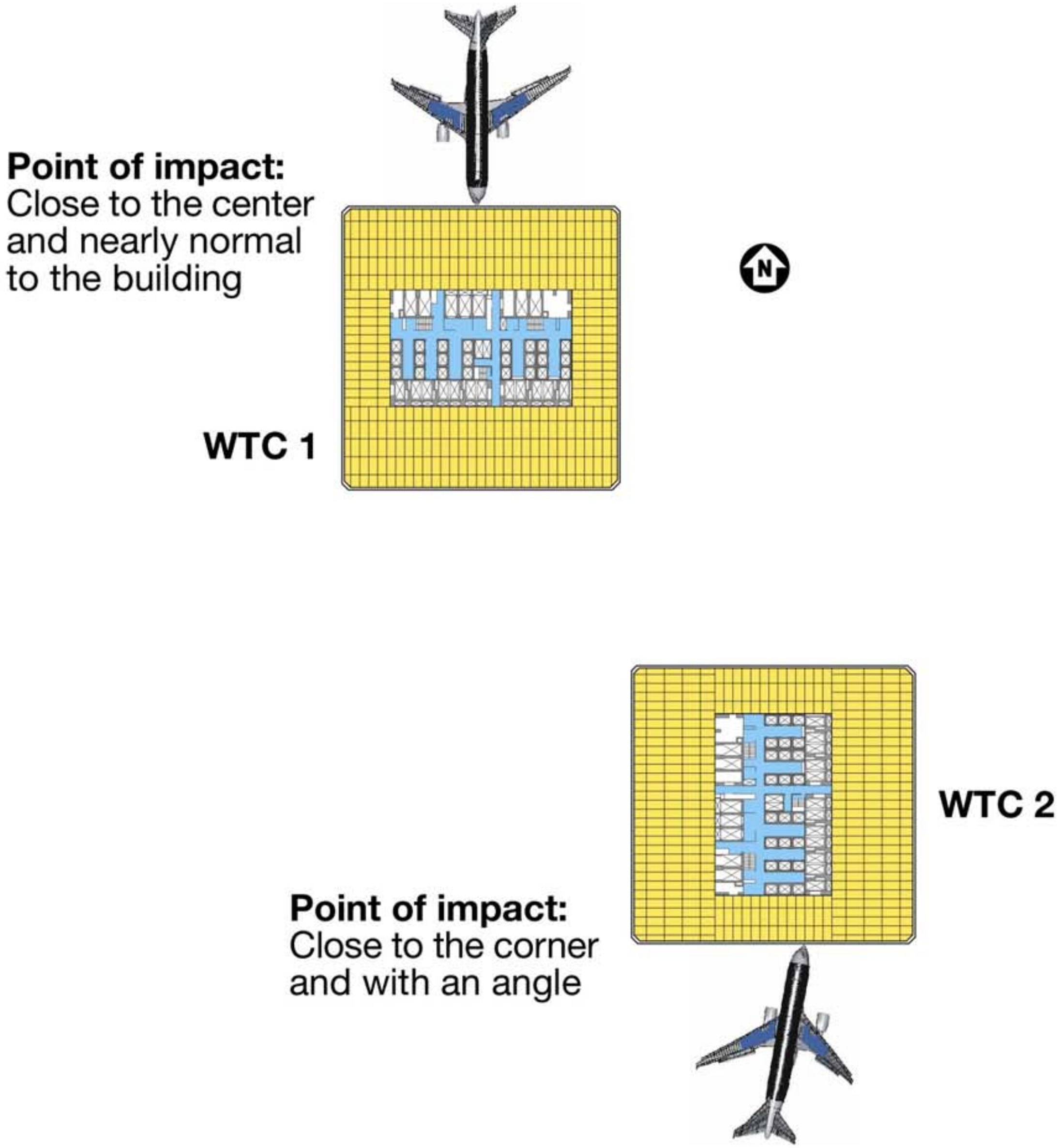


WTC 2: Hit at 9:02:59 a.m.
Collapsed after 56 minutes

WTC 1: Hit at 8:46:30 a.m.
Collapsed after 102 minutes


Point of impact:
Close to the center and nearly normal to the building
WTC 1
N
WTC 2
Point of impact:
Close to the corner and with an angle

Some Specific Questions

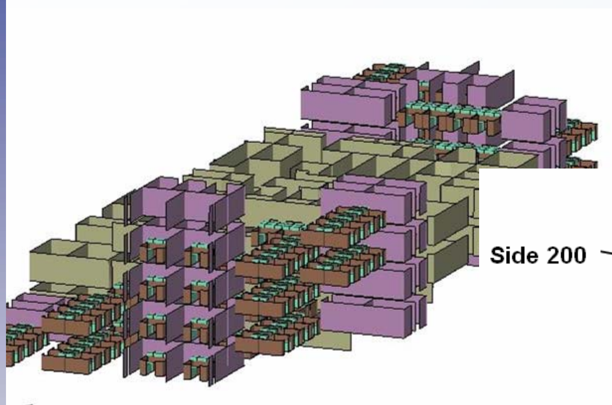
- How and why did WTC 1 stand nearly **twice** as long as WTC 2 before collapsing (102 min. vs. 56 min.) though they were hit by virtually identical aircraft?
- What factors related to **normal** building and fire safety considerations not unique to the terrorist attacks of September 11, 2001, if any, could have delayed or prevented the collapse of the WTC towers?
- Would the undamaged WTC towers have remained standing in a **conventional** large building fire scenario?
- 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?
- 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?

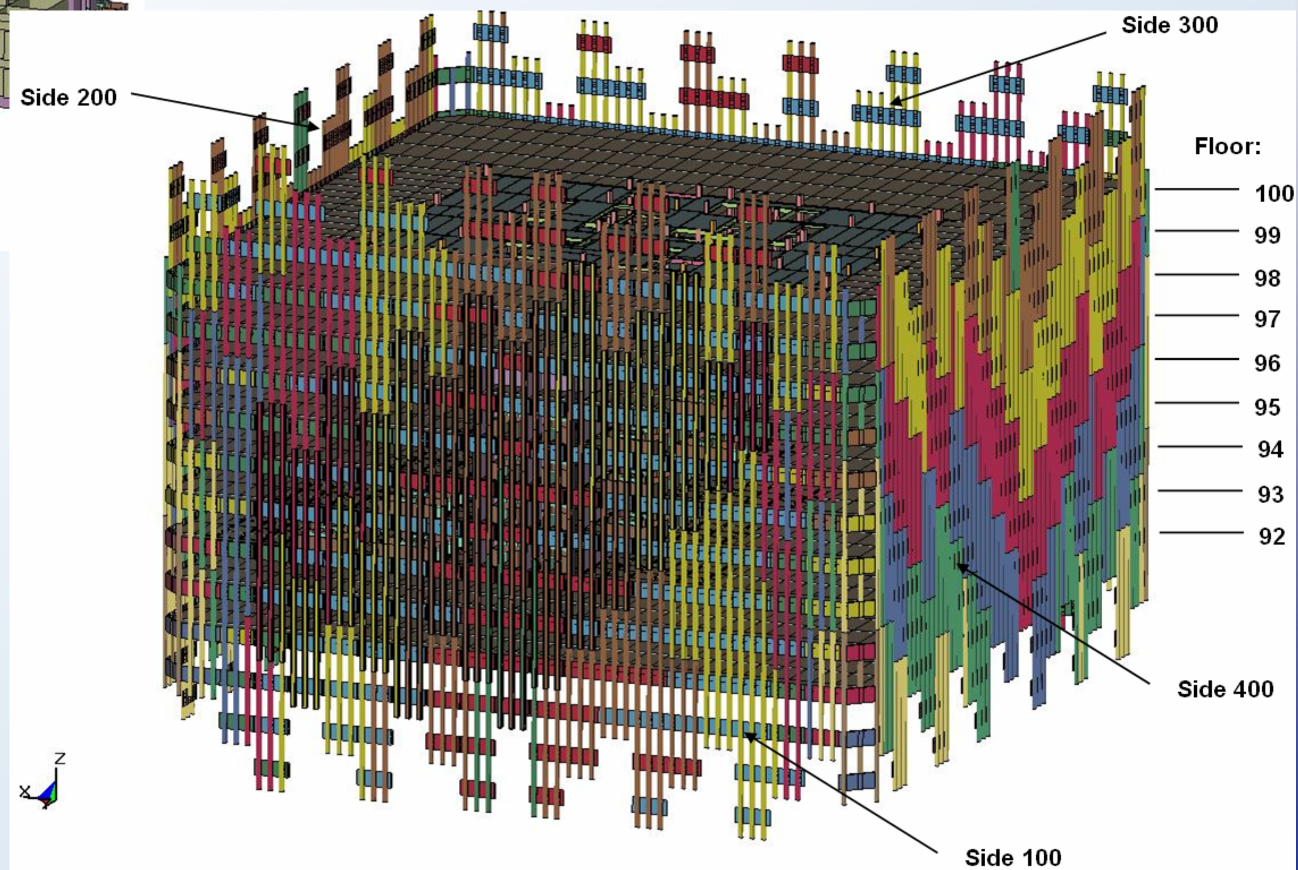
Analysis of Probable Collapse Sequences

NIST developed and used a series of rigorous and comprehensive models to determine the probable collapse sequence for the WTC towers, from aircraft impact to collapse initiation. The approach:

- Analyzed the complete sequence of events from aircraft impact to the spread of jet-fuel-ignited multi-floor fires, thermal weakening of structural components, and the progression of local structural failures that ultimately initiated collapse of the buildings.
- Combined mathematical modeling, well-established statistical and probability-based analysis methods, laboratory experiments, and analysis of visual and physical evidence—**significantly advancing the current state-of-the-art and testing the limits of current computational capabilities.**
- Required use of **advanced strategies for managing computational demands due to unprecedented analysis complexity and sophistication**; **adequately captured the physics of phenomena essential to determining the probable collapse sequence**.

WTC 1 Tower Model for Aircraft Impact Analysis





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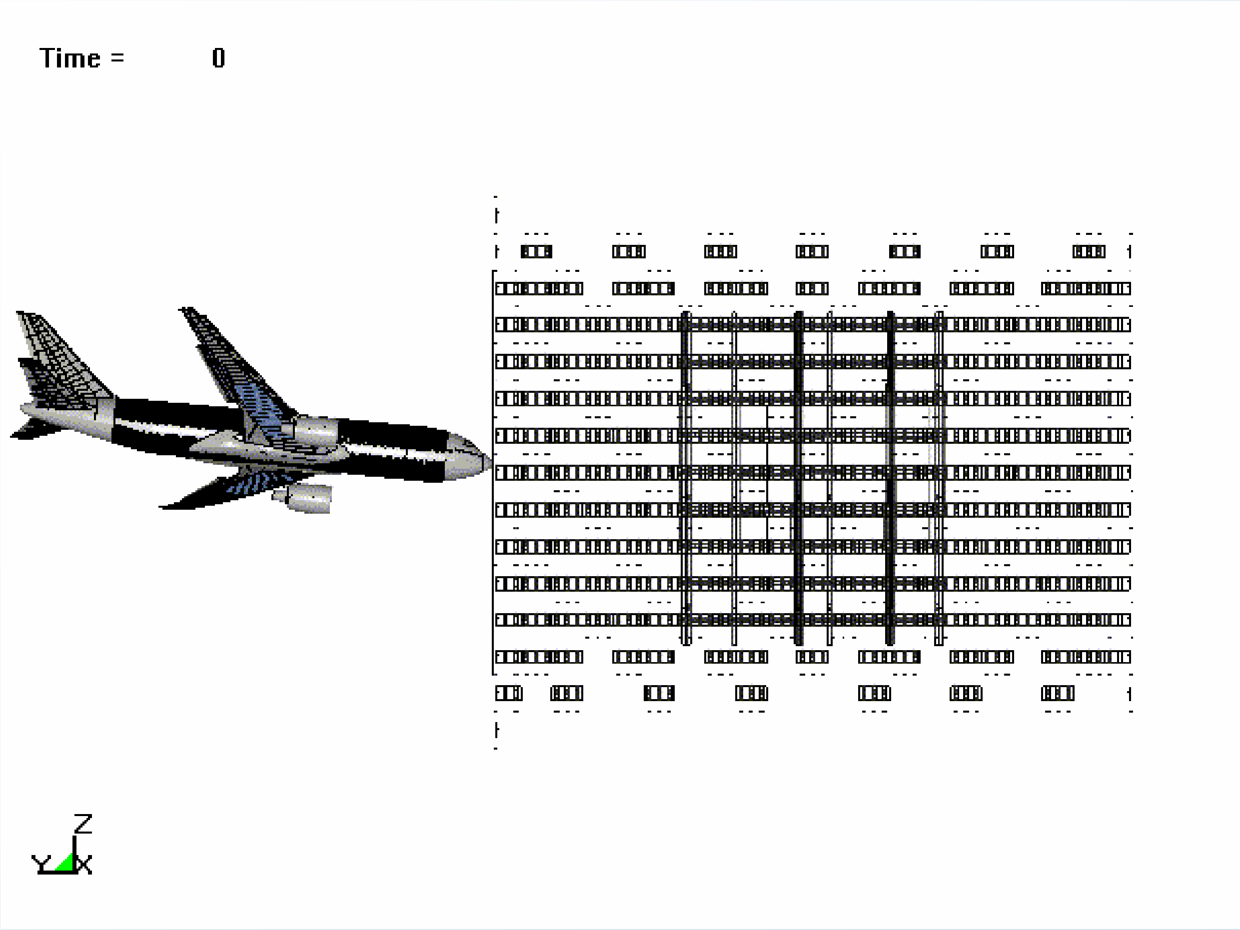
WTC 1



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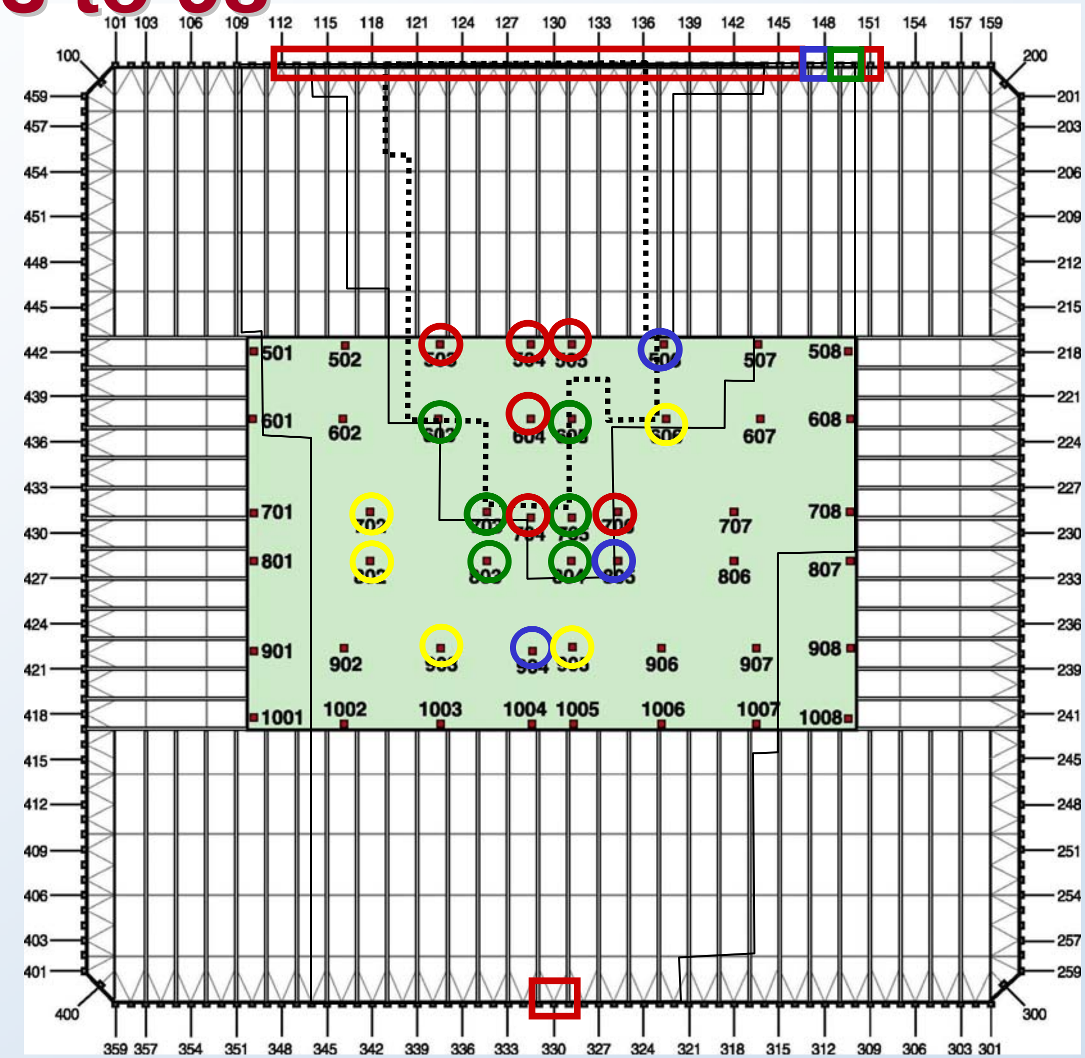
WTC 1 Damage: Composite Summary for Floors 93 to 98



