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

Fire Resistance Testing of WTC Floor System

August 25, 2004

S. Shyam Sunder, Sc.D.
Acting Deputy Director and Lead Investigator
and
John L. Gross, Ph.D., P.E.
Research Structural Engineer
Building and Fire Research Laboratory
National Institute of Standards and Technology
U.S. Department of Commerce

NIST

Background on WTC Investigation

- Good, solid technical progress on investigation; drawing on talent from NIST, outside experts, and contractors; $16 million investigation; $5.5 million awarded in contracts

- Two public updates issued (December 2002, December 2003); two technical progress reports issued (May 2003, June 2004)

- NYC Public Meeting (February 12, 2004) to solicit comments on (1) technical aspects of investigation, (2) additional information that NIST might consider, and (3) areas to be considered for recommendations

- Second technical progress report released June 18, 2004; 1,054 pages; full text available on Web site http://wtc.nist.gov

  - Investigation is ongoing; current findings may be revised and additional findings will be presented in final report

  - **NIST has not made any recommendations at this time; all recommendations will be made in the final report**

- NIST expects to release the draft of the final investigation report for public comment in **December 2004**

NIST WTC 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 national building and fire codes, standards, and practices that warrant revision**

NIST

Background on Fire Resistance Testing

- Results of a standard fire resistance test provide a means to compare relative performance of different building assemblies under standard fire conditions.

- Such tests do not represent, in absolute terms, the performance of an entire 3D structural system under “real” fire conditions which may be more or less severe than the standard exposure, considering factors such as combustible fuel load, the extent and number of floors involved, rate of fire spread, and ventilation conditions.

- Role of the floor truss in the collapse of the WTC Towers is still under investigation; the effect on the outcome of September 11, 2001 cannot be evaluated based on the results of the fire resistance tests.

Motivation for Conducting Standard Fire Resistance Tests of WTC Floor System

Fireproofing of the floors in the WTC towers was an issue from the original design of the floor system and throughout the service life.

- Decision to spray trusses directly was innovative
- Need for test was expressed by Architect of Record and Engineer of Record
- Uncertainty in how SFRM thickness was specified
- LERA report reviewed fire resistance of floor system after 1975 fire
- PANYNJ's decision to upgrade fireproofing around 1995

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.

- **Lack of technical basis in the selection of fireproofing thickness** to meet 2 h fire rating:
  - 1/2 in. specified when WTC towers were built
  - 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 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.

NIST

NYC Building Code Provisions (Fire Resistance in hours)

	1938	1968*	2001**
Columns	4	3	2
Floors	3	2	1-1/2

*** Building code governing original design and occupancy**
**** Sprinklers required for buildings of unlimited height**

NIST

Specification of Fireproofing Thickness*

In October 1969, … , the Port Authority stated, in a letter to the fireproofing contractor, that

- "All Tower beams, spandrels, and bar joists requiring spray-on fireproofing are to have a ½ inch covering of Cafco.
- The above requirements must be adhered to in order to maintain the Class 1-A Fire Rating of the New York City Building Code."[1]

[1] Letter dated October 30, 1969 from Robert J. Linn (Manager, Project Planning, The World Trade Center) to Mr. Louis DiBono (Mario & DiBono)

* See Interim Report (May 2003) on Procedures and Practices Used for Passive Fire Protection of the Floor System of the World Trade Center Tower Structures

NIST

Structural Frame Approach

- The “structural frame” approach to fire resistance ratings requires certain structural members, other than columns, 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.” NFPA 5000 is in the process of adopting this requirement.
- 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.

Fire Resistance Rating Requirements Using Structural Frame Approach*

	1938	1968	2001
Columns	4	3	2
Floors	3	3	1-1/2

- **Required by 2000 IBC and under consideration by NFPA 5000; not required by New York City Building Code**

Technical Issues Investigated

- Fireproofing Thickness
- Scale of Test
- Test Restraint Conditions

Fireproofing Thickness

	Specified Thickness (in)	As-applied Average Thickness (COV) (in)	Thermally Equivalent Uniform Thickness* (in)
As Specified (Representative of WTC 2 conditions on 9/11)	0.5	0.75 (0.4)	0.6
Upgraded (Representative of WTC 1 conditions on 9/11)	1.5	2.5 (0.24)	2.2

* Appendix I, June 2004 WTC Investigation Progress Report

Fireproofing Thickness

Thicknesses of SFRM as originally installed:

