NIST NCSTAR 1-6A (Draft)

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

Passive Fire Protection (Draft)

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For Public Comment

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

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Kuldeep R. Prasad
Richard W. Bukowski
Building and Fire Research Laboratory
National Institute of Standards and Technology

*Scott R. Kukuck's current affiliation:
U.S. Army Research Laboratory
Aberdeen Proving Grounds, Maryland

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U.S. Department of Commerce
Carlos M. Gutierrez, Secretary

Technology Administration
Michelle O' Neill, Acting Under Secretary for Technology

National Institute of Standards and Technology
Hratch G. Semerjian, Acting Director

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Pursuant to section 7 of the National Construction Safety Team Act, the NIST Director has determined that certain evidence received by NIST in the course of this Investigation is "voluntarily provided safety-related information" that is "not directly related to the building failure being investigated" and that "disclosure of that information would inhibit the voluntary provision of that type of information" (15 USC 7306c).

In addition, a substantial portion of the evidence collected by NIST in the course of the Investigation has been provided to NIST under nondisclosure agreements.

Disclaimer No. 4

NIST takes no position as to whether the design or construction of a WTC building was compliant with any code since, due to the destruction of the WTC buildings, NIST could not verify the actual (or as-built) construction, the properties and condition of the materials used, or changes to the original construction made over the life of the buildings. In addition, NIST could not verify the interpretations of codes used by applicable authorities in determining compliance when implementing building codes. Where an Investigation report states whether a system was designed or installed as required by a code *provision*, NIST has documentary or anecdotal evidence indicating whether the requirement was met, or NIST has independently conducted tests or analyses indicating whether the requirement was met.

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ABSTRACT

This report deals with the passive fire protection used in the WTC towers. The main objective is to provide background information that can be used to assess the in-place conditions of the passive protection before and after aircraft impact. The report includes a review of key building code provisions related to structural fire protection. It also includes a review of key decisions related to passive fire protection made during design, construction, and occupancy of the towers. Copies of documents to support key findings are included in an Appendix. A summary is provided of available data on in-place measurements of the sprayed fire-resistive materials (SFRMs) applied to the floor trusses and to core members. Measurements of thermophysical properties of the passive fire protection materials, including gypsum panels, are presented. The effects of gaps in thermal insulation and the effects of variability of insulation thickness are evaluated. The rationale for selecting the effective thickness of thermal insulation for use in thermal-structural analyses is presented. Measurements of adhesive and cohesive strengths of a selected SFRM are summarized. Simplified models are presented for estimating the acceleration required to dislodge SFRM from planar surfaces and encased round bars. The report concludes with a summary of key findings.

Keywords: adhesive strength, building code, cohesive strength, construction classification, density, equivalent thickness, retrofit, specific heat capacity, sprayed fire-resistive materials (SFRM), thermal conductivity, thermal insulation, thickness, thickness variability, World Trade Center.

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronyms

ASTM	ASTM International (formerly American Society for Testing and Materials)
BFRL	Building and Fire Research Laboratory
BOCA	Building Officials and Code Administrators
DSC	Differential Scanning Calorimetry
DTA	Differential Thermal Analysis
ER&S	Emory Roth & Sons
FDNY	New York City Fire Department
IBC	International Building Code
ICBO	International Conference of Building Officials
ICC	International Code Council
LERA	Leslie E. Robertson Associates
NCST	National Construction Safety Team
NIST	National Institute of Standards and Technology
NYCDOB	New York City Department of Buildings
SHCR	Skilling, Helle, Christiansen, & Robertson
SFRM	sprayed fire-resistive material
STA	Simultaneous Thermal Analyzer
TGA	Thermal Gravimetric Analysis
TPRL	Thermophysical Properties Research Laboratory
UBC	Uniform Building Code
UL	Underwriters Laboratories, Inc.
USM	United States Mineral Products Co.
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."
WTC	World Trade Center
WTC 1	World Trade Center 1 (North Tower)
WTC 2	World Trade Center 2 (South Tower)

WTC 7	World Trade Center 7

Abbreviations

a	acceleration
Btu	British thermal unit
°C	degrees Celsius
d_i	steel bar diameter
d_0	outside diameter of SFRM on round bar
°F	degrees Fahrenheit
f_b	cohesive strength normal to surface or adhesive strength
f_t	in-plane cohesive strength of SFRM
ft	foot
ft^2	square foot
g	acceleration of gravity
g	gram
h	hour
in.	inch
J	joule
K	kelvin (absolute temperature)
kg	kilogram
lb	pound
m	meter
m^2	square meter
m^3	cubic meter
min	minute
pcf	pounds per cubic foot
psf	pounds per square foot
psi	pounds per square inch
s	second
t	thickness of SFRM
W	watt
α	ratio of adhesive strength to in-plane cohesive strength of SFRM
ρ	mass density of SFRM

METRIC CONVERSION TABLE

To convert from	to	Multiply by
inch (in.)	meter (m)	2.54 E-02
degree Fahrenheit (°F)	degree Celsius (°C)	t/ °C = (t/ °F - 32)/1.8
foot (ft)	meter (m)	3.048 E-01
pcf (pound per cubic foot) (lb/ft^3)	kilogram per cubic meter (kg/m^3)	1.601 846 E+01
$Btu_{IT} \cdot in./(ft^2 \cdot h \cdot °F)$	W/(m · K)	1.442 279 E-01
psf (pound-force per square foot) (lbf/ft^2)	kilopascal (kPa)	4.788 026 E-02
psi (pound-force per square inch) (lbf/in^2)	kilopascal (kPa)	6.894 757 E+00

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PREFACE

Genesis of This Investigation

Immediately following the terrorist attack on the World Trade Center (WTC) on September 11, 2001, the Federal Emergency Management Agency (FEMA) and the American Society of Civil Engineers began planning a building performance study of the disaster. The week of October 7, as soon as the rescue and search efforts ceased, the Building Performance Study Team went to the site and began their assessment. This was to be a brief effort, as the study team consisted of experts who largely volunteered their time away from their other professional commitments. The Building Performance Study Team issued their report in May 2002, fulfilling their goal "to determine probable failure mechanisms and to identify areas of future investigation that could lead to practical measures for improving the damage resistance of buildings against such unforeseen events."

On August 21, 2002, with funding from the U.S. Congress through FEMA, the National Institute of Standards and Technology (NIST) announced its building and fire safety investigation of the WTC disaster. On October 1, 2002, the National Construction Safety Team Act (Public Law 107-231), was signed into law. The NIST WTC Investigation was conducted under the authority of the National Construction Safety Team Act.

The goals of the investigation of the WTC disaster were:

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

The specific objectives were:

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

NIST is a nonregulatory agency of the U.S. Department of Commerce's Technology Administration. The purposes of NIST investigations under the National Construction Safety Team Act are to improve the safety and structural integrity of buildings in the United States, and the focus is on fact finding. NIST investigative teams are required to assess building performance and emergency response and evacuation procedures in the wake of any building failure that has resulted in substantial loss of life or that posed significant potential of substantial loss of life. NIST does not have the statutory authority to make findings of fault or negligence by individuals or organizations. Further, no part of any report resulting from a NIST investigation into a building 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 Public Law 107-231).

Organization of the Investigation

The National Construction Safety Team for this Investigation, appointed by the NIST Director, was led by Dr. S. Shyam Sunder. Dr. William L. Grosshandler served as Associate Lead Investigator, Mr. Stephen A. Cauffman served as Program Manager for Administration, and Mr. Harold E. Nelson served on the team as a private sector expert. The Investigation included eight interdependent projects whose leaders comprised the remainder of the team. 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 and Project Leader	Project Purpose
Analysis of Building and Fire Codes and Practices; Project Leaders: Dr. H. S. Lew and Mr. Richard W. Bukowski	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 WTC 1, 2, and 7.
Baseline Structural Performance and Aircraft Impact Damage Analysis; Project Leader: Dr. Fahim Sadek	Analyze the baseline performance of WTC 1 and WTC 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; Project Leader: Dr. Frank W. Gayle	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; Project Leader: Dr. David D. Evans	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; Project Leader: Dr. Richard G. Gann	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; Project Leaders: Dr. John L. Gross and Dr. Therese P. McAllister	Analyze the response of the WTC towers to fires with and without aircraft damage, the response of WTC 7 in fires, the performance of composite steel-trussed floor systems, and determine the most probable structural collapse sequence for WTC 1, 2, and 7.
Occupant Behavior, Egress, and Emergency Communications; Project Leader: Mr. Jason D. Averill	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.
Emergency Response Technologies and Guidelines; Project Leader: Mr. J. Randall Lawson	Document the activities of the emergency responders from the time of the terrorist attacks on WTC 1 and WTC 2 until the collapse of WTC 7, including practices followed and technologies used.

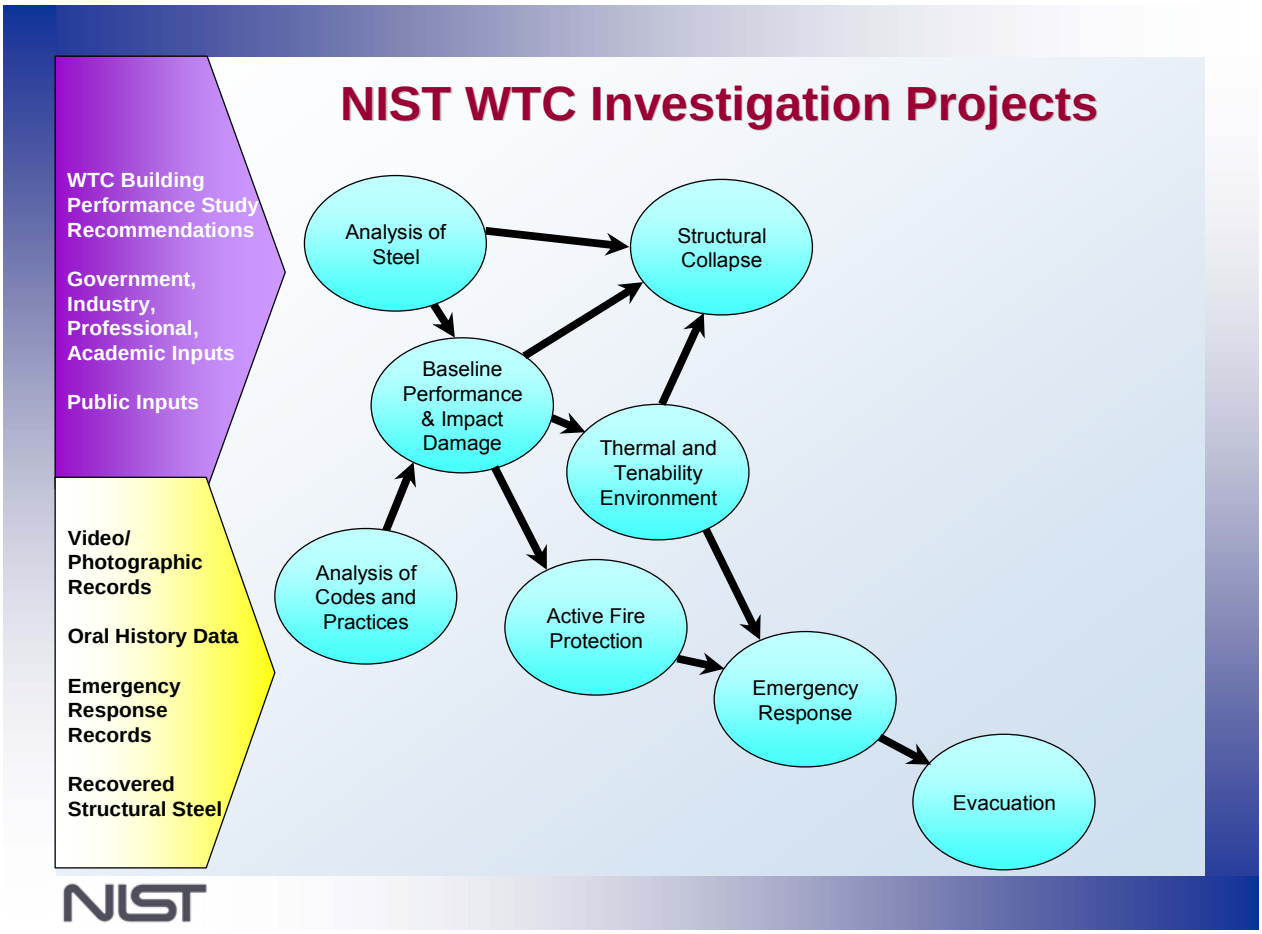

Figure P–1. The eight projects in the federal building and fire safety investigation of the WTC disaster.

National Construction Safety Team Advisory Committee

The NIST Director also established an advisory committee as mandated under the National Construction Safety Team Act. The initial members of the committee were appointed following a public solicitation. These were:

- Paul Fitzgerald, Executive Vice President (retired) FM Global, National Construction Safety Team Advisory Committee Chair
- John Barsom, President, Barsom Consulting, Ltd.
- John Bryan, Professor Emeritus, University of Maryland
- David Collins, President, The Preview Group, Inc.
- Glenn Corbett, Professor, John Jay College of Criminal Justice
- Philip DiNenno, President, Hughes Associates, Inc.

- Robert Hanson, Professor Emeritus, University of Michigan
- Charles Thornton, Co-Chairman and Managing Principal, The Thornton-Tomasetti Group, Inc.
- Kathleen Tierney, Director, Natural Hazards Research and Applications Information Center, University of Colorado at Boulder
- Forman Williams, Director, Center for Energy Research, University of California at San Diego

This National Construction Safety Team Advisory Committee provided technical advice during the Investigation and commentary on drafts of the Investigation reports prior to their public release.

Public Outreach

During the course of this Investigation, NIST held public briefings and meetings (listed in Table P–2) to solicit input from the public, present preliminary findings, and obtain comments on the direction and progress of the Investigation from the public and the Advisory Committee.

NIST maintained a publicly accessible Web site during this Investigation at http://wtc.nist.gov. The site contained extensive information on the background and progress of the Investigation.

NIST's WTC Public-Private Response Plan

The collapse of the WTC buildings has led to broad reexamination of how tall buildings are designed, constructed, maintained, and used, especially with regard to major events such as fires, natural disasters, and terrorist attacks. Reflecting the enhanced interest in effecting necessary change, NIST, with support from Congress and the Administration, has put in place a program, the goal of which is to develop and implement the 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 building, and the associated evacuation and emergency response experience.
- A research and development (R&D) program to (a) facilitate the implementation of recommendations resulting from the WTC Investigation, and (b) provide the technical basis for cost-effective improvements to national building and fire codes, standards, and practices that enhance the safety of buildings, their occupants, and emergency responders.

Table P–2. Public meetings and briefings of the WTC Investigation.

Date	Location	Principal Agenda
June 24, 2002	New York City, NY	Public meeting: Public comments on the *Draft Plan* for the pending WTC Investigation.
August 21, 2002	Gaithersburg, MD	Media briefing announcing the formal start of the Investigation.
December 9, 2002	Washington, DC	Media briefing on release of the *Public Update* and NIST request for photographs and videos.
April 8, 2003	New York City, NY	Joint public forum with Columbia University on first-person interviews.
April 29–30, 2003	Gaithersburg, MD	National Construction Safety Team (NCST) Advisory Committee meeting on plan for and progress on WTC Investigation with a public comment session.
May 7, 2003	New York City, NY	Media briefing on release of the *May 2003 Progress Report.*
August 26–27, 2003	Gaithersburg, MD	NCST Advisory Committee meeting on status of WTC investigation with a public comment session.
September 17, 2003	New York City, NY	Media briefing and public briefing on initiation of first-person data collection projects.
December 2–3, 2003	Gaithersburg, MD	NCST Advisory Committee meeting on status and initial results and the release of the *Public Update* with a public comment session.
February 12, 2004	New York City, NY	Public meeting: Briefing on progress and preliminary findings with public comments on issues to be considered in formulating final recommendations.
June 18, 2004	New York City, NY	Media briefing and public briefing on release of the *June 2004 Progress Report.*
June 22–23, 2004	Gaithersburg, MD	NCST Advisory Committee meeting on the status of and preliminary findings from the WTC Investigation with a public comment session.
August 24, 2004	Northbrook, IL	Public viewing of standard fire resistance test of WTC floor system at Underwriters Laboratories, Inc.
October 19–20, 2004	Gaithersburg, MD	NCST Advisory Committee meeting on status and near complete set of preliminary findings with a public comment session.
November 22, 2004	Gaithersburg, MD	NCST Advisory Committee discussion on draft annual report to Congress, a public comment session, and a closed session to discuss pre-draft recommendations for WTC Investigation.
April 5, 2005	New York City, NY	Media briefing and public briefing on release of the probable collapse sequence for the WTC towers and draft reports for the projects on codes and practices, evacuation, and emergency response.
June 23, 2005	New York City, NY	Media briefing and public briefing on release of all draft reports and draft recommendations for public comment.

- A dissemination and technical assistance program (DTAP) to (a) engage leaders of the construction and building community in ensuring timely adoption and widespread use of proposed changes to practices, standards, and codes resulting from the WTC Investigation and the R&D program, and (b) 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 buildings, occupants, and first responders safer in future disaster events.

National Construction Safety Team Reports on the WTC Investigation

A draft of the final report on the collapses of the WTC towers is being issued as NIST NCSTAR 1. A companion report on the collapse of WTC 7 is being issued as NIST NCSTAR 1A. The present report is one of a set that provides more detailed documentation of the Investigation findings and the means by which these technical results were achieved. As such, it is part of the archival record of this Investigation. The titles of the full set of Investigation publications are:

NIST (National Institute of Standards and Technology). 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Final Report of the National Construction Safety Team on the Collapses of the World Trade Center Towers.* NIST NCSTAR 1. Gaithersburg, MD, September.

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EXECUTIVE SUMMARY

The structural steel in the World Trade Center (WTC) towers was protected against the effects of fire with sprayed fire-resistive materials (SFRMs) or rigid fire-rated gypsum panels. The majority of the types of SFRMs used in the WTC towers are packaged as dry ingredients composed of a binder and insulation materials. At the job site, water is added by a pressurized system as the materials are sprayed onto the steel. The water mixes with the cementitious materials and provides "stickiness" that allows the SFRM to adhere weakly to the steel. With time, the cementitious materials harden, and excess water evaporates. When dry, SFRMs provide an insulation barrier to limit excessive temperature rise in the protected steel member during a fire.

The thermal-structural analysis of the WTC towers focused on two objectives: (1) analysis of the undamaged buildings exposed to conventional building fires, and (2) analysis of the buildings damaged by the aircraft impact and exposed to the subsequent fires. To reduce the uncertainties in the calculated thermal histories of various structural elements, the condition of the passive fire protection as it existed on September 11, 2001, was estimated as accurately as possible. In addition, reasonable estimates of the extent of SFRM dislodged by aircraft impact and the resulting debris field had to be made.

To provide context for the information in this report, an overview of concepts used in U.S. building regulations for structural fire resistance is presented first. This is followed with a summary of the construction history of the sprayed fire-resistive materials in WTC 1 and WTC 2. To gain an understanding of the effect of SFRM thickness and its variability on the steel temperature during exposure to fire, results are presented of a sensitivity study based on a simple finite-element model. This is followed by a quantitative assessment of in-place thickness and its variability based on available data. The rationale for the thickness of SFRM to be used in the structural fire endurance analyses is presented. The tests conducted to determine the thermal properties of insulation materials similar to those used in the WTC towers are reviewed. The results of mechanical property tests conducted on laboratory specimens are presented, and a simplified approach for estimating the acceleration required to dislodge thermal insulation during impact is discussed.

BUILDING CODE CONCEPTS FOR STRUCTURAL FIRE RESISTANCE

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

The intent of building height limits is to restrict taller buildings to non-combustible structural members and the greatest fire resistance is assigned to members supporting multiple floors. The primary concern with combustible structural members is that they can become ignited by an exposing fire and can continue to burn (often in concealed spaces) even after the exposing fire has been extinguished, leading to collapse. The intent of increased fire resistance for members supporting multiple floors is directly related to the

higher risk of property loss in the event of failure of multiple floors. Fire resistance requirements, however, do not take into account the actual number of stories being supported by these elements.

Construction Types

The main categories of constructions defined in building codes are Type I (fire resistive), Type II (non-combustible), Type III (combustible), Type IV (heavy timber), and Type V (ordinary). Construction Types I and II include non-combustible exterior and interior bearing walls and columns, where fire resistance ratings are greatest for Type I, and Type II is any (non-combustible) construction not meeting Type I requirements. Within each construction type are several sub-categories determined by the fire resistance ratings of the columns (vertical structural elements that support gravity loads and resist the actions of lateral loads), beams (horizontal structural elements that support predominantly gravity loads), and floor systems. In some codes these sub-categories are identified by letters following the type (e.g., 1B or 3A) (IBC 2003) or by a set of three numbers that represent the fire resistance required (in hours) of the columns, beams, and floors, respectively (e.g., Type 1 (3,3,2)).

Fire Resistance of Structural Elements

Building codes require that structural elements are to be protected to achieve a specified fire resistance rating, expressed in hours. The fire rating of structural materials and assemblies is generally determined through testing, and in the United States, such testing is frequently conducted in accordance with ASTM Test Methods E 119. The intent is for the building to withstand design loads (including fire) without local structural collapse until occupants can escape and the fire service can complete search and rescue operations.

Building codes generally require the highest fire resistance for columns and elements supporting multiple floors, and somewhat less resistance for columns supporting single floors, for beams, and for floors. The required fire resistance ratings have been reduced in recent years as fire sprinklers have become universal in new high-rise buildings and common in most other commercial buildings. In the past, high-rise buildings generally required a 4 h rating for columns; this was reduced to 3 h in recent codes, and can be as low as 2 h in current codes based on the additional mandatory requirement for sprinklers. Some codes allow a reduction in fire-resistance rating for high-rise buildings that have been retrofitted with sprinklers.

HISTORICAL REVIEW RELATED TO PASSIVE FIRE PROTECTION

Port Authority Relationships with New York City Department of Buildings and Fire Department

As an interstate agency, the Port Authority was not required to comply with the New York City Building Code or any other building code in the design and construction of the WTC towers. The Port Authority, however, made explicit statements that it would comply with the New York City Code. In a letter dated May 15, 1963, the Port Authority instructed its consulting engineers and architects to comply with the New York City Building Code. In the areas where the Code was not explicit or where technological advances made portions of the Code obsolete, it directed that design could be based on acceptable engineering practice. At this time, the 1938 edition of the New York Building Code was in effect and a revised Code was being drafted. In September 29, 1965, the Port Authority instructed its consultants to

revise WTC design plans to comply with the second and third drafts of the Code revision. The revised Building Code became effective in December 1968.

In 1993, the Port Authority and the New York City Department of Buildings entered into a memorandum of understanding to establish procedures to be followed by the Port Authority for any building construction project located in the City's jurisdiction. Among the key points, it was agreed that:

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

A supplement to this memorandum of understanding was executed in June 1995, which permitted tenants to use New York State licensed architects or engineers, in lieu of a Port Authority review, to certify that construction plans conformed to the Code and that construction was performed in accordance with the plans. In September 1995, the supplement was modified to permit a single licensed consultant to certify the plans and the construction, except if the alteration would change the occupancy group of the space.

In 1993, the Port Authority signed a memorandum of understanding with the Fire Department of the City of New York (FDNY). The agreement restated the Port Authority's policy to implement recommendations after a fire safety inspection of a Port Authority facility by a local fire department. The agreement included the following points:

- The FDNY shall have the right to conduct fire safety inspections at any Port Authority facility in New York City.
- FDNY will issue to the Port Authority a letterhead report of its fire safety inspections for correction of any deficiencies.
- The Port Authority will continue to assure that new or modified fire safety systems comply with local codes and regulations.

In 1995, the memorandum of understanding with FDNY was amended with respect to additions to or modifications of fire safety systems. The Port Authority was required to notify the Bureau of Fire Protection prior to installing new systems or modifying existing systems. In addition, plans for these systems were to be prepared by New York State licensed professional engineers or architects.

New York City Building Code Requirements

Application of the 1968 New York City Building Code provisions affected the assigned building classification and thus the required fire rating of the WTC towers and their structural members. The WTC towers were classified as Occupancy Group E—Business. The 1968 Code identified two construction groups: Noncombustible Construction (Group 1) and Combustible Construction (Group 2). The WTC towers were classified as Construction Group 1 because their walls, exit ways, shafts, structural

members, floors, and roofs were constructed of noncombustible materials. At the time of design and construction, the towers were not sprinklered.

The 1968 New York City Building Code defined five Classes within Construction Group 1. For Business occupancy, each Class required a fire endurance rating as follows:

- Class 1A: 4 hour protected
- Class 1B: 3 hour protected
- Class 1C: 2 hour protected
- Class 1D: 1 hour protected
- Class 1E: unprotected

Construction Classes 1A and 1B permitted buildings of unlimited height. Thus the WTC towers could have been designed to meet either Class 1A or Class 1B.

Classification of WTC Towers

It was the practice at the time, and continues to be the practice, for the architect to establish the building classification, fire rating of members and systems, and thermal protection requirements. The review of documents uncovered during the investigation indicated a discrepancy in the classification, and therefore the fire ratings, to be used in the design of the towers. Documents issued in the early stages of the design appear to indicate that the towers were classified as Class 1A. With the directive in 1965 to comply with the 1968 New York City Building Code, it appears that the towers were classified ultimately as Class 1B.

According to the 1968 New York City Building Code, construction classification 1B provided, in part, the following fire protection requirements:

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

Thus the columns were required to have a 3 hour fire endurance rating and the floor system was required to a have a 2 hour rating when tested in accordance with ASTM E 119.

Response to Local Law 5/1973

In 1973, New York City Local Law No. 5 amended the New York City Building Code (effective January 18, 1973). Local Law No. 5 required, in part, the retrofit of existing unsprinklered office buildings 100 ft or higher. The New York City Department of Buildings permitted either:

- Subdividing the floor area into compartments of specified square footage by fire separations (1 h or 2 h fire rated depending on the size of the compartment), or
- Providing sprinkler protection.

A code compliance evaluation conducted in 1997 indicated that that all tenant floors in the two towers had been retrofitted with sprinklers (sprinklered) with the exception of four floors in WTC 1. In a 1999 update by the Port Authority it was noted that all tenant floors had been sprinklered and work was underway to complete sprinklering of the sky lobbies. In 2000, a property condition assessment report stated that the WTC towers were classified as "Class 1B – noncombustible, fire-protected, retrofitted with sprinklers in accordance with New York City Local Law 5/1973."

Selection of Fire-Resistive Materials

Classification of a building leads to its overall fire endurance rating and ratings of the various structural components. The New York City Building Code, however, does not prescribe how the required fire endurance rating is to be achieved. The Port Authority chose to protect the main structural components such as columns, spandrel beams, and floor trusses with sprayed fire-resistive material. This thermal protection technique was an established method for protecting columns, beams, and walls. In the 1960s, however, composite steel joist-supported floor systems were usually protected using "lath and plaster" enclosures or fire-rated ceiling tiles.

Since application of sprayed fire-resistive materials to floor trusses was an innovative fire protection method, the Port Authority arranged for demonstrations to establish its feasibility for the World Trade Center. The demonstrations were considered to be successful and in November 1968, the Port Authority awarded the contract for "spray fireproofing" of the interior portions (floor system and core) of the WTC Towers. The fire protection of the exterior columns was included in the contract for the exterior aluminum cladding.

Several materials were considered for the sprayed thermal insulation. The exterior columns required insulation not only for fire protection but also to control column temperatures under service conditions. Alcoa recommended for the exterior columns the use of a sprayed material produced by U.S. Mineral Products, Co. known as CAFCO BLAZE-SHIELD Type D. The same material was eventually selected for the floor trusses and core beams and columns. This product, however, contained asbestos fibers. On April 13, 1970, New York City issued restrictions on the application of sprayed thermal insulation containing asbestos. The use of CAFCO BLAZE-SHIELD Type D was discontinued in 1970 at the 38th floor of WTC 1. The asbestos-containing material was subsequently encapsulated with a sprayed material that provided a hard coating. A green dye was added to the encapsulating material so that the asbestos containing SFRM could be identified. Thermal protection of the remaining floors of WTC 1 and all of WTC 2 was carried out using CAFCO BLAZE-SHIELD Type DC/F, a product that contained mineral wool (glassy fibers) in place of the crystalline asbestos fibers. On the basis of tests, it was reported that

the thermal properties of CAFCO Type DC/F were equal to or "slightly better" than those of CAFCO Type D.

Specified Thickness of Fire-Resistive Material

The thickness of fire-resistive material necessary to achieve the required fire endurance was being assessed in 1965, more than three years before the award of the thermal protection contract. At that time, the Architect of Record recommended 1 in. of thermal protection for the top and bottom chords of the floor trusses and 2 in. for other members of the trusses. WTC project specifications for sprayed fire protection do not provide required material thickness or hourly ratings. In October 1969, the manager of project planning for the WTC provided the following instructions to the contractor applying the sprayed fire protection:

> "…Tower 'A' columns that are less than 14WF228 will require 2 3/16″ thick of 'Cafco Glaze [sic]-Shield 'Type D'' spray-on fireproofing. All Tower columns equal to or greater than 14WF228 will require 1 3/16″ of fireproofing…
>
> All Tower beams, spandrels and bar joists requiring spray-on fireproofing are to have a 1/2″ 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."

NIST's review of available documents has not uncovered the reasons for selecting CAFCO BLAZE-SHIELD or the technical basis for specifying ½ in. thickness of insulation for the floor trusses. The last sentence in the above excerpt indicates that in October 1969 it appeared that the towers were considered as Class 1A construction.

In February 1975, a fire occurred in WTC 1, spreading from the 9th to the 19th floor. After the fire, the Port Authority contracted Skilling, Helle, Christiansen, Robertson (SHCR), the Structural Engineer of Record for the design of the WTC towers, to assess the resulting structural damage and to report, in general, on the fire resistivity of the floor system. In its report dated April 1, 1975, SHCR communicated to the Port Authority that the fire did not cause structural damage, but it caused buckling of some top chord members of main trusses, buckling of bridging trusses, and distortion of deck support angles. The report provided valuable information on the history of the passive fire protection of the towers.

The 1975 post-fire report by SCHR stated further that thermal protection of the top chords of the floor trusses was not necessary, except for the corners of the buildings where the floor acted as a two-way system in bending. Additionally, it was stated that protection of the bridging trusses was not required because the bridging trusses were "not required as a part of the structural system."

In February 2003, NIST asked the Port Authority a series of questions related to the sprayed thermal protection for the floor system. The Port Authority replied in March that the top chords of the main trusses and the bridging trusses were protected.

Upgrading SFRM on Floor Trusses

In 1995, the Port Authority performed a study to establish requirements for retrofit of sprayed insulation to the floor trusses during major alterations (new construction) when tenants vacated spaces in the towers. The study estimated the thermal protection requirements based on "the fireproofing requirements" for Design No. G805 contained in the Fire Resistance Directory published by Underwriters Laboratories. The study concluded that "a two hour fire rating for the steel floor joist trusses can be achieved by applying a 1½ inch thickness of spray-on mineral fiber fire protection material directly to the steel truss chords and webs." In the years between 1995 and 2001, thermal protection was upgraded in a number of the floors affected by the fires on September 11, 2001. Specifically, in WTC 1, floors 92 through 100 and 102 were upgraded; and in WTC 2, floors 77, 78, 88, 89, 92, 96 and 97 were upgraded.

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

- For full floors undergoing new construction or renovation, the floor trusses should be protected with 1½ in. of sprayed mineral fiber fire-resistive material. Retrofit of thermal protection requires removal of existing material and controlled inspection.

- For "tenant spaces less than a full floor undergoing with new construction or renovation," the floor trusses "need only meet the original construction standard. Fireproofing shall be inspected and patched as required to the greater of ¾ in. or to match existing" if it has already been upgraded to 1½ in.

In July 2000, an engineering consultant, commissioned by the Port Authority to conduct a fire-engineering assessment of the fire protection of the floor trusses, issued a report on the requirements of the fire resistance of the floor system of the towers. This report stated that CAFCO BLAZE-SHIELD DC/F was used on the majority of the floor trusses. Based on calculations and risk assessment, the consultant concluded that:

- "The structural design has sufficient inherent fire performance to ensure that the fire condition is never the critical condition with respect to loading allowances.

- A single coat application is possible.

- Significant savings are possible.

- The target reduction of fiber content and increased long term durability can be achieved.

- Alternative materials should be considered."

As quoted, the report states that significant savings were possible by reducing the fiber content and considering alternative materials. The report suggested that the thickness of the SFRM could be reduced to ½ in. if the material properties at ambient temperature are applicable at higher temperatures. The report recognized the lack of available temperature-dependent material data for BLAZE-SHIELD Type DC/F. Thus, considering the uncertainties in the material properties and having the understanding of material degradation with temperature and time, it was recommended that 1.3 in. of fire-resistive material be used for the floor trusses.

Later, in December 2000, the final draft of a report on *Property Condition Assessment of World Trade Center Portfolio* stated that, based on existing conditions "The rating of the structural fireproofing in the Towers and subgrade has been judged to be an adequate 1 hour rating considering the fact that all Tower floors are now sprinklered." The report also noted the ongoing Port Authority program to upgrade the fire-resistive material thickness to 1½ in. in order to achieve a 2 hour fire rating.

Need for Fire Endurance Tests

The fire protection of a truss-supported floor system by directly applying sprayed fire-resistive material to the trusses was innovative and not consistent with prevailing practice at the time the WTC towers were designed and constructed. While the benefits of conducting fire endurance tests were realized by individuals involved in the 1967 demonstrations of the application of SFRM, apparently no tests were conducted on the floor system used in the WTC towers. The Architect of Record and the Structural Engineer of Record stated that the fire rating of the floor system of the WTC towers could not be determined without testing. Communication from the Port Authority in 2003 confirms that there is no record of fire endurance testing of assemblies representing the thermally protected floor system.

Maintenance of SFRM in Elevator Shafts

Throughout the life of the WTC towers, the structural members that required the largest amount of inspection and maintenance within the core were the exposed columns and beams within the elevator shafts. These columns and beams were the only accessible fire-protected elements in the buildings. Adhesion failures were common, likely because of the exposed conditions of the columns and the inherently low strength of the SFRM.

Inspections of the shafts and accessible columns were reported as early as 1971. Problems were noted in the form of fallen insulation or with the over-spray material used to provide a harder surface. In 1993, the Port Authority commissioned Leslie E. Robertson Associates to carry out a continuing program to appraise the condition of the accessible columns located in the core of the towers. The columns were inspected visually for signs of rusting, cracking, bowing, and loss of thermal insulation. During the first inspection, carried out in 1993, particular shafts were chosen based on the quantity and types of accessible columns, and the convenience to the Port Authority. Subsequent inspections involved sampling of the structural components and assemblies, which were more important to the structural integrity of the towers, and at locations with a relatively higher potential for defects and problems. The inspection report stated that the accessible columns in selected elevator shafts in WTC 1 and 2 were "generally in good condition, no structural deficiencies such as cracking or bowing were found, the most common irregularities observed were missing fireproofing and light surface rusting of the exposed steel." Based on the inspections, LERA recommended "that remedial action to be taken where spray fireproofing is damaged, deteriorated or missing and where there is corrosion of the column base due to water leaks at elevator pits." Earlier in 1992, LERA performed calculations to determine the thickness of replacement thermal insulation for selected beams and columns within elevator shafts.

AS-APPLIED THICKNESS OF SFRM

1994 Measurements from WTC 1 Floors 23 and 24

In its search of documents, NIST has found no information related to measurements of the thickness of thermal insulation taken during original construction. Reviewed documents, however, indicate that thickness appears to have been checked during construction. Recorded information on the in-place condition of the sprayed thermal insulation for the floor system first appeared in 1990 in the form of "Sample Area Data Sheets," which provided qualitative comments on the state of the in-place SFRM. Information regarding quantitative inspection of existing fire-resistive material appeared in documentation from 1994. That year, the Port Authority performed a series of thickness measurements of the existing SFRM on floors 23 and 24 of WTC 1. Six measurements were taken from "both flanges and web" of each of 16 randomly chosen trusses on each floor. Measured average thickness varied between 0.52 in. and 1.17 in. For the 32 measurements (16 on each floor), the overall average was 0.74 in. and the standard deviation of these averages was 0.16 in. Four of the 32 floor trusses had average thicknesses between 0.52 in. and 0.56 in. These measurements suggest that the minimum average thickness exceeded ½ in. Analysis of the reported mean thicknesses indicated that a lognormal distribution gave a better representation of the distribution rather than did a normal distribution.

Analysis of Photographs

Additional SFRM thickness data were developed by evaluating photographs of floor trusses taken during inspections. Two groups of photographs were used. The first group included images of floor trusses from WTC 1 (floors 22, 23, and 27). These photographs were taken in the mid-1990s and illustrated conditions before the upgrade carried out by the Port Authority. Thus, SFRM thickness on the photographed trusses would be expected be at least ½ in. The second group of photographs, taken in 1998, illustrated conditions after the upgrade program that was initiated in 1995. The photographs were of trusses for floor 31 and below in WTC 1. Selection of the photographs to be used to estimate thickness of SFRM was based on clarity of SFRM edges and the presence of a feature of known dimensions to provide a reference measurement.

For floors that had not been upgraded, it was observed that the estimated thickness of SFRM on the webs (inclined bars) of the main trusses tended to be greater than that on either the diagonal struts or on the webs of the bridging trusses. Hence, estimates of SFRM thickness for non-upgraded floors were divided into three groups:

- Webs (inclined bars) of main trusses,
- Webs (inclined bars) of bridging trusses, and
- Diagonal strut at the exterior wall end of the truss.