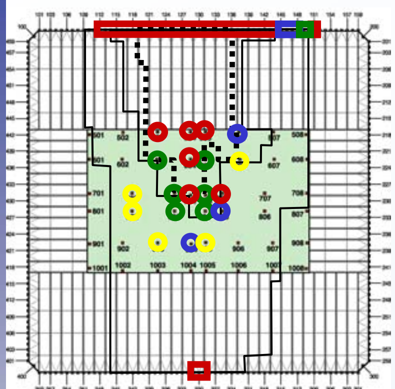
Severe Floor Damage

- Fireproofing and partitions
- Floor system structural damage
- Floor system removed

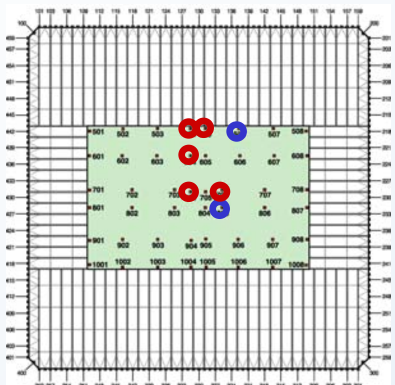
Column Damage

- Severed
- Heavy Damage
- Moderate Damage
- Light Damage

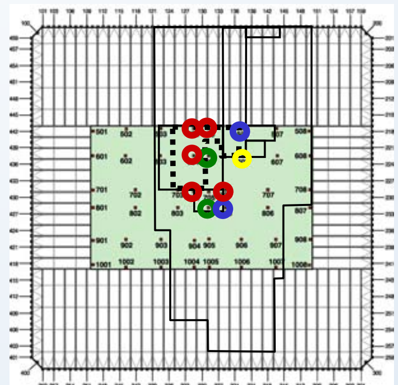
WTC 1 Damage by Floor



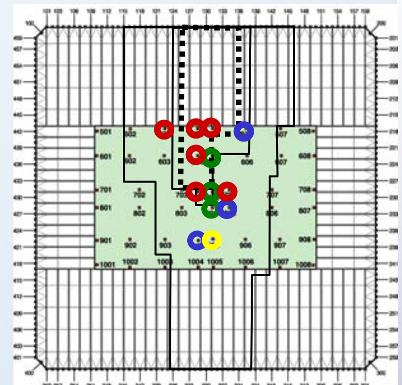
Floors 93 to 98
Cumulative Damage



Floor 93



Floor 94



Floor 95

Severe Floor Damage

Fireproofing and partitions

Floor system structural damage

Floor system removed

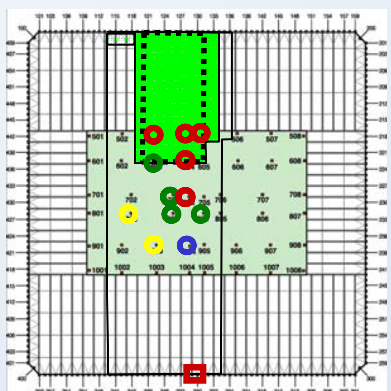
Column Damage

Severed

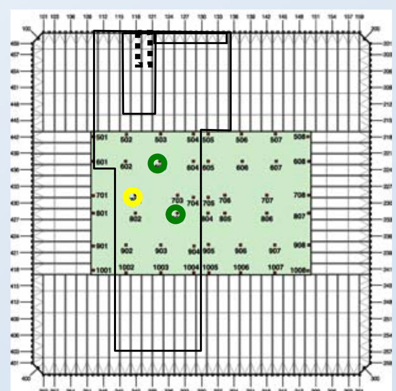
Heavy Damage

Moderate Damage

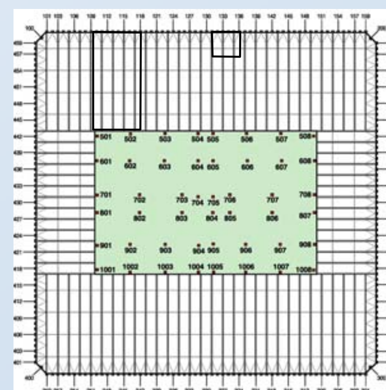
Light Damage



Floor 96



Floor 97



Floor 98

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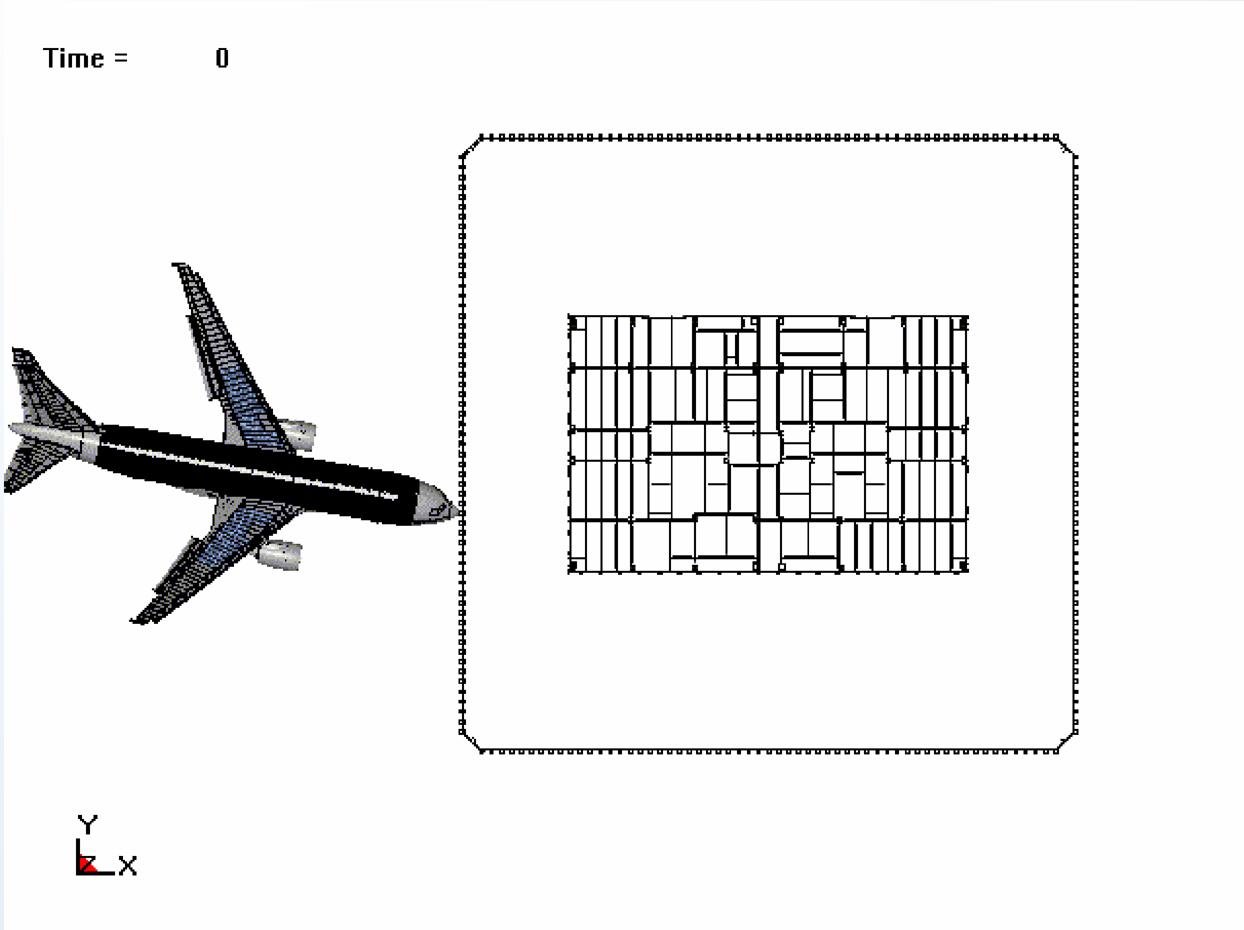
WTC 2



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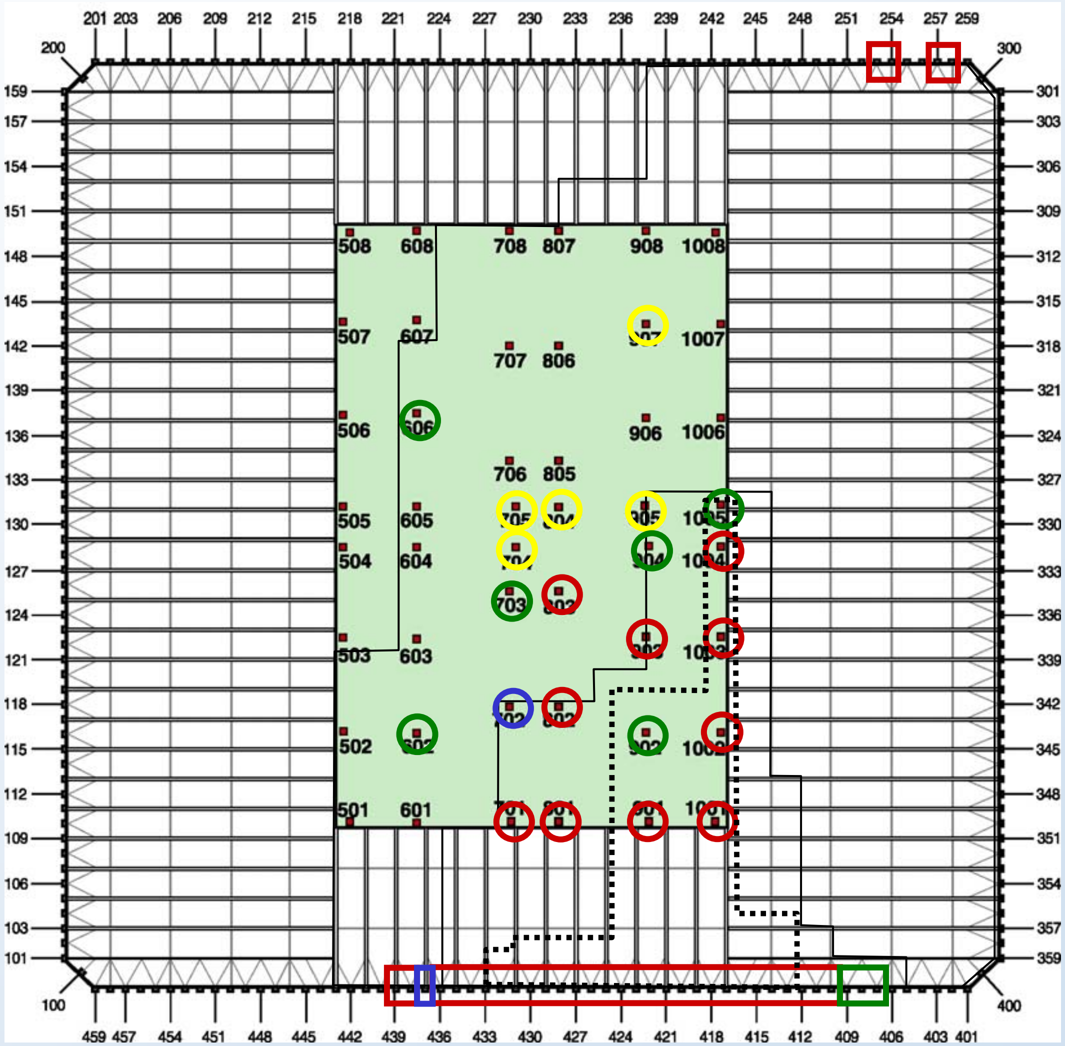
WTC 2 Damage: Composite Summary for Floors 78 to 83

Floor Damage

- Fireproofing and partitions
- Floor system structural damage
- Floor system removed

Column Damage

- Severed
- Heavy Damage
- Moderate Damage
- Light Damage



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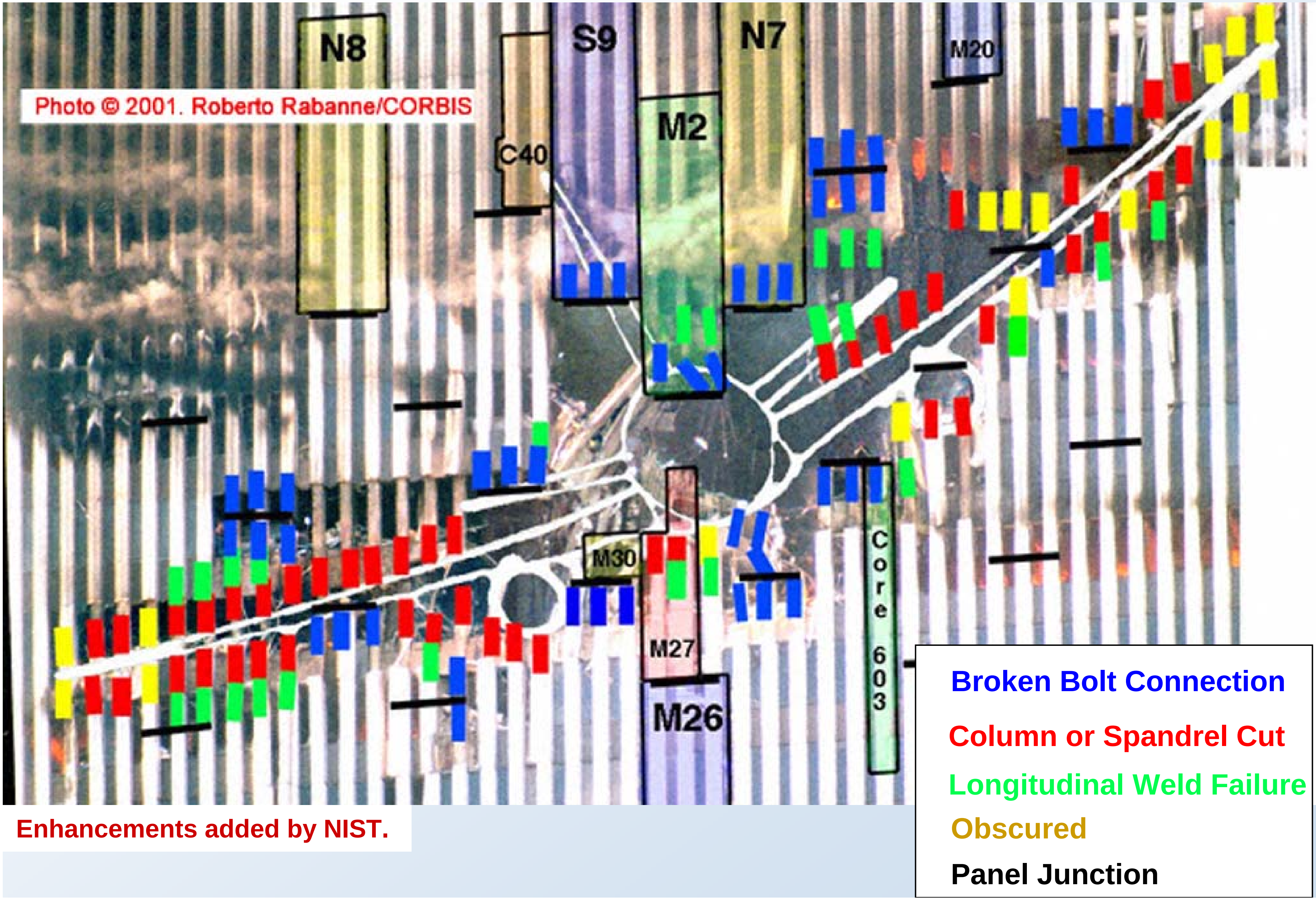

Enhancements added by NIST.