- "As Specified" = 0.5 in
  - Letter dated October 30, 1969 from Robert J. Linn (Manager, Project Planning, The World Trade Center) to Mr. Louis DiBono (Mario & DiBono)
- "As applied" = 0.75 in
  - Determined from thickness measurements of the existing fireproofing on floors 23 and 24 of WTC 1 - performed by the Port Authority in 1994

Thickness of SFRM as "upgraded" (since 1995)

- "As specified" = 1.5 in
  - PANYNJ white paper titled "Fireproofing Requirements for World Trade Center Tenant Floor Joist Construction that Requires Installation Due to Asbestos Removal or Local Removal to Facilitate Construction," August, 1995.
- "As applied" = 2.5 in
  - Determined from thickness measurements – PANYNJ Construction Audit Reports for floors affected by fire

Scale of Tests

- Two tests conducted in 17 foot furnace at UL's Northbrook, IL, facility.
  - Representative of U.S. fire resistance testing practice
  - Scaling of test specimen is an issue

- Two tests conducted in 35 foot furnace at UL's Toronto, Canada, facility.
  - Full-scale test specimens for WTC floor system (short span)
  - Tests of full-scale floor assemblies are not usually conducted

Test Restraint Conditions

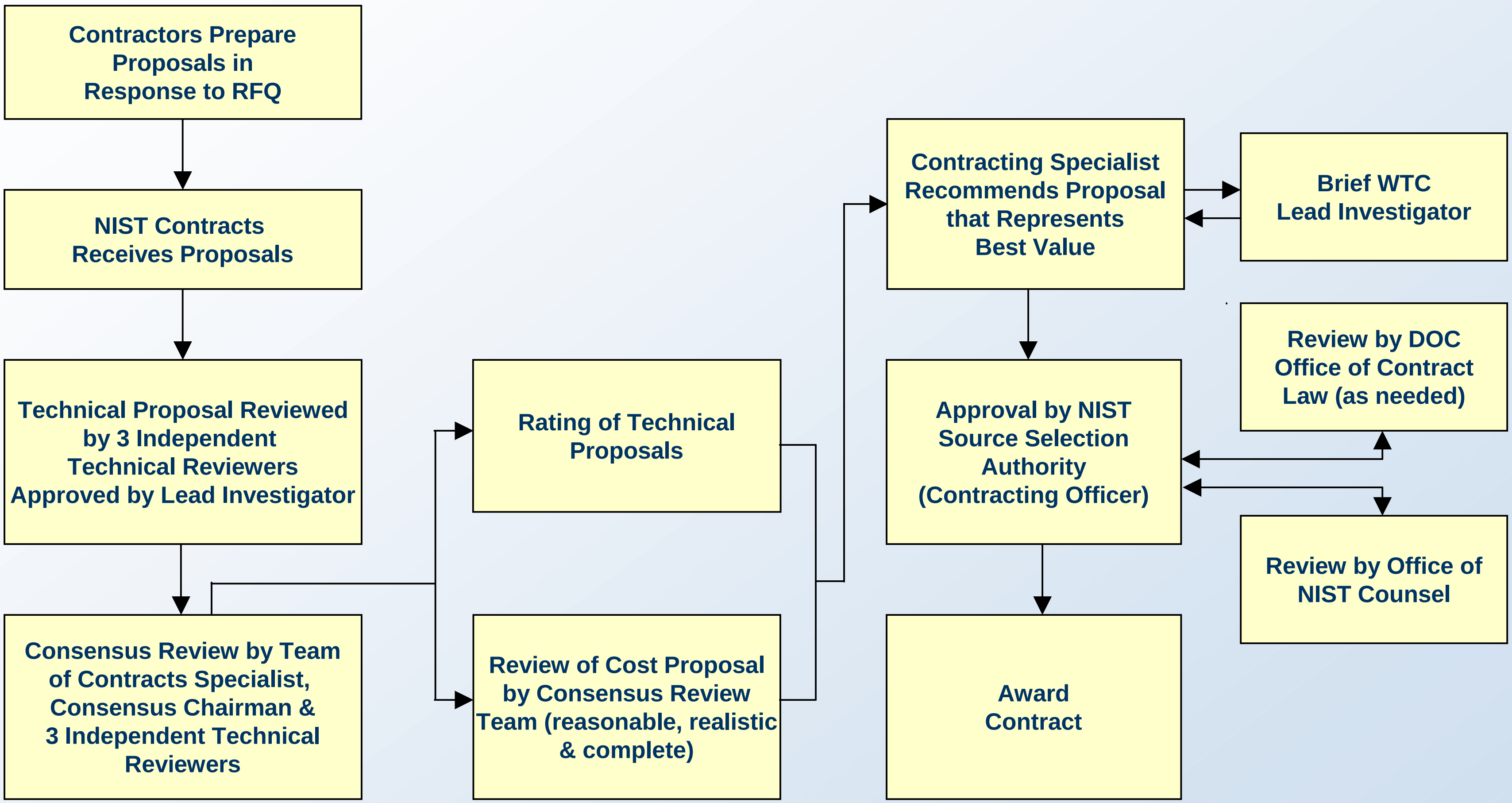
- The two tests conducted in the 17 foot furnace are both tested in the thermally restrained condition.
- One of the tests conducted in the 35 foot furnace was conducted in a thermally restrained condition; the other in a thermally unrestrained condition.
- In practice, fire resistance tests are almost always conducted in the thermally restrained condition.
- The restrained and unrestrained test conditions bound structural performance; actual WTC floor system was neither fully restrained nor fully unrestrained.