It was not possible to estimate the thickness of the SFRM on any truss element except the round web bars. Consequently, for the upgraded floors in WTC 1 that were included in the second group of photographs, only estimates of the thickness on the web bars of the main trusses were made. The average, standard

deviation, and coefficient of variation were computed for the total number of measurements in each of these groups. The results are summarized as follows:

- Main trusses before upgrade (85 measurements): Average thickness 0.6 in., standard deviation = 0.3 in., and coefficient of variation = 0.5.
- Bridging trusses before upgrade (52 measurements): Average thickness 0.4 in., standard deviation = 0.25 in., and coefficient of variation = 0.6.
- Diagonal struts before upgrade (26 measurements): Average thickness 0.4 in., standard deviation = 0.2 in., and coefficient of variation = 0.5.
- Main trusses after upgrade (52 measurements): Average thickness 1.7 in., standard deviation = 0.4 in., and coefficient of variation = 0.2.

Port Authority Data on Upgraded SFRM on Trusses

In the 1990s, the thermal protection for some floor trusses was upgraded to a specified thickness of 1½ in. as tenants vacated their space. According to the Port Authority, 18 floors of WTC 1 and 13 floors of WTC 2 were upgraded. The Port Authority also stated that: "The entire impact zone for Tower 1 (92-99) was upgraded with 1½" spray-on fireproofing. Only the 78th floor was upgraded with the 1½" spray-on fireproofing within the impact zone in Tower 2 (78-84)." The Port Authority provided Construction Audit Reports that included the density, average thickness, and strength characteristics of the upgraded SFRM (BLAZE-SHIELD II) as of 2000. In 2004, the Port Authority provided NIST reports of the individual measurements for many of the average thicknesses recorded in the Construction Audit Reports. These individual measurements permitted analysis of the variation of thickness at a cross section of a truss member and the variation in average thickness from truss to truss. A total of 18 data sets for WTC 1 (including floors 93, 95, 98, 99, and 100) and 14 data sets for WTC 2 (including floors 77, 78, 88, 89, and 92) were analyzed.

Data analysis indicated that the thickness measurements from the two towers represented similar distributions, and so the data were combined. It was also found that the distribution of thickness values could be approximated as lognormal distribution.

The overall average thickness determined from the 256 individual measurements was found to be 2.5 in. with a standard deviation of 0.6 in. Thus, the average thickness on the upgraded upper floors appears to be greater than that estimated from photographs taken on upgraded lower floors.

The overall standard deviation of 0.6 in. includes two contributions: (1) the variation of thickness at a cross section (within-truss variability), and (2) the variation of average thickness between trusses (between-truss variability). From analysis of variance, it was found that the within-truss standard deviation was 0.4 in., and the between-truss standard deviation was also 0.4 in. The within-truss standard deviation of 0.4 in. is similar to the standard deviation of the estimated individual thicknesses obtained from analysis of the photographs of upgraded main trusses.

Column SFRM Thickness

NIST requested that the Port Authority provide available information on the actual thickness of fire-resistive material on the exterior and interior columns of the WTC towers. The Port Authority replied that, due to inaccessibility of exterior columns and core columns, there were no records of SFRM thickness measurements for these elements. The only available measurements were for thickness of SFRM that was reapplied to accessible beams and columns within elevator shafts.

The most complete data set included measurements on beams and columns taken within shaft 10/11 in WTC 1. These measurements were taken in April 1999 and included measurements from floor 1 to floor 45. The thicknesses were recorded to the nearest 1/8 in., with a few thicknesses recorded to the nearest 1/16 in. The columns included 10 to 18 replicate measurements, and the beams included 11 to 16 replicate measurements.

The average thickness for the columns was found to be 0.82 in., with a standard deviation of 0.20, resulting in a coefficient of variation is 0.24. The average thickness for the beams was 0.97 in., with a standard deviation is 0.21 in., for a coefficient of variation is 0.21. The information from the Port Authority indicated that the minimum required thicknesses for the SFRM (Monokote Type Z-106) that was reapplied to the columns and beams were ½ in. and ¾ in., respectively.

The above data may not have a direct bearing on the outcome of the investigation because they deal with lower stories. They do, however, provide some useful information on the variability of SFRM applied to beams and columns. As might be expected, the variation in thickness of SFRM for the beams and columns is lower than the variation computed for the floor trusses. The flat surfaces of the beams and columns result in more uniform application of the sprayed fire-resistive material than for the slender truss members.

EFFECT OF SFRM GEOMETRY ON THERMAL RESPONSE

As would be expected, and as confirmed by analyses of available data, the thickness of thermal insulation can have high variability. The effects of thickness variation on thermal response of a member are not well known. A sensitivity study using the finite element analysis to simulate heat transfer was conducted to investigate the sensitivity of steel temperature rise to the variability in SFRM thickness.

Effects of Thickness Variability and Gaps in SFRM

A finite element model for thermal analysis was developed for a plate protected on both faces with SFRM of variable thickness. A random number generator was used to assign a lognormally distributed random thicknesses of insulation along the length of the plate, and the plate was subjected to a thermal flux representative of a 1,100 °C fire. A parametric study was conducted with average thickness of fire-resistive material varying from 0 in. to 2 in. in increments of ¼ in. and a standard deviation varying from 0 to 1 in. Steel temperatures at five locations in the plate were recorded at 30 min, 60 min, 90 min, and 120 min of exposure to the thermal flux.

The simulations showed that when the SFRM thickness is variable, the isotherms in the steel follow the shape of the SFRM surface contour. Thus the temperature history at any point in the steel depends on the

local thickness of the insulation. If the time to reach a specified high temperature is used as an indicator of protection efficiency, it was shown that an increase in thickness variability reduced the time to reach the critical temperature. Conversely, for a give time to reach a critical temperature, the required average thickness of thermal insulation increased with increasing variability in thickness of SFRM.

In addition to the effect of variation in thickness, the effect of missing SFRM over a portion of a member was studied. As expected, the bare steel at the missing insulation reached the gas temperature quickly, but more importantly the "gap" in the insulation led to transmission of heat into the interior steel.

The combined effects of variation in insulation thickness and extent of missing material were examined by a factorial study with the following factors:

- Average thickness of insulation varying from 0 in. to 2.0 in. in 1/4 in. increments;
- Standard deviation of insulation thickness of 0 in., 0.25 in., 0.5 in., 0.75 in., and 1.0 in.; and
- Length of missing insulation varying from 0 in. to 30 in., in 6 in. increments.

The results were summarized by a series of temperature-time plots representing the response for different combinations of the three factors. As expected, increasing the variability of insulation thickness or gap length reduced the time to reach a given critical temperature. Because there was not sufficient information to determine the frequency of occurrence of these gaps or their typical locations, gaps in insulation were not considered in the thermal modeling.

Equivalent thickness of SFRM

The sensitivity study indicated that increased variation in thickness reduced the "effective thickness" of the SFRM. It would be impractical to attempt to account for the variation in SFRM thickness in the thermal modeling of the WTC towers by introducing variable thickness insulation material in the finite-element models. As an alternative, an "equivalent uniform thickness" was determined that would result in the same thermo-mechanical response of a member as the variable thickness thermal protection. In the analyses, an insulated 1 in. diameter by 60 in. long steel bar was subjected to the heat flux arising from a 1,100 °C fire. The thermal history along the length of the bar was calculated, and that history was used to calculate the length change of the unrestrained bar under a tensile stress of 12,500 psi. The bar was assumed to be similar to the steel used in the WTC floor trusses, and the temperature dependence of the coefficient of thermal expansion and the modulus of elasticity were based on NIST measurements.

The average SFRM thickness and variability in thickness used in the models were based on the measurements for the web bars of the main trusses with both the original insulation and upgraded insulation. The following values were investigated:

- Original conditions: Average thickness = 0.75 in., standard deviation = 0.3 in., lognormal distribution.
- Upgraded conditions: Average thickness = 2.5 in., standard deviation = 0.6 in., lognormal distribution.

The variation of thermal insulation thickness along the length of the bar was established by using a pseudo random number generator to select values from a lognormal distribution with central value and dispersion consistent with the above average values and standard deviation. Three sets of random data were generated for each condition.

When the randomly selected thicknesses of each element were applied to the bar, it resulted in abrupt changes in insulation thickness along the length of the bar. This resulted in a "rough" surface texture that was not representative of actual conditions. As an alternative, 5-point averaging was used to reduce the roughness of the insulation profile and produce a profile that was consistent with photographic evidence.. Care was taken to ensure the "smoothed" profiles maintained the required dispersion.

The calculated thermal histories of the bar elements were used to calculate the unrestrained length changes of the bar due to thermal expansion and the applied stress. For comparison, elongations of the bar with different uniform thicknesses of thermal insulation were calculated. The "equivalent thickness" was taken as the uniform thickness that resulted in approximately the same elongation of the bar as produced with the variable thickness insulation.

On the basis of these analyses, it was concluded that SFRM with an average thickness of 0.75 in. and a standard deviation of 0.3 in. provides protection equivalent to 0.6 in. of uniform thickness. Similarly, an average SFRM thickness of 2.5 in. with a standard deviation of 0.6 in. is equivalent to 2.2 in. of uniform thickness.

Recommended Thickness of SFRM for Thermal Analyses

Analyses of available data on SFRM thickness and thermal modeling revealed the following:

- From measurements of SFRM thickness, the average values exceeded the specified thickness.
- SFRM thickness was variable, and the distribution of thickness in the floor trusses appeared to be described best by a lognormal distribution.
- The standard deviation of SFRM thickness on the trusses varied between about 0.3 in. and 0.6 in.
- The standard deviation of SFRM on columns and beams from the core tended to be lower, with a value of 0.2 in. for the available data.
- No information was available on the SFRM thickness on the exterior columns and spandrel beams.
- Variation in thickness reduces the effectiveness of SFRM, and the equivalent uniform thickness was less than the average thickness.

Based on the above findings, the following uniform thickness for the undamaged SFRM were determined for use in calculating thermal response of the WTC towers under various fire scenarios:

- Original SFRM thickness on floor trusses: 0.6 in.

- Upgraded SFRM thickness on floor trusses: 2.2 in.
- Thermal protection on other elements: the specified thickness.

The choice of specified thickness for those members lacking data is justified by the following offsetting factors: (1) measured average thicknesses exceed specified values, and (2) variation in thickness reduces the effectiveness of the SFRM.

THERMOPHYSICAL PROPERTIES

To provide thermophysical property data for modeling the fire-structure interaction of the towers, the thermal conductivity, specific heat capacity, and density of the SFRMs used in the WTC towers were determined as a function of temperature up to 1200 °C (2190 °F). Since there are no ASTM test methods for characterizing the thermophysical properties of SFRMs as a function of temperature, ASTM test methods developed for other materials were used. Samples were prepared by the manufacturers of the fire-resistive materials, which included CAFCO BLAZE-SHIELD DC/F, CAFCO BLAZE-SHIELD II, and Monokote MK-5. Since Monokote MK-5 is no longer on the market, the samples were manufactured specially for this study according to the original MK-5 formulation. Testing services were provided by a commercial testing agency.

Thermal Conductivity

The thermal conductivity measurements were performed according to ASTM C 1113, Standard Test Method for Thermal Conductivity of Refractories by Hot Wire (Platinum Resistance Thermometer Technique). The room temperature values were in general agreement with the manufacturer's published values for CAFCO BLAZE-SHIELD DC/F and CAFCO BLAZE-SHIELD II. No published values were available for Monokote MK-5. The thermal conductivities increased with temperature.

Specific Heat Capacity

Specific heat capacity determinations were made with the same instrument as for thermal conductivity with a slight modification. A thermocouple was added to the system, which permitted determination of the thermal diffusivity of the material. Knowing the thermal conductivity, the thermal diffusivity, and the density obtained from other tests, the specific heat capacity was calculated. The inherently indirect nature of the technique used precluded the direct measurements of specific heat capacity peaks associated with chemical reactions.

To examine the chemical reactions associated with heating of SFRMs, samples were sent to another laboratory to perform differential scanning calorimetry (DSC) measurements in accordance with ASTM E 1269, Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry. Differential thermal analysis (DTA) which is a "fingerprinting" technique that provides information of the chemical reactions, phase transformations, and structural changes that occur in a specimen during a heating or a cooling cycle. These tests revealed large peaks in the specific heat capacities in the range of 125 °C to 140 °C.

Density

Bulk densities of the SFRMs were not measured directly (except at room temperature) but were calculated from thermal gravimetric analysis (TGA) and thermal expansion measurements. The TGA tests to measured mass loss were performed according to ASTM E 1131, Standard Test Method for Compositional Analysis by Thermogravimetry. Thermal expansion measurements were performed according to ASTM E 228, Standard Test Method for Linear Thermal Expansion of Solid Materials. Since the materials were not isotropic, separate measurements were performed in the plane of the SFRM sample and perpendicular to the free surface of the sample. From the thermal expansion measurements, the change in volume for each material was calculated at each temperature. The density values were calculated from the results of the TGA and thermal expansion. The room temperature densities were 15.7 pcf for CAFCO BLAZE-SHIELD DC/F, 20.8 pcf for CAFCO BLAZE-SHIELD II, and 19.4 pcf for Monokote MK-5.

Thermophysical Properties of Gypsum Panels

Thermophysical properties of four types of gypsum panels produced by U.S. Gypsum Co. were examined. The materials were:

5. Firecode Core Type X 5/8 in. SHEETROCK gypsum panel,
6. Firecode C Core ½ in. SHEETROCK gypsum panel,
7. Firecode C Core 5/8 in. SHEETROCK gypsum panel, and
8. 1 in. SHEETROCK gypsum liner panel.

Thermal conductivity was measured using the heated probe technique described in ASTM D 5334, Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure. In general, the thermal conductivity initially decreased as the temperature increased to 200 °C and the increased with increasing temperature above 300 °C.

Specific heat capacities of the cores of the four gypsum panel samples were measured using a differential scanning calorimeter according to ASTM E 1269, Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry. The four panels had similar specific heat capacities as a function of temperature, with a high peak at about 150 °C and a smaller peak at about 250 °C.

Densities were calculated from the thermogravimetric analysis (TGA) and linear thermal expansion measurements. All four materials show the same trend as a function of temperature. The variation of density with temperature is associated with the mass loss and the change in volume of the gypsum material.

ADHESIVE AND COHESIVE STRENGTH

To analyze the thermo-structural response of the WTC towers during the fires after aircraft impacts, it was necessary to estimate the extent of dislodged thermal insulation on structural members. Dislodgement could occur as a result of direct impact by debris or due to inertial forces as a result of the aircraft impact. Photographic evidence suggested that thermal insulation was dislodged from portions of exterior columns of the towers that were likely not subjected to direct impact by debris. This study focused on dislodgement due to inertial forces.

The magnitude of the inertial forces depends on the density and thickness of the thermal insulation. The insulation would dislodge if the stresses resulting from inertial forces exceed the strength of the insulation. Therefore, the focus of the NIST study was to determine tensile strength characteristics of the thermal insulation. In addition, a simplified approach was developed for estimating the magnitude of accelerations required to dislodge thermal insulation.

In-place Density and Bond Strength

The Port Authority provided data on in-place density and bond strength characteristics of the thermal insulation (CAFCO BLAZE-SHIELD II) applied to the floor trusses during tenant alterations. According to the manufacturer, BLAZE-SHIELD II is about 20 % denser and has about 20 % greater adhesive/cohesive strength compared with BLAZE-SHIELD DC/F. The Port Authority test reports indicate that bond strength was determined in accordance with ASTM E 736, Standard Test Method for Cohesion/Adhesion of Sprayed Fire Resistance Materials Applied to Structural Members. The method involves gluing a jar screw cap to the surface of the thermal insulation, and after the glue has cured, the cap is pulled. The force required to pull off the cap is divide by the area of the cap, and reported as the "cohesive/adhesive strength." Failure is described as "cohesive" if it occurs within the insulation and is defined as "adhesive" if it occurs at the interface with the substrate.

Analysis of the reported density values indicated no statistically significant differences between the average SFRM densities in the two towers. The overall average density was 18.9 pcf with a standard deviation of 3.2 pcf, giving a coefficient of variation of 16 %.

Analysis of the bond strength values indicated that there were statistically differences between the average bond strengths for the different floors, but there was no statistically significant difference between the average bond strengths for the two towers. The overall average bond strength was 302 psf, with a standard deviation of 91 psf, giving a coefficient of variation of 30 %. This average value is less than the "tested performance" value of 360 psf indicated in the manufacturer's catalogs, but this publishe value is for tests under controlled conditions and may not be representative of field strengths. The manufacturer's product literature dated February 2002 refers to average bond strength of 150 psf as "standard performance" and this same value is used in its guide specification for BLAZE-SHEILD II.

Specimen Preparation and Test Procedures

While the in-place bond strength data of BLAZE-SHIELD II reported by the Port Authority appear to indicate acceptable performance, ASTM E 736 tests do not provide sufficient information for predicting whether insulation would be dislodged from structural members under various impact conditions. The

standard test does not provide unambiguous values of cohesive and adhesive strengths and it does not provide tensile strength in a direction parallel to the surface, that is, the in-plane cohesive strength. Thus tests were conducted by NIST to determine different tensile strength properties of sprayed thermal insulation. BLAZE-SHIELD DC/F was used because the Port Authority data did not include tests of this material.

Test specimens were made by applying the SFRM to ¼ in. steel plates measuring 8 in. by 16 in. One half of the plates were coated with primer paint. Nominal SFRM thicknesses of ¾ in. and 1½ in. were applied. Thickness was built up in several passes of the spray nozzle. Gentle hand rubbing was used to remove local high spots and produce reasonably uniform thicknesses. The plate specimens were allowed to dry for over five months in the laboratory before testing. Companion specimens were weighed periodically for loss of water and it was found that the 1½ in. thick specimen reached equilibrium in about one month.

Tests were devised to determine adhesive strength, cohesive strength normal to the surface, and cohesive strength parallel to the surface of the SFRM. The first two properties were determined by adapting the pull-off test method described in ASTM C 1583, Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method). The SFRM layer was cut carefully in two orthogonal directions to create a prismatic test specimen, and a 3/8 in. by 2.7 in. by 2.7 in. aluminum plate was glued to the surface. The advantages of this approach over the ASTM 736 technique are that the resisting area is easily determined and it offers the ability to measure both adhesive and cohesive strengths.

From each plate, three specimens were prepared for measuring both density and in-plane cohesive strength, and two specimens were prepared for measuring adhesive strength and cohesive strength normal to the surface. Prismatic specimens were prepared by carefully removing strips of SFRM from the steel plates and sanding them to obtain uniform thickness. These specimens were weighed to determine their densities. Then the specimens were glued to a steel plate and small plate was glued to the other end for application of a tensile load.

The adhesive strength and cohesive strength normal to the surface were obtained using the modified pull-off procedure. An aluminum plate was bonded to the top surface of the SFRM using a fast curing, two-component urethane foam adhesive. After the adhesive had cured, the SFRM layer was cut to produce a prismatic test specimen. A hook was screwed into the aluminum plate and a load was applied by hand using a 50-lb. digital force gage. The average length and width of the failure area was measured and used to compute the adhesive or cohesive strength. After the first test, the specimen was repaired with the same polyurethane adhesive and the test was repeated. If the first test was an adhesive failure, the second test of the repaired specimen measured cohesive strength of the bulk SFRM. If the first test resulted in cohesive failure, the second test measured adhesive strength.

Test Results

Table E–1 summarizes the results of the test described in the previous section.

Table E–1. Summary of physical characteristics of BLAZE-SHIELD DC/F specimens tested at NIST

Property	Bare Steel		Primed Steel	
	¾ in.	1½ in	¾ in.	1½ in.
Density (pcf)			27.2 (0.8)[a]	29.7 (1.3)
In-plane cohesive strength (psf)			1120 (390)	1740 (540)
Adhesive strength (psf)	450 (63)	666 (151)	185 (96)	171[b](196)
Cohesive strength normal to surface (psf)	433 (99)	610 (142)	367 (79)	595 (163)

a. First number is the average and the number in parentheses is the standard deviation.
b. Based on testing selected samples.

The densities of the CAFCO BLAZE-SHIELD DC/F measured in this study were higher than published in the manufacturer's catalogs and higher than the in-place average density of 18.9 pcf reported in Port Authority test reports for BLAZE-SHIELD II. The difference in average densities of the two thicknesses was statistically significant. The higher values in this study are attributed to the details of the specimen preparation procedures, which tended to result in denser test specimens than would be representative of field application.

The difference in average adhesive strength for the two plate thicknesses is statistically significant. The relative strengths are consistent with the difference in density for the two thicknesses.

The presence of primer reduced the adhesive strength, especially for the 1½ in. thick specimens. Two-thirds of the thicker SFRM plates had no adhesion to the coated steel plates.

Analysis of the cohesive strength normal to the surface indicated that there was no statistically significant effect due to the presence or absence of primer. This is logical, because the condition of the steel surface is not expected to influence the properties of the bulk SFRM. There was a statistically significant difference in the average strengths for the two thicknesses, with the 1½ in. SFRM having higher strength.

For comparison with the measured cohesive strength normal to the surface, two tests were done in accordance with ASTM E 736. The two tests results were in agreement with those obtained by the pull-off technique. This suggests that the ASTM E 736 procedure probably provides a measure of cohesive strength.

A comparison was made of the adhesive strength and cohesive strength normal to the surface for the plates made with bare steel. A formal analysis of variance indicated that there is an 8 % probability that the difference could be the result of randomness. Generally, if this probability is greater than 5 %, it can be concluded that the difference is not statistically significant. Thus for the case of good adhesion, the test results do not contradict the assumption that the adhesive strength and cohesive strength normal to the surface are equal. If this assumption is accepted, the average of the adhesive and cohesive strengths is 409 psf for the ¾ in. SFRM, and the average is 622 psf for the 1½ in. SFRM. These values are considerably greater than the manufacturer's published strength of 295 psf obtained using the ASTM E 736 method under laboratory conditions.

Simplified Approach to Predict Dislodging of SFRM

When a member is subjected to an impact, it will undergo various modes of vibration. These vibrations result in local cyclic accelerations that are transferred to the SFRM by forces at the interface between the steel and SFRM. The forces are proportional to the mass of the SFRM, and if they exceed the adhesive or cohesive strength of the SFRM, the SFRM will separate from the member. Two limiting cases are considered:

- Case 1 is a planar element with SFRM applied to one face of the element. This would be representative of SFRM applied to large webs and flanges of beams and columns. In this case, adhesive strength or cohesive strength normal to the surface would be the controlling SFRM properties.

- Case 2 is a slender bar encased with SFRM. This would be representative of SFRM applied to elements of the floor trusses. In this case, in-plane tensile strength and bond strength are the controlling SFRM properties.

To arrive at the ranges of accelerations that could be expected to dislodge SFRM from a planar surface, the following plausible ranges of values were assumed:

- SFRM thickness: 0.75 in and 2.5 in.;

- SFRM density: 15 and 25 pcf [1];

- SFRM bond strength: 100 and 500 psf

For the combination of low thickness, low density, and high bond strength, the required acceleration is about 530 *g*, where g is the gravitational acceleration. For the other extreme combination of high thickness, high density, and low strength, the required acceleration is about 20 *g*. For values representative of the upgraded thermal insulation on the floor trusses, an acceleration of about 80 *g* would be required to dislodge a 2.5 in. thick layer of well-bonded SFRM from a planar surface.

To arrive at the ranges of accelerations that could be expected to dislodge SFRM from a round bar, the following ranges of values were assumed:

- Bar diameter: 0.9 in. and 1.2 in;

- SFRM thickness: 0.75 in and 2.5 in.;

- Density: 15 and 25 pcf;

- In-plane cohesive strength: 500 and 2000 psf; and

- Ratio of bond strength to in-plane cohesive strength: 0 and 0.3.

[1] These numbers need to be converted to units of mass by dividing by the gravitational acceleration.

The smallest required acceleration is about 40 *g*, which corresponds to a large bar having a thick layer of the higher density SFRM with low strength. At the other extreme, the required acceleration is about 730 *g*. For a 1.2 in. diameter bar with 2.5 in. thickness of SFRM and density of 19 pcf, which are representative of the conditions of the upgraded insulation on the floor trusses, the acceleration required to dislodge the SFRM would vary from 55 *g* to 230 *g*, depending on the strength characteristics within the assumed ranges given above.

These simplified models are intended to provide insight into the important variables that affect the magnitude of the disturbance (that is, acceleration) required to dislodge SFRM from different kinds of structural members. These models do not consider the fact that the applied acceleration in an actual structure subjected to impact would vary with time. Also these models apply to members not directly impacted by debris.

Chapter 1
INTRODUCTION

When steel is heated it loses strength and stiffness. This characteristic allows steel to be formed into different shapes with relatively little effort. When steel is used in a structure, however, measures have to be taken to protect the steel from premature temperature rise in case of fire. The objective is for the structure to remain stable for the time needed to permit evacuation of occupants and for fire service personnel to complete search and rescue operations. This report deals with the passive fire protection materials used in the WTC towers.

1.1 FIRE-RESISTIVE MATERIALS

The structural steel in the World Trade Center (WTC) towers was protected against the effects of fire with sprayed fire-resistive materials (SFRMs)[1] or rigid fire-rated gypsum panels. There are many types of SFRMs, but they can be characterized in terms of how they protect the steel and their density (Gewain et al. 2003). One class of SFRMs protects the steel by providing a material with a low thermal conductivity, such as mineral fibers. The fibers and binder are packaged as dry ingredients, and water is added by a pressurized system as the materials are sprayed onto the steel. The water mixes with the binder materials and provides "stickiness" that allows the SFRM to adhere weakly to the steel. With time, the binder hardens, and excess water evaporates. When dry, these SFRMs provide a low thermal conductivity barrier to reduce the rate of temperature rise during a fire.

The other class of SFRMs can be termed as "energy absorbing" (Gewain et al. 2003). This means that they incorporate cementitious materials that have chemically bound water (water of crystallization). When the material is heated, energy is absorbed in transforming the chemically bound water to free water, and this hinders the temperature rise of the coated steel. Examples of cementitious materials that have been used successfully include gypsum and magnesium oxychloride (Gewain et al. 2003). These types of SFRMs may also include very low-density aggregate particles, such as vermiculite or perlite, to reduce density and thermal conductivity. Cementitious SFRMs are typically mixed with water to produce a cohesive and pumpable mixture that is sprayed unto the steel.

Figure 1-1 is a photograph of two types of SFRMs. The material on the left is a gypsum based cementitious SFRM containing vermiculite aggregate, and the material on the right is a fibrous SFRM. Note that the cementitious SFRM specimen in the photograph was prepared by casting in a mold, not by spraying unto a surface. Thus the surface texture is not representative of what would be obtained in the field.

Sprayed fire-resistive materials are also characterized by their density. Low-density materials have densities in the range of 15 to 20 lbs/ft^3; medium density materials are generally in the range of 20 to 40 lbs ft^3. The density of the SFRM is closely related to its cohesive strength and its durability. Low-

[1] These sprayed fire-resistive materials are commonly referred to as "fireproofing." This term is, however, not used in the technical literature. In this report "SFRM" and "thermal insulation" are used to refer to the passive fire protection materials.

density SFRMs can be removed readily with hand tools and are not suitable for applications where the surface is exposed to weather or abrasion in service (Gewain et al. 2003).

Source: NIST.

Figure 1–1. Examples of sprayed fire-resistive materials: (left) material based on gypsum and vermiculite aggregate; (right) material based on mineral fibers and cementitious binder.

Analysis of the effects of the fires on the structural capacity of the damaged WTC towers as a function of time requires knowledge about the condition of fire-resistive materials on the various structural components, namely, the exterior columns, the spandrel beams, the floor trusses, and the core columns. Because of the method of application, sprayed fire-resistive material will have variable thickness, especially when applied to long, thin elements such as the diagonals and chords of the floor trusses. In addition, the insulation was dislodged during the impact, either from direct impact by debris or from vibrations of the members. The thermal properties of the insulation also need to be known as a function of temperature.

1.2 SCOPE OF REPORT

The thermal-structural analysis of the WTC towers focused on two objectives: (1) analysis of the undamaged buildings exposed to conventional building fires, and (2) analysis the buildings damaged by aircraft impact exposed to the subsequent fires. To reduce the uncertainties in the calculated thermal histories of various structural elements, the thermophysical properties and condition of the passive fire protection as it existed on September 11, 2001, had to be estimated as accurately as possible. In addition, reasonable estimates of the extent of SFRM dislodged by aircraft impact and the resulting debris field had to be made.

To provide context for the information in this report, an overview of concepts used in U.S. building regulations for structural fire resistance is presented first. This is followed with a summary of the construction history of the sprayed fire-resistive material in WTC 1 and WTC 2. To gain an understanding of the effect of SFRM thickness and its variability on the steel temperature during exposure to fire, results are presented of a sensitivity study based of a simple finite-element model. This is followed by a quantitative assessment of in-place thickness and its variability based on available data.

The rationale for the thickness of SFRM to be used in the structural fire endurance analyses is presented. The tests conducted to determine the thermal properties of insulation materials similar to those used in the WTC towers are reviewed. The results of mechanical property tests conducted on laboratory specimens are presented, and a simplified approach for estimating the acceleration required to dislodge thermal insulation during impact is discussed.

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Chapter 2
BUILDING CODE CONCEPTS FOR STRUCTURAL FIRE RESISTANCE

2.1 ORIGINS AND INTENT OF BUILDING CODES

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

The origins of the regulation of building construction are in insurance regulations developed in the late 19th century to limit property losses in fires (Bukowski 1997). Thus the intent of building height limits is to restrict taller buildings to non-combustible structural members and the greatest fire resistance is assigned to members supporting multiple floors. The primary concern with combustible structural members is that they can become ignited by an exposing fire and can continue to burn (often in concealed spaces) even after the exposing fire has been extinguished, leading to collapse. The intent of increased fire resistance for members supporting multiple floors is directly related to the higher risk of property loss in the event of failure of multiple floors. Fire resistance requirements, however, do not take into account the actual number of stories being supported by these elements. Thus the same ratings are required irrespective of whether columns support 10 stories or 100 stories.

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

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

2.2 CONSTRUCTION TYPES

Construction types (or groups) are defined in the model building codes and in NFPA 220 (NFPA 1999) and, while there are some variations in categories, they are reasonably consistent. The main categories are Type I (fire resistive), Type II (non-combustible), Type III (combustible), Type IV (heavy timber) and Type V (ordinary).

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

Combustibility of the materials in the structural element is determined in accordance with ASTM E 136 (ASTM 2004a) in which the material is placed in a furnace at 750 °C (1380 °F). Some minor surface burning (e.g., from paint or coatings) is allowed in the first 30 seconds but there cannot be any significant energy released as determined by more than 30 °C (54 °F) increase in the furnace temperature, and the sample cannot lose more than half its initial mass. Materials that pass are designated non-combustible and the rest are combustible. In 1973, an in-between category of "limited combustible" was added to ASTM E 136 to regulate some structural materials.

Within each construction type are several sub-categories determined by the fire resistance ratings of the columns (vertical structural elements that support predominantly gravity loads and the actions of lateral loads), beams (horizontal structural elements that support predominantly live loads), and floor supports. In some codes these sub-categories are identified by letters following the type (e.g., 1B or 3A) (IBC 2003) or by a set of three numbers that represent the fire resistance required (in hours) of the columns, beams, and floors, respectively (e.g., Type 1 (3,3,2)) (NFPA 2003).

2.3 FIRE RESISTANCE OF STRUCTURAL ELEMENTS

Building codes require that structural elements be protected to achieve a specified fire resistance rating, expressed in hours. The fire resistance rating of structural materials and assemblies is generally determined through testing, and in the United States, such testing is frequently conducted in accordance with ASTM Test Method E 119 (refer to NCSTAR 1-6B[1] for a discussion of this procedure). The objective of requiring minimum fire ratings is for the building to support design loads (including fire) without local structural collapse until occupants can escape and the fire service can complete search and rescue operations. Further, in high-rise buildings, local collapse is to be prevented while the fire service undertakes suppression operations.

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

Building codes generally require the highest fire resistance for columns and elements supporting multiple floors, and somewhat less resistance for columns supporting single floors, for beams, and for floors. For example, the NFPA Building Construction and Safety Code (NFPA 2003) requires exterior bearing walls or columns supporting one or more floors to have the same fire resistance rating, but for interior bearing

[1] This reference is to one of the companion documents from this Investigation. A list of these documents appears in the Preface to this report.

walls or columns the fire resistance rating is one hour less if only a single floor is supported. Historically similar requirements were found in other model codes such as the BOCA Basic Building Code and the SBCCI Standard Building Code.

The required fire resistance ratings have been reduced in recent years as fire sprinklers have become universal in high-rise buildings and common in most other commercial buildings. Where high-rise buildings generally required a 4 h rating for columns, this has been reduced to 3 h in recent codes, and can be as low as 2 h in current codes based on the additional mandatory requirement for sprinklers. This reduction in fire rating requirements for structural components in sprinklered buildings is usually referred to as "sprinkler trade-offs." Some codes, such as the International Building Code and the New York City Building Code, allow a reduction in fire-resistance rating for high-rise buildings that have been retrofitted with sprinklers.

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Chapter 3
HISTORICAL REVIEW RELATED TO PASSIVE FIRE PROTECTION OF WTC TOWERS

3.1 RELATIONSHIPS BETWEEN PORT AUTHORITY AND NEW YORK CITY DEPARTMENT OF BUILDINGS AND FIRE DEPARTMENT

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

In a letter dated May 15, 1963 (see Appendix A Figure A-1), the Port Authority instructed its consulting engineers and architects to comply with the New York City Building Code. In the areas where the Code was not explicit or where technological advances made portions of the Code obsolete, it directed that design may be based on acceptable engineering practice. At that time, the 1938 edition of the New York Building Code was in effect and a revised code was being drafted. In September 29, 1965, in a letter from Malcolm P. Levy to Minoru Yamasaki, the Port Authority instructed the designers of the WTC towers to revise the design plans to comply with the second and third drafts of the Code revision (see Appendix A Figure A-2). The revised Building Code became effective in December 1968.

In 1993, the Port Authority and the New York City Department of Buildings entered into a memorandum of understanding (see Appendix A Figure A-3) to establish procedures to be followed by the Port Authority for any building construction project undertaken by the Port Authority or any of its tenants at buildings owned or operated by the Port Authority and located in the City's jurisdiction. While the long-standing policy of the Port Authority was to guarantee that its buildings meet or exceed the New York City Building Code requirements, the 1993 agreement restated the commitment. Among other key points, it was agreed that:

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

A supplement to this memorandum of understanding was executed in June 1995, which permitted tenants to use New York State licensed architects or engineers, in lieu of a Port Authority review, to certify that construction plans conformed to the Code and that construction was performed in accordance with the

plans. In September 1995, the supplement was modified to permit a single licensed consultant to certify the plans and the construction, except if the alteration would change the occupancy group of the space.

It has been stated that on April 15, 1993 "in order to maintain and enhance the safety" of its facilities, the Port Authority "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." This policy was stated in the introduction of a Memorandum of Understanding between the Fire Department of the City of New York and the Port Authority of New York and New Jersey executed on December 30, 1993 (see Appendix A Figure A-5). The purpose of the agreement was to restate the Port Authority's commitment to the policy, and the agreement included the following statements:

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

In 1995, the memorandum of understanding with FDNY was amended with respect to additions to or modifications of fire safety systems. The Port Authority was required to notify the Bureau of Fire Protection prior to installing new systems or modifying existing systems. In addition, plans for these systems were to be prepared by New York State licensed professional engineers or architects (see Appendix A Fig. A-5).

3.2 NEW YORK CITY BUILDING CODE REQUIREMENTS

3.2.1 Occupancy Groups

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

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

- A—High Hazard;
- B—Storage;
- C—Mercantile;
- D—Industrial;
- E—Business;

- F—Assembly;
- G—Educational;
- H—Institutional; and,
- I—Residential.

As office buildings, the WTC towers were classified as Occupancy Group E. This classification was confirmed in a letter dated May 14, 1969 from Malcolm P. Levy of the World Trade Department to Milton Gerstman of Tishman Realty & Construction Company, Inc. (see Appendix A Figure A-6).

3.2.2 Construction Classification and Fire Rating

Additionally, there were other factors that determined the "classification" of a building and, consequently, its required fire rating: combustible versus noncombustible construction, sprinklered versus unsprinklered spaces, and building height and floor area limitations. The 1968 Code identified two construction groups: Noncombustible Construction (Group 1) and Combustible Construction (Group 2). The WTC towers were classified as Construction Group 1 because their walls, exit ways, shafts, structural members, floors, and roofs were constructed of noncombustible materials. At the time of design and construction, the towers were not sprinklered.

The 1968 New York City Building Code defined five Classes within Construction Group 1. For Business occupancy, each Class required a fire endurance rating as follows (NYBC 1968):

- Construction Group 1A: 4 hour protected
- Construction Group 1B: 3 hour protected
- Construction Group 1C: 2 hour protected
- Construction Group 1D: 1 hour protected
- Construction Group 1E: unprotected

As mentioned in Section 2.3, fire endurance is a rating, given in hours, established in accordance with the ASTM E 119. Fire endurance is also referred to as fire rating or fire index.

To provide perspective, the 1961-1962 revision to the 1938 New York City Building Code required that the 110 story towers be classified as "Class 1 – Fireproof Structures," which includes office buildings (NYCBC 1961-1962). This meant that the columns were required to have 4 hour fire endurance while the floor system was required to have 3 hour fire endurance.