0:00
© Scott Myers
Clock

Relative Roles of Aircraft Impact and Fires

- **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 and the thermal response of the structures** 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 debris 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 on multiple floors;
  - Damaging and dislodging fireproofing from structural components in the direct path of the debris and due to the strong vibrations generated by aircraft impact; and
  - Damaging ceilings that enabled “unabated” heat transport over the floor-to-ceiling partition walls and to structural components.

Relative Roles of Aircraft Impact and Fires (2)

- **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.**
- **Typical office furnishings were able to sustain intense fires for at least an hour on a given WTC floor.** No structural component, however, was subject to intense fires for the entire period of burning. The duration of intense burning impacting any specific component was controlled by:
  - **The availability of combustible materials**
  - **Fuel gases released by those combustibles**
  - **Combustion air in the specific area**
- **The typical floor had on average about 4 psf of combustible materials on floors.** Mass of aircraft solid combustibles was significant in the immediate impact region of both WTC towers.

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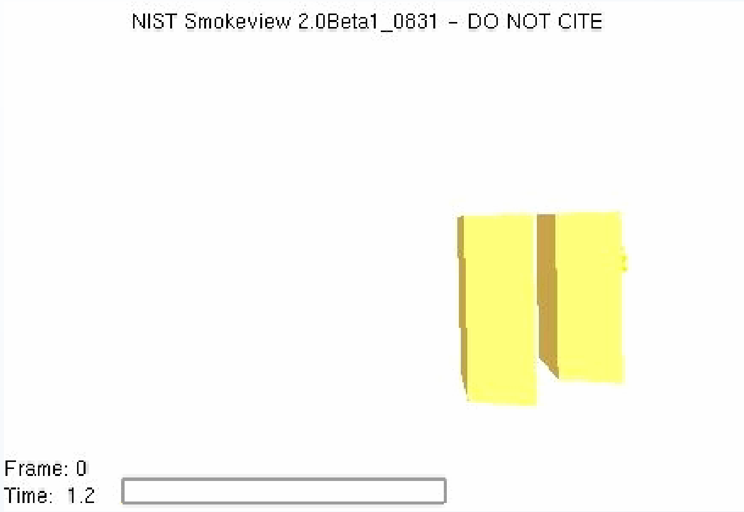
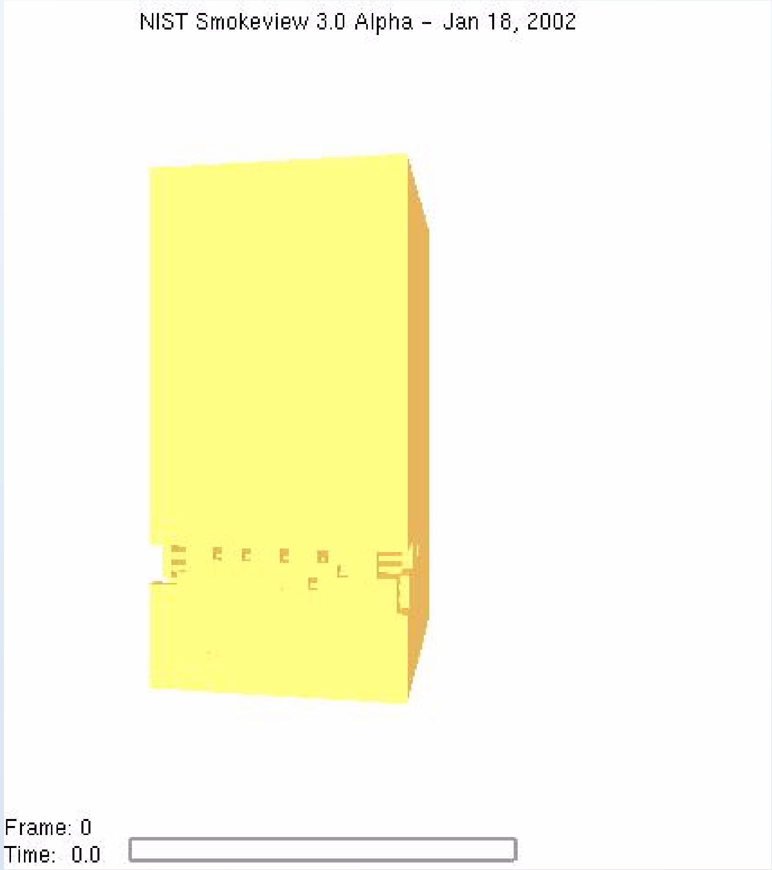
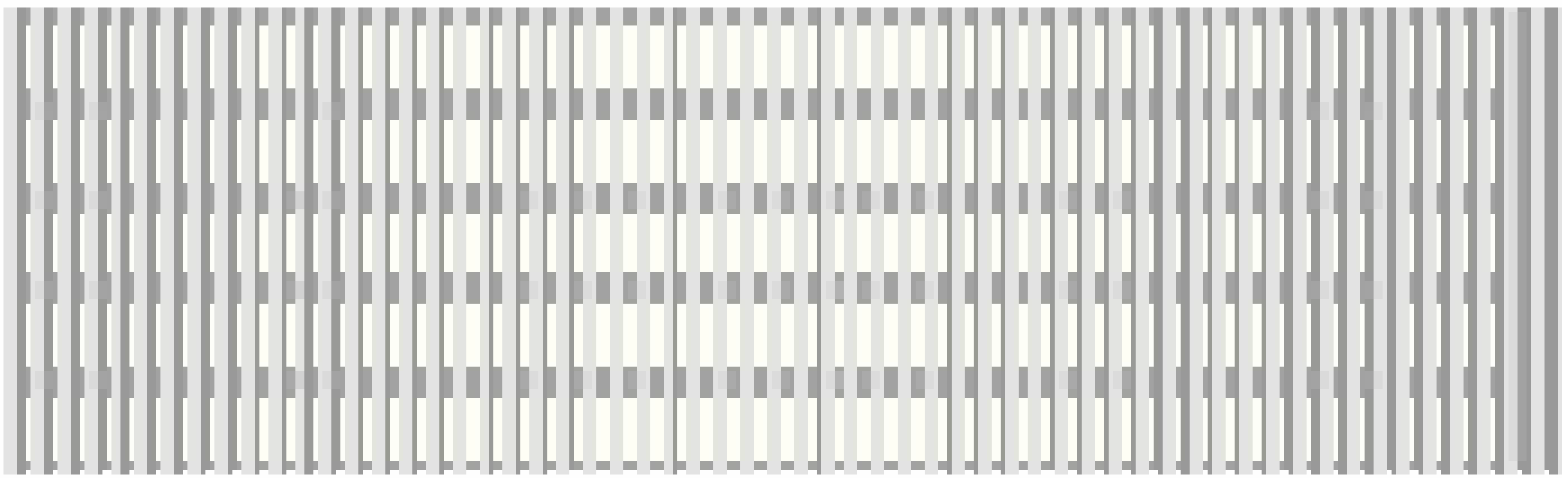
Initial Fire and Smoke Simulations: Fall 2001

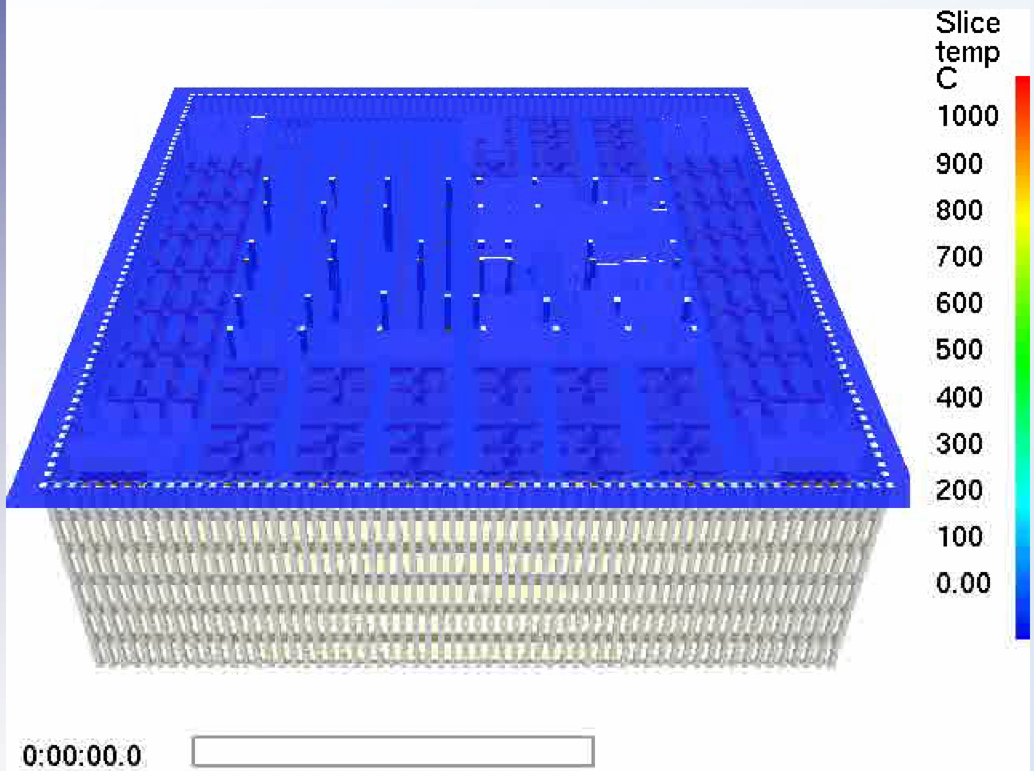


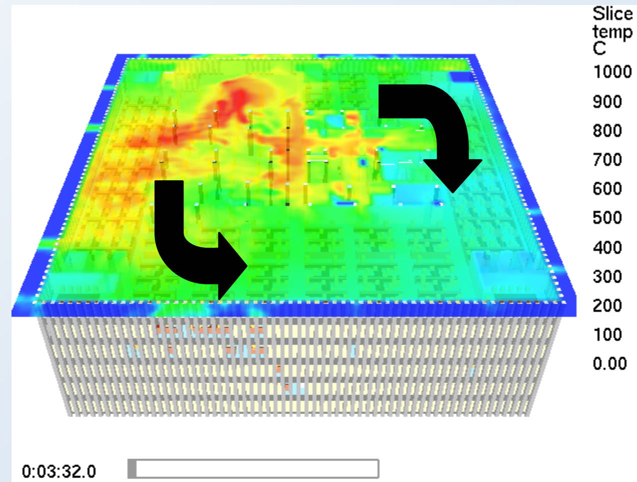


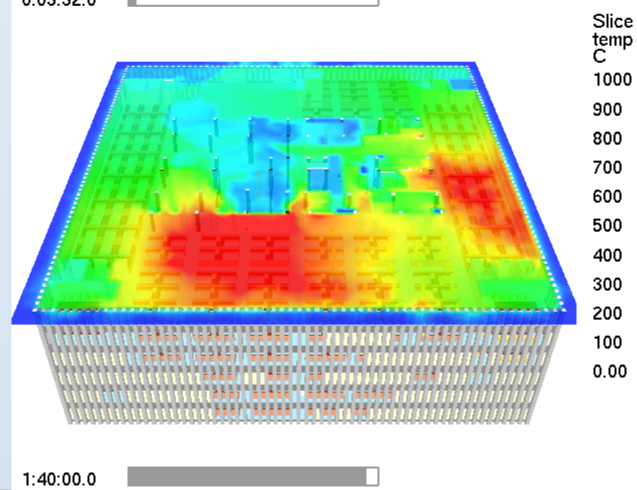
Reconstruction of the WTC Fires

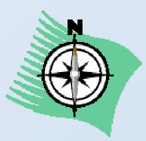


Upper Layer Temperatures (WTC 1, Floor 97)









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Structural Analysis Progression

Component Analyses

- Knuckle
- Truss seat connections
- Single truss and concrete slab
- Full floor
- Column splice connection
- Single story column
- Nine story column
- Nine story-nine column exterior wall panel

Detailed nonlinear analyses to determine component behaviors and failure mechanisms

Subsystem Analyses

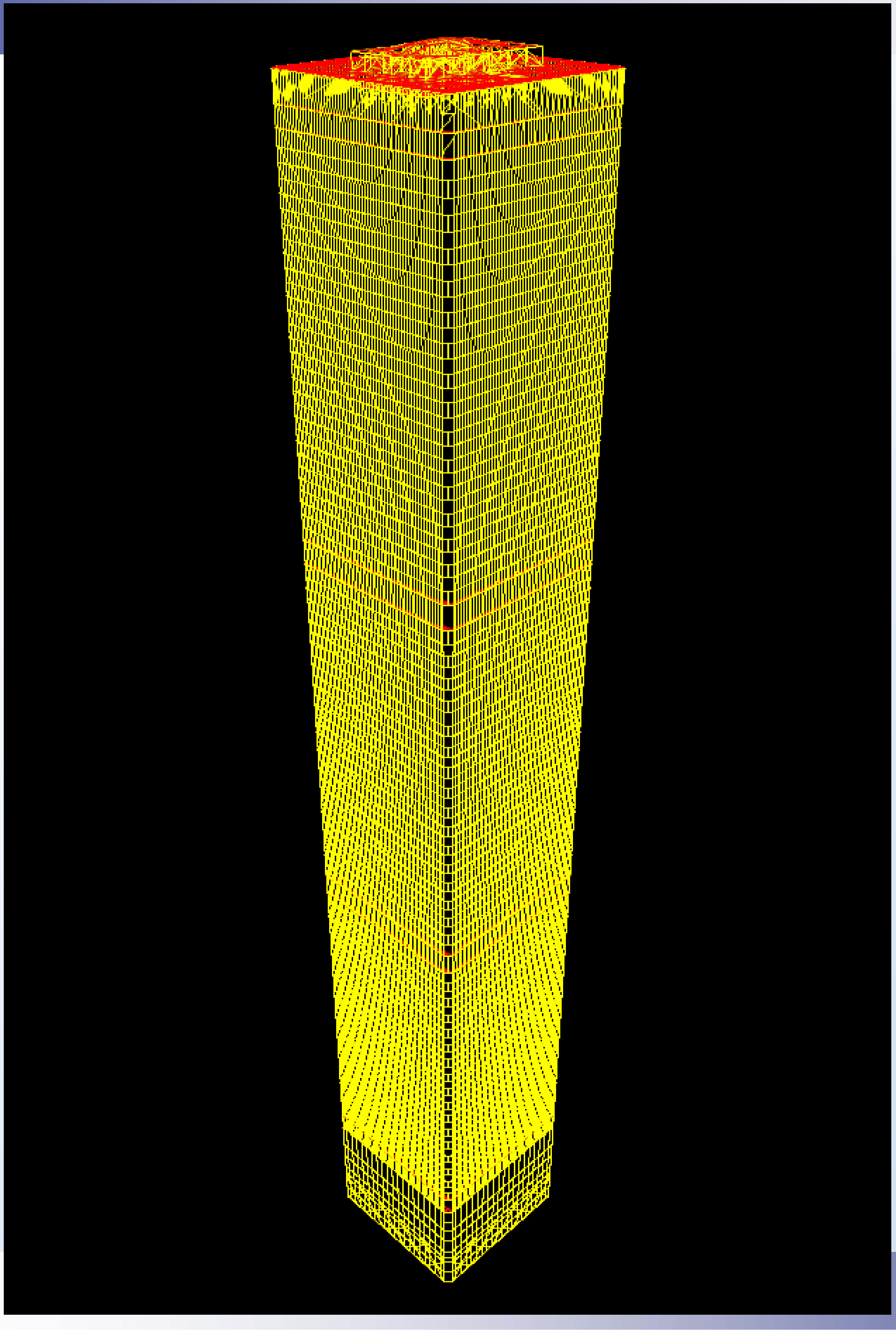
- WTC 1
  - Isolated Core
  - South Exterior Face
  - Floors 93 to 99
- WTC 2
  - Isolated Core
  - East Exterior Face
  - Floors 79 to 83