Selection of UL to Conduct Fire Resistance Tests

- Fire Resistance Testing requirements issued as a competitive, open procurement.
  - Advertised in FedBizOps
  - Multiple proposals received by NIST
  - Selection made by established process including
    - Technical review
    - Cost analysis
    - Legal review

- Underwriters Laboratories met all of the technical requirements of the solicitation.
- Underwriters Laboratories found to offer the best value to the government.

Contract Review & Selection Process



NIST-UL Coordination

- NIST has placed great technical and logistical demands on UL during preparation and conduct of the tests.
- NIST has actively monitored every step from design of the specimens through fabricating, assembly, instrumentation, testing, and data recording.
- UL has demonstrated
  - Technical excellence
  - Commitment and dedication
  - Timely and thorough execution

Context of Findings

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

- **The extensive fires on September 11, 2001 fall outside the norm of design loads considered in building codes.**

- **Fires played a major role in reducing the structural capacity of the buildings. Aircraft impact damage 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 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 stated policy is to meet and, where appropriate, exceed requirements of local building and fire codes.

Test Results Based on ASTM E119 - 2000

Scale (span)	Fireproofing Thickness (in)	Restraint Condition	Restrained Rating (hours)	Unrestrained Rating (hours)
17 ft	0.75	Restrained	2	1
17 ft	0.5	Restrained	TBD	TBD
35 ft	0.75	Restrained	1½	1
35 ft	0.75	Unrestrained	N/A	2

Comments on Scale Effects

- NIST is using a rigorous approach to properly consider scale effects.
  - ❑ Structural member loads and stresses (shear and bending) are scaled for equivalency.
  - ❑ Structural member size (cross-sectional area), slab and fireproofing thickness, and material properties are kept identical to ensure the same thermal performance and fire rating.
- Both stresses and deflections cannot be scaled for equivalency; not possible to achieve “true” scaling for determining fire resistance ratings.
- Scaling of span length or depth of truss is NOT considered in practice for determining fireproofing requirements.

Summary of Findings

- Fire resistance rating (2 hrs) for 17 ft span with ¾ in fireproofing met the 2 hour rating required by the1968 NYC Building Code for Class 1B Construction.

- Fire resistance rating for 17 ft span with specified ½ in fireproofing thickness to be observed today; this would have been the test to qualify the fire resistance of the WTC floor system before it was built.

- The above two tests will bound the fire resistance rating for the actual WTC floor system which had a thermally equivalent uniform fireproofing thickness of about 0.6 in.

Summary of Findings (Cont'd)

- The fire resistance rating of 1.5 hours for the 35 ft span test with ¾ in fireproofing is smaller than the rating of 2 hours determined from the 17 ft span test with the same fireproofing.

- Current practice assumes equivalent performance is achieved provided thermal characteristics (e.g., cross-sectional size and shape, type and thickness of fireproofing) are met or exceeded; scaling of structural aspects not considered (e.g., geometry, stresses, displacements).