In the 1968 New York City Building Code, area and height limitations for unsprinklered buildings of Construction Group 1 with a Business Occupancy were as presented in Table 3–1 (NYCBC 1968). The WTC towers, WTC 1 and WTC 2, had a roof height of 1368 ft and 1362 ft, respectively, and each tower had a floor area of approximately 43 100 ft^2. As Table 3–1 indicates, the WTC towers could have been classified as either Class 1A or Class 1B.

Table 3–1. Area and height limitations for unsprinklered buildings for Noncombustible Construction (Group 1) with a Business occupancy (NYCBC 1968).

	Class 1A	Class 1B	Class 1C	Class 1D	Class 1E
Area	No Limit	No Limit	No Limit	17,500 ft^2	10,500 ft^2
Height	No Limit	No Limit	85′-0″	75′-0″	40′-0″

3.3 CLASSIFICATION OF WTC TOWERS

It was the practice at the time, and continues to be the practice, for the architect to establish the building classification, fire rating of members and systems, and thermal protection requirements. On the subject of New York City Building Code revision effective December 6, 1986, a Port Authority memorandum dated January 15, 1987, from Lester S. Feld to Robert J. Linn states that Emery Roth & Sons (ER&S), the Architect of Record for the towers, classified the WTC towers as Class 1B since there was "no economic advantage in using Class 1A Construction" (see Appendix A Figure A-7).

According to the 1968 New York City Building Code, construction classification 1B provided, in part, the following fire protection requirements:

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

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

3.3.1 Specifications for Passive Fire Protection

In the case of the WTC towers, there appears to have been a problem related to the sprayed fire-resistive material specifications. A letter dated February 11, 1969, from Douglas Fernández of Emery Roth & Sons to Joseph A. Schwartzman of the Port Authority indicates that in early 1969 the Port Authority had rewritten the SFRM specifications (see Appendix A Figure A-8). In the process of rewriting, the following key paragraph specifying the fire rating requirements for the structural members was apparently omitted:

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

ER&S continued:

> "We cannot be expected to accept responsibility for specifications which have been revised in such a manner; that which we originally stated clearly and simply, has become a meaningless document."

3.3.2 Response to Local Law 5/1973

In 1973, New York City Local Law No. 5 amended the New York City Building Code (effective January 18, 1973). Local Law No. 5 required, in part, the retrofit of existing unsprinklered office buildings 100 ft or higher and having HVAC systems that serve more than the floor on which the equipment is located. The New York City Department of Buildings permitted either:

- Subdividing the floor area into compartments of specified square footage by fire separations (1 h or 2 h fire rated depending on the size of the compartment), or
- Providing sprinkler protection.

Owners of unsprinklered buildings were required to comply according to the following timetable from the effective date of the law:

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

A code compliance evaluation conducted in 1997 indicated that that all tenant floors in the two towers had been retrofitted with sprinklers (sprinklered) with the exception of four floors in WTC 1. In a 1999 update by the Port Authority it was noted that all tenant floors had been sprinklered and work was underway to complete sprinklering of the sky lobbies (see Appendix A Fig. A-9).

The 1999 revision of the New York City Building Code placed a 75 ft height limitation on unsprinklered buildings of Construction Groups 1A, 1B, 1C, and 1D. Sprinklered buildings, however, had no height limitations for Construction Group 1A, 1B, and 1C. Thus the WTC towers could have been reclassified as Class 1C (2 hour protected) (NYCBC 2001). As Class 1C, the columns and floor systems would have required 2 h and 1½ h fire ratings, respectively.

In preparation for leasing the WTC to Silverstein Properties in 2000, the Port Authority commissioned a property condition assessment. The report titled "Property Condition Assessment of World Trade Center Portfolio," which was prepared for the Port Authority by Merritt & Harris, Inc. states that the WTC

towers were classified as "Class 1B – noncombustible, fire-protected, retrofitted with sprinklers in accordance with New York City Local Law 5/1973" (see Appendix A Fig. A-10).

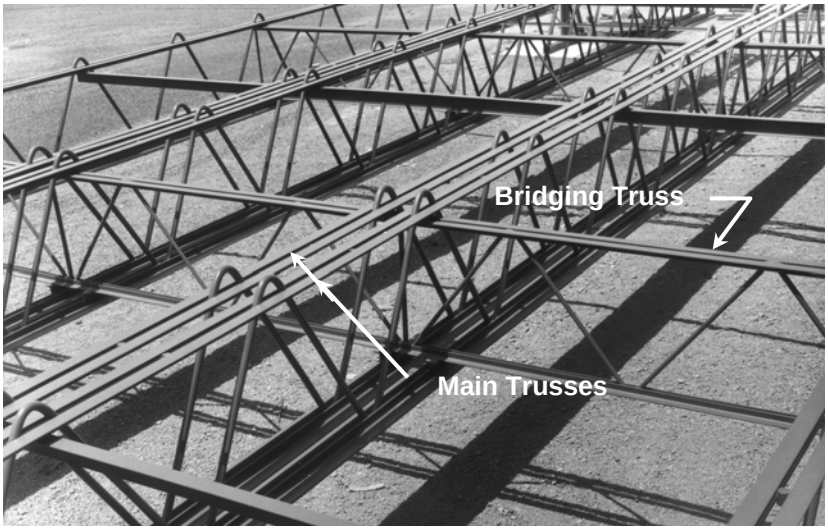
3.4 SELECTION OF FIRE-RESISTIVE MATERIALS

3.4.1 Floor Trusses

Classification of a building leads to its overall fire endurance rating and ratings of the various structural components. The New York City Building Code, however, does not prescribe how the required fire endurance rating is to be achieved. Rather, the means for providing passive fire protection is established by the Architect of Record and depends, in part, on the structural materials used in the construction.

In the case of the WTC towers, the primary structural material was steel. Steel, in general, requires passive fire protection to achieve the fire ratings prescribed in the Code. The Port Authority, in agreement with all parties, chose to protect the main structural components such as columns, spandrel beams, and floor trusses with sprayed fire-resistive material. This thermal protection technique was an established method for protecting columns, beams, and walls. In the 1960s, however, composite steel joist-supported floor systems were usually protected using "lath and plaster" enclosures or fire-rated ceiling tiles.

The floor system used in the towers consisted of open-web floor trusses acting as a composite system with a 4 in. thick reinforced lightweight concrete slab over metal decking. The main composite trusses, which were used in pairs, were spaced at 6 ft-8 in. on center and had a nominal clear span of either 60 ft or 35 ft. The steel floor trusses were fabricated with double-angles, for the top and bottom chords, and round bars for the webs. Additionally, the floor system included bridging trusses (perpendicular to main trusses) spaced 13 ft-4 in. on center. Figure 3-1 shows a mock-up of the floor truss system that was manufactured for the WTC towers by Laclede Steel Co. Figure 3-2 shows the basic configuration of the composite floor truss system.



Source: Photograph from about 1967 from Laclede Steel Co.

Figure 3–1. Mock up of floor truss system

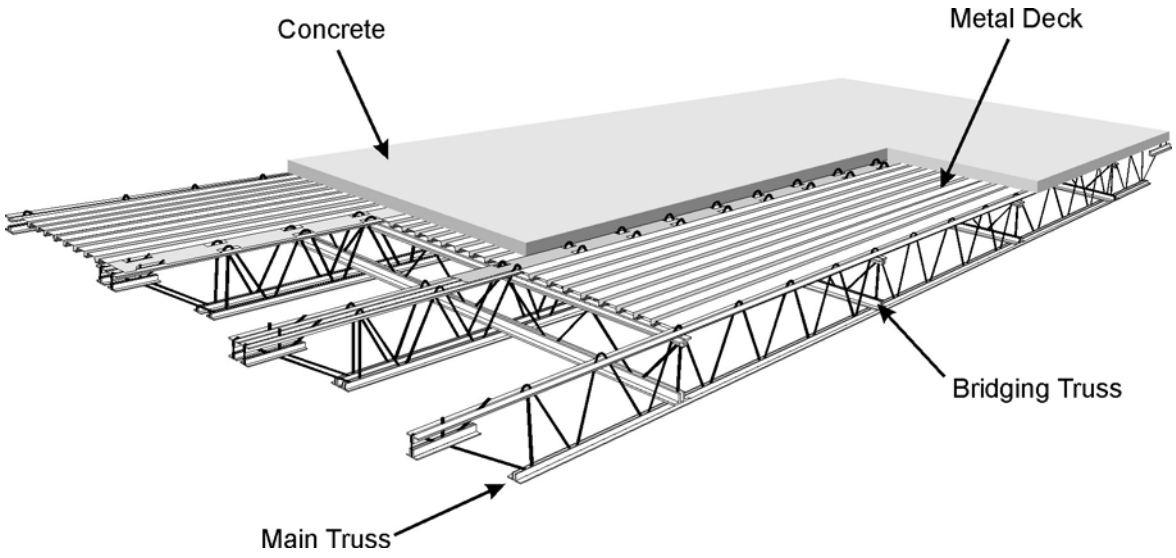


Figure 3–2. Schematic of composite floor truss system.

A review of the process involved in the selection of the thermal protection for the floor trusses is provided in a 1975 report by Skilling, Helle, Christiansen, Robertson (see Appendix A Fig. A-11). The use of "demountable ceilings" was considered as a possible method by the Port Authority and its consultants as early as 1963; but other "efficient and economical" protection methods were sought. By late 1965, the use of sprayed fire-resistive material applied directly to the floor trusses "appears to have been selected."

Since application of sprayed fire-resistive materials to slender steel members, as in the floor trusses, was an innovative fire protection method and not consistent with prevailing practice, the Port Authority arranged for demonstrations to establish its feasibility for the World Trade Center. These demonstrations were mentioned in intra-office correspondence by Laclede Steel Co. (see Appendix A Fig. A-12). The demonstrations also aimed to provide information on the amount of material loss that could be expected when spraying the floor truss elements. In August of 1967, application of Zonolite's Monokote was demonstrated to the Port Authority's engineers (Fig. 3-3) at the Madison, IL plant of Laclede Steel Co. After observing the demonstrations, Laclede Steel stated:

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

and

> "In any event, the fireproofing of joists seems to be a problem now solved, and in the World Trade Center as well as in other steel joist structures, we may be sure that an economical fireproofing can be effected in the field without the expense of heavy ceiling construction."

Source: Provided by Laclede Steel Co.

Figure 3–3. Demonstration of application of Monokote sprayed fire-resistive material to floor trusses,

A similar demonstration of CAFCO BLAZE-SHIELD Type D from U.S. Mineral Products Co.[4] was conducted in September 1967 (see Appendix A Fig. A-13).

In November 1968, the Port Authority authorized award of Contract WTC-113.00 on Spray Fireproofing to Mario & Di Bono Plastering Co., Inc. (see Appendix A Fig. A-14). The company was the subcontractor to Alcoa for application of sprayed thermal insulation to the exterior columns, and the Port Authority reasoned that "contract administration problems would be minimized and coordination between fireproofing work on the interior structural steel and the exterior columns would be facilitated if a single contractor were to perform such work" (see Appendix A Fig. A-15).

3.4.2 Perimeter Columns

By May 1966, several thermal insulation materials were being considered for the perimeter columns (see Appendix A Fig. A-16). This insulation was needed not only for fire protection but also to control steel temperatures under service conditions (see next paragraph). The materials under consideration were Spraycraft (sprayed asbestos fiber), Monokote[5] (sprayed cementitious vermiculite), U.S. Gypsum Fire Code (laminated gypsum board), Vonco (sprayed magnesium oxychloride material), and CAFCO Type D. The thermal insulation for the inside face of the columns was assumed to be 1 3/8 in. gypsum plaster, having a conductivity of 1.56 Btu·in/hr·ft^2·°F. An overall transmission coefficient of 0.396

[4] The CAFCO is the acronym for Columbia Acoustics and Fireproofing Co., a subsidiary of U.S. Mineral Products Co.

[5] The document shown in Fig. A-16, refers to this material as "Monocoat."

Btu/hr·ft^2·°F between the room and column was also assumed for calculation purposes (see Appendix A Fig. A-17).

In December 1966, Aluminum Company of America (Alcoa) presented its proposal for participation in the wall construction of the World Trade Center towers. The proposal stated (see Appendix A Fig. A-18):

> "The "insulation materials applied to the structural steel components of the wall (columns and spandrels) must serve to control column temperature to a minimum of 50° with 70° inside and 0° outside, provide fireproofing to meet a four hour test on a heavy column, and minimize heat loss and gain to satisfy HVAC requirements."

Alcoa proposed the application of CAFCO (of a type described in UL report R3749-10) to three sides of exterior columns. The fire-resistive material would be thick enough to provide 4 h fire rating. Specifically, Alcoa proposed fire-resistive material thicknesses of 1 7/16 in. for exterior columns and ½ in. for spandrels (see Appendix A Fig. A-18).

For the inside face of the columns, Alcoa proposed to apply a high "k" value (thermal conductivity) material. This application would provide thermal protection while permitting heat migration from the room air to the column steel under service conditions. Figure 3-4 illustrates the thermal protection design for the perimeter columns.

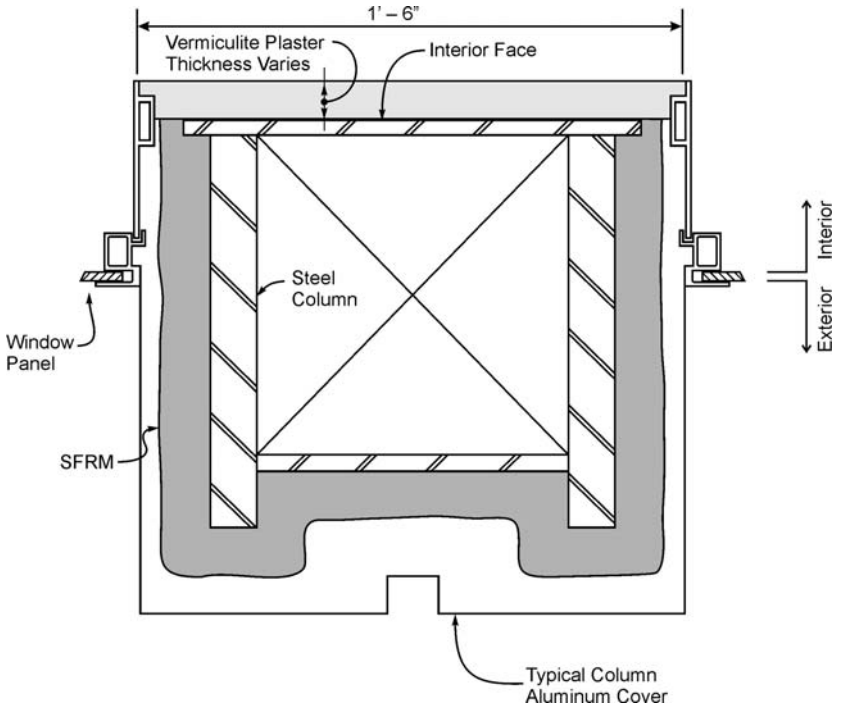


Figure 3–4. Thermal insulation for perimeter columns.

On August 3-4, 1967, an inspection of the quality of fire-resistive material application on an exterior column and spandrel was carried out on a mock-up developed at the Alcoa-Cupples plant in St. Louis, MO. Representatives of Mario & Di Bono Plastering Co., Inc, United States Mineral Products Co., and the Port Authority were present during the inspection. Columns and spandrels were sprayed using

CAFCO BLAZE-SHIELD Type D. In an internal Port Authority memorandum dated August 8, 1967, it was noted that the application of thermal insulation "was done in a workmanship like manner… with ease and very little spillage" (see Appendix A Fig. A-19).

3.4.3 Core Columns

Core columns were protected with fire-rated gypsum wallboard, sprayed fire-resistive material, or a combination of these. Core columns located in rentable and public spaces, in closets, and mechanical shafts were enclosed typically with two layers of ½ in. gypsum wallboard and were inaccessible for inspection. The extent of gypsum enclosure around a core column varied depending on the location of the column within the core (see NCSTAR 1-6). In all cases, however, sprayed fire-resistive material was applied on those faces that were not in direct contact with the gypsum enclosure. Again, the selected sprayed fire-resistive material was CAFCO BLAZE-SHIELD Type D.

Columns located at the elevator shafts were the only columns in the core that were not enclosed and thus were accessible for routine inspections. The columns located at the elevator shafts were protected originally with CAFCO BLAZE-SHIELD Type D., but other materials were used when dislodged thermal insulation was reapplied (see Chapter 4).

3.5 SPECIFIED THICKNESS OF FIRE-RESISTIVE MATERIALS

3.5.1 During Construction

The thickness of fire-resistive material necessary to achieve the required fire endurance was being assessed in 1965, more than three years before the award of the thermal protection contract. Correspondence from Julian Roth (ER&S) to Malcolm P. Levy (Port Authority) stated that "the one-inch thick material meets the 3 hour requirements of both the new code and Underwriters. (See Appendix A Fig. A-20). Follow-on correspondence from Julian Roth to Malcolm Levy stated the following (see Appendix A Fig. A-21):

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

Neither of these communications identified the manufacturer or type of fire-resistive material.

WTC project specifications for spray-applied fire-resistive material do not provide required material thickness or hourly ratings. Correspondence in September 1969 from Mario & Di Bono Plastering Co. to Tishman Realty & construction Co. indicated the following thicknesses (see Appendix A Fig. A-22):

> "1. Beams throughout buildings - ½ inch.
> 2. Columns 1 3/16 inches.

> 3. Elevator columns – 1 inch total including overspray.
> 4. Bar joist – 1 inch overall thickness.".

A letter dated October 30, 1969, from Robert J. Linn (manager, Project Planning, WTC) to Mario & Di Bono Plastering Co. stated, in part (see Appendix A Fig. A-23):

> "…Tower 'A' columns that are less than 14WF228 will require 2 3/16″ thick of 'Cafco Glaze-Shield 'Type D'' spray-on fireproofing. All Tower columns equal to or greater than 14WF228 will require 1 3/16″ of fireproofing…
>
> All Tower beams, spandrels and bar joists requiring spray-on fireproofing are to have a 1/2″ 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."

NIST's review of available documents has not uncovered the reasons for selecting CAFCO BLAZE-SHIELD or the technical basis for specifying ½ in. thickness of insulation for the floor trusses. Note that this letter indicates that in October 1969 it appeared that the towers were considered as Class 1A construction.

Technical literature from U. S. Mineral Products Co. (USM) dated 1966-1967, included a table indicating that ½ in. of CAFCO BLAZE-SHIELD Type D would provide a 4 hour rating for beams, girders and spandrels, citing authority of UL tests performed according to ASTM E 119 (see Appendix A A Fig. A-24). The 1966-1967 USM product literature does not address bar joists with thermal insulation sprayed directly on the truss members. Instead the fire protection for joists was shown as an enclosure of thermal insulation. By way of comparison, the product catalog recommended 2-3/16 in. of CAFCO BLAZE-SHIELD Type D for light columns (columns lighter than W14×228) to achieve the same 4 hour rating.

The October 30, 1969 letter from Linn to Di Bono did not make explicit reference to the required thickness of thermal insulation for core box columns or exterior built-up columns. Alcoa was the supplier of the aluminum cladding on the exterior columns (Contract WTC 400.00). As indicated in Fig. A-18 of Appendix A, Alcoa's contract included providing thermal insulation for the exterior columns and spandrels. The following "Note 11" was included among the "General Notes" of the Alcoa drawings (See Appendix A Fig. A-25):

> 11. Exterior column and spandrel fireproofing–Cafco Blaze Shield Type D Fireproofing. Interior column and spandrel fireproofing–Vermiculite plaster aggregate fireproofing with finished plaster coat on exposed areas of columns. (3 hr on spandrels, 4 hr on cols)

	Fireproofing Thickness	
Rating	**Cafco**	**Vermiculite Aggregate**
4 hr (heavy column)	1 3/16″	7/8″
3 hr (spandrels)	1/2″	1/2″

Note the 4 h and 3 h ratings within the parentheses are consistent with Class 1A construction.

In a letter dated July 25, 1966, from Emery Roth and Sons to the Port of New York Authority, it is stated "Since the deck is non-structural it will not be fire proofed" (see Appendix A Fig. A-26). Photographs taken after construction show that in some areas the underside of the metal deck was not protected, while in other areas fire-resistive material appears to be present but of undetermined thickness and possibly resulting from over spray. Photographs also show that the dampers and damper saddles were not protected. Additionally, it is unclear whether the bridging trusses were required to be protected in all areas.

On April 13, 1970, New York City issued restrictions on the application of sprayed thermal insulation containing asbestos. Since asbestos fiber was a key component of CAFCO BLAZE-SHIELD Type D, the use of this material was discontinued in 1970 at the 38th floor of WTC 1 (see Appendix A Fig. A-27). The asbestos-containing material was "subsequently encapsulated with a spray-on hardening material" and left in place. A green dye was added to the encapsulating material so that the asbestos containing SFRM could be identified. Thermal protection of the remaining floors of WTC 1 and all of WTC 2 was carried out using CAFCO BLAZE-SHIELD Type DC/F, a product that contained mineral wool (glassy fibers) in place of the crystalline asbestos fibers. In May 1970, the construction manager for the World Trace Center wrote a memorandum that summarized considerations in changing from Type D to Type DC/F (see Appendix A Fig. A-28). Correspondence dated April 24, 1970 from Underwriters Laboratories, Inc. to the Port Authority) stated that the thermal properties of CAFCO Type DC/F were equal to or "slightly better" than those of CAFCO Type D (see Appendix A Fig. A-29). There is no record that the required thickness of the fire-resistive material was reconsidered following the change to Type DC/F.

Table 3-2 summarize information on the fire-resistive materials for the WTC towers after April 1970 based on the reviewed construction documents and correspondence. The "Implied Class" refers to the construction classification implied by the hourly ratings or classification mentioned in correspondence and construction documents.

Table 3–2. Specified fire-resistive materials after April 1970.

Structural Component	Members	Material	Thickness (in.)	Implied Class	Rating (h)
Floor trusses	All	CAFCO DC/F	½	1A	3
Interior columns	< 14WF228	CAFCO DC/F	2 3/16	1A	4
	≥ 14WF228	CAFCO DC/F	1 3/16	1A	4
	Box columns	CAFCO DC/F	NA[a]	1A	4
Interior beams	All	CAFCO DC/F	½	1A	3
Exterior columns	"Heavy" Exterior faces	CAFCO DC/F	1 3/16	1A	4
	"Heavy" Interior face	Vermiculite aggregate	7/8	1A	4
Spandrel beams	Exterior face	CAFCO DC/F	½	1A	3
	Interior face	Vermiculite aggregate	½	1A	3

a. NA, not available.

3.5.2 Report on 1975 Fire

In February 1975, a fire took place in WTC 1, spreading from the 9th to the 19th floor (Powers 1975). Most of the damage occurred on the 11th floor where the fire affected 9000 ft^2. After the fire, the Port Authority contracted Skilling, Helle, Christiansen, Robertson (SHCR) to assess the resulting structural damage and to report, in general, on the fire resistance of the floor system. In its report dated April 1, 1975, SHCR communicated to the Port Authority that the fire did not cause structural damage, but it caused buckling of some top chord members of main trusses, buckling of bridging trusses, and distortion deck support angles (see Appendix A Fig. A-30). The SHCR transmittal letter for the report stated that it was "intended to provide background … as to the development of the fire-resistive standards for World Trade Center and looks also at the adequacy of existing systems."

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

The SHCR report suggested that the required thickness of CAFCO BLAZE-SHIELD for the various structural members could have been determined from catalog information (1966-1967 CAFCO BLAZE-SHIELD product literature, U.S. Mineral Products Co). As mentioned previously, CAFCO's catalog from 1967 indicated that the product had been tested by Underwriters Laboratories, and that for beams, girders, and spandrels, a thickness of ½ in. of CAFCO BLAZE-SHIELD Type D provided a 4 h rating. As mentioned, the catalog did not provide any information on thermal protection applied directly to members of bar joists.

Table 3-3 summarizes the "fire retardant ratings" from about 1960 to 1972 for CAFCO BLAZE-SHIELD products applied directly to beams, girders, and spandrels. The information is based primarily on ASTM E 119 fire endurance tests. The table also presents the thermal conductivity, k, for some of the fire-resistive material (the higher the value of k, the lower the thermal insulation). Two items are particularly noteworthy. First, the thickness requirement was nearly halved for CAFCO BLAZE-SHIELD Type D from 1965 to 1966 based on two different test results. Second, the 1966-1967 fire rating, based on two different test results, using ½ in. of the Standard product (with better insulation properties) is one-half of that with ½ in. of the CAFCO Type D product.

The 1975 post-fire report by SCHR stated further that thermal protection of the top chord of the floor trusses was not necessary, except for the corner 60 ft × 35 ft quadrants of the buildings, where the floor acted as a two-way system in bending. In the one-way portion of the floor, "the concrete slab becomes the dominant element of the top chord." Thus if the shear knuckle remains intact, "the structural integrity of the top chord is not required." Additionally, for resistance to wind load "the structural steel top chord provides only a small increment in the diaphragm strength," so the insulation may be omitted. (see Appendix A Fig. A-30). The report also stated that fire protection of the bridging trusses was not required because they were used "for reduction in floor 'tremor' and to reduce the effects of differential deflections associated with gravity loads." Bridging trusses were "not required as a part of the structural system" and, therefore, insulation could be omitted from them.

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

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

In February 2003, NIST asked the Port Authority a series of questions related to the sprayed thermal protection for the floor system. The Port Authority replied in March, and indicated that the top chords of the main trusses and the bridging trusses were protected (see Appendix A Fig. A-31).

Table 3–3. Information in Sweets Catalogs regarding CAFCO BLAZE-SHIELD products applied directly to beams, girders, or spandrels (with protected deck) from 1960 to1972.

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

[†] U.S. Mineral Products Co. catalogs incorrectly report units of thermal conductivity as Btu/in/hr/ft^2/°F.
[§] Thermal conductivities are reported only at ambient temperature.
[‡] Reported to be extrapolations based on formulae contained in National Bureau of Standards Report, *Fire Resistance Classifications of Building Constructions*, Building Materials Structures Report, BMS-92, Washington, DC 1942.
[*] Underwriters Laboratory Inc.

3.5.3 In-Place Thickness and Upgrading of SFRM

No information has been found related to the results of measurements during construction of the thickness of thermal insulation, although thickness appears to have been checked during construction (see Appendix A Fig. A-32). Recorded information on the in-place condition of the sprayed thermal insulation for the floor system first appears in Sample Area Data Sheets from 1990 (see Appendix A Fig. A-33). The data sheets commented on the state of the in-place SFRM. As an example, the data sheet for floor 29 of WTC 1 states the following for the South West quadrant of the floor:

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

Similar statements were recorded for the remaining quadrants of the floor. Apparently, these inspections were related to litigation and focused on the lower floors of WTC 1, where CAFCO BLAZE-SHIELD Type D had been applied.

In 1995, the Port Authority performed a study to establish requirements for retrofit of sprayed insulation to the floor trusses during major alterations (new construction) when tenants vacated spaces in the towers (see Appendix A Fig. A-34). The study estimated the thermal protection requirements for the floor trusses of the towers based on "the fireproofing requirements" for Design No. G805 contained in the Fire Resistance Directory (UL 2002) published by Underwriters Laboratories (see Appendix A Fig. A-35). The study concluded that "a two hour fire rating for the steel floor joist trusses can be achieved by applying a 1½ inch thickness of spray-on mineral fiber fire protection material directly to the steel truss chords and webs." In the years between 1995 and 2001, thermal protection was upgraded in a number of the floors affected by the fires on September 11, 2001. Chapter 4 discusses data made available by the Port Authority on the thickness of the upgraded SFRM.

In 1999, the Port Authority established "guidelines regarding fireproofing repairs, replacement, and upgrades" for the towers (see Appendix A Fig. A-36). The guidelines for tenant spaces may be summarized as follows:

- For full floors undergoing new construction or renovation, the floor trusses should be protected with 1½ in. of sprayed mineral fiber fire-resistive material. Retrofit of thermal protection requires removal of existing material and controlled inspection.
- For "tenant spaces that are less than a full floor, undergoing either new construction or renovation," the floor trusses "need only meet the original construction standard. Fireproofing shall be inspected and patched as required to the greater of ¾" or to match existing" if it has already been upgraded to 1½ in.

While the primary material used to provide thermal protection to the floor system was CAFCO BLAZE-SHIELD DC/F, small areas with damaged SFRM were patched using the Monokote fire-resistive material instead of CAFCO BLAZE-SHIELD. For patching, Monokote was troweled-on rather than sprayed. In February 2000, a consultant to the Port Authority reported that, in the majority of the cases, the existing fire-resistive material required so much patching that it was more effective to replace it (see Appendix A

Fig. A-37). The same report stated that proper application of 1½ in. of CAFCO BLAZE-SHIELD took between 2 and 3 passes. When fewer passes were used, the material usually failed the adhesion tests conducted after application.

The Port Authority provided examples of specifications used in alterations that required reapplication of thermal insulation. Figure A-38 in Appendix A is an excerpt from the specifications related to 1998 upgrades to public corridors and bathrooms on the 15th, 18th, and 22nd floors of WTC 2. In this case the specified fire resistive material was Monokote 6. Figure A-39 is an excerpt from the specifications for a tenant alteration in 2001 on the 48th floor of WTC 2. It is seen that the 2001 specifications are not as detailed as the 1998 specifications with respect to application of fire resistive material.

Buro Happold, an engineering consultant, was commissioned by the Port Authority to "conduct a fire-engineering assessment of the fire-proofing requirements of the open-web, steel joists that support the floors in the tenant areas of Towers 1 and 2 of the World Trade Center." The final report issued in July 2000, focused on the requirements of the fire resistance of the floor system of the towers. This report stated that CAFCO BLAZE-SHIELD DC/F was used on the majority of the floor trusses. Based on calculations and risk assessment, the consultant concluded that (see Appendix A Fig. A-40).

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

As quoted, the report states that significant savings could be possible by reducing the fiber content and considering alternative materials. The report suggested that the thickness of the SFRM could be reduced to ½ in. if the material properties at ambient temperature are valid at higher temperatures (see Appendix A Fig. A-40). The report recognized the lack of available temperature-dependent material data for BLAZE-SHIELD Type DC/F. Thus, considering the uncertainties in the material properties and having the understanding of material degradation with temperature and time, Buro Happold recommended a thickness of 1.3 in. of fire-resistive material for the floor trusses.

Later, in December 2000, the final draft of the *Property Condition Assessment of World Trade Center Portfolio,* prepared by Merritt & Harris, Inc., was presented to the Port Authority. The report stated that, based on existing conditions (see Appendix A Fig. A-41): "The rating of the structural fireproofing in the Towers and subgrade has been judged to be an adequate 1 hour rating considering the fact that all Tower floors are now sprinklered." The report also noted the ongoing program, established by the Port Authority, to upgrade the fire-resistive material thickness to 1½ in. in order to achieve a 2 hour fire rating.

3.5.4 Need for Fire Endurance Tests

Section C26-501.1 of the 1968 New York City Building Code had the following requirement with respect to testing to establish fire resistance ratings:

> "**Tests**—Sample of all materials or assemblies of materials required by this code to have a fire-resistance rating, or flame spread rating, or required to be noncombustible, fire-retardant treated, or slow burning shall be tested under the applicable test procedures specified herein…The fire resistance rating of materials and assemblies listed in reference standard RS 5-1[6] may be use to determine conformance with the fire resistance requirements of this code…"

The fire protection of truss-supported floor system by directly applying sprayed fire-resistive material to the 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 realized by individuals involved in the 1967 demonstrations of the application of SFRM (see Appendix A Fig. A-42), apparently no tests were conducted on the specific floor system used in the WTC towers. ER&S, the Architect of Record, and SHCR, the Structural Engineer of Record, both stated that the fire rating of the floor system of the WTC towers could not be determined without testing (see Appendix A Figs. A-26 and A-43). Communication from the Port Authority in 2003 (see Appendix A Fig. A-31) confirms that there is no record of fire endurance testing of assemblies representing the thermally protected floor system.

In the 1975 post-fire report, the Structural Engineer of Record noted that a floor truss system similar to that used in the WTC had been tested in 1970[7] by Underwriters Laboratories (see Appendix A Fig. A-44). This test was unrelated to the WTC project, but the test assembly included trusses from Laclede Steel Co., a normal density concrete floor slab on steel decking, and sprayed thermal insulation. The thermal insulation was Mono-Kote, a gypsum-based product containing vermiculite aggregate. The thermal insulation was 1½ in. thick on the web bars and ½ in. on the sheet metal deck. The test assembly attained a 3 h rating. In the same 1975 post-fire report, the Structural Engineer of Record noted that Mono-Kote had about twice the thermal conductivity of CAFCO BLAZE-SHIELD. Based on "many simplifying assumptions" and approximate calculations, it was estimated that ½ in. of CAFCO BLAZE-SHIELD applied to 1 in. diameter web bars and chord angles thicker than 3/16 in. would provide a 3 h fire rating (see Appendix A Fig. A-46). He emphasized "however, that theoretical extrapolations of fire endurance tests must the viewed with caution." He stated further in another section of the 1975 report that: "Without benefit of a full-scale fire test we cannot establish a rating for the floor assembly."

3.5.5 Calculations of SFRM Thickness for Core Members

In the 1990s, the Port Authority commissioned Leslie E. Robertson Associates (LERA) to perform a series of structural integrity inspections on the WTC towers (see Section 3.6 and NCSTAR 1-1C). One of the tasks was to determine the thickness of fire-resistive material required to re-coat accessible beams and columns that had missing thermal insulation within the elevator shafts. Calculations presented in a 1992

[6] Reference Standard 5-1 lists the applicable fire protection standards and includes ASTM Test Method E 119.

[7] The 1975 report refers to the testing date as June 26, 1969. The actual testing date was February 27, 1970. The former date was that of a drawing that was used in designing the fire endurance test. See Appendix Fig. A-45 for clarification.

report illustrate the accepted procedure used to determine the required thickness based on the size of the members and designs that have been tested and are listed in the *Fire Resistance Directory* published by Underwriters Laboratory, Northbrook, Illinois. Extracts from the 1992 report are shown in Appendix A Fig. A-47 to illustrate the procedure. The underlying principle is that the SFRM thickness used in the UL fire resistance tests can be modified to provide the same fire resistance rating for similar shaped members, but with different dimensions. These calculations involve a cross-sectional property known as *W/D*, where *W* is the weight of the structural member per foot and *D* is the perimeter of the member through which heat is transferred to the steel. A higher value of *W/D* means that the member has a higher ratio of volume to fire exposed surface area, and would require less thickness of thermal insulation to have the same fire rating as a member with a lower *W/D* value. The UL *Fire Resistance Directory*, for example, provides equations for computing the required thickness of SFRM for beams and columns that are similar to those in the UL designs, but with different *W/D* values.

The 1992 LERA calculations were for the accessible columns in elevator shafts 12 and 13 in WTC 1. Thicknesses were determined for four types of fire-resistive materials: Monokote Type Z-106, CAFCO 560, ALBI Duraspray, and ALBI Duraspray 30. These materials are denser and more durable than the SFRM used to protect the floor trusses, and were intended to provide for better performance within the elevator shafts. Table 3-4 lists the required thickness of Monokote Z-106 to achieve a 3 h fire rating for the accessible columns in shafts 12 and 13. As noted in Appendix A Fig. A-47, the UL directory provided a thickness conversion equation only for columns protected with Monokote Type Z-106. For the other fire-resistive materials, the required thickness was the same an in the UL listed designs, even if the *W/D* values of the WTC columns were different. The following were the required thicknesses on the columns for the other SFRMs:

- CAFCO 560: thickness = 2 11/16 in.
- ALBI Duraspray and Duraspray 30: thickness = 1 11/16 in.

Another example of re-application of SFRM to core members is a 1994 document on "Refireproofing Elevator Shafts 6 & 7 1 WTC" produced for the Port Authority by LERA. The document reported the required thickness of Monokote Z-106 for columns 903 and 904 and for beams A and B in shafts 6 and 7 of Tower 1 (see Appendix A Fig. A-48). Table 3-5 summarizes the thermal insulation thickness requirements for those members. Only floors from the second basement to floor 33 were scheduled for reapplication of thermal insulation.

Table 3–4. Design thickness of thermal insulation for reapplication to accessible columns in elevator shafts 12 and 13 of WTC1.

Floor	Monokote Type Z-106	
	UL-Design	Calculated Thickness
Column 601		
69–79	15/16 in.	15/16 in.
63–68	15/16 in.	13/16 in.
48–62	15/16 in.	11/16 in.
43–47	15/16 in.	9/16 in.
41, 42	15/16 in.	7/16 in.
33–40	15/16 in.	9/16 in.
18–32	15/16 in.	7/16 in.
7–17	3/8 in.	3/8 in.
Elevation 274 - 6	3/8 in.	3/8 in.
Column 602		
69–79	15/16 in.	7/8 in.
54–68	15/16 in.	5/8 in.
43–53	15/16 in.	9/16 in.
41, 42	3/8 in.	3/8 in.
36–40	15/16 in.	9/16 in.
18–35	15/16 in.	7/16 in.
7–17	3/8 in.	3/8 in.
Elevation 274 - 6	3/8 in.	3/8 in.
Columns 501 and 502		
Elevation 310	3/8 in.	3/8 in.

Table 3–5. Design thickness of thermal insulation for reapplication to accessible columns and beams in elevator shafts 6 and 7 of WTC1.