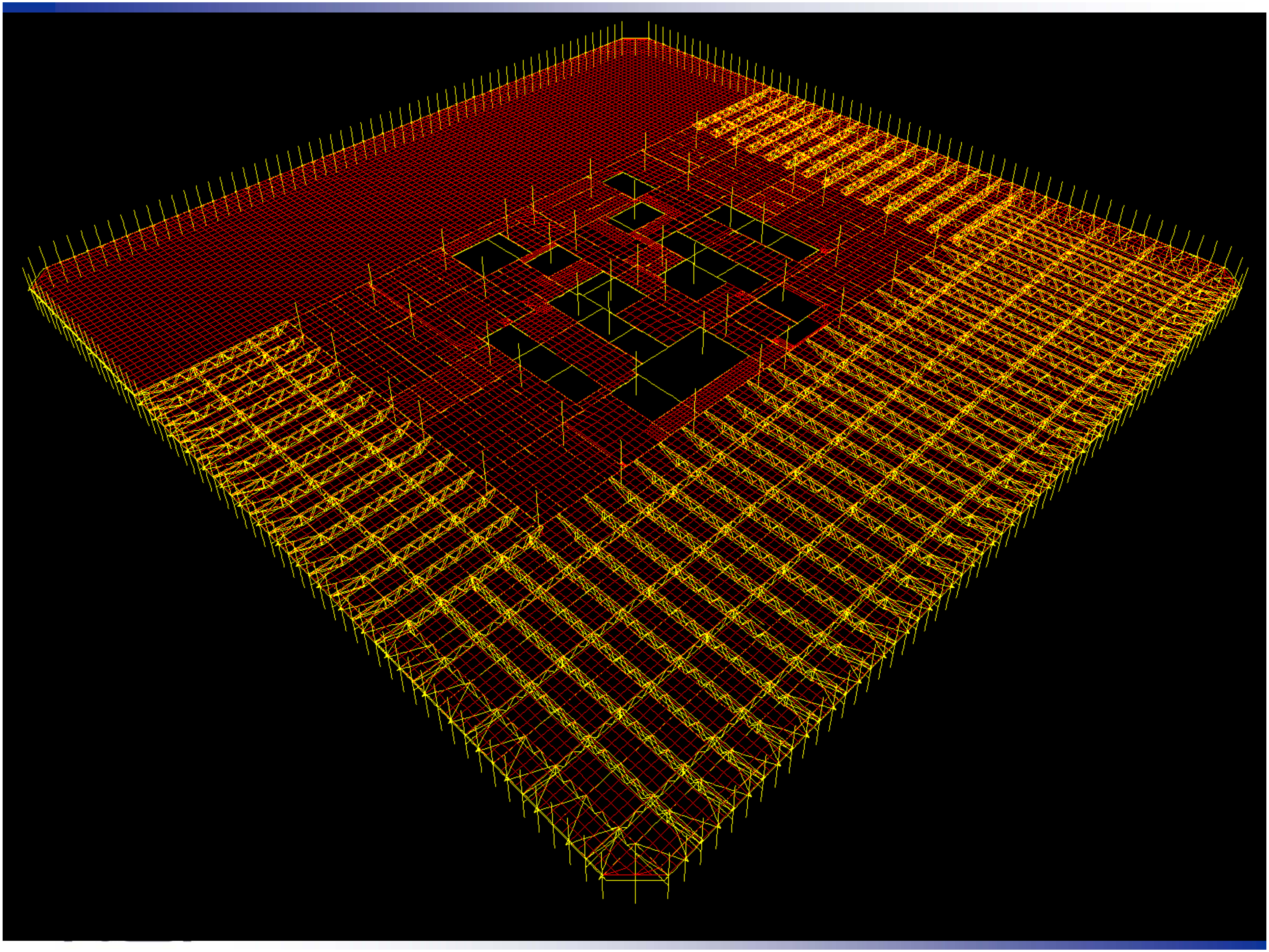
Nonlinear analyses with component simplifications and failure mechanism simplifications to determine major subsystem behavior and sequential failure mechanisms.

Global Analyses

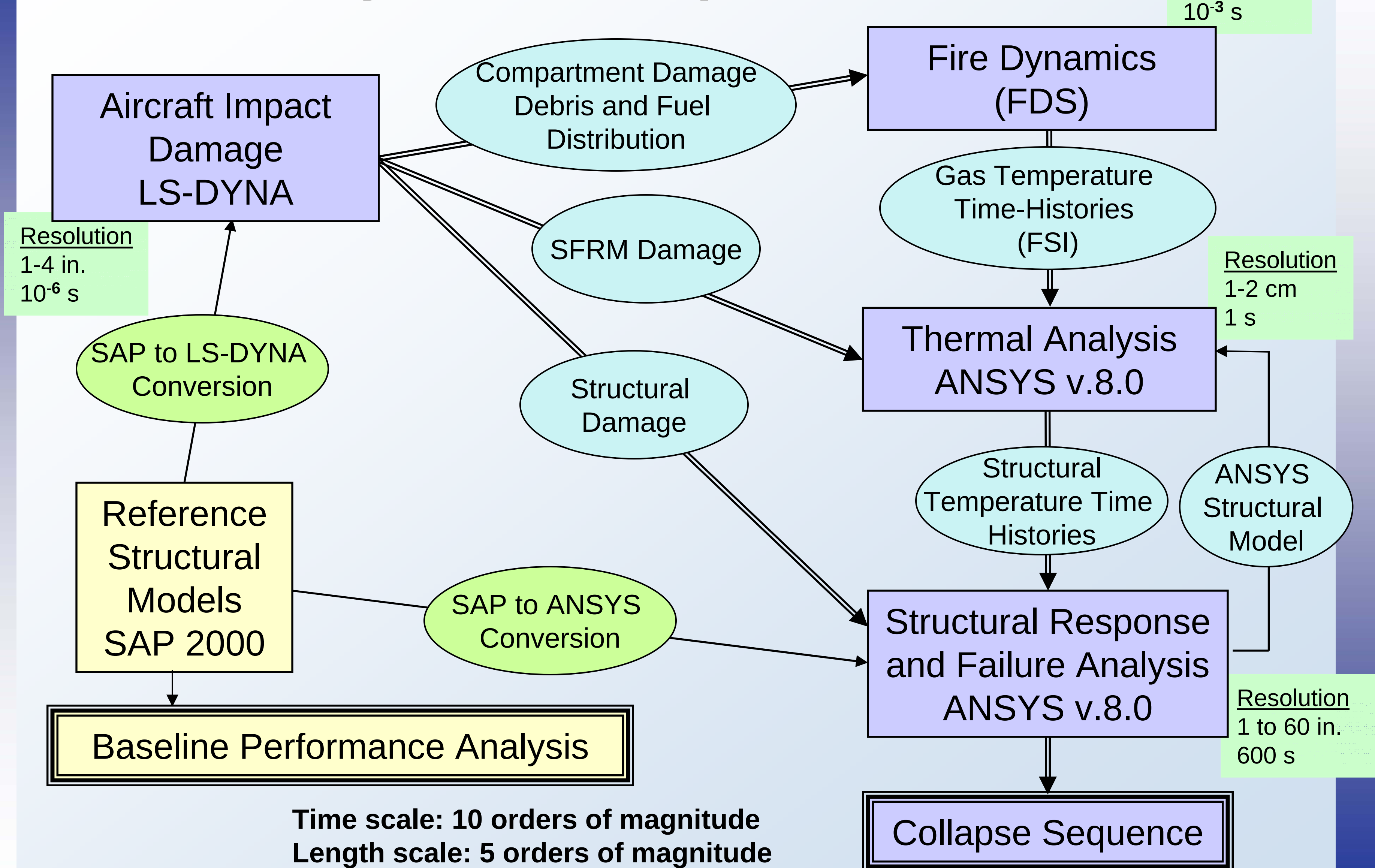
- WTC 1
- WTC 2

Nonlinear analyses to determine global behavior and sequential failure mechanisms.





Critical Analysis Inter-Dependencies



Time scale: 10 orders of magnitude
Length scale: 5 orders of magnitude

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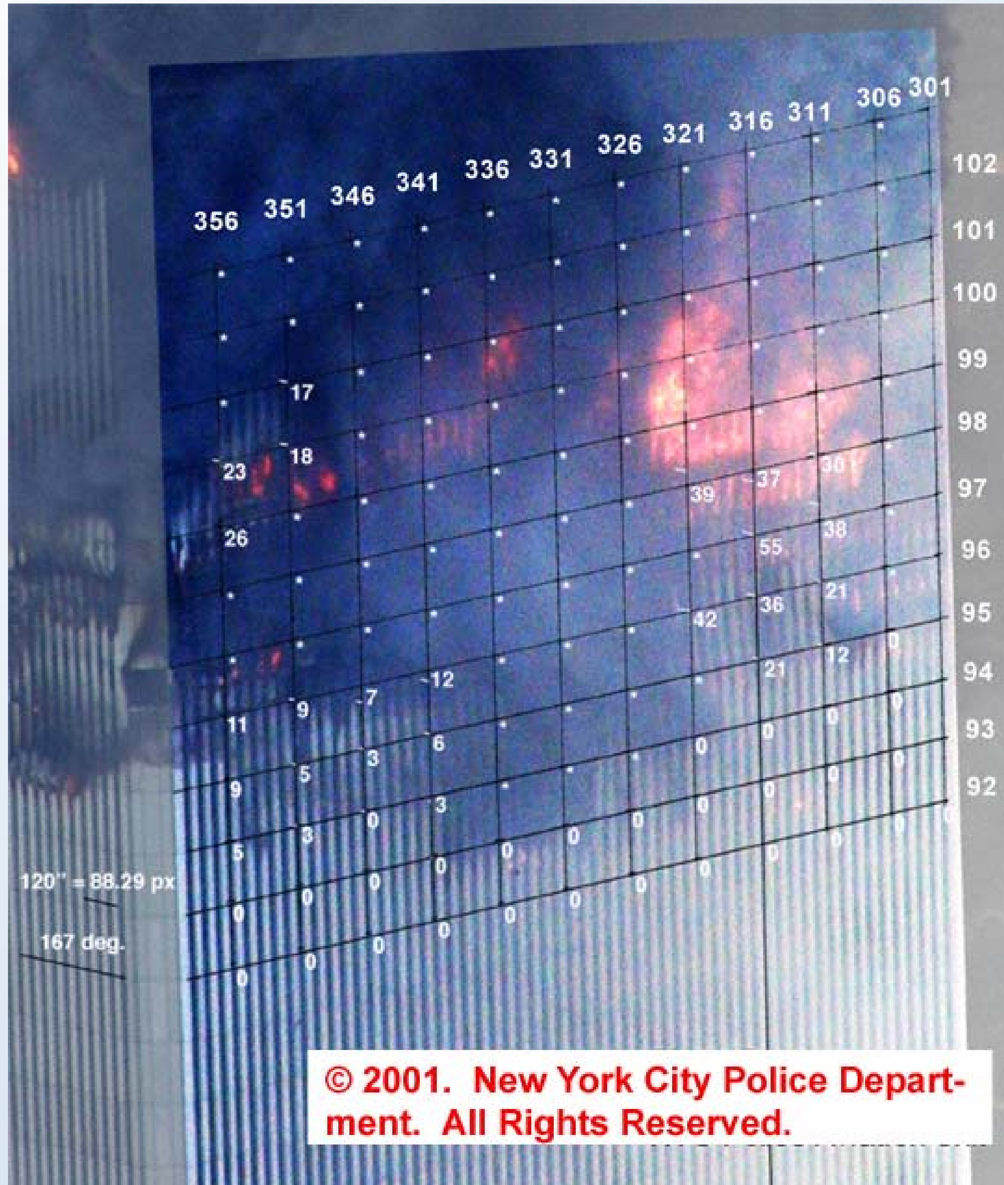
South Face of WTC1

- Time: 10:22 AM
- Measurements of inward bowing (inches)

- **Maximum = 55 inches**
  (uncertainty ~ +/- 6 inches)



- Floor locations approximate
- Blue tinted region digitally enhanced

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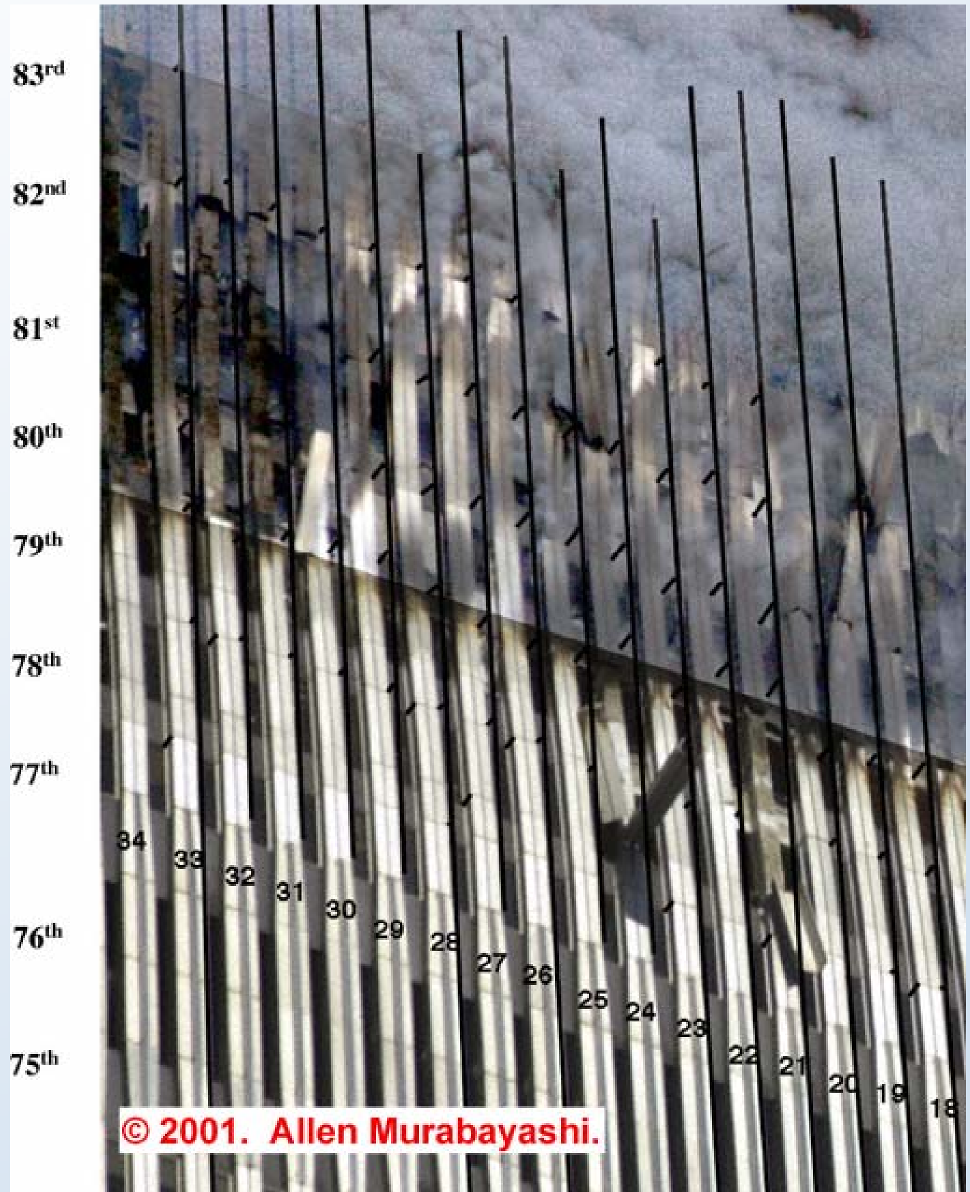
WTC2: East Face