- Test results suggest that **scale effects should be considered when prototype applications far exceed (are much larger than) conditions under which ratings are obtained.**

Summary of Findings (Cont'd)

- For the 35 ft span tests with ¾ in fireproofing, the unrestrained fire resistance rating of 2 hours determined from the unrestrained test was greater than the rating of 1.5 hours determined from the restrained test; the two restraint conditions bound actual performance of the WTC floor system.
- **Result is contrary to expectation based on current testing practice**; expectation is that unrestrained assembly will not perform as well as restrained assembly; therefore hourly rating would generally be lower.
- Both assemblies continued to carry load beyond the point where steel temperature criteria were exceeded; unrestrained rating from restrained test is based on maximum steel temperature criteria.
- **Rating established by deflection limitations**; **the specimen had not collapsed and the unexposed slab temperature criteria was not yet exceeded.**

Summary of Findings (Cont'd)

- The test results are based on a single test for each condition and further study of the fire resistance rating test procedures is needed; reproducibility of results has not been studied here and is not considered in current practice where a single test is used to characterize the rating of an assembly.

- Current fire test facilities and test protocols do not always allow testing to complete collapse.

- The ASTM E119 Standard does not provide guidance for continuing a test to collapse while safeguarding the test facility from damage.

Review of Code Provisions

Construction Classes – Unsprinklered

- Class 1A and 1B: NYC 68, NYS 64, BOCA 65 (Unlimited height)
- Class 1A,1B, 1C, 1D: NYC 01 (Height limited to 75 ft. unless sprinklered)
- Class 1A only: Chicago 67 (Unlimited height)

Fire Resistance Rating (all codes, except NYC 01)

- Class 1A
  - Columns: 4 hours (supporting more than one floor)
  - Beams : 3 hours (floor construction)
- Class 1B
  - Columns: 3 hours (supporting more than one floor)
  - Beams : 2 hours (floor construction)
- Class 1C
  - Columns: 2 hours (supporting more than one floor)
  - Beams : 1-1/2 hours (floor construction)

Mitigation of Potential Conflicts of Interest

RFQ includes OCI Clause & Instructions

↓

Offerors Disclose Potential Conflicts and Submit Mitigation Plan with Proposal

↓↑

OCI Review Coordinated by Office of NIST Counsel Prior to Award

↓

Mitigation Plan Approved by Contracting Officer with Required Changes & Incorporated into Terms and Conditions of Award

Organizational Conflicts of Interest Requirement: Offerors must identify all business relationships in which they will provide data, research services or advice concerning the WTC disaster, including any involvement in related litigation. If any such relationship would constitute a real or apparent conflict of interest, they must provide a plan for mitigation of the conflict. Third party reviews of such plans may be required to assure that contract deliverables will be completely objective. These reviews may include, but are not limited to, other government agencies, non-profits, academia, or an independent contractor.

No contractor deliverables shall include findings, conclusions or recommendations.

Results (Ratings) of Tests to Date Using ASTM E119-2000

Conventional scale (17 ft span) - restrained

- Restrained Rating: 2 hours
- Unrestrained Rating: 1 hour

Full scale (35 ft span) - restrained

- Restrained Rating: 1 ½ hours
- Unrestrained Rating: 1 hour

Full scale (35 ft span) - unrestrained

- Unrestrained Rating: 2 hours

(Extremely) Brief History of Fire Endurance Testing

The Great Baltimore Fire

- On February 7, 1904, a fire broke out in the John E. Hurst wholesale dry goods house in the heart of Baltimore's business district. It moved rapidly through the building, and quickly spread to other buildings. (Washington Post Article, 2001)
- Fire departments from New York, Philadelphia and Washington, DC responded immediately to a desperate telegram sent by George W. Horton, chief engineer of the city's fire department.
- When the hoses would not fit Baltimore hydrants, the reinforcements were forced to watch helplessly as the flames spread, destroying approximately 1,500 buildings and burning for more than 30 hours.

Some Specific Questions

- How and why did WTC 1 stand nearly **twice** as long as WTC 2 before collapsing (103 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 **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?

- 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?

Comments on Restraint Conditions

- Unrestrained rating from restrained test is based on maximum steel temperature criteria.
- Unrestrained rating from unrestrained test was greater than that from restrained test.
- Result is contrary to expectation; expectation is that unrestrained assembly will not perform as well as restrained assembly; therefore hourly rating would generally be lower.
- Assembly continued to carry load beyond the point where steel temperature criteria were exceeded
- Rating established by deflection limitations; the specimen had not collapsed and the unexposed slab temperature criteria was not yet exceeded