Floor	Column 903	Column 904	Beam A	Beam B
B2	3/8 in.	7/16 in.	Note 1	15/16 in.
B1	3/8 in.	7/16 in.	1/2 in.	Note 1
Elevation 294	3/8 in.	7/16 in.	7/16 in.	15/16 in.
1	3/8 in.	7/16 in.	7/16 in.	1 1/16 in.
Intermediate	3/8 in.	7/16 in.	1/2 in.	Note 1
2	3/8 in.	7/16 in.	1/2 in.	1 in.
3–7	3/8 in.	7/16 in.	1/2 in.	1 3/16 in.
8–18	3/8 in.	1/2 in.	1/2 in.	1 3/16 in.
19–33	3/8 in.	5/8 in.	1/2 in.	1 3/16 in.

Note 1: Beams are concrete encased.

3.6 MAINTENANCE OF SFRM IN ELEVATOR SHAFTS

Throughout the life of the WTC towers, the structural members that required the largest amount of inspection and maintenance within the core were the exposed columns and beams within the elevator shafts. These columns and beams were the only accessible fire-protected elements in the buildings. Adhesion failures were common, likely because of the exposed conditions of the columns (see Appendix A Fig. A-49) and the inherently low strength of the SFRM.

3.6.1 Bond Strength

Internal memoranda from U.S. Mineral Products Co., dating from 1960 to 1969, warned of the poor adherence or bond performance of CAFCO BLAZE-SHIELD, and specifically CAFCO Type D. As communicated in an intra-office memorandum dated July 29, 1960, vibration tests performed in 1960 apparently indicated poor bond characteristics of CAFCCO BLAZE-SHIELD as manufactured in the plant compared with laboratory mixtures (see Appendix A Fig. A-50).

In March 1968, the Port Authority investigated the adherence of CAFCO Type D under field conditions. Based on letters from both U.S. Mineral Products Co. and Mario & Di Bono Plastering Co. relative to an "on-the-job" application of CAFCO BLAZE-SHIELD in January 1968 to evaluate the ability of the material to adhere to the steel and to itself, the Port Authority stated in March 1968 that "this material can be applied successfully to the exterior steel under adverse weather conditions" (see Appendix A Fig. A-51). The Port Authority transmitted this information to the New York City Department of Buildings in January 1970 along with a U.S. Mineral Products Co. report on the material and application techniques and a product catalog (see Appendix A Fig. A-52).

Adhesion problems with CAFCO Type D, however, were reported in December 1969 during construction of the World Trade Center. U.S. Mineral Products Co. intra-office correspondence on December 11, 1969 stated that "Of the 20 tons [800 bags] of material sprayed to the 10th floor exterior columns on this project, approximately 600-700 bags of the material washed off as clean as a whistle from the exterior columns on this job" (see Appendix A Fig. A-53).

3.6.2 Inspections

Inspections of the shafts and accessible columns were reported as early as 1971. After one of these inspections, the WTC inspector wrote "it was noted that the Cafco fireproofing treated with Mark II overspray had not cured or hardened according to specifications" due to the extremely cold temperature conditions existing during construction (see Appendix A Fig. A-54). The inspector recommended that shafts 39, 40, and 41 of WTC 1 be re-sprayed with Mark II sealer. Additional WTC office correspondence dated September 24, 1973 mentioned that the sprayed thermal insulation had come loose and fallen from perimeter box beams in elevator shafts 10 and 11 of WTC 2 (see Appendix A Fig. A-55).

In 1993, the Port Authority commissioned Leslie E. Robertson Associates to carry out a continuing program to appraise the condition of the accessible columns in the World Trade Center complex. These inspection programs are described in greater detail in NCSTAR 1-1C. Accessible columns were those columns that were not enclosed in any kind of architectural finish and could be inspected visually. All accessible columns were located in the core of the towers. The columns were inspected visually for signs of rusting, cracking, bowing, and loss of thermal insulation. During the first inspection, carried out in 1993, particular shafts were chosen based on the quantity and types of accessible columns, and convenience to the Port Authority. The findings were summarized in LERA's Structural Integrity Inspection Report for Accessible Columns at 1, 2, 4, and 5 WTC dated 29 January 1993 (see Appendix A Fig. A-56).

Subsequent inspections involved sampling of the structural components and assemblies, which were more important to the structural integrity of the towers, and at locations with a relatively higher potential for defects and problems. As indicated in the Structural Integrity Inspection Report dated 14 April 1995, a statistical sampling approach was used since concurrent visual inspection of all the accessible columns was "not a practical goal" (see Appendix A Fig. A-57). The report stated that the accessible columns in selected elevator shafts in WTC 1 and 2 were "generally in good condition, no structural deficiencies such as cracking or bowing were found, the most common irregularities observed were missing fireproofing and light surface rusting of the exposed steel." Based on the inspections, LERA recommended "that remedial action to be taken where spray fireproofing is damaged, deteriorated or missing and where there is corrosion of the column base due to water leaks at elevator pits." LERA also recommended painting steel with a zinc-rich paint on areas affected by water leaks prior to re-fireproofing. Refer to NCSTAR 1-1C for a comprehensive discussion of the structural integrity inspection reports.

Chapter 4
AS-APPLIED THICKNESS OF SFRM

Because both towers collapsed totally on September 11, 2001, and most of the SFRM was either dislodged or abraded (or scraped) off in the collapse, no examples remain of the "as installed" condition of the SFRM. To make an estimate of the as-applied thickness and variability in thickness, several sources of information have been employed, including measurements taken by the Port Authority, condition surveys and anecdotal information, and photographs and video clips showing the condition of the fire-resistive material in selected areas. Each of the structural components or systems is considered here separately.

4.1 TRUSS-SUPPORTED FLOOR SYSTEM

As mentioned in Section 3.5.3, qualitative information on the in-place condition of the SFRM for the floor system first appeared in Sample Area Data Sheets from 1990. Information regarding quantitative inspection of existing fire-resistive material appears in documentation from 1994. That year, the Port Authority performed a series of thickness measurements of the existing SFRM on floors 23 and 24 of WTC 1 (see Appendix A Fig. A-58). Six measurements were taken from "both flanges and web" of each of 16 randomly chosen trusses on each floor at those locations where the SFRM was not damaged or absent. The averages of six measurements per joist that were recorded on the two floors are presented in Table 4-1. Measured average thickness varied between 0.52 in. and 1.17 in. For the 32 measurements (16 on each floor), the overall average was 0.74 in. and the standard deviation of these averages was 0.16 in. Four of the 32 floor trusses had average thicknesses between 0.52 in. and 0.56 in. These measurements suggest that the minimum average thickness exceeded 1/2 in.

This same report stated that, on floor 23,

> "... truss members located adjacent to the outside walls (within 3 ft) are devoid of fireproofing material. Visual inspection on floor 24 was not possible, as this area still has a lowered ceiling in place."

The data in Table 4-1 can be examined further to understand the variability of the SFRM thickness in the non-upgraded locations. Figure 4-1 (a) shows the average thicknesses measured on the floor trusses of floors 23 and 24. The values appear to be similar for the two locations in terms of overall average thicknesses and the variation in average thickness. A formal analysis of variance indeed indicated no statistically significant differences between the overall mean thicknesses for the two floors. Thus, the two groups of data can be combined into one. A question to be answered is whether the values of average thickness follow a normal distribution. To answer this question, histograms and normal probability plots are used. Figure 4-1 (b) shows a histogram of the average thicknesses, and it appears to be non-symmetrical and skewed to the right, which is characteristic of a lognormal distribution. As reference, in a lognormal distribution, the natural logarithms of the values of a variate have a normal distribution. Figure 4-1 (c) is the normal probability plot of the average thicknesses for the combined data. If the points fall approximately on a straight line, it indicates that the data are normally distributed. It is seen

that there are systematic deviations of the data from the best-fit line. To examine whether the data are represented better by a lognormal distribution, the average thicknesses, in Table 4–1 were transformed by taking their natural logarithm. Figure 4-1 (d) is a histogram of the natural logarithms of thickness, and Fig. 4.1 (e) is the corresponding normal probability plot. It is seen that the data are slightly less dispersed about the straight line, and the correlation coefficient has increased form 0.97 to 0.99. Thus, there is some indication that the distribution of SFRM thickness may be represented by the lognormal distribution in the non-upgraded floor trusses.

Table 4–1. Average fireproofing thickness from six measurements taken in 1994 on each of 16 random floor trusses on floors 23 and 24 of WTC 1.

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

Source: Data provided by Port Authority of New York and New Jersey.

A lognormal distribution for the average thickness of the SFRM on the non-upgraded floor trusses is explained as follows. It is expected that the thickness of SFRM will be highly variable due to the difficulty in spraying the material on the relatively thin members. If the overall thickness is low and the variability is high, a normal distribution would require a fraction of the surfaces to have negative values of SFRM thickness. If the thickness distribution is lognormal, the thickness cannot be zero, and there is a low likelihood of having thickness close to zero. If the underlying distribution of SFRM thickness is lognormal, the average thickness overestimates the thickness expected to be exceeded with 50 percent probability, and the median is the appropriate statistic for the 50-percentile value. For the values in Table 4-1, the median thickness is 0.71 in., which is not much different from the overall average thickness of 0.74 in.

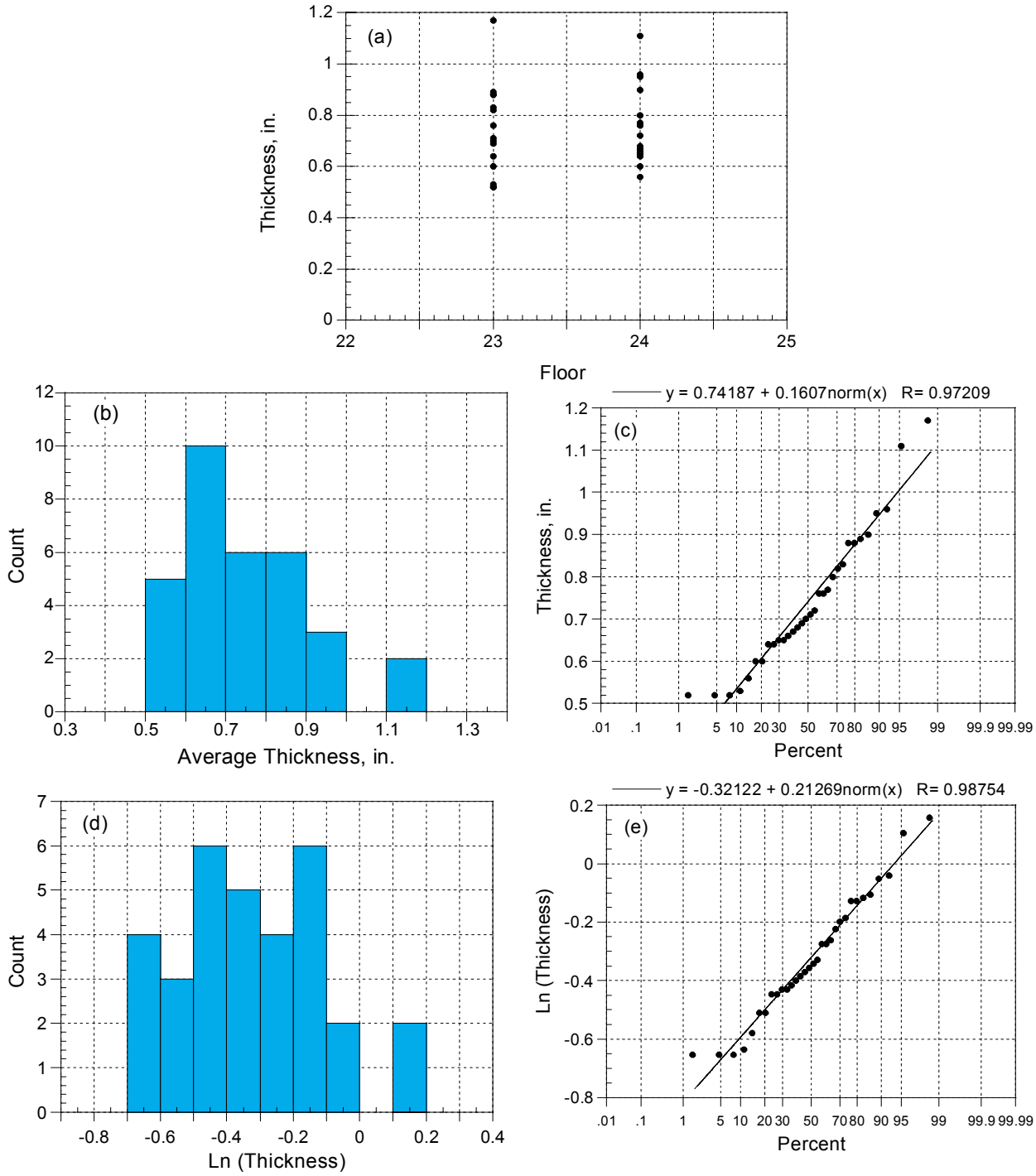


Figure 4–1. (a) Dotplot of average thickness from floor trusses for floors 23 and 24, (b) histogram of average thickness, (c) normal probability plot of average thickness, (d) histogram of natural logarithm of average thickness, and (e) probability plot of natural logarithm of average thickness.

As stated, the standard deviation of the average thicknesses in Table 4-1 is 0.16 in. Since each of the averages is based on six individual measurements, the variability in average thickness is less than the variability of the SFRM thickness on a given element. If it is assumed that the true average thicknesses of SFRM at the truss locations represented in Table 4-1 are the same, it is possible to estimate the variability of individual measurements from the following well-known relationship:

$$S_{\overline{X}} = \frac{S}{\sqrt{n}} \quad (1)$$

where:

$S_{\overline{X}}$ = standard deviation of the average thicknesses

S = standard deviation of the individual thickness measurements

n = number of measurements to obtain the average thickness

Thus, an estimate of the standard deviation of the individual measurements is $0.16\sqrt{6} \approx 0.4$ in. Since it is unlikely that there is no difference in average SFRM thickness at different cross sections, the standard deviation of 0.4 in. is a lower limit for the variability of SFRM thicknesses in the non-upgraded floor trusses on the basis of the information provide in Table 4-1.

4.2 ANALYSIS OF PHOTOGRAPHS

Additional data regarding the thickness of SFRM was gathered by evaluating photographic evidence. Although photographic evidence of the state of the SFRM was limited, two groups of photographs were located and used for estimating SFRM thickness.

The first group of photographs was provided to NIST by Morse Zehnter Associates and includes images of floor trusses from WTC 1 (floors 12, 22, 23, and 27) and WTC 2 (floor 26). From this group, only photographs from floors 22, 23, and 27 of WTC 1 were analyzed. Photographs provided by Morse Zehnter Associates were taken in the mid-1990s and illustrate the fire-resistive material conditions prior to the upgrade carried out by the Port Authority. Thus, SFRM thickness on the photographed trusses would be expected to be at least ½ in. as specified by the Port Authority on October 1969.

The second group of photographs, taken in 1998, was provided by Gilsanz Murray Steficek (consulting engineers). This group illustrates the state of fire-resistive material after the upgrade program that was initiated in 1995. The photographs were of trusses for floor 31 and below in WTC 1.

Selection of which photographed trusses were used to estimate thickness of SFRM was based on clarity of SFRM edges and whether a feature of known dimensions was present to provide a reference measurement. Thus, only photographs where reference measurements could be performed were used. The general approach to the analysis involved the estimation of distances based on the computed reference length per pixel. The procedure is summarized as follows:

- A feature of known dimension (based on construction drawings) that could be used as reference was located in the photograph. For example, the dimension of the bare vertical leg of a damper saddle was a dimension that could be obtained from shop drawings.

- In the photograph, the length of the reference dimension was measured in pixels.
- The scaling factor of length per pixel was computed by dividing the known dimension in inches by the number of pixels. For example, if the vertical leg of the damper saddle was measured as 48.2 pixels in the photograph, and it is known that the actual size of the leg was 3.13 in., the scaling factor would be 3.13 in./48.2 pixels = 0.065 in./pixel.
- Only truss webs or struts (diagonal bar at end of truss) located near and in the same plane as the reference object were selected for analysis. This selection was made to minimize error due to perspective.
- It was assumed that the fire-resistive material on web bars was applied evenly around the perimeter of the bar. Based on this assumption, a "virtual" centerline along the length of the bar was drawn in the photograph.
- Lines were drawn perpendicular to the "virtual" centerline. The number of pixels along the lines from the "virtual" centerline to the edge of the SFRM was determined from the cursor positions indicated by the software. Measurements were made at regularly spaced intervals to avoid bias. Figure 4-2 is an example of a series of measurements made on a strut.
- Each measurement in pixels was multiplied by the scaling factor (in./pixel) to estimate the bar radius plus SFRM thickness.
- The radius of the bar was subtracted to provide the estimate of the SFRM thickness.

Figure 4–2. Example of measurement procedure used to estimate SFRM thickness from photographs.

For floors that had not been upgraded, it was observed that the estimated thickness of SFRM on the webs of the main trusses tended to be greater than that on either the diagonal struts or on the webs of the bridging trusses. Hence, estimates of SFRM thickness for non-upgraded floors were divided into three groups:

- Webs of main trusses,
- Webs of bridging trusses, and
- Diagonal strut at the exterior wall end of the truss.

It was not possible to estimate the thickness of the SFRM on any truss element except the round web bars. Consequently, for the upgraded floors in WTC 1 that were included in the second group of photographs, only estimates of the thickness on the web bars of the main trusses were made. Figure 4-3 (a) shows normal probability plots of the SFRM thickness estimated from the photographs. It is seen that the points for the "upgraded" main trusses follow a generally linear trend, which indicates that the estimated thicknesses for the upgraded main trusses are approximately normally distributed. The estimated thicknesses from the non-upgraded floors, however, do not follow linear trends on the normal probability plot. Figure 4-3 (b) shows normal probability plots of the natural logarithms of the thicknesses. The transformed values for the non-upgraded thermal protection now follow generally linear trends, which means that a lognormal distribution is more appropriate for the non-upgraded floors. This reinforces the observation noted in the previous section. Thus, there is strong evidence that the original SFRM thickness on the floor trusses follows a log normal distribution.

The average, standard deviation, and coefficient of variation were computed for the total number of measurements in each of these groups. The results are summarized as follows:

- Main trusses before upgrade (85 measurements): Average thickness 0.6 in., standard deviation = 0.3 in., and coefficient of variation = 0.5; median = 0.55 in..
- Bridging trusses before upgrade (52 measurements): Average thickness 0.4 in., standard deviation = 0.25 in., and coefficient of variation = 0.6; median = 0.36 in..
- Diagonal struts before upgrade (26 measurements): Average thickness 0.4 in., standard deviation = 0.2 in., and coefficient of variation = 0.5; median = 0.38 in..
- Main trusses after upgrade (52 measurements): Average thickness 1.7 in., standard deviation = 0.4 in., and coefficient of variation = 0.2; median = 1.80 in.

4.3 PORT AUTHORITY DATA ON UPGRADED SFRM ON TRUSSES

In the 1990s, the floor trusses of several floors were upgraded to a specified thickness of 1½ in. of fire-resistive material as tenants vacated their space. According to the Port Authority (see Appendix A Fig. A-59), 18 floors of WTC 1 and 13 floors of WTC 2 were upgraded. The Port Authority also stated that: "The entire impact zone for Tower 1 (92-99) was upgraded with 1½" spray-on fireproofing. Only the 78th floor was upgraded with the 1½" spray-on fireproofing within the impact zone in Tower 2 (78-84)." The Port Authority provided information from Construction Audit Reports regarding the characteristics of

SFRM that was upgraded as of 2000 in the aircraft impacted regions of the WTC towers. The provided test reports state that the material used for the upgrade was BLAZE-SHIELD II (see Appendix A Fig. A-60).

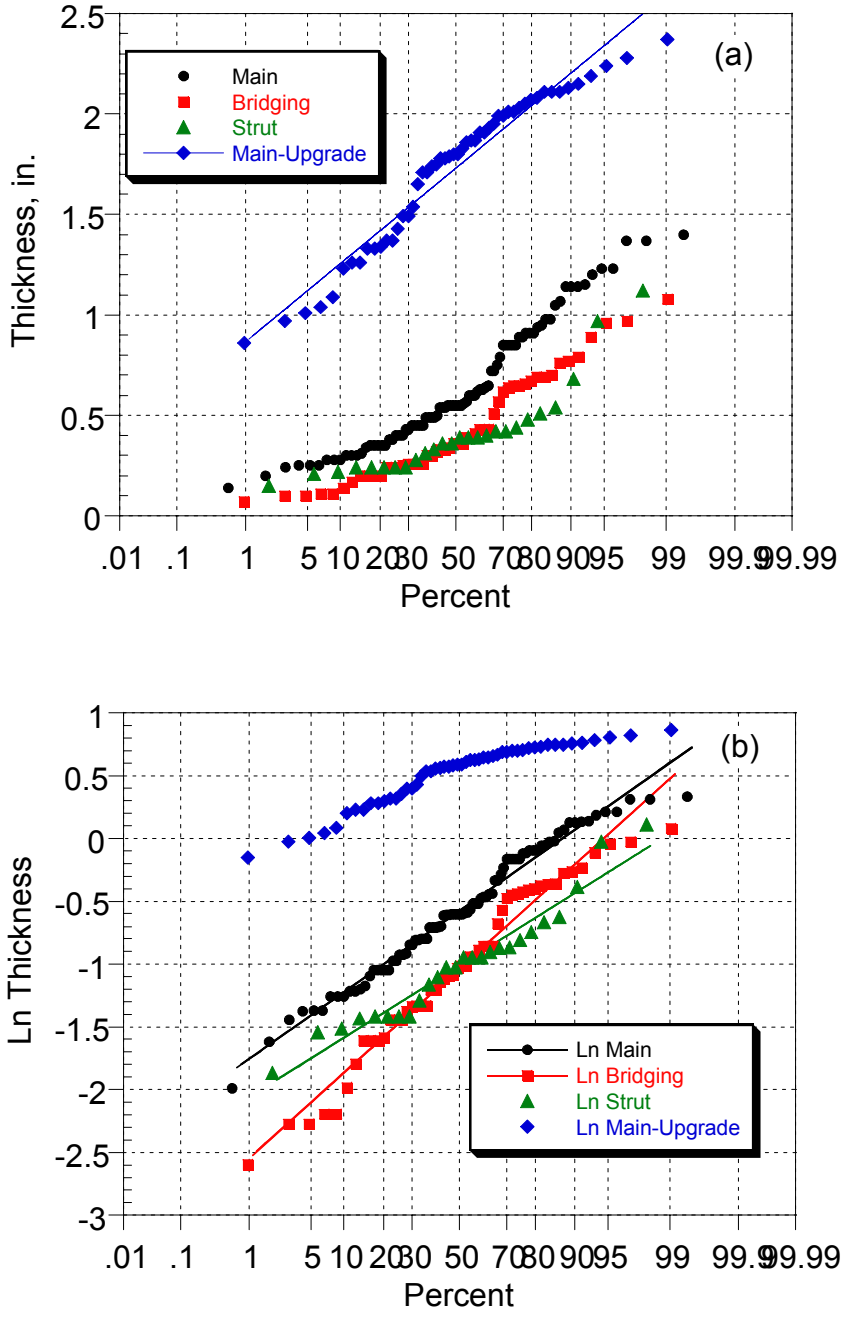


Figure 4–3. (a) Normal probability plot of estimated SFRM thickness based on photographs, and (b) normal probability plot of natural logarithms of thickness.

Port Authority documents state that tests of upgraded SFRM were performed in accordance with ASTM E 605 for thickness and density (ASTM 1993) and in accordance with ASTM E 736 for adhesive/cohesive strength (ASTM 1992). ASTM E 605 requires that thickness measurements be taken at "One bay per

floor or one bay for each 10 000 ft^2, whichever provides the greater number of tests." In addition, it is stated that: "Thickness determinations for the following structural elements shall be conducted in each randomly selected bay: one selected area of metal deck, concrete slab, or wall section; one column; and one beam (joist or truss)." For each preselected joist (or truss), the test method requires that one 12 in. length be laid out and seven thickness measurements be taken at each end of the 12 in. length. The seven measurements at each cross section are to be distributed as follows: two at the top chord, two at the web, and three at the bottom chord.

Table 4-2 shows the test data provided by the Port Authority for the impact-affected floors. Shown are the average thickness, bond strength, and density for each test area on a given floor. The specified minimum requirements are 1½ in. for thickness, 150 psf for bond strength, and 15 lb/ft^3 for density. The reported average thickness for each test area, with few exceptions, is reported to be based on measurements taken from the "bottom of truss" only. Note that some of the average thicknesses shown in Table 4-2 equal or exceed 3.5 in. No photos were available of upgraded floors to show the appearance of a truss with such high average thickness of SFRM. There is no record in the test reports of whether the top chord and bridging trusses were protected in the upgraded floors.

In 2004, the Port Authority provided NIST reports of the individual measurements for many of the average thicknesses shown in Table 4-2. With the individual measurements, it was possible to investigate the variation of thickness at a cross section of a truss member and the variation in average thickness from truss to truss. To permit such analyses, only those data having the same number of individual measurements at each cross section were used. This resulted in 18 data sets for WTC 1 (including floors 93, 95, 98, 99, and 100) and 14 data sets for WTC 2 (including floors 77, 78, 88, 89, and 92).

Table 4–2. Summary of test reports for upgraded SFRM on floor trusses.

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

† Repeated test

An analysis of the individual measurements was carried out to determine the underlying distribution for the measured thicknesses. Figure 4-4(a) is a dotplot of the individual measurements in WTC 1 (144 measurements) and in WTC 2 (112 measurements). It is observed that the central values and ranges are similar for the two towers, and the two groups of measurements were combined into one group. Figure 4-4 (b) is the histogram of the individual measurements, and Fig. 4-4 (c) is the corresponding normal probability plot. A straight line fit to the normal probability plot shows a tendency of the points to deviate from the line. Figure 4-4 (d) is a histogram of the natural logarithms of the individual thickness values, and Fig. 4-4 (e) is the corresponding lognormal probability plot. A comparison of the probability plots shows that natural logarithms fall closer to a straight line. Thus, it appears that the thickness of the upgraded SFRM on the floor trusses is described by a lognormal distribution. This contradicts the observation based on analysis of photographs from lower floors discussed in the previous section. The overall average thickness of the 256 individual measurements is 2.5 in. with a standard deviation of 0.6 in. The median was also 2.5 in. Thus, the average thickness on the upgraded upper floors appears to be greater than that estimated from photographs taken on upgraded lower floors.

As shown in Fig. 4-4, there were a number of points representing individual thicknesses of 3 ½ in. or greater. As mentioned, there are no corroborating data, such as photographs, of such reported high thicknesses. The probability distributions in Fig. 4-4 show, however, that the high thicknesses were consistent with the remainder of the distributions. In any case, statistics were recomputed after removing thicknesses of 3 ½ in. and greater (this amounted to 20 out 256 points). The resulting average thickness was reduced to 2.4 in., and the standard deviation was reduced to 0.5 in. The median remained unchanged. Thus it was concluded that the high reported thicknesses would not have a dramatic effect on the overall statistics of the SFRM thickness in the upgraded floors.

The overall standard deviation of 0.6 in. includes two contributions: (1) the variation of thickness at the cross section (within-truss variability), and (2) the variation of average thickness between trusses (between-truss variability). Figure 4-5 shows these two components of the thickness variability for the two towers. Figures 4-5 (a) and (c) show the within-truss variability, and Figs. 4–5 (b) and (d) show the variation of average thickness of each truss. From analysis of variance, it was found that the within-truss standard deviation is 0.4 in., and the between-truss standard deviation is also 0.4 in. The within-truss standard deviation of 0.4 in. is similar to the standard deviation of the estimated individual thicknesses obtained from analysis of the photographs of upgraded main trusses.

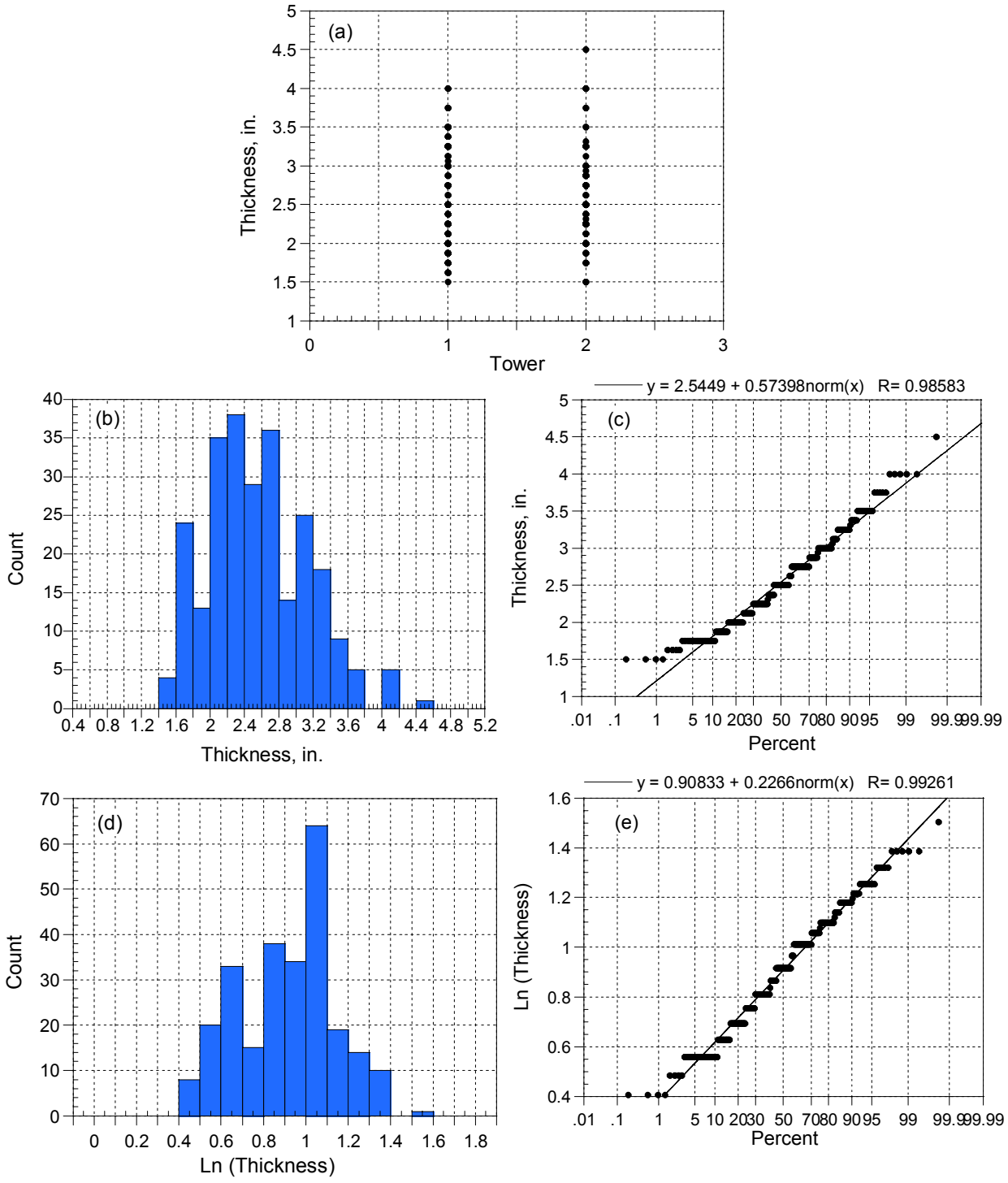


Figure 4–4. (a) Dotplot of individual thickness measurements on floor trusses from Port Authority Construction Audit Reports, (b) histogram of thickness measurements, (c) normal probability plot of thickness measurements, (d) histogram of natural logarithms of thickness measurements, and (e) normal probability plot of natural logarithm of thickness measurements.

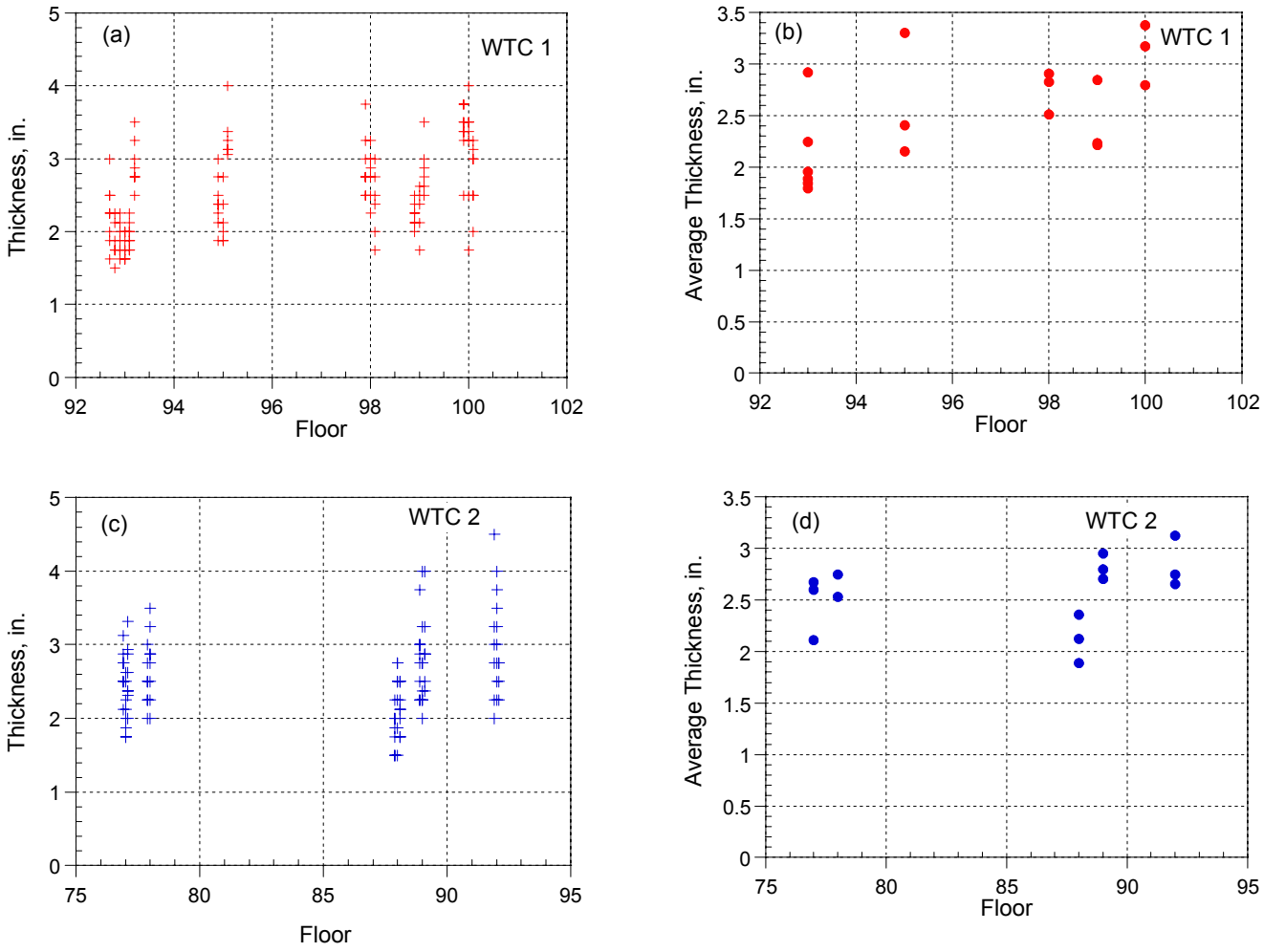


Figure 4–5. SFRM thickness on floor trusses in upgraded portions of WTC towers: (a) individual measurements in WTC 1, (b) average thickness in WTC 1, (c) individual measurements in WTC 2, and (d) average thickness in WTC 2.

4.4 COLUMN SFRM THICKNESS

NIST requested that the Port Authority provide available information on the thickness of fire-resistive material for the exterior and interior columns of the WTC towers (see Appendix A Fig. A-62). Specifically, the request included the following:

- The fire-resistive material used and the thickness on the various plates comprising the exterior columns and spandrels.
- The fire-resistive material used and the thickness on core columns.
- Confirmation that the wide flange column sections were protected with CAFCO BLAZE-SHIELD Type DC/F with specified thickness of 2 3/16 in. for sections smaller than 14WF228 and 1 3/16 in. for 14WF228 and larger.
- Information on in-place SFRM thickness.

The Port Authority replied that, due to inaccessibility of exterior columns and core columns, there were no recent records of SFRM thickness for these elements (see Appendix A Fig. A-62). The only available measurements of SFRM thickness were for beams and columns accessible within elevator shafts. These measurements were, however, for re-applied thermal insulation.

The most complete data set included measurements on beams and columns taken within shaft 10/11 in WTC 1. These measurements were taken in April 1999 and included measurements from floor 1 to floor 45. The thicknesses were recorded to the nearest 1/8 in., with a few thicknesses recorded to the nearest 1/16 in. The columns included 10 to 18 replicate measurements, and the beams included 11 to 16 replicate measurements.

Figure 4-6 (a) shows the individual and average SFRM thickness on the core columns. Analysis of variance indicated no statistically significant differences among the average values and all data were pooled together. The average thickness for the columns is 0.82 in., the standard deviation is 0.20, and the coefficient of variation is 0.24. The information from the Port Authority indicated that the "minimum thickness required" for the columns was ½ in. As noted in Appendix A Fig. A-62, the required thickness was based on calculations performed by LERA for re-applied thermal insulation (Monokote Type Z-106), similar to what was discussed in Section 3.5.5. Figure 4-6 (b) is the normal probability plot of the individual thickness measurements. Because most of the thicknesses were reported to the nearest 1/8 in., the points are staggered in steps instead of uniformly distributed. The plot, however, shows that the points follow a linear trend, and it appears that the thickness of the reapplied SFRM on the core columns could be described by a normal distribution. Figures 4-6 (c) and (d) shows the corresponding plots for the thickness of SFRM reapplied to beams surrounding shaft 10/11 of WTC 1. The average thickness is 0.97 in., the standard deviation is 0.21 in. and the coefficient of variation is 0.21. The information from the Port Authority indicated that the "minimum thickness required" for the thermal insulation reapplied to the beams was 3/4 in.