Time: 9:21:29 AM

~18 minutes post impact

Maximum inward bowing of columns approximately 10 inches



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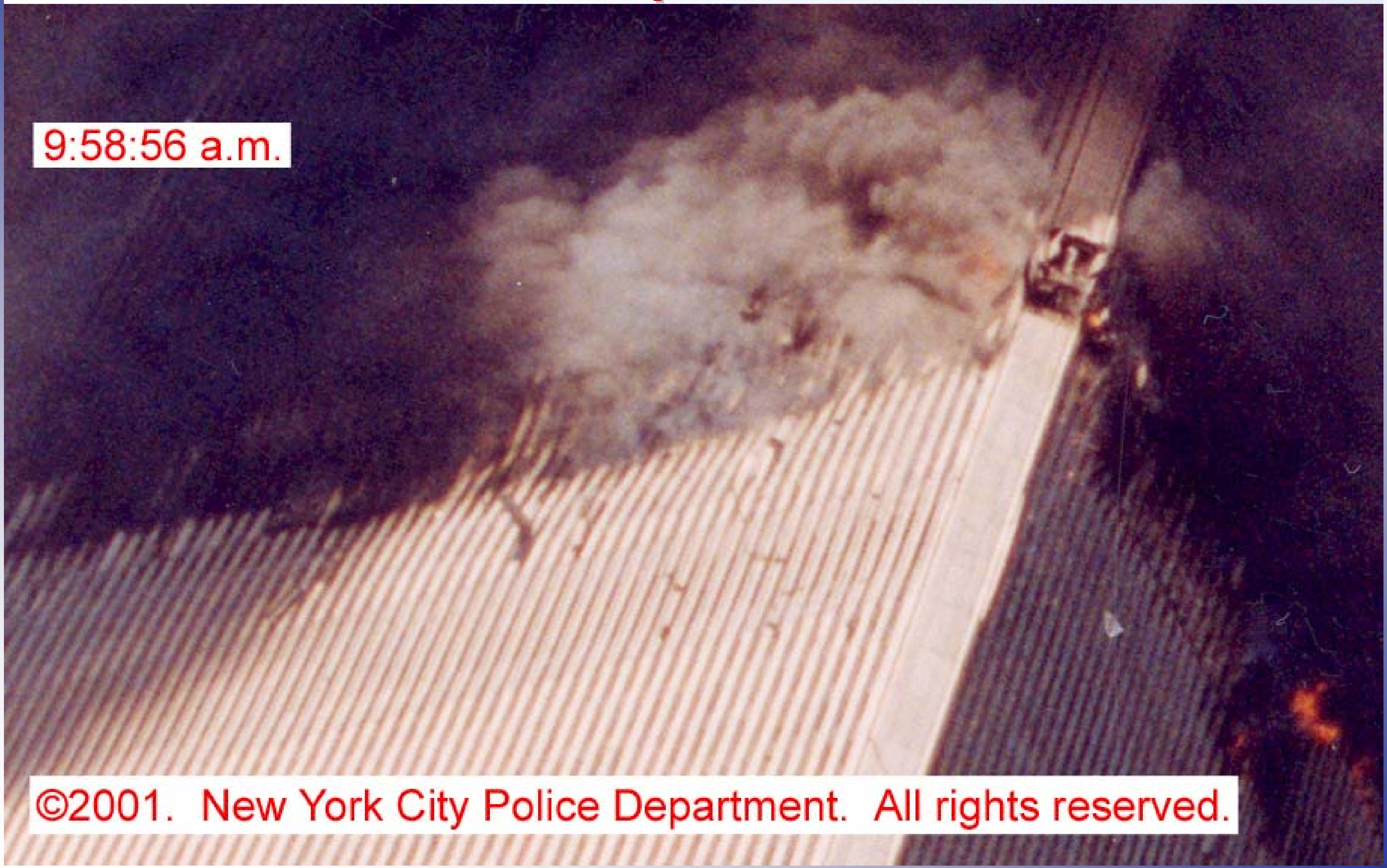
Inward Bowing of Perimeter Columns About 2 Minutes Prior to Collapse: WTC 2 East Face



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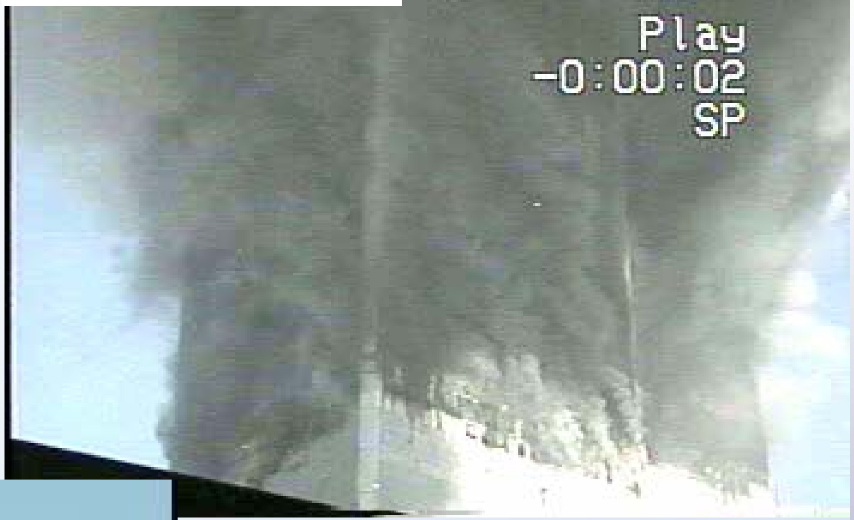
Tilting of Building Sections

WTC 1 tilted to the south; WTC 2 tilted to the east and south.



Initiation of global collapse was first observed by the tilting of building sections above the impact regions of both WTC towers.

Factors that Enhanced Building Performance on September 11, 2001

- The unusually dense spacing of perimeter columns, coupled with deep spandrels, that was an inherent part of both the architectural and structural design of the exterior walls, resulted in a robust building that was able to redistribute loads from severed perimeter columns to adjacent intact columns.

- The wind loads used for the WTC towers, which governed the design of the perimeter frame-tube system, significantly exceeded the prescriptive requirements of the New York City building code and selected other building codes of the era (Chicago, New York State), including the relevant national model building code (BOCA).

- The robustness of the perimeter frame-tube system and the large dimensional size of the WTC towers helped the buildings withstand the aircraft impact.

- The composite floor system with open-web bar joist elements, framed to provide two-way flat plate action, enabled the floors to redistribute loads without collapse from places of aircraft impact damage to other locations, avoiding larger scale collapse upon impact.

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Factors that Enhanced Building Performance on September 11, 2001 (2)

- The hat truss resisted the significant weakening of the core, due to aircraft impact damage and subsequent thermal effects, by redistributing loads from the damaged core columns to adjacent intact columns and, ultimately, by redistributing loads to the perimeter walls from the thermally weakened core columns that lost their ability to support the buildings' weight.

- **The buildings would likely not have collapsed under the combined effects of aircraft impact and the subsequent jet-fuel ignited multi-floor fires, if the fireproofing had not been dislodged or had been only minimally dislodged by aircraft impact. The existing condition of the fireproofing prior to aircraft impact and the fireproofing thickness on the WTC floor system did not play a significant role in initiating collapse on September 11, 2001.**

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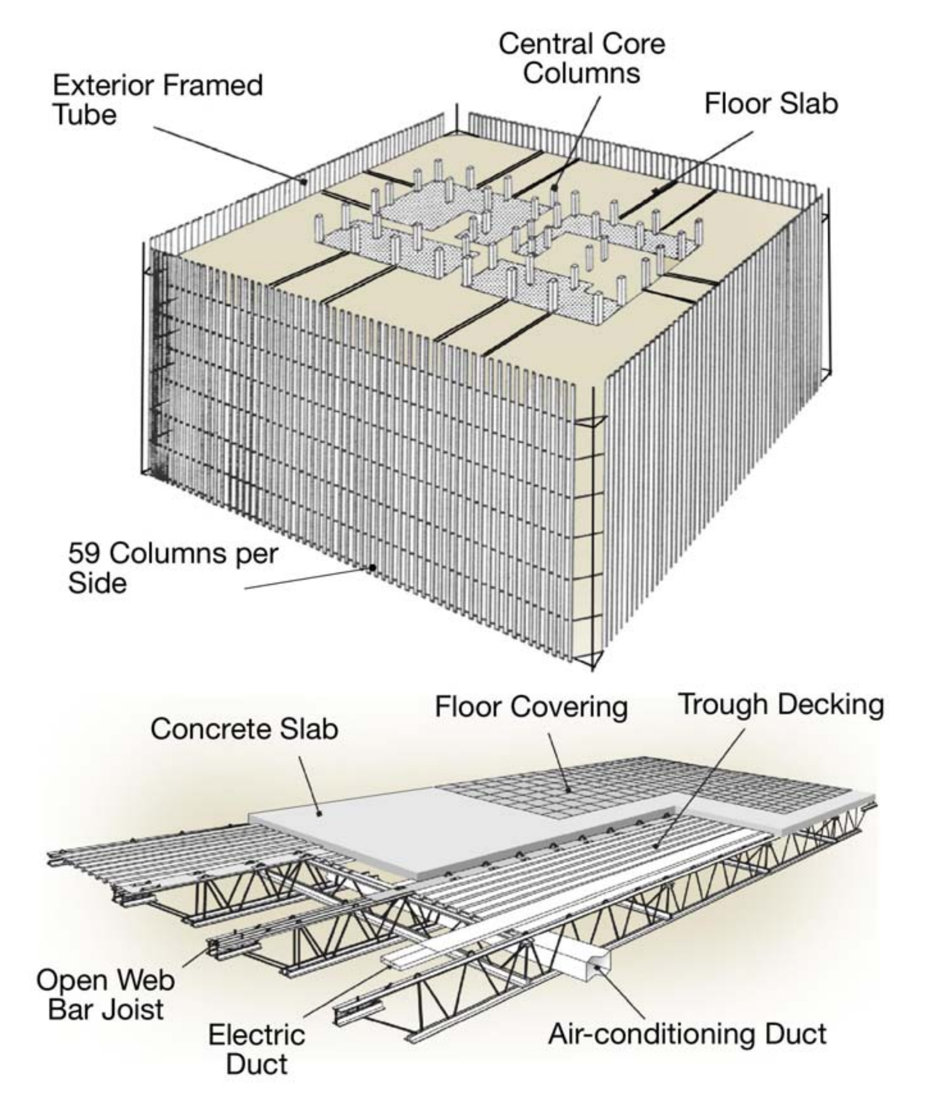
Innovative WTC Tower Structural System



- Innovative structural system when built; incorporated two new and unusual features that require additional consideration:
  - Composite floor truss system using long span open-web bar joists and spray-applied fireproofing
  - Design for wind loads and control of wind-induced vibrations

Fire Performance of Composite Floor System

- Fire-protection of a truss-supported floor system with spray-on fireproofing was innovative and not consistent with then-prevailing practice.

- **No evidence found of technical basis in the selection of fireproofing thickness** to meet 2 h fire rating:
  - 1/2 in. specified when WTC towers were built to maintain Class 1-A (not 1-B) fire rating requirement of the NYC Building Code
  - 1-1/2 in. specified for upgrades some years prior to 2001
  - 2 in. for similar floor system in an unrestrained test (model code evaluation service recommendation in June 2001, unrelated to WTC buildings)

- **No evidence that full-scale fire resistance test of the WTC floor system was conducted** to determine the required fireproofing thickness; in 1966, the Architect of Record and, in 1975, the Structural Engineer of Record stated that the fire rating of the WTC floor system could not be determined without testing.

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Results From NIST Sponsored Tests at UL

Test	Description	Times to Reach End-Point Criteria (min)					Test Termin-ated (min)	Standard Fire Test Rating		
		Temperature on Unexposed Surface		Steel Temperatures		Failure to Support Load		ASTM E 119-61	ASTM E 119-00	
		Average (Ambient +250ºF)	Maximum (Ambient +325ºF)	Average (1100ºF)	Maxi-mum (1300ºF)			Rating (hr)	Restr-ained Rating (hr)	Unrestr-ained Rating (hr)
1	35 ft, restrained, ¾ in fireproofing	---	111	66	62	(3)	116(1)	1½	1½	1
2	35 ft, unrestrained, ¾ in fireproofing	---	---	76	62	(3)	146(2)	2	---	2
3	17 ft, restrained, ¾ in fireproofing	180	157	86	76	(3)	210(2)	2	2	1
4	17 ft, restrained, ½ in fireproofing	---	58	66	58	(3)	120(1)	¾	¾	¾

(1) Imminent collapse
(2) Vertical displacement exceeded capability to measure accurately
(3) Did not occur

The end-point criterion that determined the rating is shown in matching color.

Wind Load Estimates for WTC 2

Source	Year	Base Shear 10^3 kips			Base Moment 10^6 kips-ft		
		N-S	E-W	Resultant	About N-S	About E-W	Resultant
NYC Building Code	Prior to 1968	5.3	5.3		4.2	4.2	
NYC Building Code	1968 - 2001	9.3	9.3		7.6	7.6	
RWDI / NYC Building Code	2002	9.7	11.1	12.3	10.1	9.2	11.3
RWDI / ASCE 7-98	2002	10.6	12.2	13.5	11.1	10.1	12.4
CPP / NYC Building Code	2002	NA	NA	NA	NA	NA	NA
CPP / ASCE 7-98*	2002	15.1	15.3	17.1	15.5	14.0	17.0
NIST / third-party SOM review / ASCE 7-02	2004	12.2	14.0	15.6	12.8	11.6	14.3
Original WTC Design (Clarified by designer in July 2004)	1960's	13.1	10.1	16.5	8.8	12.6	15.2

* Using ASCE 7-98 sections 6.5.4.1 and 6.6

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Results and Findings of Drift Analysis

Loading Case	WTC 1				WTC 2			
	E–W		N–S		E–W		N–S	
	Total Drift (in.)	Drift Ratio	Total Drift (in.)	Drift Ratio	Total Drift (in.)	Drift Ratio	Total Drift (in.)	Drift Ratio
Original design case	56.6	H/304	55.7	H/309	51.2	H/335	65.3	H/263
SOP case	56.8	H/303	68.1	H/253	59.7	H/287	56.1	H/306
Refined NIST case	70.6	H/244	83.9	H/205	75.6	H/227	71.0	H/242

- **The calculated drift ratios correspond to a damping ratio of 2.5% in estimated wind loads.**
- **Typical drift ratios considered in practice (not required by building codes):**
  - H/500 (~ 32.9 in.)
- **Under the original design wind loads, the WTC towers would need to have been between 1.5 to 1.9 times stiffer to achieve a H/500 drift limit; this can be efficiently achieved by increasing exterior column areas in the lower stories and/or significant additional damping.**

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Evacuation and Emergency Response

Based on 1,056 interviews of surviving WTC occupants and 116 interviews of emergency responders.