The above data may not have a direct bearing on the outcome of the investigation because they deal with lower stories. They do, however, provide some useful information on the variability of SFRM applied to beams and columns. The variation in SFRM thickness for the beams and columns shown in Fig. 4-6 is

lower than the variation observed in the floor trusses. This is not unexpected because the planar surfaces of the beams and columns result in more uniform application of the sprayed fire-resistive material than for the slender truss members. This results in reduced differences in the average thickness of SFRM on different members and less variability within a member.

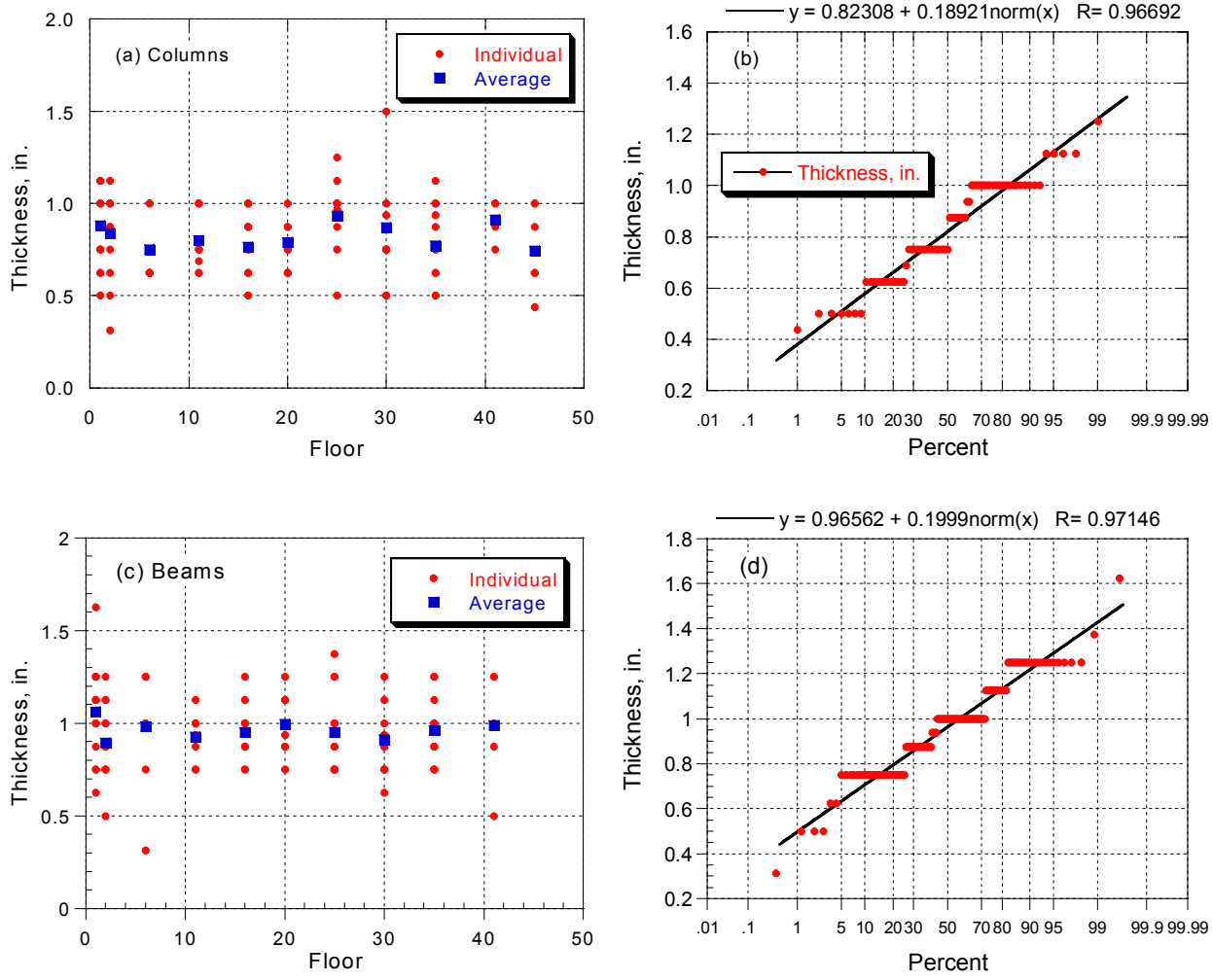


Figure 4–6. Thickness of re-applied SFRM in elevator shaft 10/11 of WTC 1: (a) Individual and average thickness for core columns, (b) normal probability plot of individual measurements on columns, (c) individual and average thickness for core beams, and (d) normal probability plot of individual measurements on beams.

Chapter 5
EFFECT OF SFRM GEOMETRY ON THERMAL RESPONSE

The SFRM thickness has a great effect on the thermal response of the structural elements for a given fire condition. While others have considered the effect of thickness of SFRM, the effect of the variation of thickness along the length of a member is not well known. A sensitivity study using finite element modeling of heat transfer was conducted to investigate the sensitivity of steel temperature to the variability in SFRM thickness.

5.1 EFFECTS OF THICKNESS VARIABILITY AND GAPS IN SFRM

The simplified model that was used is shown in Fig. 5-1. A 1 in. thick, 60 in. long steel plate (cyan color) was coated with fire-resistive material (purple color) and subjected to the uniform radiative flux arising from a 1,100 °C fire. As shown in Fig. 5-1 (b), the fire-resistive material is modeled with a layer of finite elements (0.125 in. thick and 0.6 in. long) having the thermal properties of fire-resistive material (purple). A parametric study was conducted with average thickness of fire-resistive material varying from 0 in. to 2 in. in increments of 1/4 in. The effect of variability in thickness was modeled by imposing a normal probability distribution on the SFRM thickness along the length of the steel plate. The assumed standard deviation varied from 0 in. (uniform thickness) to 1 in. A pseudo-random number generator was employed to determine the thickness at each cross section based on the assumed average thickness and standard deviation. The layer representing SFRM was taken to be twice the average thickness, and the thickness of SFRM at any cross section was modeled by assigning a low heat capacity and a high thermal conductivity to those elements that do not provide thermal protection. Figure 5-1 (c) shows an example of variable thickness SFRM; in this case, the average thickness is 1 in. and the standard deviation is 3/8 in.

When the model in Fig. 5-1 is exposed to the thermal flux representing an 1,100 °C fire, the surface of the insulation heats up quickly to the gas temperature (1,100 + 273 = 1,373 K). Numerical simulation was performed over a 2 h period, and the steel temperature at five locations was recorded at 30 min, 60 min, 90 min, and 120 min of exposure. The temperature recording locations are 6 in. from each end and at 12 in. intervals, which are shown as numbers 1 to 5 in Fig. 5-1 (a). The initial temperature of the model is 300 K.

Figure 5-2 shows temperature contours (in K) through the fire-resistive material and steel at 60 min after initial exposure for the model shown in Fig. 5-1 (a). The surface temperature of the fire-resistive material is close to the gas temperature of 1,373 K, while the steel temperature is 311 K. If the SFRM were of uniform thickness, the isotherms would be a series of lines parallel to the plate. It is seen that, when the thickness is variable, the isotherms follow the shape of the SFRM surface contour. Thus, the temperature history at any point in the steel depends on the local thickness of the fire-resistive material.

Figure 5-3 shows the steel temperature at the far sensor #1 (6 in. from the end) as a function of time for various insulation thicknesses ranging from 0 in. to 2 in. (the thickness is indicated by the numbers on the curves). For the case in Fig. 5-3 (a), the fire-resistive material is of uniform thickness, and for the cases in

Fig. 5-3 (b), the thickness varies with a standard deviation of 1 in. The time to reach a temperature of 600 °C is used as a measure of relative performance. It is seen that the presence of high variability in thickness has a detrimental effect of the protection provided by the fire-resistive material. For example, for a uniform thickness of 0.5 in., it takes about 60 min for the steel at point #1 to reach 600 °C; but when the standard deviation of the thickness is 1 in., the average thickness has to be 1.75 for the same level of thermal protection.

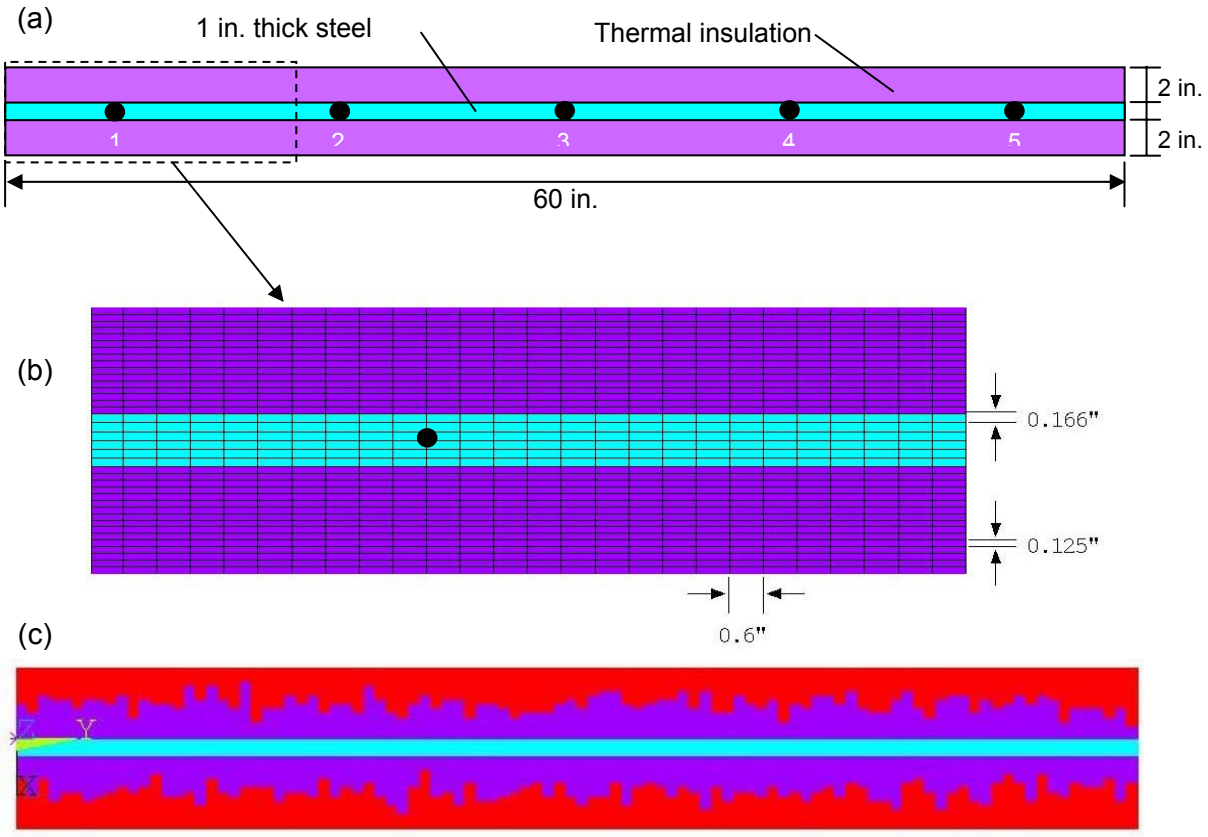


Figure 5–1. Model used to study effects of SFRM thickness and variability of thickness on steel temperature: (a) physical model used in analyses (points 1 to 5 are locations where temperatures are monitored), (b) finite element mesh used to represent physical model, and (c) finite element model to represent variable thickness of SFRM (purple) (the elements in red represent material of high thermal conductivity).

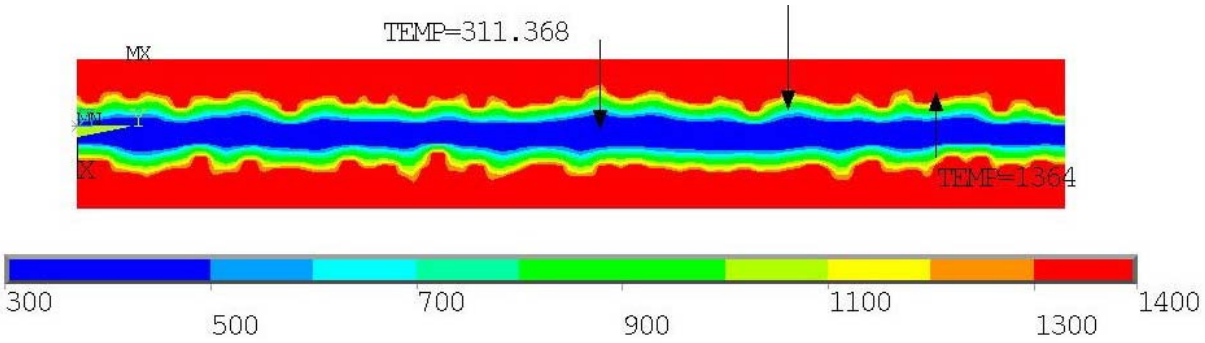


Figure 5–2. Temperature distribution after 1 h of exposure to gas temperature of 1,100 °C (1,373 K).

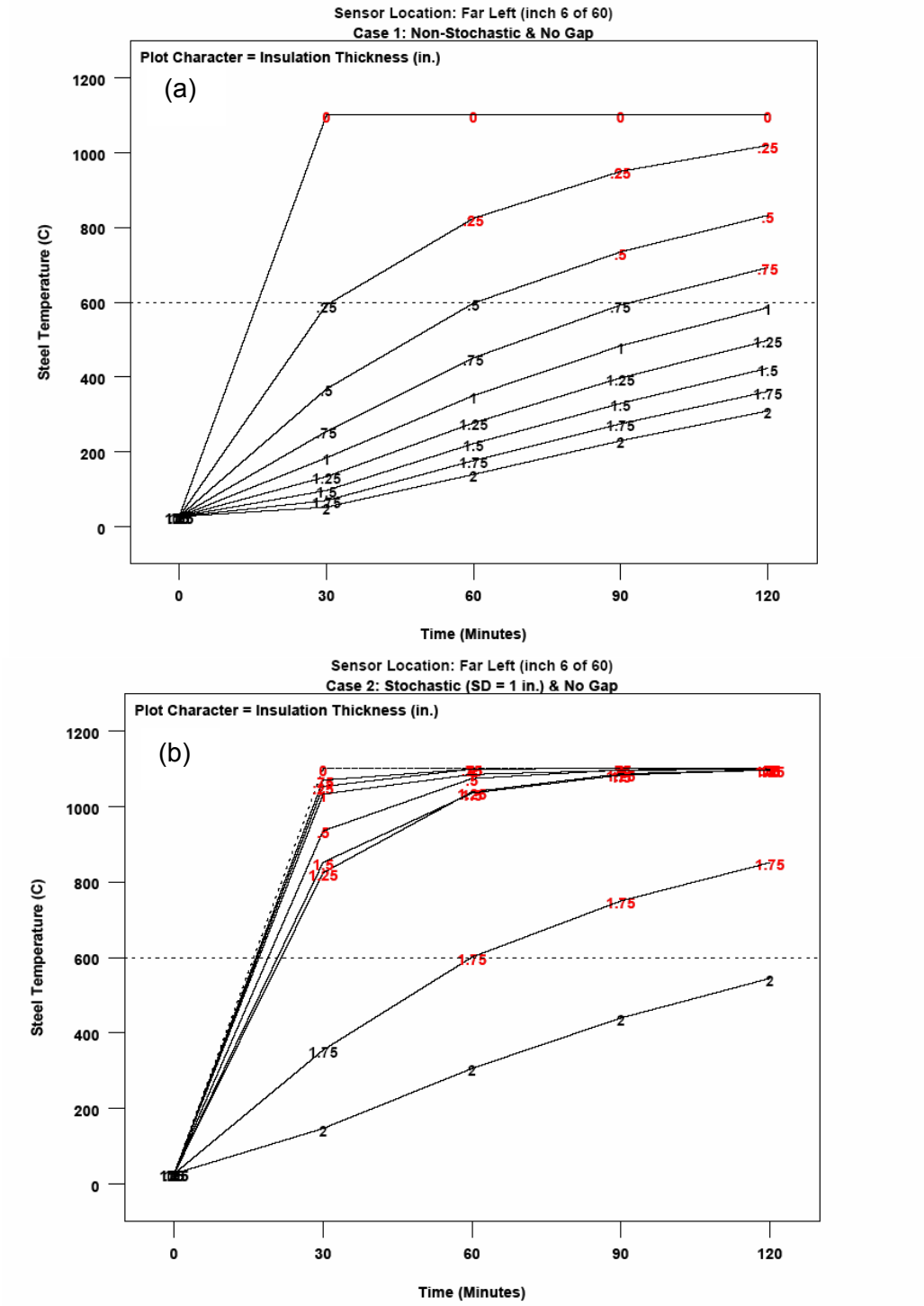


Figure 5–3. Variation of steel temperature (at a point 6 in. from end of plate) with time for different average thicknesses of fire-resistive material (shown as numbers on the curves): (a) uniform thickness, and (b) variable thickness with standard deviation = 1 in.

In addition to the effect of variation in thickness, it is important to understand the effect of missing SFRM over a portion of a member. As an example, Fig. 5-4 shows missing SFRM from a diagonal of a bridging truss of the WTC towers floor system. Note that this photograph is from a lower story and may not be representative of conditions in the upper stories, especially following the upgrade of thermal insulation. Figure 5-5 (a) shows an example of a numerical model with missing fire-resistive material. In this case, there is 12 in. of missing SFRM on the steel plate, which is otherwise protected by 2 in. of uniform thickness fire-resistive material. Figure 5-5 (b) shows the temperature contours (isotherms) at time 50 min. For comparison, Fig. 5-5 (c) shows isotherms at the same time in a plate with no gap in the fire-resistive material. As expected, the bare steel at the missing fire-resistive material is at the gas temperature, but more importantly the "gap" in SFRM leads to a "leakage" of heat into the interior steel.

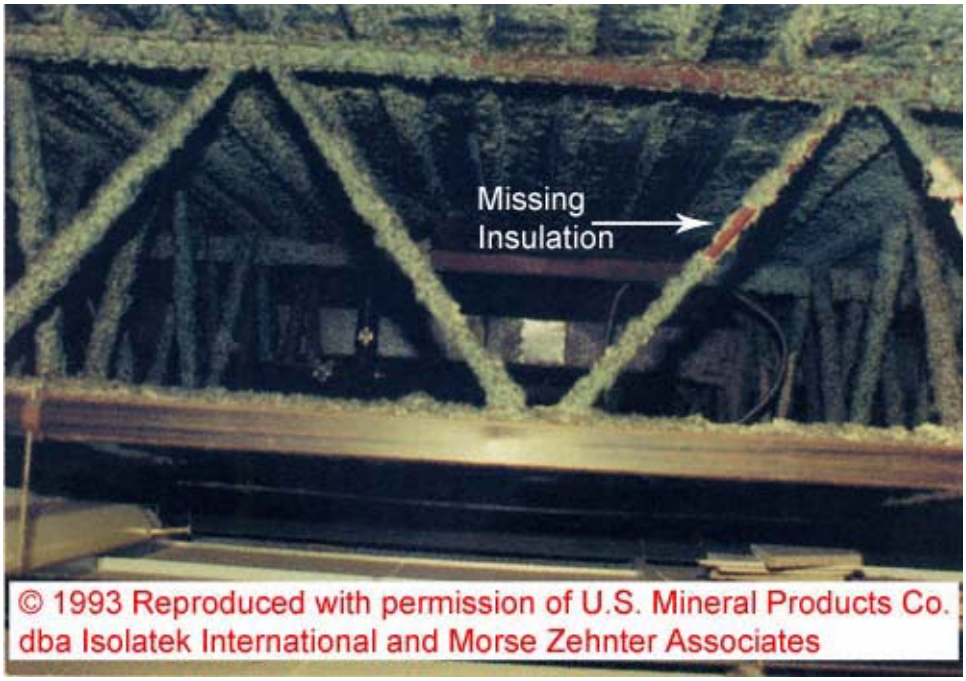


Figure 5–4. Example of "gap" in fire-resistive material on diagonal member of a bridging floor truss.

The combined effects of variation in thickness of the fire-resistive material and length of missing material were examined by a factorial study with the following factors:

- Average thickness of fire-resistive material varying from 0 in. to 2.0 in. in 1/4 in. increments;
- Standard deviation of fire-resistive material thickness of 0 in., 0.25 in., 0.5 in., 0.75 in. and 1.0 in.; and
- Length of missing fire-resistive material varying from 0 in. to 30 in., in 6 in. increments.

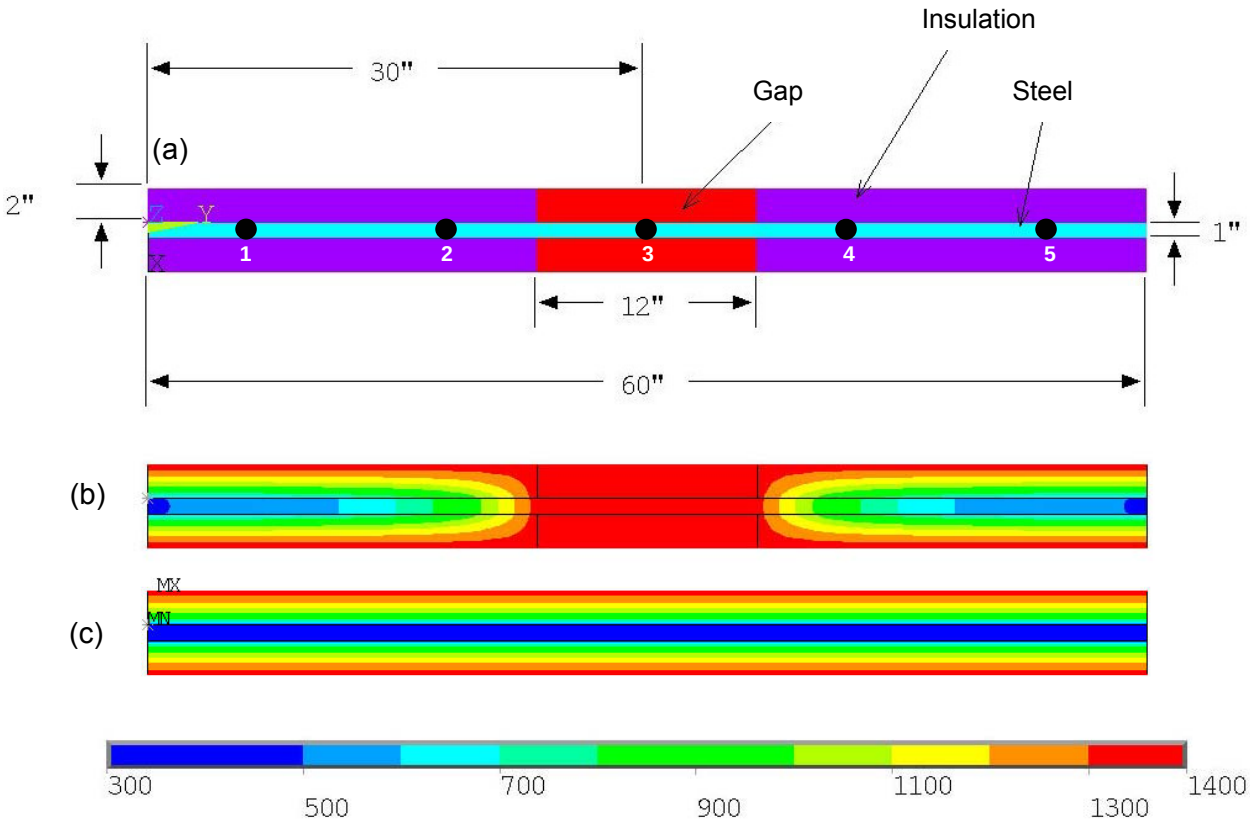


Figure 5–5. Effects of gap in fire-resistive material: (a) model of plate with SFRM having 2 in. uniform thickness and 12 in. gap, (b) isotherms (K) at time = 50 min with 12 in. gap, and (c) isotherms without gap.

The results of the sensitivity study can be summarized in a series of plot matrices, which show the time histories of the steel temperature for different combinations of gap length and variability in SFRM thickness. For example, Fig. 5-6 shows the plot matrix for the temperature history at point #2 (18 in. from the end of the plate). Each plot contains a series of curves representing different average thickness of fire-resistive material, as in Fig. 5-3. Each column of plots represents a constant value of thickness variability (standard deviation), and each row represents a constant gap length. The plot in the upper left corner represents the case of uniform thickness of SFRM and no gap, which is the same plot as in Fig. 5-3(a). (Note that for the case of uniform thickness and no gap, the steel temperature at any point in a cross section is the same along the length of the plate, as shown in Fig. 5-5(c).) For gaps of 24 in. and 30 in., the temperature at point #2 rises rapidly because there is no SFRM on the plate at that location. This explains the shapes of the curves in the two lower rows. In going from left to right in one of the top four rows it is seen that as variability of thickness increases, the time histories shift upward, thereby reducing the time to reach 600°C. This is the same observation as shown in Fig. 5-3. Moving from the top to the bottom in any column shows the effects of increasing gap length. The effect of gap length depends, of course, on where the steel temperature is measured. At a point within the portion of steel that is bare, the temperature rises quickly. At points within the steel that are surrounded with fire-resistive material, the gap provides a path for heat flow, as shown in Fig. 5-5 (b). As a result, points in the steel within the vicinity of the missing SFRM will experience higher temperatures, as indicated by the rising

trend of the curves in going downward from the top of a column in Fig. 5-6. The National Institute of Standards and Technology (NIST) does not have sufficient information to determine the frequency of occurrence of these gaps or their typical locations within the fire-affected floors. Therefore, gaps in insulation were not considered in the thermal modeling.

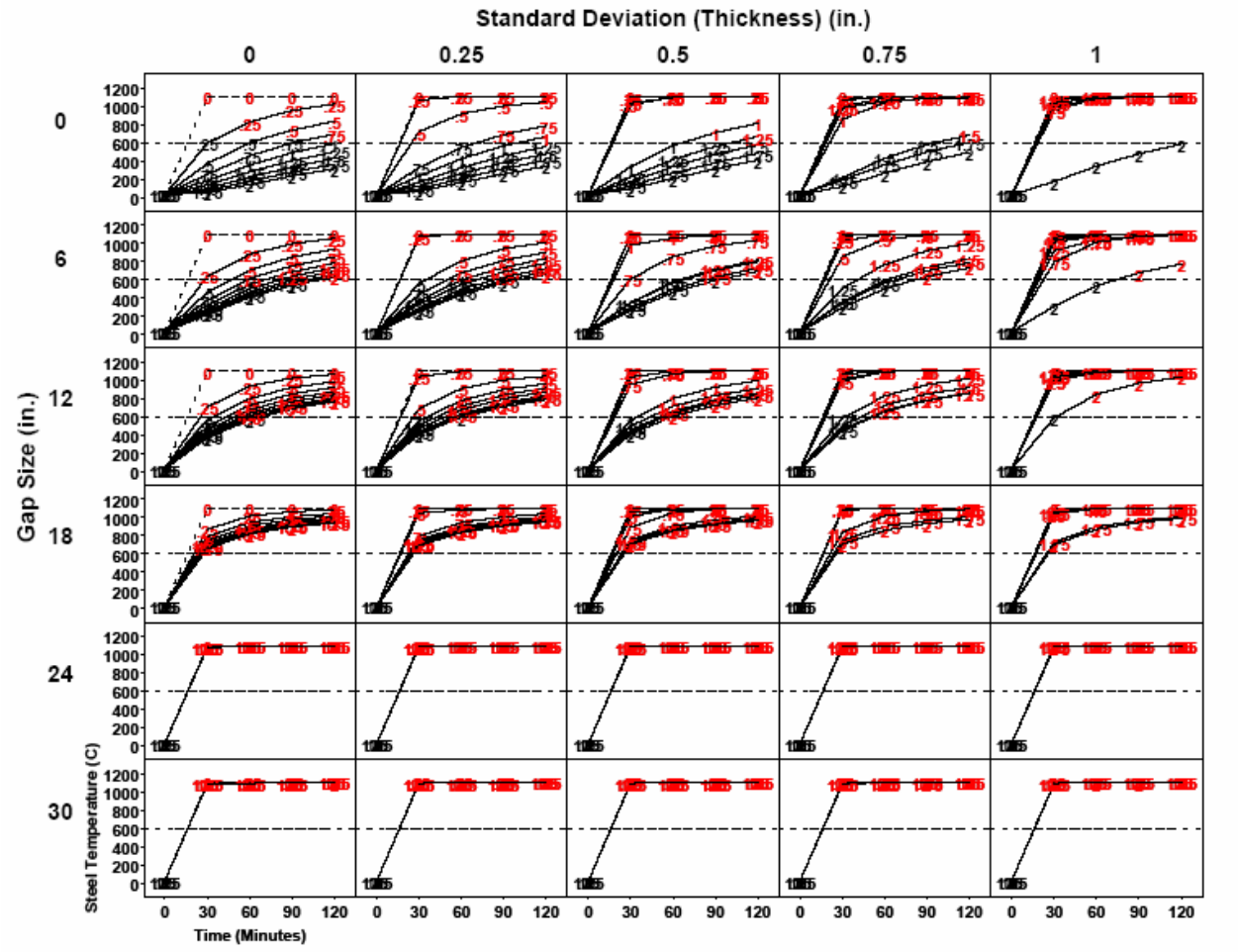


Figure 5–6. Example of plot matrix from sensitivity study of the effects of missing SFRM and variability of SFRM thickness on steel temperature. Each graph is a temperature history of the steel at point #2 (see Fig. 5-5 for location) for different thicknesses of SFRM.

5.2 EQUIVALENT THICKNESS

The sensitivity study summarized in Section 5.1 indicated that variation in the thickness of SFRM reduced the "effective thickness" of the material. It would be impractical to attempt to account for the variation in SFRM thickness in the thermal modeling by introducing variable thickness insulation material in the finite-element models. As an alternative, it was decided to attempt to determine the "equivalent uniform thickness" of fire-resistive material that would result in the same thermo-mechanical response of a member as variable thickness thermal protection. An approach similar to the methodology described in Section 5.1 was used to model a 1 in. diameter by 60 in. long bar with thermal insulation and subjected to the heat flux arising from a 1,100 °C fire. The bar was subdivided into 0.6 in. long elements,

so that there were 100 elements along the length of the bar. The thermal history of the bar was calculated, and that history was used to calculate the length change of the unrestrained bar under a tensile stress of 12,500 psi. The bar was assumed to be similar to the steel used in the floor trusses, and the temperature dependence of the coefficient of thermal expansion and the modulus of elasticity were based on NIST measurements.

The thermal insulation thickness in the models was based on the measurements summarized in Chapter 4 for the web bars of main trusses in the original condition and after the upgrade. Specifically, the following target values were investigated:

- Original: average thickness = 0.75 in., standard deviation = 0.3 in., lognormal distribution.
- Upgrade: average thickness = 2.5 in., standard deviation = 0.6 in., lognormal distribution.

The variation of thermal insulation thickness along the length of the bar was established by using a pseudo random number generator to select values from a lognormal distribution with central value and dispersion consistent with the above average values and standard deviation. Three sets of random data were generated for each condition.

When the randomly selected thicknesses of each element were applied to the bar, it resulted in sudden changes in insulation thickness along the length of the bar. This resulted in a "rough" surface texture as shown by the dotted thickness profile in Fig. 5-7 (a). It was felt that this rough texture (see also Fig. 5-1 (c) might not be representative of actual conditions, so an alternative approach was to use 5-point averaging to reduce the roughness of the insulation profile. The solid line in Fig. 5-7 (a) shows such a "smooth" profile. The two profiles in Fig. 5-7 (a) have approximately the same average value and standard deviation and have similar cumulative distribution of thermal protection thickness as shown in Fig. 5-7 (b).

As stated, the calculated thermal histories of the bar elements were used to calculate the unrestrained length change of the bar due to thermal expansion and an applied stress of 12,500 psi. For comparison, the deformation of the bar with different but uniform thickness of thermal insulation was calculated. The "equivalent thickness" was taken as the uniform thickness that resulted in similar deformation as under the variable thickness conditions. Figure 5-7 (c) shows the results of these calculations for the original SFRM thickness. The three continuous curves are the deformation-time relationships for uniform thickness of 0.4 in., 0.5 in., and 0.6 in. The solid symbols represent the results for three cases with "rough" texture, and the open symbols are for the "smooth" texture. The following values summarize the six variable thickness profiles:

- Rough 1: average = 0.79 in., standard deviation = 0.29 in.
- Rough 2: average = 0.77 in., standard deviation = 0.27 in.
- Rough 3: average = 0.79 in., standard deviation = 0.31 in.

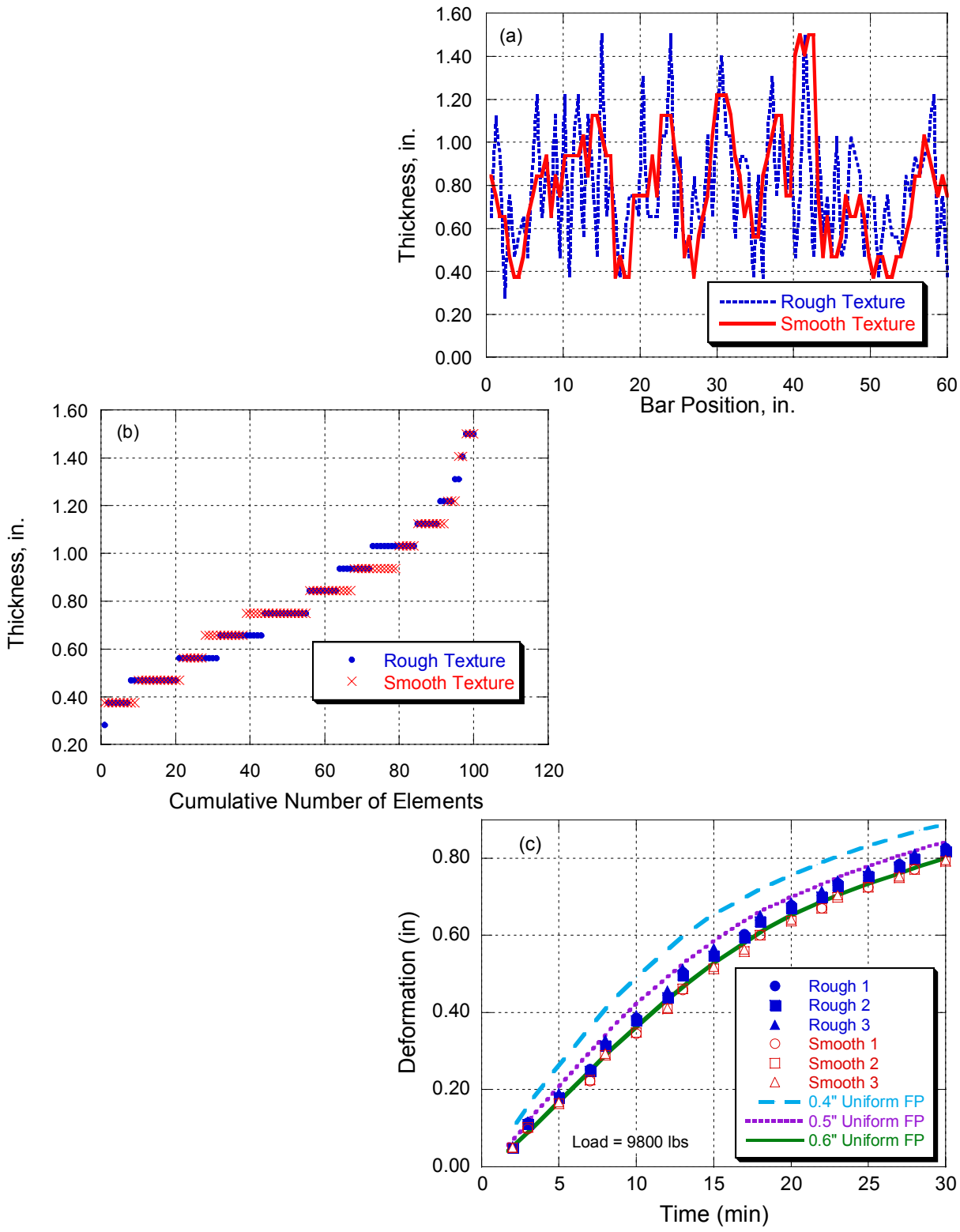


Figure 5–7. (a) Randomly generated thickness profiles with average thickness of 0.75 in. and standard deviation of 0.3 in., (b) cumulative element size, and (c) deformation of 1 in. bar compared with deformation for uniform thickness of thermal insulation.

- Smooth 1: average = 0.79 in., standard deviation = 0.28 in.
- Smooth 2: average = 0.78 in., standard deviation = 0.31 in.
- Smooth 3: average = 0.78 in., standard deviation = 0.32 in.

Figure 5-7 (c) shows that the "rough" texture reduces the effectiveness of the insulation by a small amount compared with the "smooth" texture. As noted above, it is believed that the "smooth" texture is more representative of the actual conditions. On the basis of these analyses, it is concluded that SFRM with an average thickness of 0.75 in. and a standard deviation of 0.3 in. provides protection equivalent to 0.6 in. of uniform thickness.

The results for the upgraded thermal protection are shown in Fig. 5-8. Only the "smooth" texture was used, and the values for the three cases are as follows:

- Case 1: average = 2.50 in., standard deviation = 0.71 in.
- Case 2: average = 2.43 in., standard deviation = 0.51 in.
- Case 3: average = 2.55 in., standard deviation = 0.63 in.

Figure 5-8 (a) shows the three profiles, and Fig. 5-8 (b) shows the normal probability plots of thickness values. Because the three randomly generated profiles do not have the same averages and dispersions, the responses show more scatter than in Fig. 5-7 (c). On the basis of these analyses, it is concluded that an average SFRM thickness of 2.5 in. with a standard deviation of 0.6 in. is equivalent to 2.2 in. of uniform thickness.

5.3 RECOMMENDED THICKNESS OF SFRM FOR THERMAL ANALYSES

Analyses of available data on SFRM thickness and thermal modeling revealed the following:

- From measurements of SFRM thickness, the average values exceeded the specified thickness.
- SFRM thickness was variable, and the distribution of thickness in the floor trusses appears to be described best by a lognormal distribution.
- The standard deviation of SFRM thickness on the trusses varied between about 0.3 in. and 0.6 in.
- The standard deviation of SFRM on columns and beams from the core tended to be lower, with a value of 0.2 in. for the available data.
- No information is available on the SFRM thickness on the exterior columns and spandrel beams.
- Variation in thickness reduces the effectiveness of SFRM, and the equivalent uniform thickness is less than the average thickness.

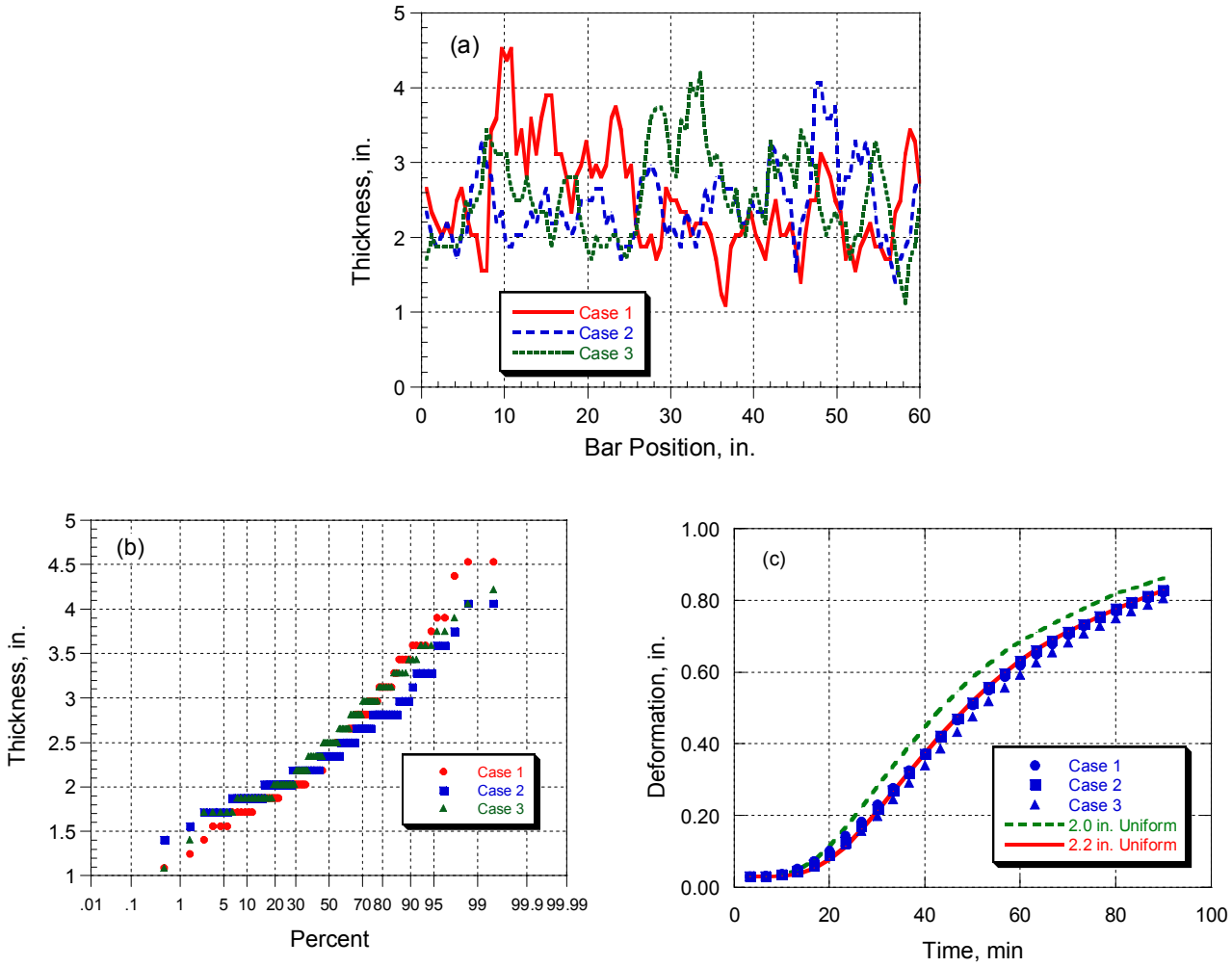


Figure 5–8. (a) Randomly generated thickness profiles with average thickness of 2.5 in. and standard deviation of 0.6 in., (b) normal probability plots of thickness values, and (c) deformation of 1 in. bar compared with deformation for uniform thickness of thermal insulation.

Based on the above findings, the following uniform thickness for the undamaged SFRM were determined for use in calculating thermal response of the WTC towers under various fire scenarios:

- Original SFRM thickness on floor trusses: 0.6 in.
- Upgraded SFRM thickness on floor trusses: 2.2 in.
- Thermal protection on other elements: the specified thickness.

The choice of specified thickness for those members lacking data is justified by offsetting factors as follows: (1) measured average thicknesses exceed specified values, and (2) variation in thickness reduces the effectiveness of the SFRM.

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Chapter 6
THERMOPHYSICAL PROPERTIES

Based on the information provided by the manufacturers, four sprayed fire-resistive materials have been identified in WTC 1, 2, and 7: (1) CAFCO BLAZE-SHIELD Type DC/F, (2) CAFCO BLAZE-SHIELD Type II, and (3) Monokote MK-5, (4) vermiculite aggregate plaster. Of the four SFRMs, only CAFCO BLAZE-SHIELD Type II is sold currently in the U.S., and CAFCO BLAZE-SHIELD Type DC/F is sold in Canada. Table 6-1 summarizes where these materials were used.

Table 6–1. Summary of SFRMs used in WTC.

	Fire-Resistive Material	Locations			
		Interior Columns	Floor Systems	Exterior Columns	
WTC 1	BLAZE-SHIELD DC/F	Yes	Yes	Outside	
	BLAZE-SHIELD II		Yes (Upgrade)		
	Vermiculite plaster				Inside
WTC 2	BLAZE-SHIELD DC/F	Yes	Yes	Outside	
	BLAZE-SHIELD II		Yes (Upgrade)		
	Vermiculite plaster				Inside
WTC 7	Monokote MK-5	Yes	Yes	Yes	Yes

CAFCO BLAZE-SHIELD Type DC/F is manufactured by Isolatek International (formerly U.S. Mineral Products Co., Stanhope, New Jersey) and was used in the interior columns, floor systems, and the exterior faces of the exterior columns of WTC 1 and WTC 2. CAFCO BLAZE-SHIELD Type II, also from Isolatek, was used in subsequent upgrades of the passive fire protection to WTC 1 and 2 floor systems. CAFCO BLAZE-SHIELD Type DC/F and Type II are portland cement based products in which mineral fibers are the primary insulation materials. Monokote MK-5, a gypsum-based SFRM containing vermiculite aggregate, was manufactured by W.R. Grace and Co. (Cambridge, Massachusetts) and used in WTC 7. W.R. Grace stopped the production of Monokote MK-5 in the 1980s. Vermiculite aggregate plaster, manufactured by W.R. Grace until the 1970s, was used on the interior faces of the exterior columns of WTC 1 and WTC 2 (see Fig. 3–4).

No information on the thermophysical properties of vermiculite plaster has been located in the open literature. During the construction of the WTC, the Monokote product was sometimes referred to as sprayed vermiculite. See, for example, Appendix A Fig. A-17, where the description “Sprayed (Cementitious) Vermiculite (Monokote)” is used. Discussions with a former W. R. Grace researcher revealed that Monokote products, with a slightly higher density (20 to 25 pcf) than the conventional sprayed material (minimum of 15 pcf), were referred to as vermiculite plasters. Based on this information, the thermophysical properties of Monokote MK-5 will be taken to be representative of the vermiculite plaster specified for the interior face of the exterior columns.

In addition to the SFRMs, the thermophysical properties of four types of gypsum boards were also examined to provide technical support to other aspects of the WTC investigation. They were: (1)

Firecode Core Type X 5/8″ SHEETROCK gypsum panel, (2) Firecode C Core ½ in. SHEETROCK gypsum panel, (3) Firecode C Core 5/8 in. SHEETROCK gypsum panel, and (4) 1 in. SHEETROCK gypsum liner panel.

6.1 ASTM TEST METHODS FOR SFRMS

Since 1977, a number of ASTM test methods have been developed specifically for testing different characteristics of SFRMs. These methods were developed mainly for characterizing mechanical and physical properties. For completeness, these test methods are summarized in Table 6-2.

Table 6–2. Current ASTM test methods for SFRMs.

ASTM Designation	Summary of Test Method
ASTM E 605 – 93 (Reapproved 2000) Test Method for Thickness and Density of Sprayed Fire-Resistive Material (SFRM) Applied to Structural Members	Density and thickness are determined using a thickness gage, scales, steel rules, and templates
ASTM E 736 – 00 Test Method for Cohesion/Adhesion of Sprayed Fire-Resistive Materials Applied to Structural Members	The cohesion/adhesion of SFRM to structural members is determined using a metal or plastic cap with a hook attached. The cap is attached to the SFRM with a suitable adhesive. An increasing load, measured by a scale, is applied manually until failure occurs.
ASTM E 759 – 92 (Reapproved 2000) Test Method for Effect of Deflection on Sprayed Fire-Resistive Material Applied to Structural Members	A cellular steel deck panel sprayed with SFRM is subjected to bending by a vertical center load while supported horizontally at its ends.
ASTM E 760 – 92 (Reapproved 2000) Test Method for Effect of Impact on Bonding of Sprayed Fire-Resistive Material Applied to Structural Members	A cellular steel deck with a concrete topping sprayed with SFRM is subjected to a leather bag drop impact while supported horizontally at its ends.
ASTM E 761 – 92 (Reapproved 2000) Test Method for Compressive Strength of Sprayed Fire-Resistive Material Applied to Structural Members	The compressive strength of SFRM applied to a steel sheet is determined by a compressive load normal to the surface of the specimen.
ASTM E 859 – 93 (Reapproved 2000) Test Method for Air Erosion of Sprayed Fire-Resistive Materials (SFRMs) Applied to Structural Members	The SFRM is subjected to a tangential air stream for a minimum of 24 h. Collection filters downstream from the specimen are weighed at frequent intervals to determine the amount of material removed from the specimen.
ASTM E 937 – 93 (Reapproved 2000) Test Method for Corrosion of Steel by Sprayed Fire-Resistive Material (SFRM) Applied to Structural Members	Replicate panels of bare, shop-coated, and galvanized steel are sprayed with SFRM and subjected to room temperature and humidity conditions and to 240 h of conditioning in a chamber with temperature and humidity control. Corrosion induced under these conditions is determined by mass loss of the sheets as related to sheets not so conditioned.

6.2 REPORTED SFRM PROPERTIES

For comparison with measurements to be reported in this Chapter, the nominal physical and mechanical characteristics taken from product literature (see Appendix A Fig. A-61)[8] of the manufacturers of the SFRMs are listed in Table 6-3.

Table 6–3. Properties from tests of SFRMs reported by manufacturers.

Characteristic	ASTM Method	SFRM		
		BLAZE-SHIELD DC/F	BLAZE-SHIELD II	Monokote MK 5
Cohesion/adhesion	E 736	300 psf[a]	360 psf[a]	320 psf
Deflection	E 759	No cracks or delaminations	No cracks or delaminations	No cracks or delaminations
Bond impact	E 760	No cracks or delaminations	No cracks or delaminations	No cracks or delaminations
Compressive strength	E 761	830 psf	2380 psf	3110 psf
Air erosion resistance	E 859	0.000 g/m^2	0.000 g/m^2	0.022 g/m^2
Density	E 605	13 pcf	16 pcf	15 pcf[b]
Corrosion resistance	E 937	Does not promote corrosion of steel	Does not promote corrosion of steel	Not available
Thermal conductivity	C 518	0.042 W/(m · K) @ 24 °C	0.043 W/(m · K) @ 24 °C	Not available

a. Based on laboratory tests under controlled conditions.
b. Based on information from former employee of W.R. Grace

6.3 MEASURED THERMOPHYSICAL PROPERTIES OF SFRMS

To provide thermophysical property data for modeling the fire-structure interaction of the towers, the thermal conductivity, specific heat capacity, and density of each SFRM were determined as a function of temperature up to 1200 °C (2190 °F). Since there are no ASTM test methods for characterizing the thermophysical properties of SFRMs as a function of temperature, ASTM test methods developed for other materials were used. Testing services were provided by Anter Laboratories, Inc., Pittsburgh, Pennsylvania, through a competitive open procurement. Anter Laboratories is an ISO 9002 certified company. Test results were presented to NIST in the form of a letter report with data and plots as attachments.

6.3.1 Sample Preparation

Samples of CAFCO BLAZE-SHIELD DC/F and II were prepared by Isolatek, Inc. in Stanhope, New Jersey, and samples of Monokote MK-5 were prepared by W.R. Grace and Co. in Cambridge, Massachusetts, according to their respective application manuals. Since Monokote MK-5 is no longer on

[8] In Fig. A-61, thermal conductivity is reported as an R-value per in. thickness. The inverse of this value is the thermal conductivity. Thus a reported R value of 3.45 indicates a thermal conductivity of 0.29 Btu-in./(ft2 · °F · h) or 0.042 W/(m · K).

the market, it was manufactured specially by W.R. Grace according to the original MK-5 formulation. The samples were made from the same batch of raw materials, shipped to NIST for examination and documentation, and sent to Anter Laboratories for testing. The samples were 9 in. long, 4.5 in. wide, and 3 in. thick. These dimensions were dictated by the test methods used. Three samples of each material were sent for testing. Two of them were used for the thermal conductivity measurements, and the third was used to prepare specimens for the other measurements involved. Figures 6-1, 6-2, and 6-3 show photographs of samples of BLAZE-SHIELD DC/F, BLAZE-SHIELD II, and Monokote MK-5.

Source: NIST.

Figure 6–1. BLAZE-SHIELD DC/F sample used for thermophysical property measurements.

Source: NIST.

Figure 6–2. BLAZE-SHIELD II sample used for thermophysical property measurements.

Source: NIST.

Figure 6–3. Monokote MK-5 sample used for thermophysical property measurements.

6.3.2 Thermal Conductivity Measurements

The thermal conductivity measurements were performed according to ASTM C 1113 (ASTM 1999). This test method is based on heating two specimens with a platinum wire placed between them. The thin platinum wire serves not only as a heater, but also as a temperature sensor, since the variation of its electrical resistance during the test is converted into variation of temperature. Thermal conductivity is calculated based on the rate of temperature increase of the wire and power input.

Anter Laboratories reported that substantial shrinkage occurred during the measurements for the three materials. The two MK-5 specimens shrunk, exposing the platinum wire positioned between them. For this reason, no thermal conductivity measurement could be performed for this material at 1,200 °C. Table 6-4 summarizes thermal conductivity as a function of temperature. The results are plotted in Fig. 6-4, which also shows the results for BLAZE-SHIELD DC/F from Harmathy, which were obtained using a variable-state method (Harmathy 1983). The results show similar trends of increased thermal conductivity with increasing temperature; however, the Monokote MK-5 specimens had a different behavior than CAFCO BLAZE-SHIELD Type DC/F and Type II at temperatures above 500 °C.

Table 6–4. Measured thermal conductivity as a function of temperature.

	Thermal Conductivity (W/(m · K))[a]		
Temperature (°C)	**BLAZE-SHIELD DC/F**	**BLAZE-SHIELD II**	**Monokote MK-5**
25	0.0460	0.0534	0.0954
50	0.0687	0.0745	0.0926
100	0.0628	0.0921	0.1252
200	0.0810	0.0895	0.0919
300	0.1106	0.1057	0.1214
400	0.1286	0.1362	0.1352
500	0.1651	0.1689	0.1504
600	0.2142	0.2156	0.1622
800	0.3380	0.2763	0.1895
1000	0.5010	0.3708	0.2618
1200	0.5329	0.4081	–

a. SI units are used because this system was used to make the measurements. To convert to Btu-in./(h · ft2 · °F) divide by 0.1442279.

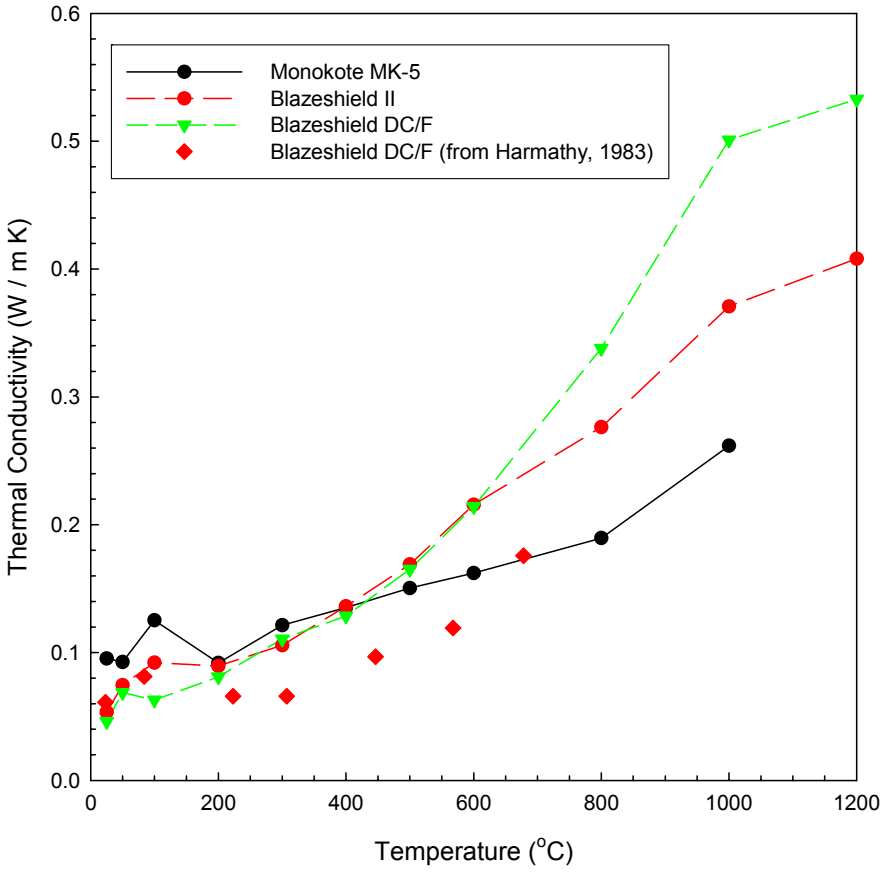


Figure 6–4. Thermal conductivities of the three SFRMs as a function of temperature.

6.3.3 Specific Heat Capacity Measurements

For the specific heat capacity measurements, the same instrument (Unitherm™ Model QL–3141) was used with a slight modification. A thermocouple was added to the system and mounted on the specimen, parallel with the platinum wire at a known distance from the wire. The test was performed in a similar manner as the thermal conductivity measurements, but from the thermocouple output the thermal diffusivity of the material was derived. Knowing the thermal conductivity, the thermal diffusivity, and the density calculated from the thermal expansion results and the thermogravimetric analysis (see Section 6.3.4), the specific heat capacity of the material was calculated. Table 6-5 tabulates the measurements. Figure 6-5 compares the present results for BLAZE-SHIELD DC/F with those from Harmathy, which were obtained using a DuPont 910 differential scanning calorimeter with a heating rate of 5 °C/min (Harmathy 1983). It is clear from the figure that the inherently indirect nature of the technique used by Anter Laboratories precludes the direct measurements of specific heat capacity associated with chemical reactions (peaks in the figure) when the SFRMs are subjected to heating.

Table 6–5. Calculated specific heat capacity of the three SFRMs.

	Specific heat capacity (J/(kg K))[a]		
Temperature (°C)	**BLAZE-SHIELD DC/F**	**BLAZE-SHIELD II**	**Monokote MK-5**
25	826.4	801.6	841.0
50	941.5	868.4	1045.8
100	723.9	708.4	1005.7
200	897.2	925.4	1205.5
300	1020.2	1084.7	1253.9
400	1070.6	1147.5	1302.9
500	1097.6	1255.3	1331.6
600	1189.7	1299.1	1400.8
800	1258.6	1369.6	1468.2
1000	1325.3	1411.3	1520.8
1200	1391.7	1461.3	–

a. SI units are used because this system was used to make the measurements. To convert to Btu /(lb · °F) divide by 4186.8.

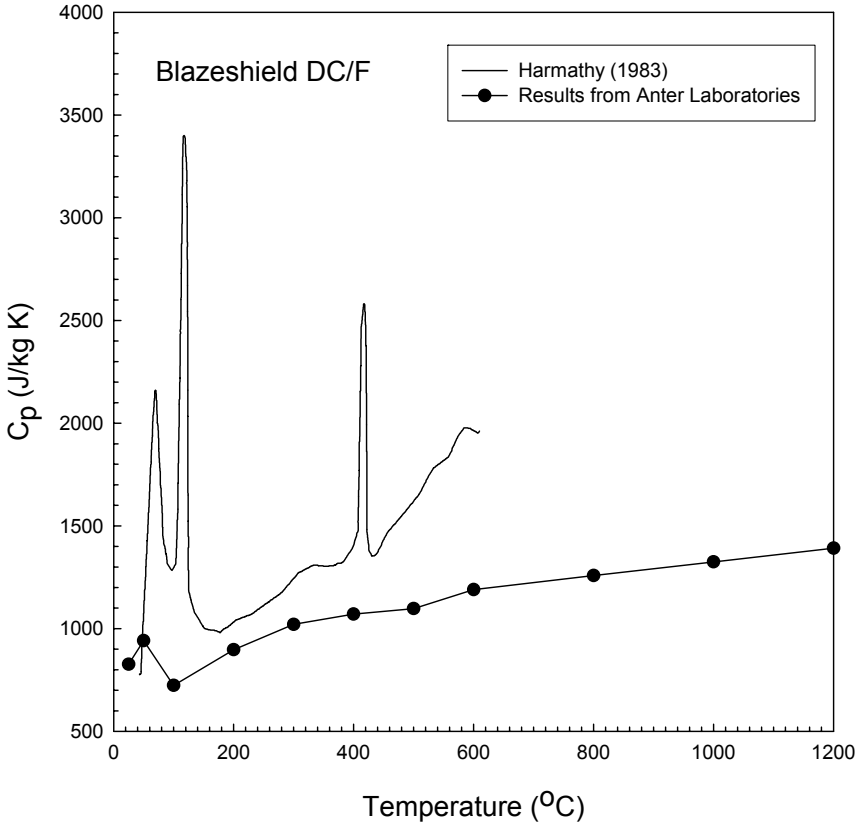


Figure 6–5. Comparison of BLAZE-SHIELD DC/F specific heat capacity measurements from Harmathy (1983) with present results from Anter Laboratories.

To examine the chemical reactions associated with heating of SFRMs, samples were sent to Thermophysical Properties Research Laboratory (TPRL) in West Lafayette, Indiana to perform differential scanning calorimetry (DSC) because the DSC in the Building and Fire Research Laboratory at NIST was not working at that time. The specimens for DSC were prepared by removing small pieces from the bulk samples. The pieces were placed into small glass vials and sent to TPRL for analysis.

Specific heat capacity was measured in accordance with ASTM E 1269 (ASTM 2001) using a Perkin-Elmer Model DSC-2 Differential Scanning Calorimeter with sapphire as the reference material. The standard and SFRM specimens were subjected to the same heat flux as a blank and the differential powers required to heat the specimen and the standard at the same rate were determined using the digital data acquisition system. The specific heat capacity of the specimen was computed from the masses of the sapphire standard and SFRM specimen, the differential power, and the known specific heat capacity of sapphire. The data were displayed visually as the test progressed. All measured quantities were directly traceable to NIST standards.

Differential thermal analysis (DTA), which is a "fingerprinting" technique that provides information of the chemical reactions, phase transformations and structural changes that occur in a specimen during a heat-up or a cool-down cycle, was used to locate the peaks and valleys during continuous heating to 600

ºC at a rate of 10 ºC/min. Once the peak and valley regions were identified, the sensitive DSC was used to examine these regions further at a heating rate of 5 ºC/min, first from room temperature to 350 ºC and then from 300 ºC to 580 ºC. It was noted by TPRL, however, that the DSC results at temperatures greater than 350 ºC were of questionable quality and problematic. Only the results (up to 350 ºC) are tabulated in Appendix B Table B-1 and are displayed in Fig. 6-6, together with the results from Anter Laboratories for comparison.

Figure 6-7 shows a comparison of specific heat capacity data for BLAZE-SHIELD DC/F from Harmathy (1983) with the results from TPRL. For temperature up to 350 °C, both results exhibit two peaks although their locations occur at different temperatures, and their magnitudes are different. In general, an increase in the heating rate results in a shift of the peaks toward higher temperatures and in increases of maxima or minima of peaks with narrowing peak widths. Both studies used the same heating rate of 5 °C/min, however, other procedural and operational factors could have affected the measurements. Since milligram quantities of SFRM are used in DSC, assurance of specimen homogeneity and representativeness of the bulk sample in the specimen holder is essential to the validity of the measurements, especially for inhomogeneous materials like SFRMs. In addition, mass loss from the specimen holder during heating could interfere with the measurements.

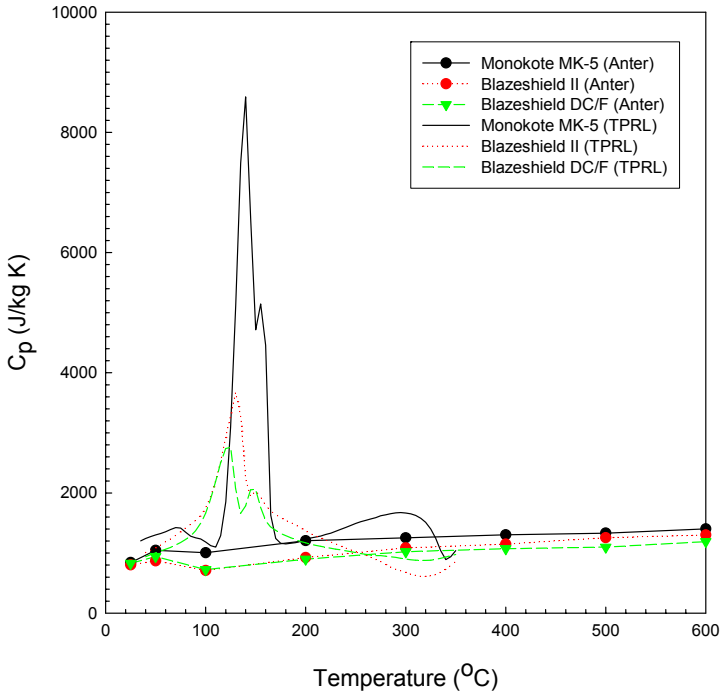


Figure 6–6. Comparison of specific heat capacity measurements from TPRL with results from Anter Laboratories.

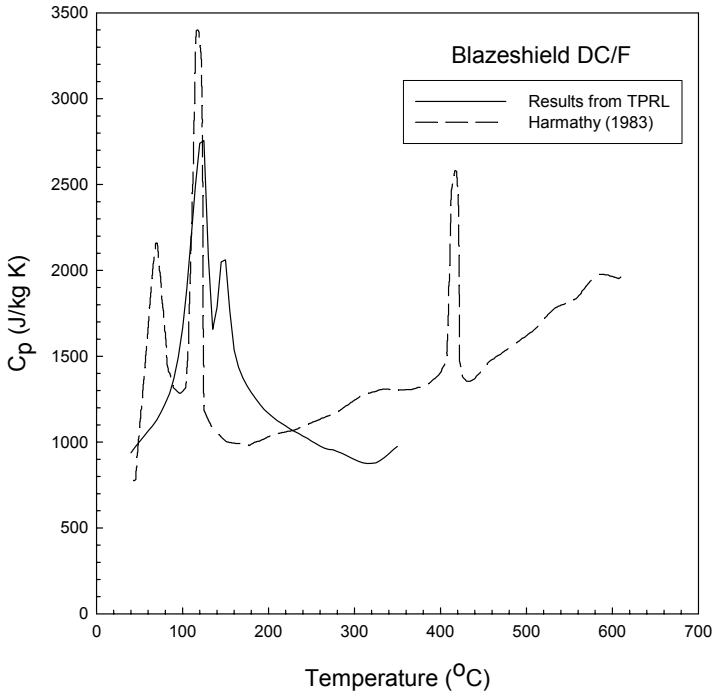


Figure 6–7. Comparison of specific heat capacity measurements for BLAZE-SHIELD DC/F from TPRL with the results from Harmathy (1983).

6.3.4 Density Measurements

Bulk densities of the SFRMs were not measured directly (except at room temperature) but were calculated from thermal gravimetric analysis (TGA) and thermal expansion measurements. The TGA tests were performed according to ASTM E 1131 (ASTM 1998) using an Orton Model ST-736 TGA. The resulting mass changes are shown in Table 6-6. The thermal expansion measurements were performed according to ASTM E 228 (ASTM 1995) using a Unitherm™ Model 1161 pushrod dilatometer. Since the materials were not isotropic, separate measurements had to be performed for the X and Z orientations. It was assumed that the X and Y directions had the same thermal expansion. The Z direction was defined as the direction perpendicular to the fibrous strands in the samples. The specimens were tested from room temperature to 1200 °C at a heating rate of 2 °C/min. All of the specimens shrunk during the tests and in all cases lost contact with the pushrod at temperature about 1100 °C before reaching the maximum test temperature. Table 6-7 shows the results of the thermal expansion measurements.

From the thermal expansion measurements, the change in volume for each material was calculated at each temperature. The density values were calculated from the results of the TGA and thermal expansion. Table 6-8 summarizes the calculations, and Fig. 6-8 displays the results. The shrinkage of the material and the specimen mass loss both contribute to the unrealistic variation in density at high temperatures. Thus the density values are only valid up to 600 °C.

Table 6–6. Mass loss of SFRMs with increasing temperature.

	Mass Change (%)		
Temperature (°C)	**BLAZE-SHIELD DC/F**	**BLAZE-SHIELD II**	**Monokote MK-5**
25	0.0	0.0	0.0
50	–0.2	–0.6	–0.5
100	–2.7	–3.9	–2.7
200	–5.1	–7.4	–15.0
300	–6.0	–8.7	–19.0
400	–6.7	–9.9	–22.0
500	–7.5	–11.0	–23.0
600	–8.6	–12.0	–24.0
800	–11.0	–16.0	–25.0
1000	–11.0	–16.0	–27.0
1200	–14.0	–20.0	–42.0

Table 6–7. Thermal expansion results of SFRMs.

	Thermal Expansion (%)					
Temperature (°C)	**BLAZE-SHIELD DC/F**		**BLAZE-SHIELD II**		**Monokote MK-5**	
	X and Y Direction	**Z direction**	**X and Y Direction**	**Z direction**	**X and Y Direction**	**Z direction**
25	0.00	0.00	0.00	0.00	0.00	0.00
50	0.02	0.02	0.02	0.02	0.03	0.03
100	0.05	0.03	0.04	–0.04	0.08	0.09
200	0.10	–0.13	0.04	–0.36	–0.06	–0.13
300	0.17	–0.12	0.09	–0.48	–0.23	–0.23
400	0.23	–0.16	0.11	–0.63	–0.65	–0.92
500	0.19	–0.38	0.08	–0.98	–0.69	–0.97
600	0.06	–0.93	–0.07	–1.45	–0.69	–0.97
800	–10.95	–26.40	–12.56	–12.42	–1.22	–2.13
1000	–11.83	–27.86	–12.80	–13.63	–7.03	–8.32

Table 6–8. Calculated densities of SFRMs.

	Density (kg/m^3)[a]		
Temperature (°C)	**BLAZE-SHIELD DC/F**	**BLAZE-SHIELD II**	**Monokote MK-5**
25	236.8	313.7	292.4
50	236.1	311.5	290.5
100	230.1	301.3	283.8
200	224.6	291.3	249.1
300	222.1	287.2	238.5
400	220.3	283.7	233.2
500	219.0	281.5	230.5
600	218.2	280.5	227.5
800	361.1	393.4	229.6
1000	375.8	401.1	269.3
1200	432.1	436.7	369.4

a. To convert to pcf multiply by 0.062428.

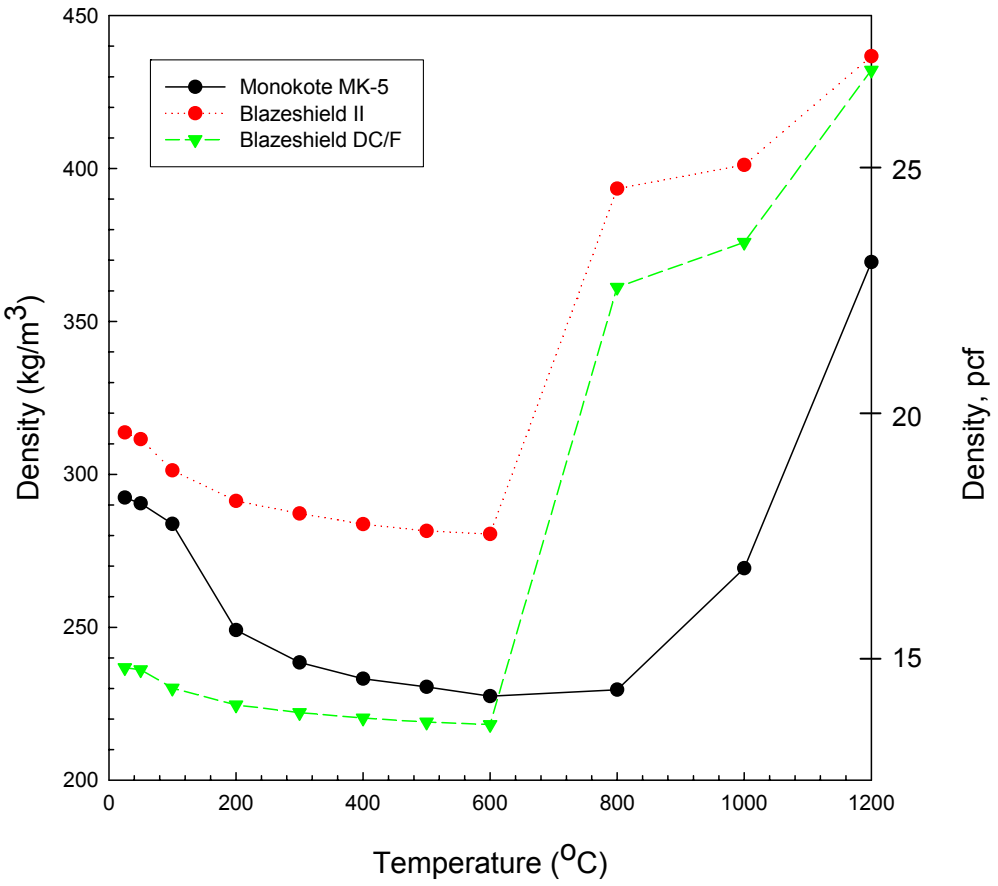


Figure 6–8. Bulk densities of the three SFRMs as a function of temperature.

6.3.5 Concluding Remarks

It should be noted that the thermal conductivity and bulk density depend on how the SFRM is sprayed or applied; therefore, it is expected that the results will vary from sample to sample. In general, the thermal conductivity of a porous material is a complex function of bulk density, porosity, and other material properties (e.g., Stephenson and Mark 1961). Recent attempts to use existing predictive methods to estimate thermal conductivities of porous media for SFRMs shows some promise, and alternative approaches have also been proposed for future research.[9]

[9] Bentz, D. P., Prasad, K. R. and Yang, J.C.. 2004. Towards a Methodology for the Characterization of Fire Protection Materials with Respect to Thermal Performance Models. *Fire and Materials* (in review).

6.4 THERMOPHYSICAL PROPERTIES OF GYPSUM PANELS

In this section, measurement results of the thermophysical properties of four gypsum materials will be presented. Unless stated otherwise, measurements were performed by Thermophysical Properties Research Laboratory Inc. (TPRL) in West Lafayette, Indiana. Four types of gypsum materials produced by U.S. Gypsum Co. were examined. They were:

1. Firecode Core Type X 5/8 in. SHEETROCK gypsum panel,
2. Firecode C Core ½ in. SHEETROCK gypsum panel,
3. Firecode C Core 5/8 in. SHEETROCK gypsum panel, and
4. 1 in. SHEETROCK gypsum liner panel.

6.4.1 Samples

The gypsum materials were all commercially available and were purchased from a local building supply store in Gaithersburg, Maryland. Samples were cut from the gypsum panel using a box cutter and then sent to the testing laboratory.