- **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 9/11, 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.
- 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**.
- Rough estimates indicate that about **20 percent or more of the 2,567 building occupants and emergency responders who were in the WTC towers and lost their lives may have been alive in the buildings just prior to their collapse**.

Evacuation Rates in the WTC Towers

- **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).**

- **After the first airplane struck WTC 1 and before the second airplane struck WTC 2**, **the rate of evacuation completion in WTC 2 was twice the rate in WTC 1.**

  - **Functioning elevators allowed many (roughly 3,000) survivors to self-evacuate WTC 2 during the 16 minutes prior to aircraft impact.**.

- 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 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 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**.

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Evacuation Rates in the WTC Towers (2)

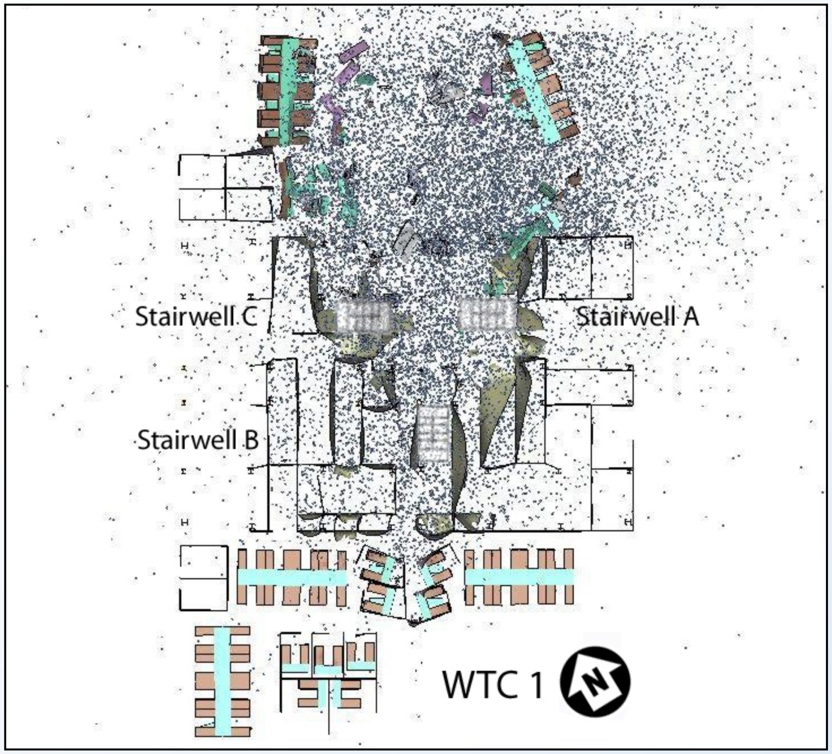
- Based on use of existing egress models and actual evacuation time on September 11, 2001, it is estimated that **a full capacity evacuation of each WTC tower with 25,000 people—three times the number present on September 11, 2001—would have required about 4 hours**.
  - **Had the buildings been full, it is possible that as many as 14,000 people may have lost their lives based on rough estimates using existing models.**
  - To achieve a significantly faster total evacuation at full capacity would have required increases in egress capacity (number and width of exits and stairways).
  - **The egress capacity required by current building codes and practice is based on a "phased" evacuation strategy, not "full" evacuation.**
- **The average surviving occupants moved slower down stairs and through stairwell exits than previously reported for non-emergency evacuations.**
  - **In WTC 1, the average surviving occupant spent 48 seconds per floor descending the stairwell. This is about 50% of the slowest speed measurement reported for non-emergency evacuations (e.g., drills).**

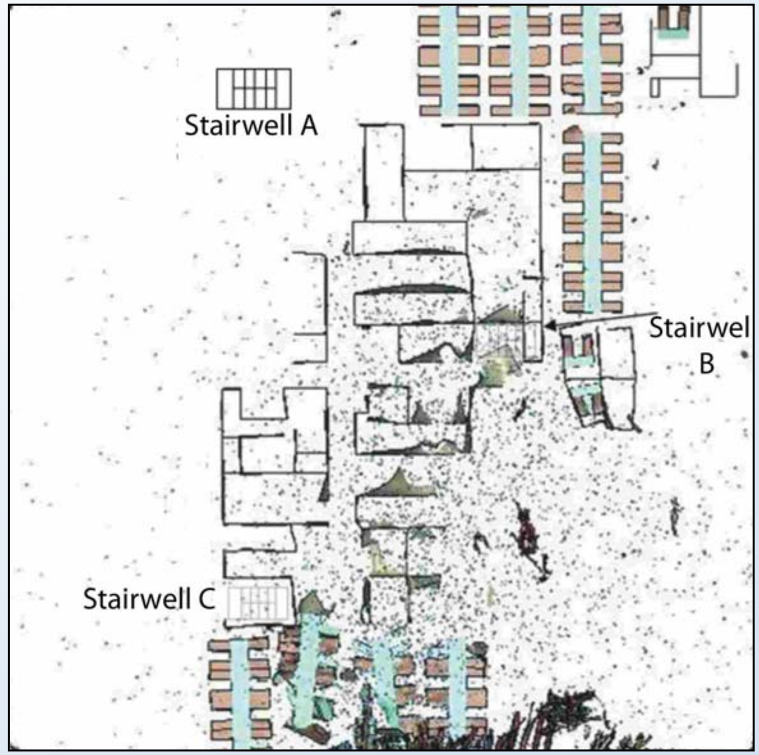
Occupant Preparedness

- **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** (NYC Local Law 5 prohibits **requiring** occupants to practice stairwell evacuation.)
- **Occupants were often unprepared for the physical challenge of full building evacuation.** Numerous occupants required one or more periods of rest during stairwell descent or turned to elevators after finding the stairwells strenuous.
- **Occupants were often unprepared to encounter transfer hallways during the stairwell descent.** Groups of evacuees occasionally hesitated or debated a course of action upon encountering a transfer hallway.

NIST

Condition of Stairwells





- 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.
- **One of the stairwells in WTC 2 (Stairwell A on the Northwest side) was passable in the region of aircraft impact for some period of time after WTC 2 was attacked.**
- All three stairwells in WTC 1 and the two other stairwells in WTC 2 were rendered impassable in the region of aircraft impact.

NIST

FDNY Access to the WTC Towers

- **After aircraft impact, only two elevators out of 198 were operating inside the two WTC towers.** WTC 1, from the lobby to the 16th floor. WTC 2, from the lobby to the 40th floor.

- The stairways were filled with occupants evacuating the buildings. **FDNY personnel and other emergency responders reported difficulty attempting to climb the stairs due to this counterflow.**

- Counter flow in the staircases made it difficult for emergency responders to carry equipment up the stairways.

- Counter flow in the staircases caused teams of emergency responders to become separated, causing delays and disrupting team operations.

NIST

Emergency Responders & High-Rise Buildings

- First responding FDNY units took from 4 to 10 minutes to get to the WTC complex. They then got their equipment and received assignments, another 3 to 5 minutes. Time to begin operations 7 to 15 minutes.

- Of the 27 emergency responders interviewed that were inside WTC 1, maximum floor height achieved before WTC 2 collapsed, a time period of 1 hour 13 minutes.

  1 – A police officer carrying no extra equipment and in a patrolman's uniform climbed to the 44th floor.

  8 – Emergency responders (FDNY, PAPD, NYPD) climbed to the 30's Two FDNY took an elevator to the 16th floor.

  16 – Emergency responders (mostly FDNY) climbed to the 20's.

  2 – Emergency responders (NYPD) climbed to the teens.

- **Estimated climbing rate based on a 60 minute climbing period to their maximum height: 1.4 to 2 minutes/floor**

High-Rise Buildings & Emergency Response

Example: Fire department response to a 60 story high-rise building, occupants trapped above fires on the 58th floor and no operating elevators.

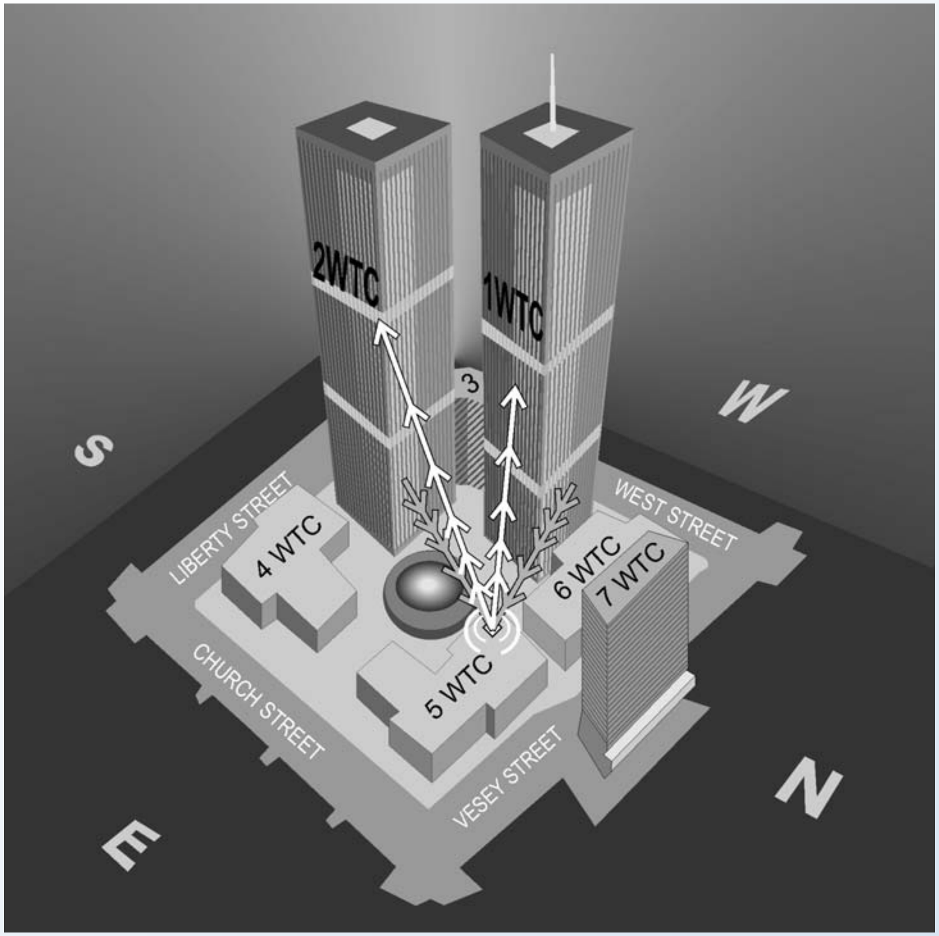
Firefighters carrying equipment and wearing PPE ~ 125 minutes
Firefighters carrying no equipment and not wearing PPE ~ 90 minutes

Firefighters carrying equipment and wearing PPE ~ 70 minutes
Firefighters carrying no equipment and not wearing PPE ~ 50 minutes

Firefighters begin to climb 10 minutes
Fire department arrival 4 minutes

NIST

Radio Communications in High-Rise Buildings



Schematic of WTC Radio Repeater System

- Challenging radio-frequency propagation environment: steel and reinforced concrete buildings.
- Large scale operations.
  - Number of first responders.
  - Communications hierarchy and protocols.
  - Surge in traffic; doubling.
- Interoperability of radio communication technologies among different emergency responder organizations.
- Identification, location, tracking first responders.

NIST

Mobility Impaired Occupants

- As the emergency responders started evacuating WTC 1 after the collapse of WTC 2, they found mobility impaired occupants still in the staircases going down.

- Ambulatory mobility impaired occupants typically walked down the stairs with one hand on each hand rail and took one step at a time going down. In addition, they were typically accompanied by one person, another occupant or an emergency responder. This blocked others behind them from moving more rapidly down the stairs.

- **FDNY and PAPD personnel found 40 to 60 mobility impaired occupants on the 12th floor of WTC 1 as they went down and attempted to clear each floor on their way out.** These impaired individuals had been placed on this floor in an attempt to clear the stairways.

- **Emergency responders were assisting approximately 20 of these mobility impaired people down the staircase just prior to the collapse of WTC 1.** It is unknown how many fatalities occurred with this group.

NIST

Key Findings

- **The buildings would likely not have collapsed due to aircraft impact and the subsequent jet-fuel ignited multi-floor fires, if the fireproofing had not been dislodged or had been only minimally dislodged by aircraft impact.**

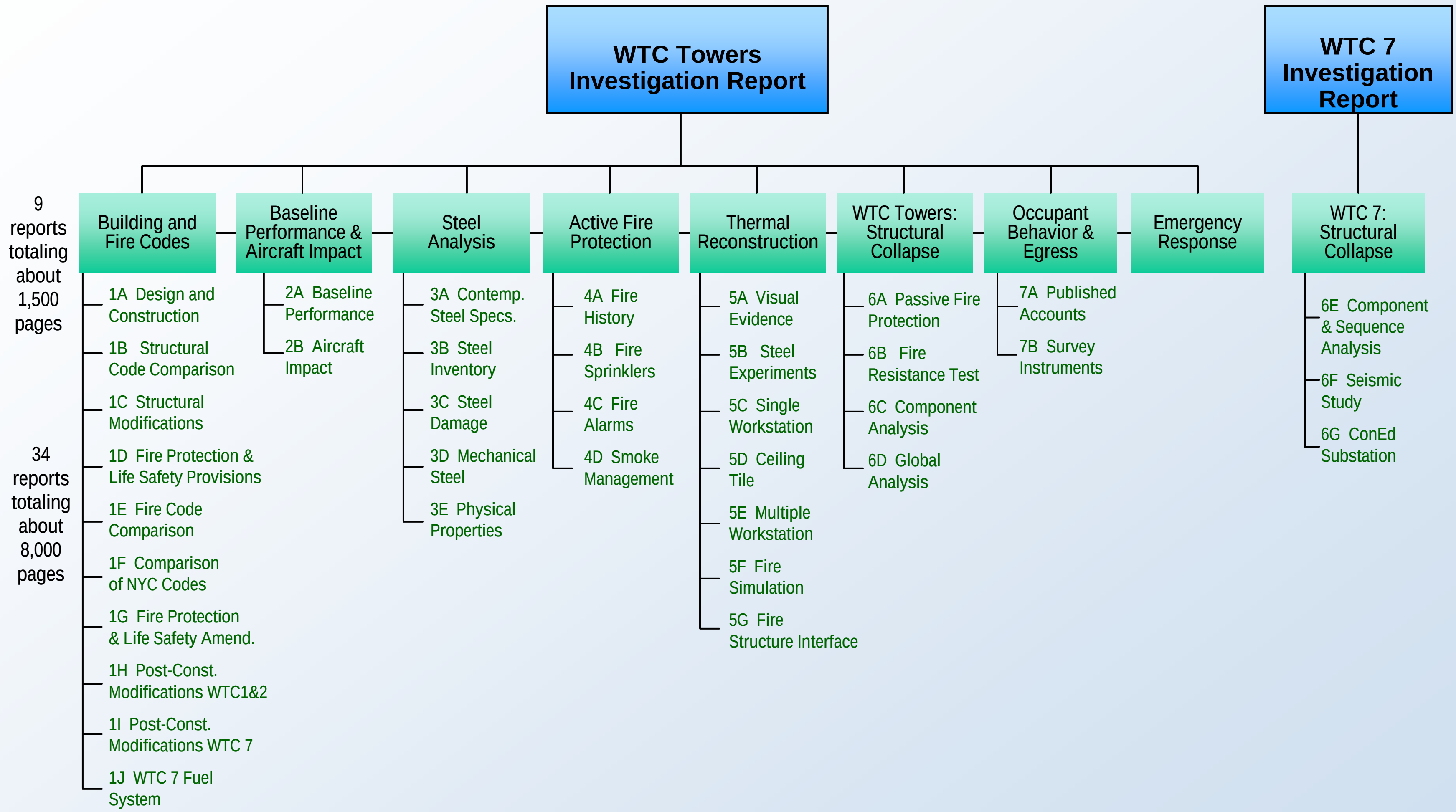
- **The existing condition of the fireproofing prior to aircraft impact and the fireproofing thickness on the WTC floor system did not play a governing role in initiating collapse on September 11, 2001.**

- Since the buildings were occupied by only about 1/3 of the building's full capacity of 25,000 occupants, **approximately 87 percent of the WTC tower occupants, including more than 99 percent below the floors of impact, were able to evacuate successfully.**

- **A full capacity evacuation of each WTC tower with 25,000 people would have required about 4 hours** and **as many as 14,000 people may have lost their lives.**

- **Documents suggest that the WTC towers generally were designed and maintained consistent with the requirements of the 1968 New York City Building Code.**

WTC Investigation Reports



43 reports for WTC Towers; 5 reports for WTC 7

NIST

Submission Process for Public Comments

- NIST released the draft WTC Towers report and 42 supporting draft reports on June 23, 2005 for public comment.
- Six week period for public comment; all comments due to NIST August 4, 2005.
- Comments encouraged on the WTC Towers Report but welcomed on all reports.
- NIST requested comments be specific in nature with recommendations for change.
- Comments were accepted via web site, e-mail, fax, and regular mail.