6.4.2 Thermal Conductivity Measurements

Thermal conductivity was measured using the heated probe technique described in ASTM D 5334 (ASTM 2000h). The following description of the heated probe method is provided by TPRL:[10]

> "In the heated probe method, which may be considered as a variant of the line source method, the line source and temperature sensor are combined in one small diameter probe. This probe is inserted into the sample and the heater turned on for a preselected time interval. During this time interval, the rate of heating of the probe is measured. This heating rate quickly becomes semi-logarithmic and from this semi-logarithmic rate, the thermal conductivity of the sample is calculated. The probe may be inserted into powders, fluids, small holes drilled into rocks, biological materials, etc. A variety of probe sizes, ranging from needle-shaped to rods are available. The data is collected by the PC based digital data acquisition system and the heating rate displayed visually. A semi-logarithmic portion of the heating curve is chosen using the mouse and the conductivity calculated based on this portion of the curve."

The measurement results are summarized in Table 6-9, and the results are plotted in Fig. 6-9..

[10] www.tpfrl.com/heatprb.html

Table 6–9. Thermal conductivities of SHEETROCK gypsum materials.

Firecode Core Type X 5/8 in.		Firecode C Core ½ in.		Firecode C Core 5/8 in.		1 in. Liner Panel	
(°C)	(W/(m K))[a]	(°C)	(W/(m K)	(°C)	(W/(m K)	(°C)	(W/(m K)
23	0.156	23	0.194	23	0.154	23	0.133
45	0.1533	47	0.184	56	0.148	48	0.135
100	0.1558	97	0.188	103	0.156	97	0.136
222	0.0963	200	0.100	230	0.090	200	0.093
296	0.0976	299	0.097	318	0.105	293	0.089
384	0.0987	406	0.106	428	0.113	413	0.107
482	0.1102	496	0.113	508	0.113	508	0.116
591	0.1276	603	0.121	609	0.131	598	0.134

a. To convert to Btu · in./(h · ft^2 · °F) divide by 0.1442279.

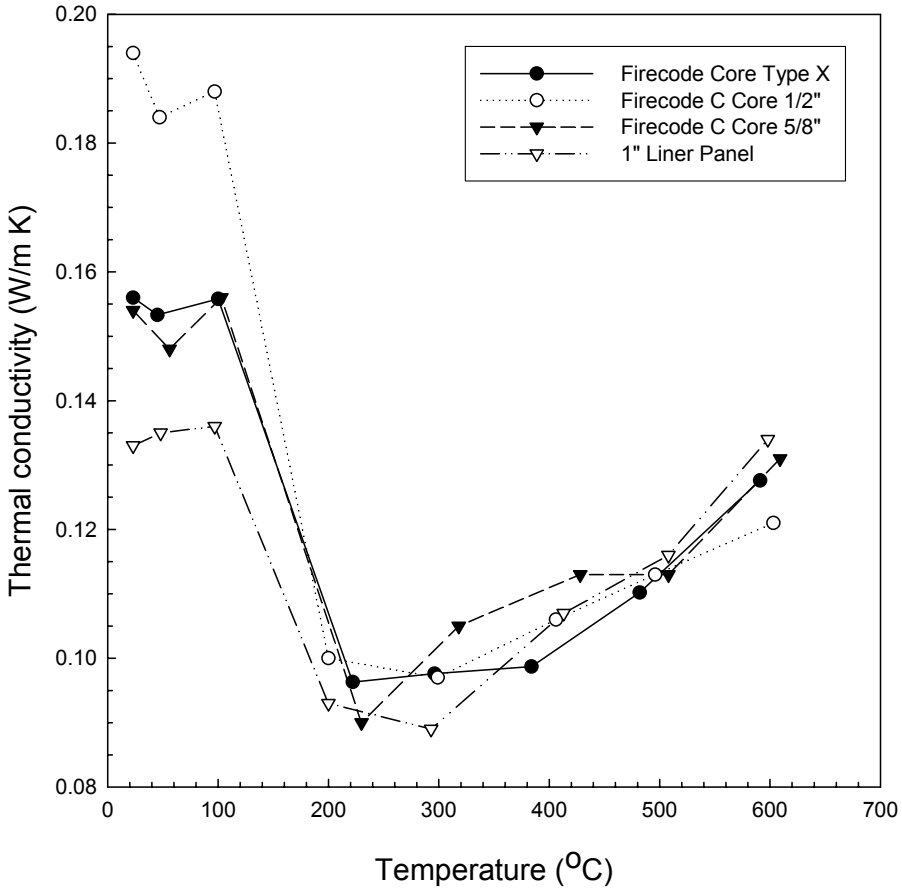


Figure 6–9. Thermal conductivities of the four gypsum materials as a function of temperature.

Figure 6-10 shows a comparison of the current thermal conductivity measurements with data from Mehaffey et al. (1994) for Firecode Core Type X gypsum panel. The data from Mehaffey et al. were obtained using a commercially available thermal conductivity meter. Both sets of data exhibit similar trends, although, in general, the values from Mehaffey et al. are higher.

A comparison of the current thermal conductivity results with the data obtained from Harmathy (1983) and Mehaffey et al. (1994) for Firecode C Core gypsum panel is shown in Fig. 6-11. The conductivities from Harmathy (1983) are higher than those obtained from other studies. In general, the thermal conductivity initially decreases and then increases with increasing temperature.

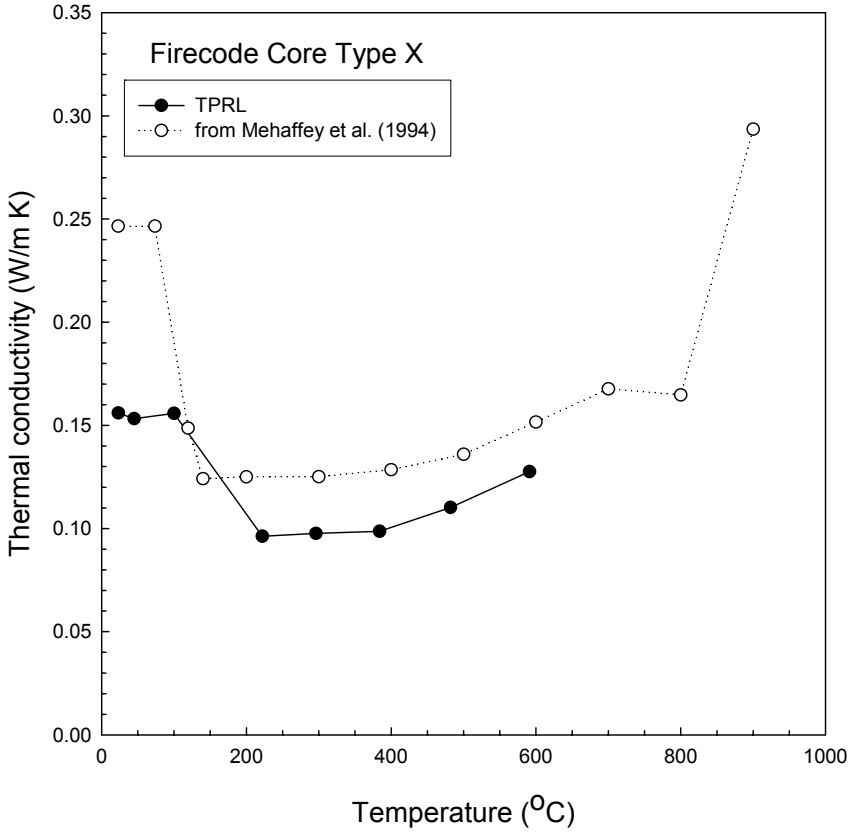


Figure 6–10. Comparison of the thermal conductivity measurements from TPRL with the data from Mehaffey et al. (1994) for Firecode Core Type X gypsum panel.

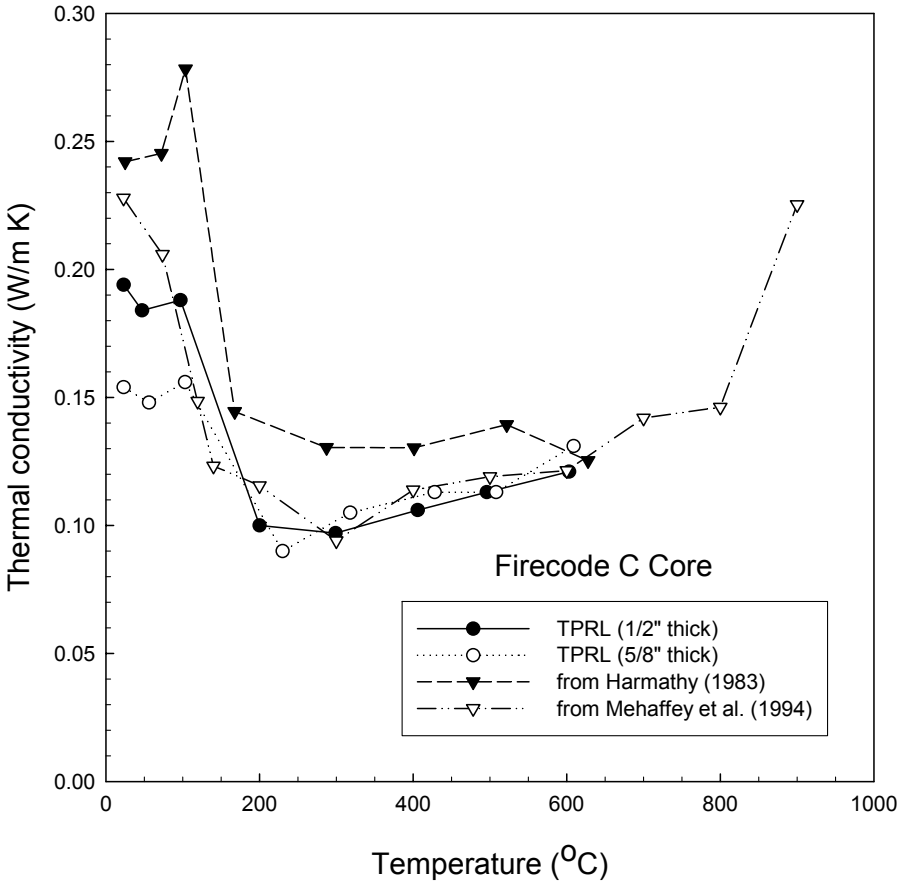


Figure 6–11. Comparison of the thermal conductivity measurements from TPRL with other literature values for Firecode C Core gypsum panel.

6.4.3 Specific Heat Capacity Measurements

Specific heat capacities of the cores of the four gypsum panel samples were measured using a TA Instruments DSC 2910 differential scanning calorimeter at NIST. Tests were conducted according to the procedure described in ASTM E 1269 (2001). Specimens of approximately 8.4 mg ± 0.1 mg in mass were held isothermally at 30 °C for 5 minutes. The temperatures were then increased at a rate of 20 °C/min to a maximum temperature of 600 °C, the operating limit of this instrument. The specimens were held isothermally at 600 °C for an additional 5 minutes. Single scans of both an empty pan and a pan containing standard reference material SRM 720 (sapphire or α-Al_2O_3) were conducted prior to testing and used to determine calorimetric sensitivity. The apparent specific heat capacity was calculated according to the formulas presented in the ASTM standard.

An additional modification to the ASTM test procedure was necessitated by the chemical nature of the material comprising the cores of the boards. The dominant material in the cores is gypsum, a naturally occurring mineral composed of calcium sulfate chemically bound to hydrated water (calcium sulfate dihydrate or $CaSO_4 \cdot 2H_2O$). As gypsum is heated, the hydrated water is liberated in two endothermic chemical reactions. If the core materials were contained within sealed hermetic pans, out-gassing of the liberated water would eventually increase the pressure beyond the accepted limits of the pans. Use of an

open pan is undesirable, however, as the dehydration reactions also depend on the partial pressure of water vapor in the gas surrounding the material. Aluminum hermetic pans with 50 μm diameter pinholes in the lids were therefore used. The small diameter hole allowed pressure to dissipate from the pan, maintaining structural integrity, but retained sufficient water vapor to resolve the two dehydration processes. As the core of the gypsum panel is porous, having a porosity of approximately 0.3 (Blondeau et al. 2003), it is further expected that the liberated water will remain locally in the form of vapor even as pressure diffuses across the porous matrix. The procedure used should, therefore, provide a better estimate of the response of gypsum panel cores to the rapid heating observed in fires.

Results are presented as apparent specific heat capacity of the material with respect to the initial mass of the specimen. Clearly as the water is driven from the samples and bleeds through the pinhole, the mass of the sample will decrease. Results of thermal gravimetric tests should also be used if the true specific heat capacity of the material is desired. The data are presented in Tables B-2, B-3, B-4 and B-5 and are plotted in Figs. B-1, B-2, B-3, and B-4 in the Appendix B. Peaks and valleys attributed to chemical changes are labeled on each graph with the corresponding chemical reaction. Figure 6-12 is a plot of the results for all four gypsum materials. It is seen that the four panels had similar specific heat capacities as a function of temperature.

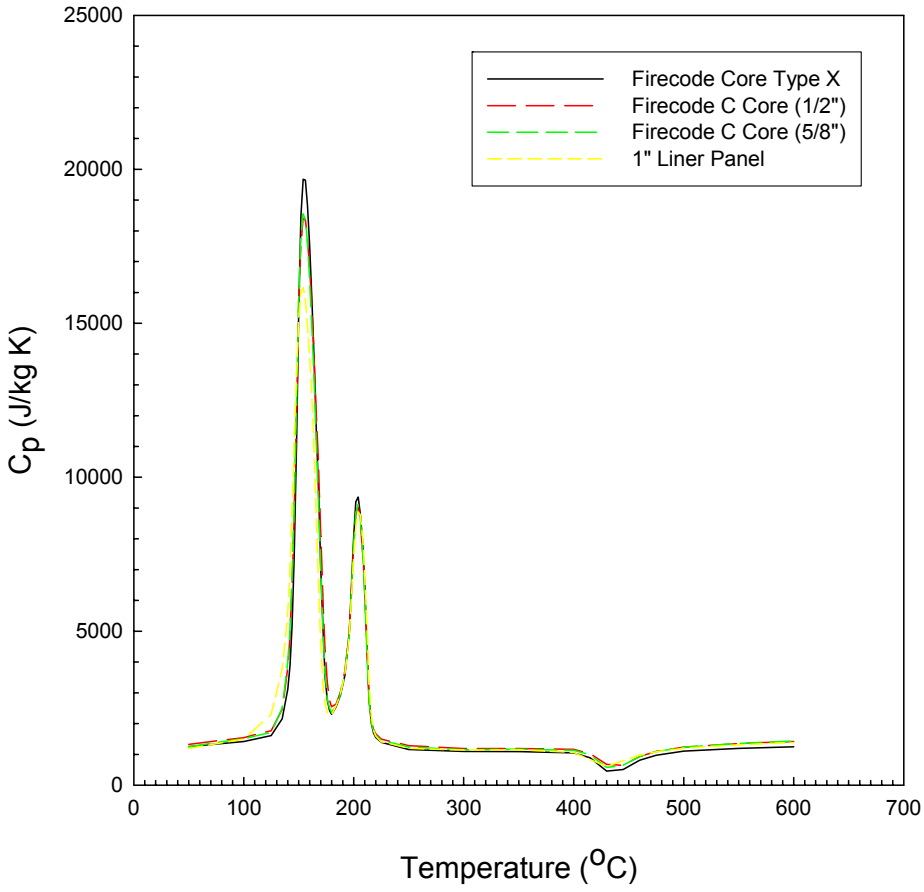


Figure 6–12. Comparison of specific heat capacities for the four gypsum materials.

6.4.4 Density Measurements

TPRL used a Netzsch Model 409 Simultaneous Thermal Analyzer (STA) equipped with both high and low temperature furnaces was used to determine mass changes as a function of temperature. The STA is vacuum tight, allowing specimens to be tested in pure inert, reducing, or oxidizing atmospheres as well as under vacuum. The unit can be operated in the differential scanning calorimetric (DSC) or thermogravimetric analysis (TGA) mode.

A dual push-rod dilatometer (Theta Dilatronics II) was used to measure linear thermal expansion following the procedure in ASTM E 228 (ATM 1995). The differential expansion between the gypsum specimen and a known standard reference material was measured as a function of temperature. The expansion of the specimen is computed from this differential expansion and the expansion of the standard. The measurements are made under computer control and linear expansion is calculated at pre-selected temperatures. Six standard reference materials for expansion were obtained from NIST and these include materials with low, moderate, and large expansions. For the purposes of calibration and checkout, one NIST standard was measured against another NIST standard.

Densities were calculated from the TGA results and linear thermal expansion measurements. Table 6-10 summarizes the calculated results, which are also plotted in Fig. 6-13. All four materials show the same trend as a function of temperature. The variation of density with temperature is associated with the mass loss and the change in volume of the gypsum material.

Table 6–10. Bulk densities of the four gypsum materials.

	Density (kg/m^3)[a]			
Temperature (°C)	**Firecode Core Type X ½ in.**	**Firecode C Core ½ in.**	**Firecode C Core 5/8 in.**	**1 in. Liner Panel**
23	709	760	787	770
50	706	759	785	767
100	680	754	780	759
150	629	725	752	721
200	586	668	691	664
250	580	636	656	638
300	581	634	654	636
350	582	634	654	638
400	597	659	679	659
450	600	665	684	663
500	600	664	682	664
550	599	663	681	664
600	605	663	682	664

a. To convert to pcf multiply by 0.062428.

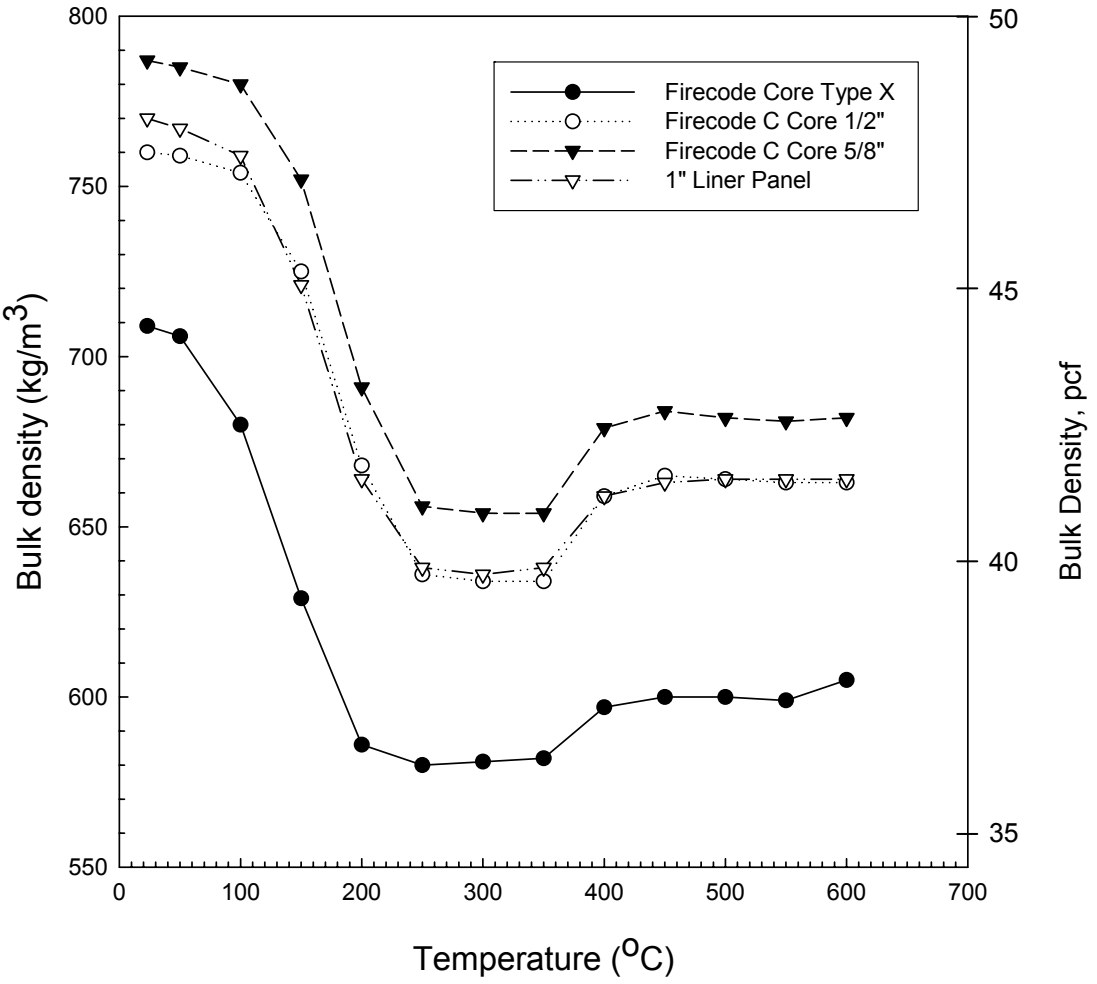


Figure 6–13 Bulk densities of the four gypsum materials as a function of temperature.

Chapter 7
ADHESIVE AND COHESIVE STRENGTH

In order to analyze the thermo-structural response of the WTC towers during the fires after aircraft impacts, it was necessary to estimate the extent of dislodged thermal insulation on structural members. Dislodgement could occur as a result of:

- Direct impact by debris resulting from breakup of the aircraft and its contents and breakup of structural elements, or
- Inertial forces due to vibration of members excited by the impact events.

For a given level of vibration, the magnitude of the inertial forces acting on the insulation depends on the density and thickness of the thermal insulation. The insulation would dislodge if the stresses resulting from inertial forces exceed the strength of the insulation. The focus of the investigation reported in this chapter was to determine tensile strength characteristics of the thermal insulation. Information on in-place measurements provide by the Port Authority are reviewed. The experimental approach used to obtain additional information is presented along with test results. Finally, a simplified approach is presented for estimating the accelerations required to dislodge the thermal insulation.

7.1 REPORTED IN-PLACE DENSITY AND BOND STRENGTH

As was mentioned in Section 4.3, the Port Authority provided data on in-place density and tensile strength characteristics of the thermal insulation applied to the floor trusses during tenant alterations. Figure A-60 shows an example of such test reports. The reports indicated that tests were done in accordance with ASTM E 605 (density) and ASTM E 736 (cohesion/adhesion strength). As mentioned in Chapter 4, CAFCO BLAZE-SHIELD II was used in the upgrade, and as noted previously in Table 6-3, the manufacturer indicated that BLAZE-SHIELD II is about 20 % denser and has about 20 % higher adhesive/cohesive strength compared with BLAZE-SHIELD DC/F.

According to ASTM E 605 (ASTM 2000a), density is determined by removing a rectangular portion of the insulation after taking 12 thickness measurements to obtain the average thickness. The length and width of the removed specimen are measured, and the volume is calculated. The equilibrium mass of the specimen is determined, and density is calculated by diving the mass by the volume. The test reports provided by the Port Authority provided no notes to indicate deviations from the standard procedure.

The technique described in ASTM E 736 (ASTM 2000b) is illustrated in Fig. 7-1. A bottle screw cap is glued to the surface of the thermal insulation, and after the glue has cured, the cap is pulled. The force required to pull off the cap is divide by the area of the cap, and reported as the "cohesive/adhesive strength." Failure is described as "cohesive" if it occurs within the insulation and is defined as "adhesive" if it occurs at the interface with the substrate. Figure 7-2 shows an example of a cohesive failure.

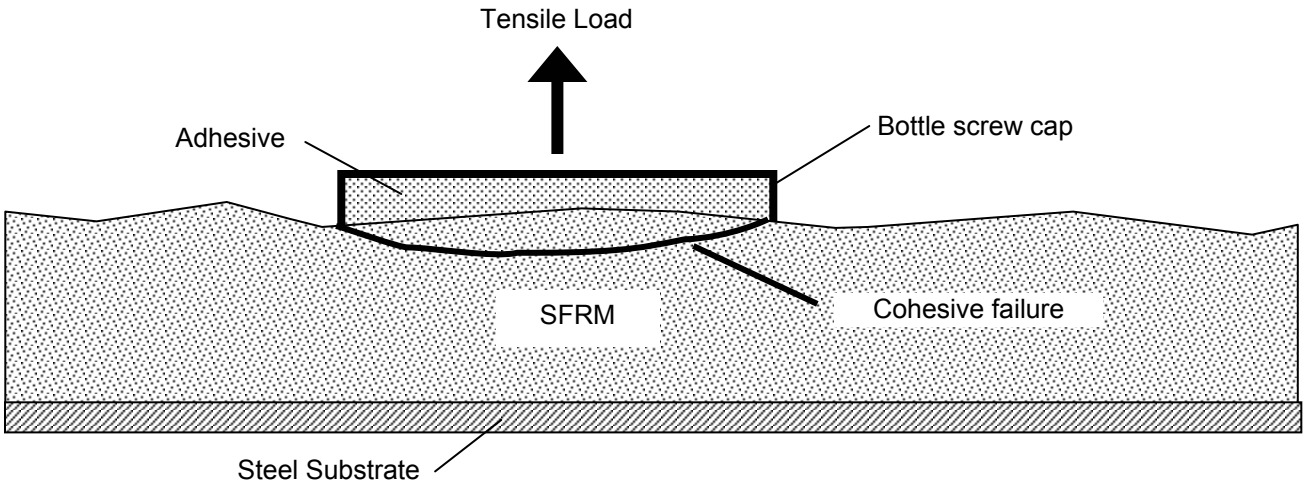


Figure 7–1. Bond strength test using screw cap in accordance with ASTM E 736.

Source: NIST.

Figure 7–2. Cohesive failure of SFRM using ASTM E 736 test (dashed circle is approximate location of cap before being pulled off.

Table 7-1 summarizes the density and strength data provided by the Port Authority (see also Table 4-2). The results of the tests are labeled as "bond strength." Test method ASTM E 736 calls for reporting the failure mode, but the Port Authority test reports did not include information on the nature of the failure associated with the reported strengths. The density values in Table 7-1 are plotted in Figs. 7-3 and the bond strength values are plotted in Fig. 7-4. Analysis of the density values indicated no statistically significant differences between the reported SFRM densities in the two towers. The overall average density was 18.9 pcf with a standard deviation of 3.2 pcf, giving a coefficient of variation of 16 %.

Table 7–1. Density and bond strength of SFRM on floor trusses reported by Port Authority.

Tower	Floor	Density, pcf	Bond Strength, psf	Tower	Floor	Density, pcf	Bond Strength, psf
1	79	16.6	333	1	98	31.3	407
	81	19.0	270			16.8	351
		17.4	352			19.6	518
		17.6	463		99	18.8	204
		17.4	315			16.6	222
	83	16.0	259			18.4	204
	85	28.7	162		100	16.4	278
		23.7	180			17.3	278
		18.6	288			19.9	333
		15.8	278		102	16.5	333
		16.4	259			16.9	333
	92	20.3	360			15.9	315
		15.4	324	2	77	19.4	351
		18.0	360			19.4	198
	93	14.3	153			17.2	297
		16.6	207		78	17.0	288
		16.1	216			18.1	270
		18.4	234		88	18.0	167
		15.1	162			16.0	333
		17.4	180			15.0	157
		21.3	216		89	22.4	370
	94	21.2	486			15.8	333
		20.5	504			15.3	270
		20.1	288		92	19.7	342
	95	18.0	270			21.1	360
		20.1	306			19.7	297
		20.4	198		99	19.5	315
	96	20.5	486			22.7	252
		19.8	288			21.9	306
		19.9	324			19.5	270
	97	26.5	360				

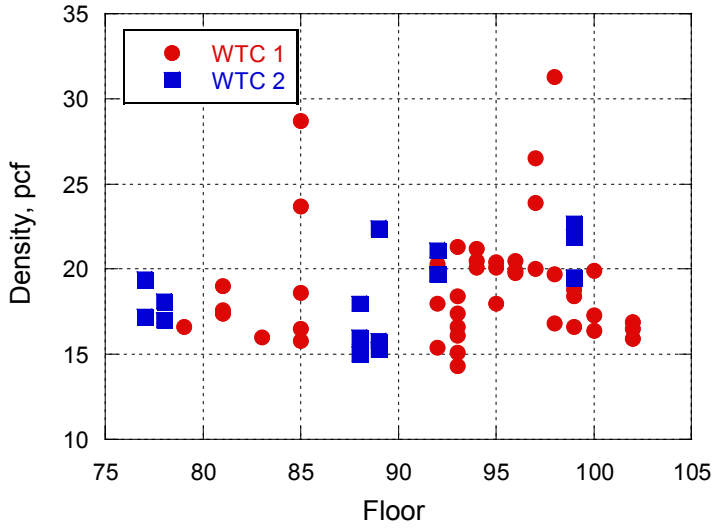


Figure 7–3. In-place density of BLAZE-SHIELD Type II on floor trusses from Port Authority test reports during the period 1997-1999.

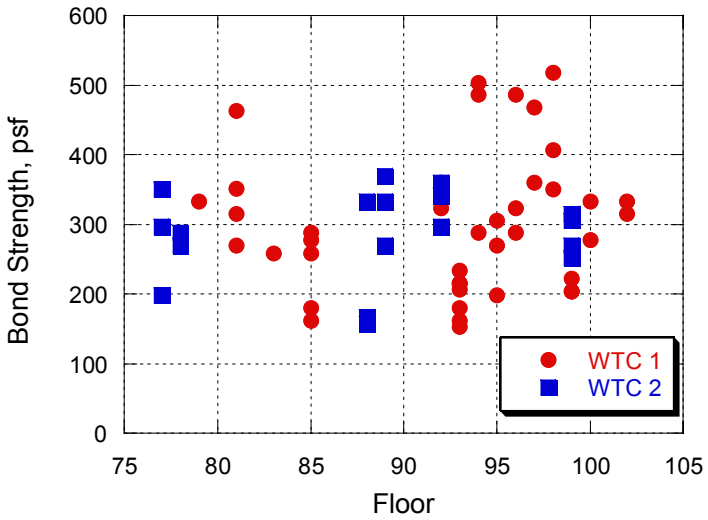


Figure 7–4. In-place bond strength of BLAZE-SHIELD Type II using ASTM E 736 from Port Authority test reports during the period 1997-1999.

Analysis of the bond strength values indicated that there were statistically significant differences between the average bond strengths for the different floors, but here was no statistically significant difference between the average bond strengths for the two towers. The overall average bond strength was 302 psf, with a standard deviation of 91 psf, giving a coefficient of variation of 30 %. This value is less than the value of 360 psf indicated in Table 6-3, but the tabulated values is for tests under controlled conditions (referred to as "tested performance" in the manufacturer's literature) and is not representative of field strengths. ISOLATEK product literature dated February 2002 refers to an average bond strength of 150 psf as "standard performance" and this same value is used in its guide specification for BLAZE-SHEILD II. Thus the reported bond strengths shown in Fig. 7-4 are consistent with expectations.

7.2 SPECIMEN PREPARATION AND TEST PROCEDURES

While the in-place bond strength data of BLAZE-SHIELD II reported by the Port Authority appear to indicate acceptable performance, results of ASTM E 736 tests do not provide sufficient information for predicting whether insulation would be dislodged from structural members under various impact conditions. The standard test does not provide unambiguous values of cohesive and adhesive strengths and it does not provide tensile properties in a direction parallel to the surface, that is, in-plane cohesive strength. As was mentioned in Section 6.3.4, because of the way a fibrous SFRM is installed, the resulting material is not isotropic. Layers of fiber bundles are deposited parallel to the surface of the substrate. It is expected that the strength perpendicular to the planes of the layers would be less than the strength parallel to the layers. Thus a series of tests were conducted that would allow different strength properties to be determined. In addition, it was decided to test BLAZE-SHIELD DC/F because the Port Authority data did not include tests of this material.

7.2.1 Preparation of Test Plates

Test specimens were made by applying the SFRM to ¼ in. steel plates measuring 8 in. by 16 in. One half of the plates were coated with Series 10 Tnemec Primer (99 red)[11], which is the primer that was specified for the exterior columns (see Appendix A Fig. A-63). Nominal SFRM thicknesses of ¾ in. and 1½ in. were applied. Thickness was controlled by surrounding the steel plates with wood strips to form molds of the desired depth. Figure 7-5 shows the application of BLAZE-SHIELD DC/F to the steel plates positioned on the floor of the laboratory. Thickness was built up in several passes of the spray nozzle. Gentle hand rubbing was used to reduce local high spots and produce reasonably uniform thicknesses. The average thickness of SFRM for the ¾ in. plates was 0.85 in. with a standard deviation of 0.08 in. For the 1½ in. plates, the average thickness was 1.62 in. with a standard deviation of 0.16 in. The plate specimens were allowed to dry for over five months in the laboratory before testing. Companion specimens were weighed periodically for loss of water and it was found that the 1½ in. thick specimen reached equilibrium in about one month.

7.2.2 Test Methods

It was desired to determine adhesive strength, cohesive strength normal to the surface, and cohesive strength parallel to the surface of the SFRM. Figure 7-6 is a schematic of the method used to measure the first two properties. This approach is based on the standard pull-off test method used in concrete technology to measure the bond strength of overlays applied to concrete substrates (ASTM 2004b). The SFRM layer was cut carefully in two directions and a 3/8 in. by 2.7 in. by 2.7 in. aluminum plate was glued to the surface. After the adhesive had cured, a tensile load was applied to the plate and the force required to pull off the SFRM was measured. The advantages of this approach over the ASTM 736 technique are that the resisting area is easily determined and it offers the ability to measure both adhesive and cohesive strengths.

[11] Tnemec Company Inc., 6800 Corporate Drive, Kansas City, Missouri 64120-1372.

Source: NIST.

Figure 7–5. Spraying steel plates with BLAZE-SHIELD DC/F.

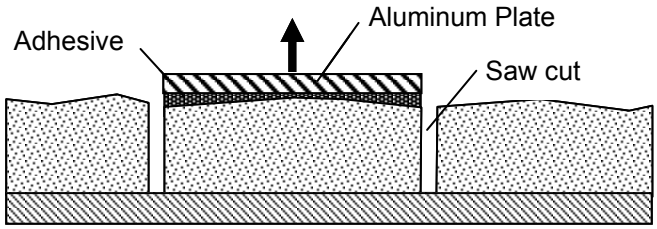


Figure 7–6. Schematic of "pull-off' test method used to measure cohesive and adhesive strengths.

In using the method shown in Fig. 7-6, one does not know before hand what type of failure will occur, that is, whether it will be adhesive failure at the SFRM/steel interface or cohesive failure in the bulk SFRM. Failure occurs at the weakest link. It is possible, however, by a simple modification of the usual procedure to measure both strengths in the same specimen. This is accomplished by bonding together the failed specimen after the first test, and performing a second test on the repaired specimen. This approach is illustrated in Fig. 7-7, where the schematics on the left represent the first test and those on the right represent the re-test. Two cases are illustrated:

- Case 1: The initial failure is an adhesive failure near the SFRM/steel interface, and after repairing the specimen the second failure is a cohesive failure in the bulk SFRM.

- Case 2: The initial failure is a cohesive failure in the bulk SFRM, and after specimen repair the second failure is an adhesive failure near the SFRM/steel interface.

As will be seen, this approach works because adhesive and cohesive strengths are similar in magnitude.

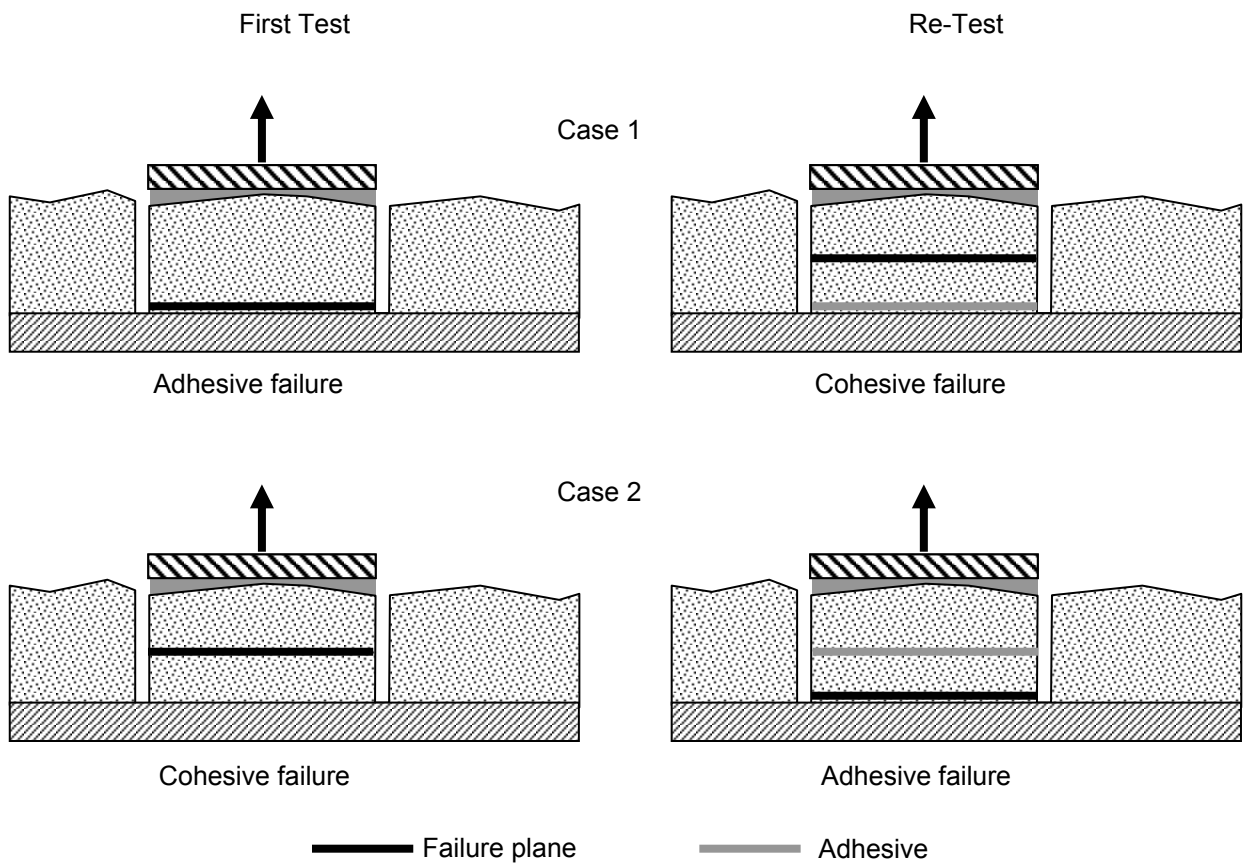


Figure 7–7. Technique used to measure both "adhesive" and "cohesive" strength in the same specimen.