NIST

Summary of Comments Received

Total number of submissions: 469

Number of Organizations Responding: 22

Number of Individuals Responding: 58

- Nearly all major building and fire safety organizations submitted comments: (e.g., ICC, NFPA, ASCE/SEI, SFPE, NCSEA, PCA, AIA, BOMA, ACI, NASFM, AFSC, NCSBCS, AMCBO, CRSI, UL, ASTM, SPI, NFSA, NRMCA)

Appreciation

- NIST appreciates the desire of organizations and individuals to state their positions on the draft WTC Reports.
- NIST was gratified by the industry interest in the WTC Investigation and our findings and recommendations and by the quality and quantity of the comments received.
- Most of the pros and cons of issues raised in the comments had been debated by the NIST team and already considered in the findings and recommendations contained in the draft reports.
- The comments have resulted in a wealth of information and insight that will guide not only follow-on work by NIST, but also the follow-on work of the standards and codes organizations, industry organizations, and academic researchers.

Nature of Changes

- Multiple additions and wording changes to emphasize and/or clarify aspects
- Numerous editorial changes
- Clarified a finding
- Modified six recommendations (3 amendments, 3 clarifications)
- Clarified the back-up text for several of the recommendations, including definition of tall buildings used in the report
- Greatly enhanced index of topics covered in the report

Approach to Recommendations

- NIST is issuing recommendations in accordance with the National Construction Safety Team Act.

- NIST considered:

  - Findings from the investigation;

  - If findings were unique to the terrorist attacks or related to normal building and fire safety considerations;

  - What technical solutions are needed to address potential identifiable risks; and

  - Whether the risks apply to all buildings or are limited to certain types of building (e.g., iconic status, critical function, or design).

Context for Recommendations

- **The tragic consequences of the September 11, 2001, attacks were directly attributable to the fact that terrorists flew large jet-fuel laden commercial airliners into the WTC towers.**
- **Buildings for use by the general population are not designed to withstand aircraft attacks;** building codes do not require building designs to consider aircraft impact.
- In our cities, there has been **no experience with a disaster of such magnitude,** nor has there been any in which the total collapse of a high-rise building occurred so rapidly and with little warning.
- NIST is making recommendations based on its findings related to **procedures and practices that are commonly used for buildings under normal conditions.**
- Public officials and building owners will need to determine appropriate performance requirements for **buildings that are at higher risk due to their iconic status, critical function, or design.**

Context for Recommendations (2)

- NIST believes that the **recommendations are realistic and achievable** within a reasonable period of time**.**
- **Implementation of the recommendations would make buildings, occupants, and emergency responders safer in future emergencies.**
- **The recommendations do not prescribe specific systems, materials, or technologies.** Instead, NIST encourages competition among alternatives that can meet performance requirements.
- **The recommendations do not prescribe specific threshold levels.** This responsibility falls within the purview of the public policy setting process, in which standards and codes development plays a key role.

Definition of Tall Buildings

- From:
  - Buildings over 20 stories in height: NIST has found that the physiological impacts on emergency responders of climbing 20 or more stories makes it difficult to conduct effective and timely firefighting and rescue operations in building emergencies without functioning elevators. Better knowledge of the physiological impacts through research could refine the definition of tall buildings used here.

- To:
  - NIST has found that the physiological impacts on emergency responders of climbing numerous (e.g., 15 to 20 or more) stories makes it difficult to conduct effective and timely firefighting and rescue operations in building emergencies without functioning elevators. Consideration and better knowledge of factors such as ladder height, physiological factors involving emergency responders and building occupants, use of working elevators, and installation and use of protected elevators could refine the currently used definition of tall buildings to include multiple threshold levels.

Clarification to Findings

Inserted a clarification into the Executive Summary and Part III (Outcome of the Investigation):

> NIST found no corroborating evidence for alternative hypotheses suggesting that the WTC towers were brought down by controlled demolition using explosives planted prior to September 11, 2001. NIST also did not find any evidence that missiles were fired at or hit the towers. Instead, photos and videos from several angles clearly showed that the collapse initiated at the fire and impact floors and that the collapse progressed from the initiating floors downward, until the dust clouds obscured the view.

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

Recommendations

Group 1: Increased Structural Integrity

The standards for estimating the load effects of potential hazards (e.g., progressive collapse, wind) -- and the design of structural systems to mitigate the effects of those hazards -- should be improved to enhance structural integrity.

Increased Structural Integrity

Consensus standards and code provisions for preventing *progressive collapse* be developed and adopted nationwide – along with tools and guidelines for their use…and a standard methodology be developed to reliably predict the potential for *complex failures* in structural systems subjected to multiple hazards. Rec. #1

Nationally accepted performance standards be developed for:

- *wind tunnel testing* of prototype structures based on sound technical methods that result in repeatable and reproducible results; and
- *estimating wind loads* and their effects on tall buildings, based on wind tunnel testing data and directional wind speed data. Rec. #2

Appropriate criterion be developed and implemented to enhance performance of tall buildings by *limiting how much they sway* under lateral load design conditions (e.g., winds and earthquakes). Rec. #3

Group 2: Enhanced Fire Resistance of Structures

The procedures and practices used to ensure the fire resistance of structures be enhanced by:

- **improving the technical basis for construction classifications and fire resistance ratings and testing methods,**
- **using the "structural frame" approach to fire resistance ratings, and**
- **developing in-service performance requirements and conformance criteria for sprayed fire resistive materials (commonly known as fireproofing).**

Enhanced Fire Resistance of Structures

Evaluate -- and where needed improve -- the technical basis for determining construction classification and fire rating requirements (*especially for tall buildings*)…and make related code changes now as much as possible by explicitly considering:

- timely access by emergency responders and *full evacuation* of occupants, or time required for burnout without local collapse;
- extent to which *redundancy* in active fire protection (sprinkler and standpipe, fire alarm, and smoke management) systems *should be credited* for occupant life safety;
- need for *redundancy* in fire protection systems critical to structural integrity;
- ability of the structure and local floor systems to withstand *maximum credible fire scenario without collapse* -- recognizing that sprinklers could be compromised, not operational, or non-existent; (continued)

NIST

Enhanced Fire Resistance of Structures (2)

- *compartmentation* requirements to protect the structure, including:
  - fire rated doors and automatic enclosures, and
  - limiting air supply (e.g., thermally resistant window assemblies)

  to retard fire spread in buildings with large, open floor plans,

- effect of spaces containing *unusually large fuel concentrations* for the expected occupancy of the building; and

- extent to which fire control systems -- including suppression by automatic or manual means -- should be credited as part of the prevention of fire spread. Rec. #4

NIST

Enhanced Fire Resistance of Structures (3)

Improve the technical basis for century-old *standard for fire resistance testing* of components, assemblies, and systems and… develop guidance for extrapolating results of tested assemblies to prototypical building systems. ***A principal step in fulfilling this recommendation is to establish a capability for studying and testing components, assemblies, and systems under realistic fire and load conditions.*** Rec. #5

Develop criteria, test methods, and standards:

- for in-service performance of fireproofing to protect structural components; and
- to ensure that these materials, *as-installed*, conform to conditions in tests used to establish the fire resistance rating. Rec. #6

Adopt and use "structural frame" approach (structural members connected to the columns carry the high fire resistance rating of the columns). Rec. #7

NIST

Group 3: New Methods for Fire Resistance Design of Structures

Procedures and practices used in the fire resistance design of structures should be enhanced by requiring an objective that *uncontrolled fires result in burnout without partial or global (total) collapse.*   Performance-based methods are an alternative to prescriptive design methods.

This effort should include the development and evaluation of:

- **new fire resistive coating materials and technologies and**
- **evaluation of the fire performance of conventional and high-performance structural materials.**

NIST

New Methods for Fire Resistance Design of Structures

Require that uncontrolled building fires result in burnout without ***partial*** or global ***(total)*** collapse. Rec. #8

Develop:

- performance-based standards and code provisions -- as an alternative to current prescriptive design methods -- to enable design and retrofit of structures to resist real fire conditions
- tools, guidelines, and test methods to evaluate fire performance of the structure as a whole system. Rec. #9

NIST

New Methods for Fire Resistance Design of Structures (2)

Develop and evaluate new fire resistive coating materials, systems, and technologies with significantly enhanced performance and durability to provide protection following major events. Rec. #10

Evaluate performance and suitability of advanced structural steel, reinforced and pre-stressed concrete, and other high-performance material systems for use under conditions expected in building fires. Rec. #11

Group 4: Improved Active Fire Protection

Active fire protection systems (i.e., sprinklers, standpipes/ hoses, fire alarms, and smoke management systems) should be enhanced through improvements to:

- **Design**
- **Performance**
- **Reliability, and**
- **Redundancy**

of such systems.

Improved Active Fire Protection

Enhance performance and possibly the redundancy of active fire protection systems to accommodate higher risks associated with tall buildings. Rec. #12

Develop advanced fire alarm and communication systems that provide continuous, reliable, and accurate information on life safety conditions to manage the evacuation process; ***all communication and control paths in buildings need to be designed and installed to have the same resistance to failure and increased survivability above that specified in present standards.*** Rec. #13

Adapt advanced fire/emergency control panels to accept and interpret more – and more reliable -- information from the active fire protection systems to provide tactical decision aids. Rec. #14

Develop and require systems for improved transmission to emergency responders, and off-site or black-box storage, of information from building monitoring systems. Rec. #15

NIST

Group 5: Improved Building Evacuation

Building evacuation should be improved to include:

- **system designs that facilitate safe and rapid egress,**
- **methods for ensuring clear and timely emergency communications to occupants,**
- **better occupant preparedness regarding their roles and duties for evacuation during emergencies, and**
- **incorporation of appropriate egress technologies.**

Improved Building Evacuation

Develop and carry out *public education* ***and training*** *campaigns* to improve building occupants' preparedness for evacuation in case of building emergencies. Rec. #16

Design tall buildings to accommodate *timely full building evacuation* of occupants due to building-specific or large-scale emergencies such as widespread power outages, major earthquakes, tornadoes, hurricanes, fires, explosions, and terrorist attack.

- Building size, population, function, and iconic status should be taken into account in designing the egress system.
- Stairwell capacity ***and stair discharge door width*** should be adequate to accommodate counterflow due to emergency access by responders. Rec. #17

NIST

Improved Building Evacuation (2)

Design egress systems:

- to *maximize remoteness of egress components* (i.e., stairs, elevators, exits) without negatively impacting the average travel distance;
- to maintain their functional *integrity and survivability* under foreseeable building-specific or large-scale emergencies; and
- with consistent layouts, standard signage, and guidance so that systems become *intuitive and obvious* to building occupants during evacuations.
  Rec. #18

Improved Building Evacuation (3)

Building owners, managers, and emergency responders should develop a joint plan and *ensure accurate emergency information is communicated* in a timely manner to enhance awareness of occupants and emergency responders through:

- better coordination of information among different emergency responder groups,
- efficient sharing of that information among building occupants and emergency responders,
- more robust design of emergency public address systems,
- improved emergency responder communication systems, and
- use of the Emergency Broadcast System (the Integrated Public Alert and Warning System) and Community Emergency Alert Networks. Rec. #19

Improved Building Evacuation (4)

Evaluate the full range of current and *next generation evacuation technologies* for future use, including:

- protected/hardened elevators,
- exterior escape devices, and
- stairwell descent devices,

which may allow all occupants an equal opportunity for evacuation and facilitate emergency response access. Rec. #20

Group 6: Improved Emergency Response Technologies and Procedures

Technologies and procedures for emergency response should be improved to enable better access to buildings, response operations, emergency communications, and command and control in large-scale emergencies

Improved Emergency Response Technologies and Procedures

Install *fire-protected and structurally hardened elevators in tall buildings* to provide timely emergency access to responders and allow evacuation of mobility impaired building occupants.

- Such elevators should be for exclusive use by emergency responders during emergencies.
- In tall buildings, consideration also should be given to installing such elevators for use by all occupants. Rec. #21

Install, inspect, and test *emergency communications systems, radio communications, and associated operating protocols* to ensure that the systems and protocols:

- are effective for large-scale emergencies in buildings with challenging radio frequency propagation environments, and
- can be used to identify, locate, and track emergency responders within indoor building environments and in the field. Rec. #22

NIST

Improved Emergency Response Technologies and Procedures (2)

Establish and implement detailed procedures and methods for gathering, processing, and delivering critical information through *integration of relevant voice, video, graphical, and written data* to enhance situational awareness of all emergency responders. Establish an *information intelligence sector* to coordinate each incident. Rec. #23

Establish and implement codes and protocols for ensuring *effective and uninterrupted operation of the command and control system* for large-scale building emergencies. Rec. #24

Group 7: Improved Procedures and Practices

The procedures and practices used in the design, construction, maintenance, and operation of buildings should be improved by:

- **encouraging code compliance by nongovernmental and quasi-governmental entities,**
- **adoption and application of egress and sprinkler requirements in codes for existing buildings, and**
- **retention and availability of building documents over the life of a building.**

Improved Procedures and Practices

Nongovernmental and quasi-governmental entities that own or lease buildings -- and are not subject to building and fire safety code requirements of any governmental jurisdiction -- should provide a level of safety that *equals or exceeds* the level of safety that would be provided by strict compliance with the code requirements of an appropriate governmental jurisdiction.

- As-designed and as-built safety should be *certified by a qualified third party*, independent of the building owner(s).
- The process *should not use self-approval* for code enforcement in areas including:
  - interpretation of code provisions,
  - design approval,
  - product acceptance,
  - certification of the final construction, and
  - post-occupancy inspections over the life of the buildings. #25

NIST

Improved Procedures and Practices (2)

State and local jurisdictions adopt and *aggressively enforce building codes to ensure that egress and sprinkler requirements are met* by existing buildings. Further, occupancy requirements should be modified where needed (such as when there are assembly use spaces within an office building) to meet the model building codes. Rec. #26

Building codes should require building owners to *retain documents* related to building design, construction, maintenance and modifications over the entire life of the building. Means should be developed for offsite storage and maintenance of the documents. Relevant information should be *easily accessible by responders* during emergencies. Rec. #27

Improved Procedures and Practices (3)

The role of the “Design Professional in Responsible Charge” be clarified to ensure that *all appropriate design professionals* (including the fire protection and structural engineers) are part of the team designing buildings that employ innovative or unusual structural and fire safety systems**.** Rec. #28

Group 8: Education and Training

The skills of building and fire safety professionals should be upgraded through a national education and training effort for fire protection engineers, structural engineers, and architects. ***The skills of the building regulatory and fire service personnel should also be upgraded to provide sufficient understanding and skills to conduct the review, inspection, and approval tasks for which they are responsible.***

NIST

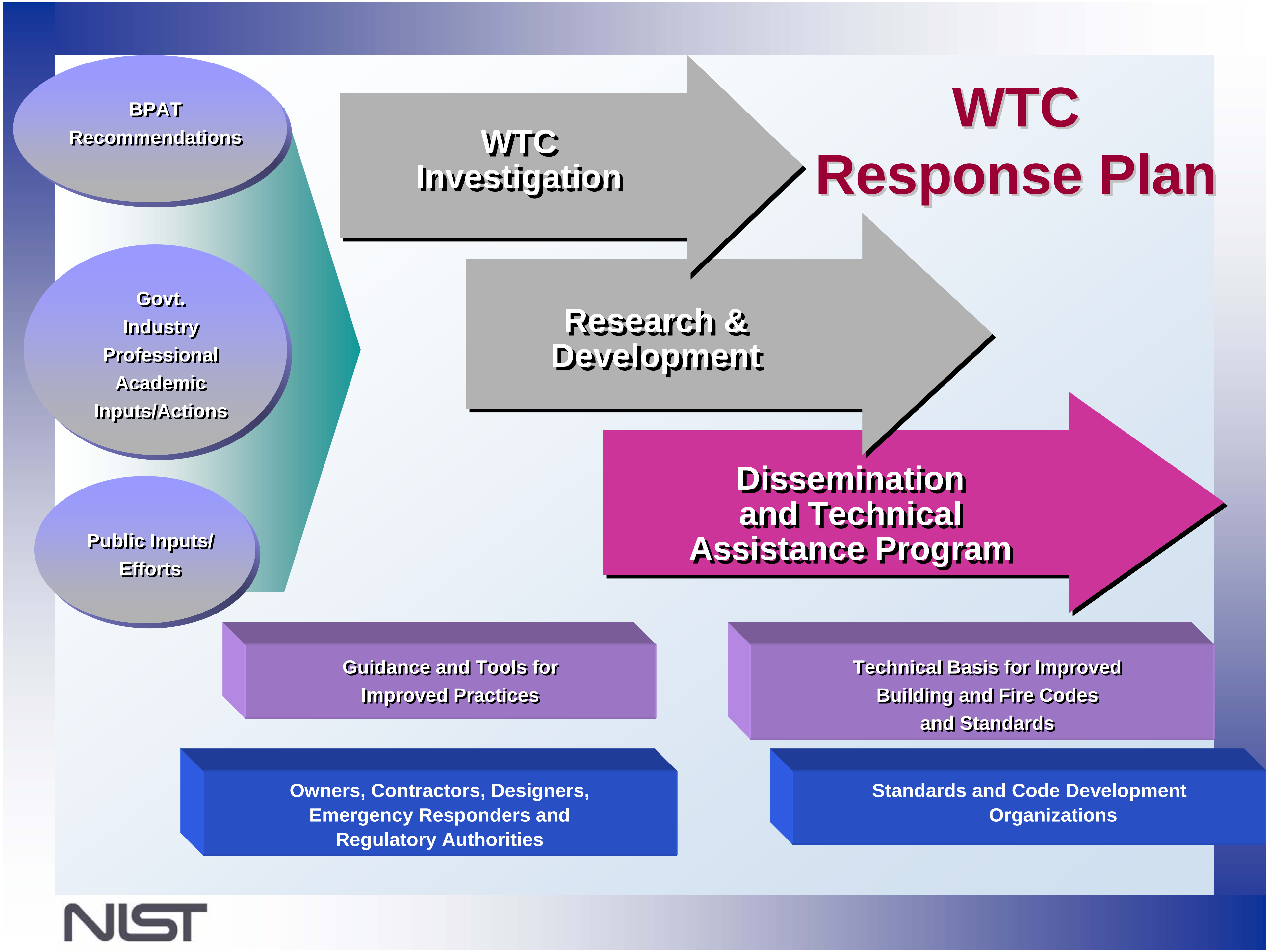
Education and Training

Continuing education curricula should be developed and programs be implemented for:

- training fire protection engineers and architects in structural engineering principles and design, and
- training structural engineers, architects, fire protection engineers, ***and code enforcement officials*** in modern fire protection principles and technologies, including fire-resistance design of structures.
- ***training building regulatory and fire service personnel to upgrade their understanding and skills to conduct the review, inspection, and approval tasks for which they are responsible.*** Rec. #29

Academic, professional short-course, and web-based training materials in the use of computational fire dynamics and thermostructural analysis tools be developed. Rec. #30

NIST



WTC
Response Plan
BPAT Recommendations
Govt. Industry Professional Academic Inputs/Actions
Public Inputs/ Efforts
WTC Investigation
Research & Development
Dissemination and Technical Assistance Program
Guidance and Tools for Improved Practices
Technical Basis for Improved Building and Fire Codes and Standards
Owners, Contractors, Designers, Emergency Responders and Regulatory Authorities
Standards and Code Development Organizations
NIST

Recommendations: Call to Action

- **NIST strongly urges:**
  - **The building and fire safety communities to give *immediate and serious consideration* to these recommendations in order to achieve appropriate improvements in the way buildings are designed, constructed, maintained, and used and in evacuation and emergency response procedures.**
  - **Building owners and public officials to:**
    1. **evaluate the safety implications of these recommendations to their *existing inventory of buildings*; and**
    2. **take the steps necessary to mitigate any *unwarranted risks* without waiting for changes to occur in codes, standards, and practices.**
  - **State and local agencies, well trained and managed, to *rigorously enforce* building codes and standards since such enforcement is critical to ensure the expected level of safety.**

Recommendations: NIST Actions

- After issuance of the final report, the National Construction Safety Team Act requires NIST to:
  - Conduct, or enable or encourage the conduct of, appropriate research recommended by the NCST Team; and
  - Promote the appropriate adoption of the recommendations by the Federal Government and other agencies and organizations.
- NIST is assigning *top priority* to work vigorously with the building and fire safety communities to assure that there is a complete understanding of the recommendations and to provide needed technical assistance.

Recommendations: NIST Actions (2)

- As part of NIST's overall WTC response plan, the Institute has begun to reach out to the building and fire safety communities to pave the way for timely, expedited consideration of recommendations stemming from this investigation.
  - Outreach to:
    - model code organizations (ICC, NFPA)
    - standards development organizations (e.g., ASCE, NFPA, ASTM, ASME, UL)
    - state and local building officials (NCSBCS, AMCBO, NYC DOB)
    - the professional community, including presentations at major conferences (e.g., NFPA, ASCE, AIA, IAFF, CTBUH, Chicago Committee on High-Rise Buildings, Structural Engineers Foundation of Chicago, NCSBCS/AMCBO, CII, CERF Corporate Advisory Board)
  - Detailed briefing for designers of the WTC and lower Manhattan redevelopment (including Silverstein, Port Authority, NYC DOB officials, and Goldman Sachs).
  - WTC Technical Conference: Putting Recommendations into Practice, September 13-15, 2005.
  - NIST will establish a web-based system to track the status of the recommendations.

Strategy for Recommendations

Separate plan for each of the 30 recommendations:

- ❑ Team leader (responsible for proactive pursuit and schedule) and support staff
- ❑ Concise objective
- ❑ Needs to meet objective (NIST and others)
- ❑ Strategy (research, consensus, public policy)
- ❑ Workshops to facilitate consensus (NIBS)
- ❑ Schedules and required format for submitting proposals to target codes and standards
- ❑ Technical and position papers to build support

Proposals for Changes to Codes

- NIST has contracted the National Institute of Building Sciences (NIBS) to coordinate preparation of code change proposals for selected recommendations.

- NIBS is organizing a panel of recognized experts to:

  - Prioritize the recommendations (e.g., those that can be translated directly into code change proposals, those that will require changes to standards, and those that will require additional research).

  - Develop proposals for changes to building codes.

- Panel will prepare proposals for ICC and NFPA 5000 and coordinate submission with code update cycles.

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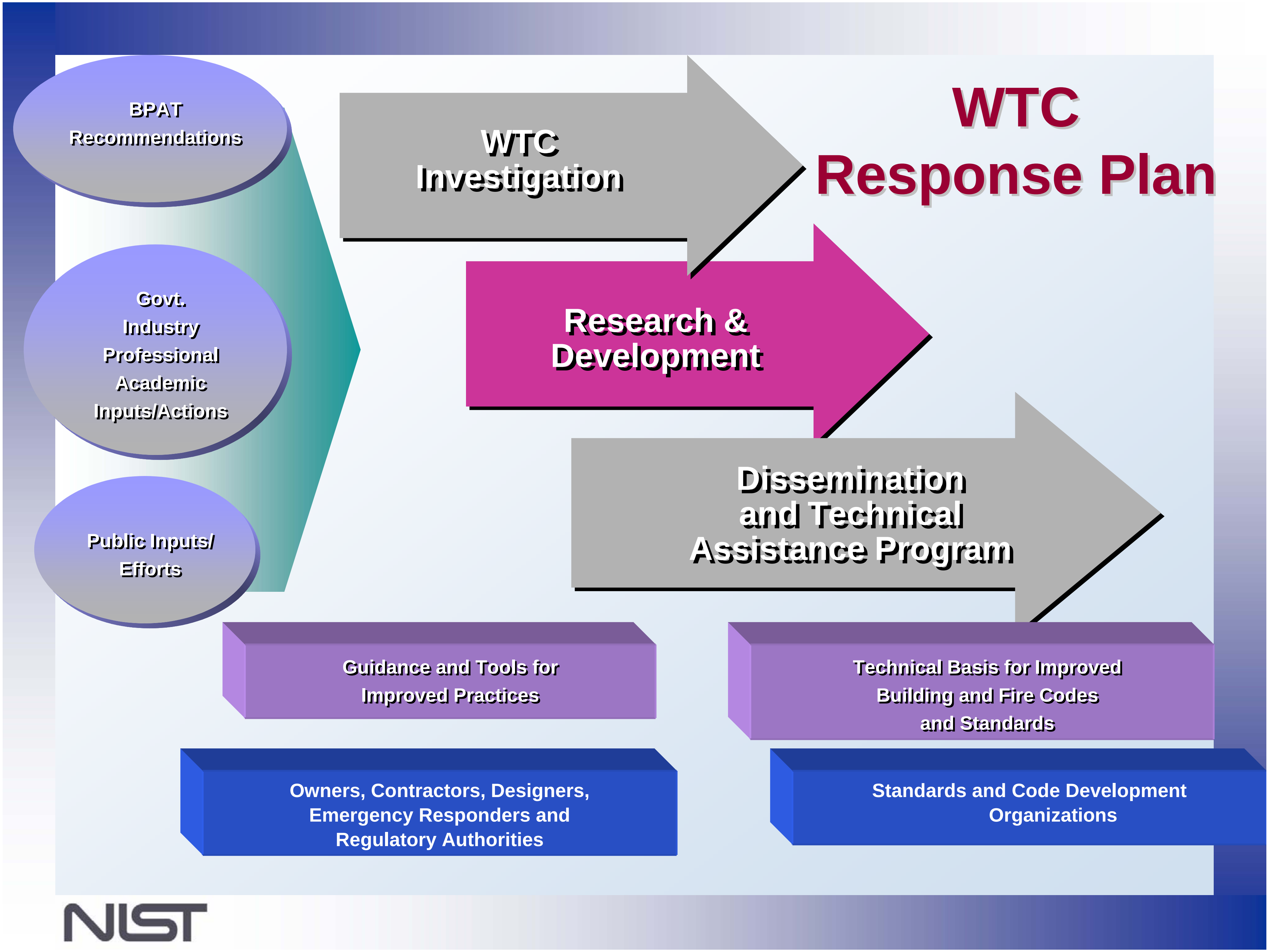
WTC Response Plan
BPAT Recommendations
Govt.
Industry
Professional
Academic
Inputs/Actions
Public Inputs/ Efforts
WTC Investigation
Research & Development
Dissemination and Technical Assistance Program
Guidance and Tools for Improved Practices
Technical Basis for Improved Building and Fire Codes and Standards
Owners, Contractors, Designers, Emergency Responders and Regulatory Authorities
Standards and Code Development Organizations
NIST

Recommendations: NIST Actions (3)

- NIST also has expanded its research in areas of high priority need. Examples include:
  - Prevention of Progressive Collapse
  - Fire Resistance Design and Retrofit of Structures
  - Fire Resistive Coatings for Structural Steel
  - Fire Resistance of Uncoated Structural Steel with Improved Thermal Properties
  - Fire Resistance of Building Partitions
  - Occupant Behavior and Egress
  - Emergency Use of Elevators
  - Equipment Standards for First Responders
  - Standard Building Information Models for Vulnerability Assessment
  - Technologies for Building Operations in CBR Attacks
  - Cost-effective Risk Management Tools

Publication of Reports on the WTC Towers

- 43 reports to be downloadable from the NIST WTC web site by late September or early October 2005
- 43 reports to be available on two CDs in October 2005
- Limited number of hard copies of NIST NCSTAR 1 available in October, 2005

NIST

Tentative Schedule for WTC 7 Reports

January 2006	Completion of technical work
March 2006	Draft reports for review
April 2006	Draft reports to NCST AC
May 2006	Reports for public comment
June 2006	Publication

Web site http://wtc.nist.gov

Email to wtc@nist.gov

Facsimile to (301) 975-6122

Regular mail:
WTC Technical Information Repository, Stop 8610,
100 Bureau Drive, Gaithersburg, MD 20899-8610.

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NCST Advisory Committee

- Appointed by the NIST Director.
- Functions…
  - Review procedures and reports
  - Evaluate activities of teams
  - Assess implementation of recommendations
  - Annual report to Congress
- Reviewed WTC Investigation plan, progress, findings, and draft recommendations at 6 meetings.
- Reviewed all WTC progress reports and final reports
- Membership balances broad scope of disciplines and interests

<u>Members</u>

Dr. Charles Thornton, Co-Chairman, Thornton-Tomasetti.

Dr. Robert Hanson, Professor Emeritus, University of Michigan.

Mr. Philip DiNenno, President, Hughes Associates.

Professor Glenn Corbett, John-Jay College, NYC.

Dr. Kathleen Tierney, University of Colorado, Boulder.

Mr. Paul Fitzgerald, FM Global, (retired).

Mr. David Collins, The Preview Group.

Professor Forman Williams, University of California at San Diego.

Dr. John Barsom, President, Barsom Consulting.

NIST

WTC Investigation Overview

- Investigation announced August 2002; drew talent from about 200 NIST, outside experts, and contractors.
- Two written public updates, two technical progress reports.
- Three public meetings:
  - June 24, 2002 (NYC) to present and solicit comments on draft investigation plan.
  - February 12, 2004 (NYC) to solicit comments on (1) technical aspects of investigation, (2) additional information that NIST might consider, (3) areas to be considered for recommendations.
  - August 24, 2004 (Chicago) to observe fire resistance test of WTC floor system at Underwriters Laboratories.
- Seven media/public briefings on progress, seven meetings of the National Construction Safety Team Advisory Committee, and one meeting to solicit public input for first-person interviews of occupants and first responders.

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