The cohesive strength parallel to the surface was determined on specimens obtained by carefully removing the SFRM layer from the steel and preparing a prism that could be loaded as shown in Fig. 7-8. The following section describes how the test specimens were prepared.

7.2.3 Preparation of Test Specimens

From each plate, three specimens were prepared for measuring both density and in-plane cohesive strength, and two specimens were prepared for measuring adhesive strength and cohesive strength normal to the surface. The first step was to cut the SFRM layer into five 2.7 in. wide strips. A fine-toothed saw blade was used, and the sawing motion was done carefully so as to minimize damage to the SFRM (see Fig. 7-9). The two outer strips and the middle strip were debonded from the steel plate by using a sharpened putty knife. Care was taken to ensure that the two strips for adhesive/cohesive strength testing were not disturbed (see Fig. 7-10).

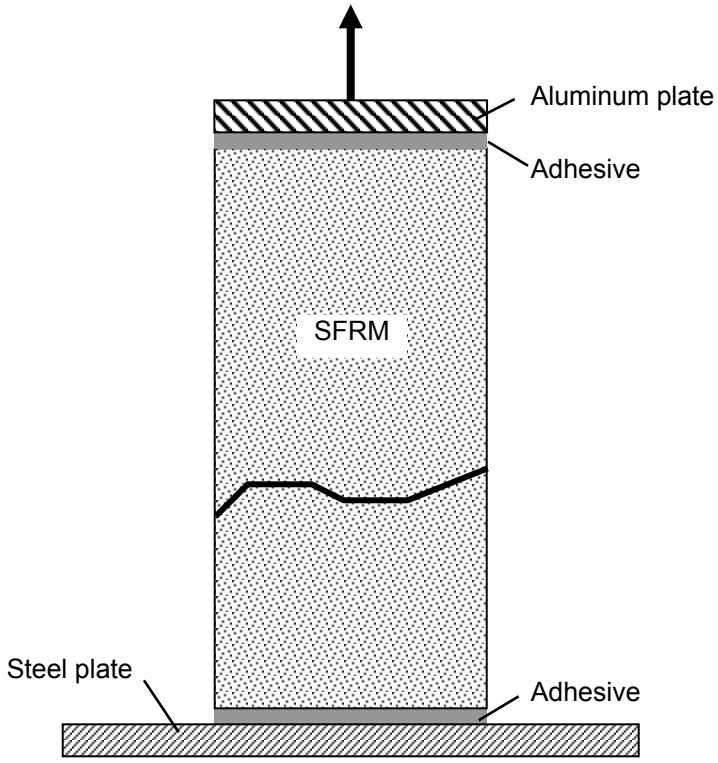
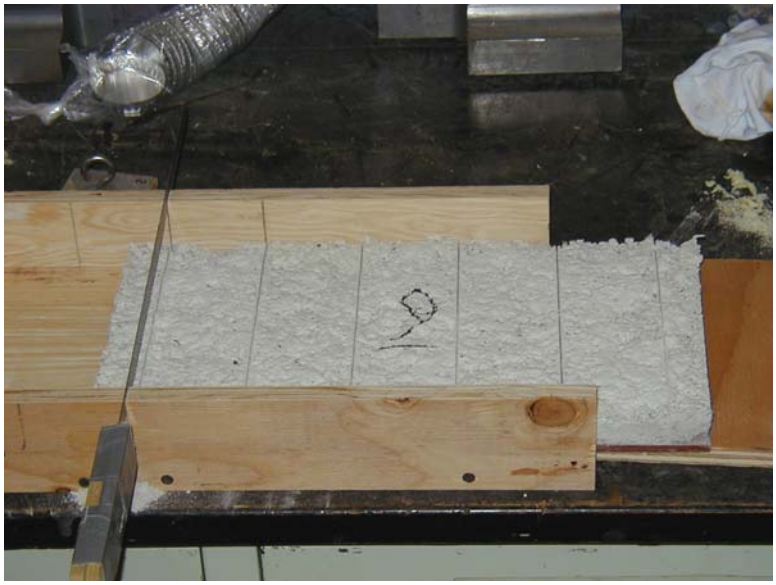
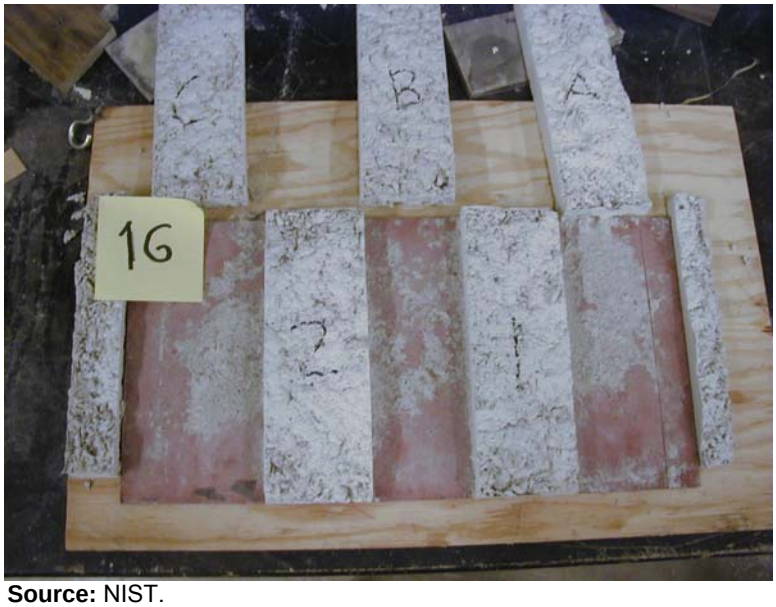


Figure 7–8. Method to measure cohesive strength parallel to SFRM surface (in-plane cohesive strength).



Source: NIST.

Figure 7–9. Cutting the SFRM layer into five strips.



Source: NIST.

Figure 7–10. Five specimens obtained from single plate; top three specimens are used for density and in-plane cohesive strength, bottom specimens are used for adhesion/cohesion tests.

For the adhesive/cohesive strength tests, an aluminum plate was bonded to the top surface using a fast curing, two-component urethane foam adhesive. Fixtures were used to ensure that the bonded plate was parallel to the steel plate (see Fig. 7-11). After the adhesive had cured, the SFRM layer was cut as shown in Fig. 7-12 so as to produce a prismatic test specimen. A hook was screwed into the aluminum plate and a load was applied by hand using a 50-lb digital force gage (see Fig. 7-13). The force gage was able to store the peak load attained during the test. During loading, the steel plate was placed on the floor and a foot was placed at each end of the plate to provide resistance to the applied tensile load. The average length and width of the failure area was measured and used to compute the adhesive or cohesive strength.

After the first test, the specimen was repaired with the same polyurethane adhesive and the test was repeated as discussed in Section 7.2.2. Figure 7-14 shows two specimens after the first test. The specimen on the left failed in the bulk material, thereby giving a measure of the cohesive strength normal to the surface. The specimen on the right failed near the SFRM/steel interface, which is taken to be the adhesive strength. Figure 7-15 shows the same two specimens after they had been repaired and subjected to the second loading. Now the specimen on the right shows a crack in the bulk material, and the specimen on the left shows separation near the SFRM/steel interface. Note that for the specimen on the right, which had an adhesive failure during the first loading, the failed specimen was bonded to a bare steel plate (not shown) for the second test to measure cohesive strength.

Source: NIST.

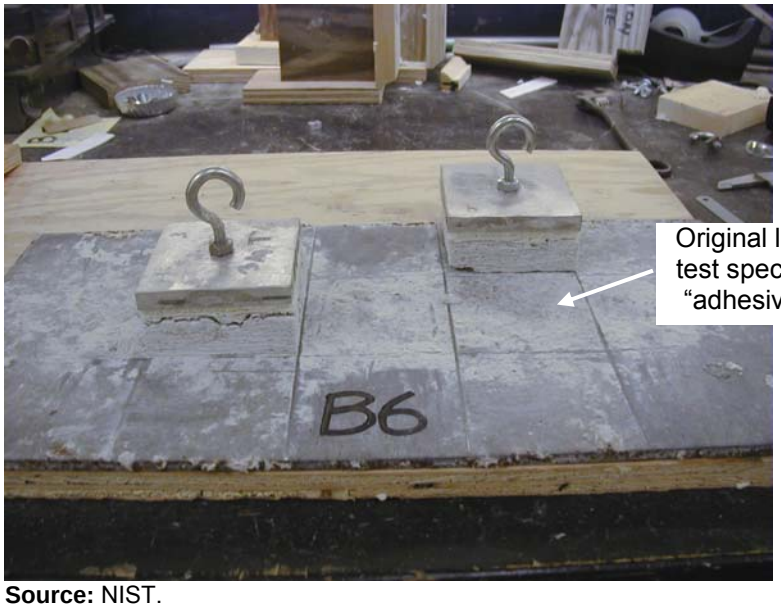
Figure 7–11. Aluminum plate being bonded to the top surface of SFRM specimen; the wooden fixture is used to maintain the correct alignment of the plate.

Source: NIST.

Figure 7–12. Preparing the SFRM specimen for adhesion/cohesion test.

Source: NIST.

Figure 7–13. Manual application of tensile load using digital force gage.



Source: NIST.

Figure 7–14. Results of first loading: specimen on left had a cohesive failure in the bulk SFRM, specimen on right failed near the SFRM/steel interface.

Source: NIST.

Figure 7–15. Results of second tests after repair: specimen on left had adhesive failure and specimen on right had cohesive failure.

The other three strips (see Fig. 7-10) were used for determining density and in-plane cohesive strength. First, the top surfaces of the debonded strips were sanded on a belt sander to obtain prismatic specimens. About 0.2 in. was removed from the ¾ in. plates and about 0.4 in. was removed from the 1½ in. plates. The prisms were weighed and their average dimensions determined. The densities were obtained from the masses and computed volumes. Each prism was then bonded to a steel plate with the polyurethane adhesive. An aluminum plate was bonded to the other end of the specimen. After the adhesive had cured, a tensile load was applied to the aluminum plate until the SFRM failed (see Fig. 7-16). The area of the fracture plane was determined and the in-plane cohesive strength calculated from the recorded maximum load.

Source: NIST.

Figure 7–16. SFRM specimen after measuring in-plane cohesive strength.

7.3 TEST RESULTS

Table 7-2 summarizes the properties that were measured and the types of SFRM plates that were tested. It was assumed that the presence or absence of primer on the steel plates would not affect density or in-plane cohesive strength. Thus only primed plates were used for these properties. The following sections summarize the test results.

Table 7–2. Test matrix.

Property	¾ in. Nominal Thickness		1½ in. Nominal Thickness	
	With Primer	Bare Steel	With Primer	Bare Steel
Density	X		X	
In-plane cohesive strength	X		X	
Adhesive/Cohesive (N)* strength	X	X	X	X

*N indicates normal to surface of SFRM

7.3.1 Density

As mentioned in Section 7.2.3, density was determined by weighing prismatic specimens prepared by sanding the irregular exposed surface of the SFRM. The specimens were about 5 months old when tested and had attained equilibrium water contents. Five plates with primed steel were chosen at random for each SFRM thickness. Table 7-3 lists the individual determinations, and Fig. 7-17 is a plot of the data. The average density of the ¾ in. thick specimens is 27.2 pcf, with a standard deviation of 0.8 pcf; and for the 1½ in. thick specimens the average density is 29.7 pcf with a standard deviation of 1.3 pcf. The difference in average values for the two thicknesses was found to be statistically significant.

Table 7–3. Density of BLAZE-SHIELD DC/F specimens.

Nominal Thickness	Specimen	Density, pcf	Nominal Thickness	Specimen	Density, pcf
¾ in.	7-a	26.1	1½ in.	24-a	29.5
	7-b	26.0		24-b	29.2
	7-c	26.6		24-c	29.3
	6-a	27.2		29-a	30.0
	6-b	27.2		29-b	29.0
	6-c	26.7		29-c	29.6
	18-a	26.2		10-a	31.2
	18-b	28.1		10-b	31.4
	18-c	27.2		10-c	29.9
	16-a	27.0		30-a	26.9
	16-b	28.2		30-b	27.7
	16-c	28.3		30-c	29.5
	2-a	27.9		11-a	31.5
	2-b	26.7		11-b	30.5
	2-c	28.0		11-c	29.7

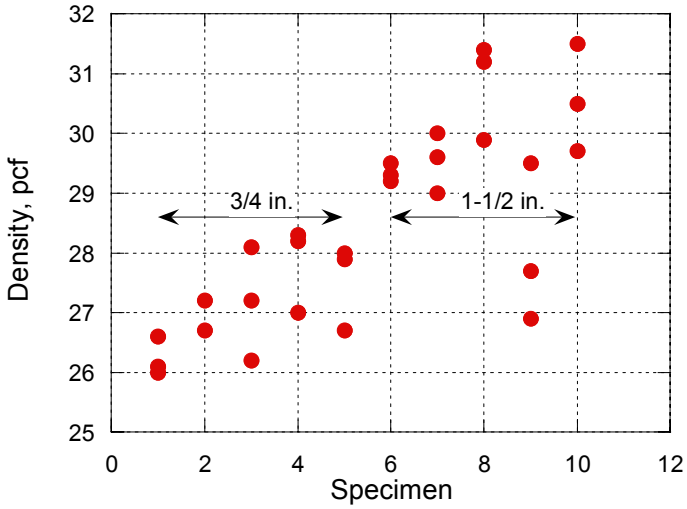


Figure 7–17. Density of BLAZE-SHIELD DC/F specimens.

These measured densities are unexpectedly high compared with published values and the values reported in Table 6-8, which indicates a room temperature density of 14.8 pcf. The 2001 IBCO Evaluation Service report E-R 1244, refers to a minimum average density of 13 pcf for BLAZE-SHIELD DC/F (ICBO 2001). The air-dry densities obtained in the NIST/UL fire endurance tests of floor truss assemblies (NIST NCSTAR 1-6B)[12] are shown in Fig. 7-18. Again, those densities are lower than obtained in this study. The exact reason for the higher density in this study is not known, but possible reasons include the following:

- The use of forms, as apposed to only a piece of sheet metal (as in ASTM E 605), may have provided confinement during spraying leading to more consolidation of the SFRM.
- The smoothing of the top surface by sanding removed the less dense material. Recall that about 0.2 in. and 0.4 in. were removed from the ¾ in. and 1½ in. plates, respectively.
- The hand screening that was done to remove local high spots may have resulted in additional consolidation.

[12] This reference is to one of the companion documents from this Investigation. A list of these documents appears in the Preface to this report.

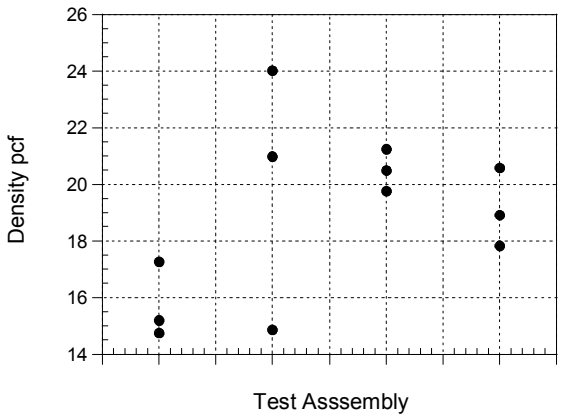


Figure 7–18. Air-dry density of BLAZE-SHIELD DC/F from NIST/UL floor truss fire endurance tests (NIST NCSTAR 1-6B).

7.3.2 In-Plane Cohesive Strength

After completing the density determinations the prismatic specimens of SFRM were bonded to a bare steel plate and an aluminum plate was bonded to the other end (see Fig. 7-8). The steel plate was placed on the floor, and a tensile load was applied to the aluminum plate until the SFRM failed. The width and thickness of the specimen adjacent to the failure plane was measured and the in-place cohesive strength was calculated.

Table 7-4 lists the individual values on in-plane cohesive strength, and Fig. 7-19 is a plot of the results. The average strength for the ¾ in. specimens is 1120 psf with a standard deviation of 390 psf. For the 1½ in. specimens the average is 1740 psf with a standard deviation of 540 psf. The difference in average strength is statistically significant. The relative strengths are consistent with the differences in density for the two thicknesses.

Table 7–4. In-plane cohesive strength for BLAZE-SHIELD DC/F specimens.

Nominal Thickness	Specimen	Cohesive Strength, psf	Nominal Thickness	Specimen	Cohesive Strength, psf
¾ in.	7-a	1095	1½ in.	24-a	2279
	7-b	1043		24-b	1607
	7-c	689		24-c	1687
	6-a	919		29-a	1473
	6-b	791		29-b	1986
	6-c	1512		29-c	3101
	18-a	1032		10-a	2006
	18-b	701		10-b	1876
	18-c	953		10-c	1304
	16-a	575		30-a	1579
	16-b	1500		30-b	636
	16-c	1254		30-c	1630
	2-a	1065		11-a	1902
	2-b	1875		11-b	1226
	2-c	1773		11-c	1861

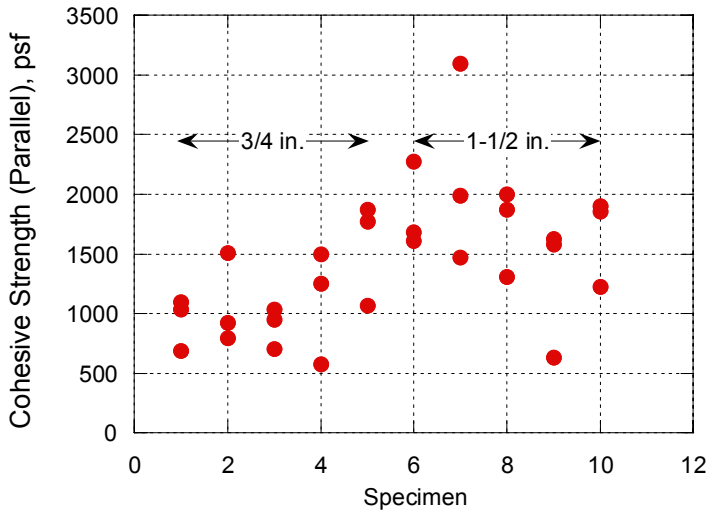


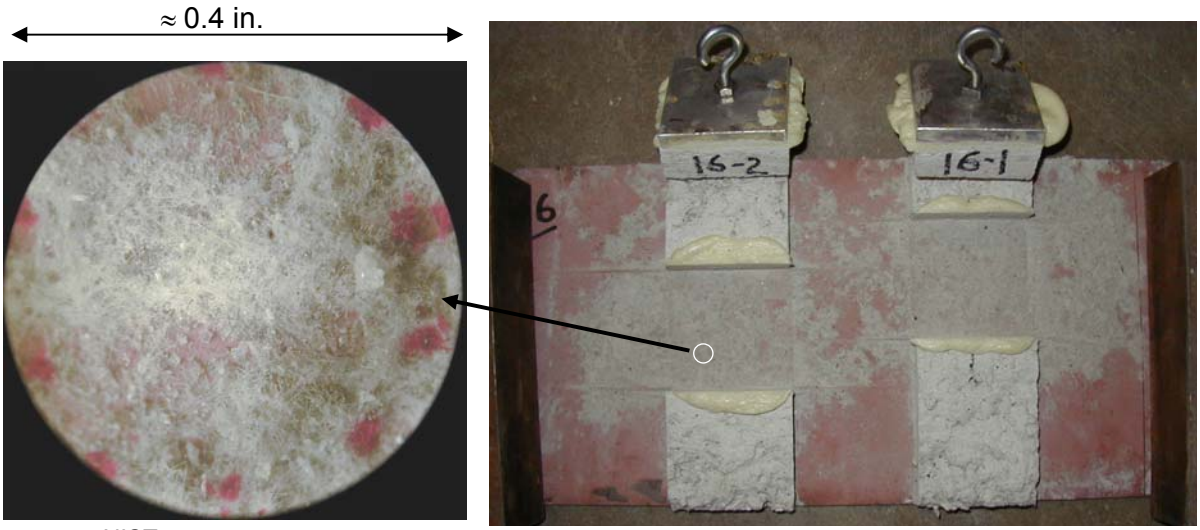
Figure 7–19. In-plane cohesive strength for BLAZE-SHIELD DC/F specimens.

7.3.3 Adhesive Strength

Adhesive failure is defined as failure near the SFRM/steel plate interface. In all cases where there was measurable adhesive strength a thin layer of cement paste and mineral fibers remained on the steel plate when the specimen separated. Figure 7-20 shows one of the ¾ in. specimens (with primed steel) after testing, and illustrates “adhesive” failure. The photo on the left is a magnified view of about a 0.4 diameter region and shows the thin layer of mineral fibers and paste. Note in the in the right photograph that there are regions on the steel with no adhering paste, indicating essentially zero adhesive strength. The locations of the specimens for the adhesion/cohesion tests were chosen based on the location of the

regions with adhesive failure when the three strips used for density determination were removed. This is illustrated in Fig. 7-20, where the specimen on the right was located toward the top of the plate and the one on the left was located at the center.

The plan was to select five plates at random for each combination of SFRM thickness and condition of steel plate (bare versus primed). It was found that for the 1½ in. plates with primed steel two of the first three specimens had essentially zero bond strength because the SFRM strips were loose after cutting with the saw. Figure 7-21 shows an example of a plate with essentially zero adhesion strength. At this point in the testing, the remaining plates were examined by applying a small force by hand to the SFRM to check whether there was any significant adhesion. Ten of the 15 plates had no adhesion. Plates 30 and 11 appeared to have some adhesion, so these were selected to complete the 5 replicate plates for this group.



Source: NIST.

Figure 7–20. Example of "adhesive" failure of SFRM (original location of test specimens are the gaps in the two strips); photo on left is magnified view of thin layer of paste and fibers (the marks around the perimeter is red ink used to locate field of view).

Source: NIST.

Figure 7–21. Example of lack of adhesion in 1½ in. SFRM on steel plate with primer.

There were no adhesion problems in the specimens made with bare steel. Figure 7-22 shows examples of specimens with bare steel. The top photograph shows the appearance of a ¾ in. SFRM plate after removal of the three strips to be used for density testing. The regions of the plates with bare steel are due to the action of the putty knife used to debond the three strips. The lower photograph shows the appearance after completion of the adhesion tests on a 1½ in. SFRM specimen, Again the bare spots are due to scraping by the putty knife.

Table 7-5 shows the adhesive strength results and Fig. 7-23 is a plot of the data. Only four plates were selected for the ¾ in. SFRM with bare steel and only three were selected for the 1½ in. SFRM with bare steel. Table 7-6 summarizes the adhesive strength test results. As a point of reference, the manufacturer of BLAZE-SHIELD DC/F indicates an adhesion/cohesion value under controlled conditions in accordance with ASTM E 736 of 295 psf (see Appendix A Fig. A-61). In the ASTM standard procedure, the SFRM is applied to a 12 in. square galvanized steel sheet (0.060 in. thick) at a thickness of ½ in. to 1 in. Note however, that in the ASTM test method, failure can be cohesive (in the bulk SFRM) as well as combination of adhesive and cohesive failure.

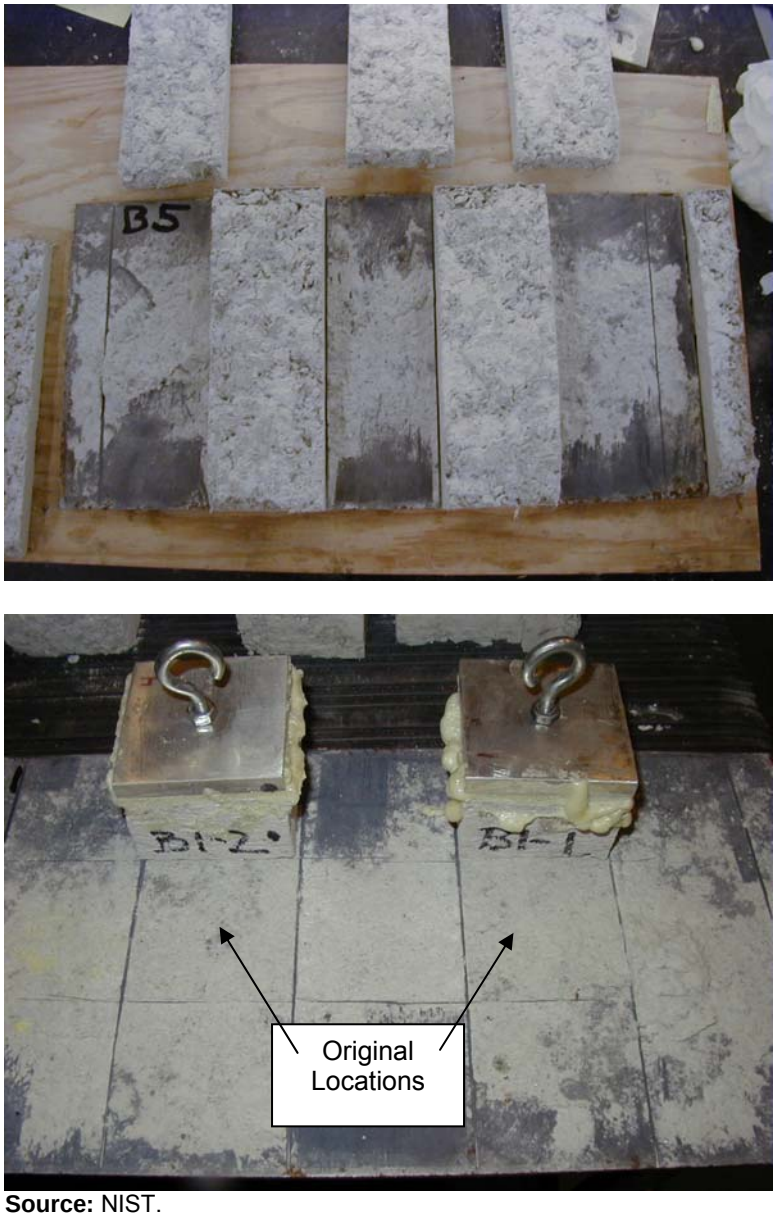
It is clear that the condition of the steel has a significant effect on the SFRM adhesive strength. Typically, manufacturers require that compatibility with primed steel be evaluated to ensure that proper materials are used for adequate adhesion. For example, the following text is taken from the ICBO evaluation of different BLAZE-SHIELD products (ICBO 2001):

> **"2.2.5 Primed or Painted Surfaces:** CAFCO BLAZESHIELD materials are permitted to cover primed or painted wide flange shapes, subject to the following requirements:
>
> 1. Beam flange width is 12 inches (305 mm), maximum.
>
> 2. Column flange width is 16 inches (406 mm), maximum.

3. Beam or column web depth is 16 inches (406 mm), maximum.

4. Bond tests of five specimens in accordance with ASTM E 736 are used to verify the bond strength of the fire-protection material to a painted or primed steel beam or column at the jobsite. Condition of acceptance is that the average bond strength is 20 times the weight of in-place fire-protection material but not less than 150 psf (7.2 kN/m^2), or the minimum average bond strength is 80 percent, with a minimum individual bond strength of 50 percent of the bond strength of fire-protection material applied to bare, clean, 1/8 inch-thick (3.2 mm) steel plate, whichever is greater. Where bond-strength values are less than these minimums, CAFCO BOND-SEAL Type E.B.S. adhesive is applied to the primed or painted surfaces, and the bond-strength tests are repeated."

The results of these tests show that BLAZE-SHIELD DC/F is not compatible, from an adhesion point of view, with the Tnemec 99 Red Metal Primer used in this study and that was specified for the exterior columns of the WTC towers..



Source: NIST.

Figure 7–22. Examples of good adhesion in specimens with unprimed steel plates: (top) ¾ in. SFRM specimen before testing; (bottom) 1½ in. SFRM specimen after completion of tests.

Table 7–5. Adhesive strength of BLAZE-SHIELD DC/F specimens.

Nominal Thickness	Primer	Specimen	Adhesive Strength, psf	Nominal Thickness	Primer	Specimen	Adhesive Strength, psf
¾ in.	Yes	7-1	175	1½ in.	Yes	24-1	0
		7-2	234			24-2	0
		6-1	197			29-1	378
		6-2	267			29-2	401
		18-1	276			10-1	0
		18-2	164			10-2	0
		16-1	257			30-1[a]	501
		16-2	246			30-2[a]	253
		2-1	5			11-1[a]	130
		2-2	32			11-2[a]	44
	No	4-1	382		No	1-1	703
		4-2	423			1-2	651
		5-1	488			2-1	543
		5-2	493			2-2	767
		6-1	365			3-1	459
		6-2	552			3-2	876
		7-1	425				
		7-2	472				

a. Not selected randomly.

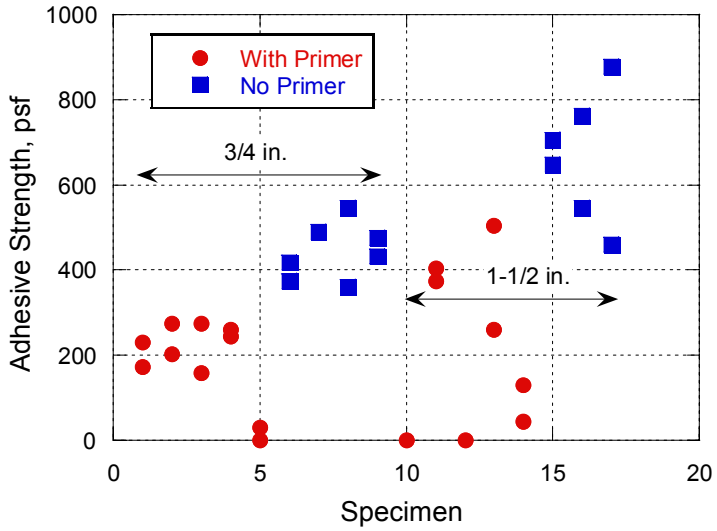


Figure 7–23. Adhesive strength of BLAZE-SHIELD DC/F specimens for primed and unprimed steel plates.

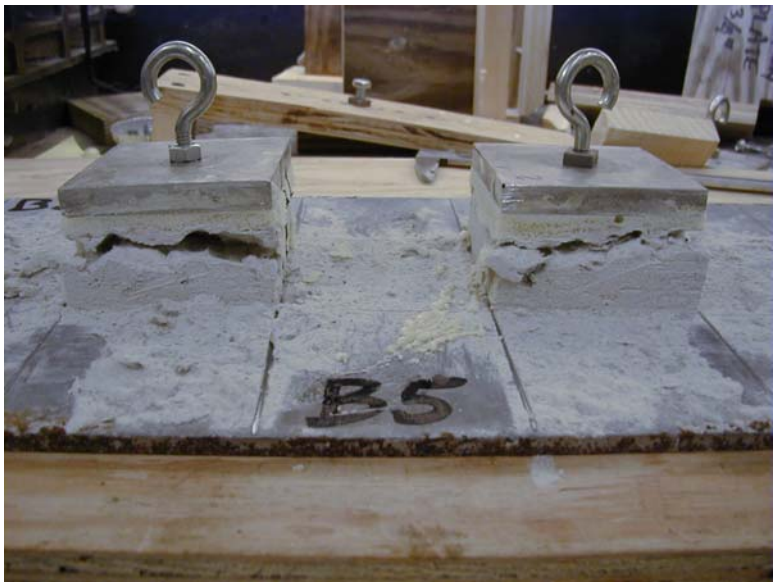
Table 7–6. Summary of adhesive strength results.

Nominal Thickness	Primer	Average, psf	Standard Deviation, psf	Coefficient of Variation, %
¾ in.	Yes	185	96	52
	No	450	63	14
1½ in.	Yes	171[a]	196	115
	No	666	151	23

a. For selected specimens

7.3.4 Cohesive Strength Normal to Surface

As discussed in Section 7.2.3, the same specimens were tested twice (in some cases three times) so as to determine the adhesive and cohesive strength normal to the surface. Figure 7-24 show examples of cohesive failures in 1½ in. SFRM specimens. These specimens were subsequently repaired with the polyurethane foam adhesive, and the adhesive strength was then determined. In general, cohesive failures tended to occur close to the surface of the SFRM layer. This is logical because less compaction would be expected near the surface and perhaps less hydration of cement due to drying.



Source: NIST.

Figure 7–24. Examples of cohesive failure in 1½ in. SFRM specimens.

To compare the results from the current test method, one of the ¾ in. plates with bare steel was also subjected to an ASTM E 736 type test with round screw cap bonded to the top surface. First, a screw-cap test was conducted at the center of the plate, and then three strips were cut as shown in top photo of Fig. 7-25. Another screw cap test was conducted on the right side of the plate, as shown in the bottom photo of Fig. 7-25. Finally, two tests with the current procedure were done on the strip on the left side of the plate. In the bottom photograph it is seen that the screw-cap pulled away in the bulk material near the top surface.

Source: NIST.

Figure 7–25. Comparative testing: current method versus ASTM E 736 method: (top) locations of two screw cap tests; (bottom) after completion of tests.

Table 7-7 shows the individual cohesive strengths normal to the surface and Fig. 7-26 is a plot of the data. Table 7-8 summarizes the average strength and variability of test results.

Table 7–7. Cohesive strength normal to surface for BLAZE-SHIELD DC/F specimens.

Nominal Thickness	Primer	Specimen	Cohesive Strength psf	Thickness	Primer	Specimen	Cohesive Strength psf
¾ in.	Yes	7-1	318	1½ in.	Yes	24-1	538
		7-2	324			24-2	709
		6-1	507			29-1	463
		6-2	381			29-2	592
		18-1	503			10-1	680
		18-2	416			10-2	834
		16-1	401			30-1	458
		16-2	548			30-2	403
		2-1	340			11-1	755
		2-2	595			11-2	667
	No	4-1	412		No	1-1	464
		4-2	373			1-2	574
		5-1	349			2-1a	372
		5-2	366			2-2a	354
		6-1	373			2-1b	661
		6-2	264			2-2b	740
		7-1	372			3-1a	700
		7-2	430			3-2a	530
		7-3	419 [a]			3-2a	836
		7-4	369 [a]			3-2b	722

a. Using screw cap in accordance with ASTM E 736.

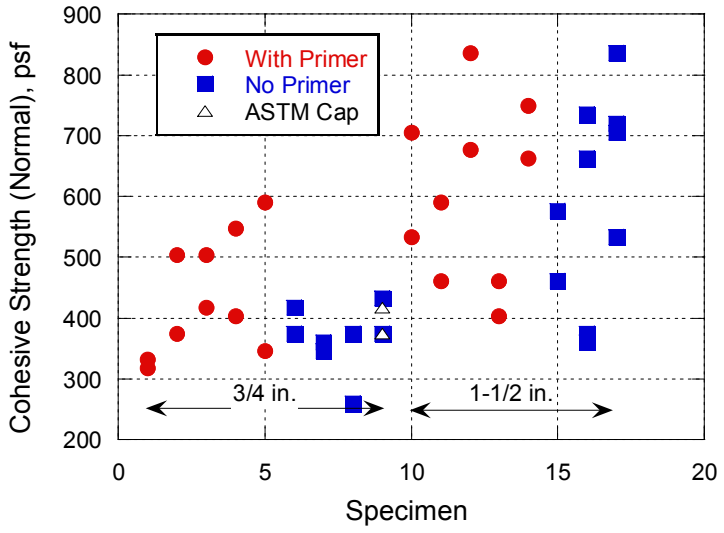


Figure 7–26. Cohesive strength normal to surface for BLAZE-SHIELD DC/F specimens for primed and unprimed steel plates.

Table 7–8. Summary of cohesive strengths normal to surface.

Nominal Thickness	Primer	Average, psf	Standard Deviation, psf	Coefficient of Variation, %
¾ in.	Yes	433	99	23
	No	367	79	13
1½ in.	Yes	610	142	23
	No	595	163	27

Analysis of the results indicated that there was no statistically significant effect due to the presence or absence of primer. This is logical, because the condition of the steel surface is not expected to influence the properties of the bulk SFRM. There was a statistically significant difference in the average strengths for the two thicknesses, with the 1½ in. SFRM having higher strength. This difference is likely related to the observed difference in density.

Examination of Fig. 7-26, shows that the two results using the screw caps resulted in values similar to those obtained with the current test method. This agrees with the view that the ASTM E 736 procedure probably provides a measure of cohesive strength.

7.3.5 Adhesive Strength Versus Cohesive Strength Normal to Surface

A comparison was made of the adhesive strength and cohesive strength normal to the surface. The individual results previously shown in Fig. 7-23 and 7-26 are shown as "dotplots" in Fig. 7-27, and the average values from Tables 7-6 and 7-8 are shown in Table 7-9. In Fig. 2-7, the circles indicate results with bare steel plates, and the blue points (darker shade) indicate adhesive strength. For the specimens with primed steel, the average cohesive strength was much greater than the average adhesive strength. For the specimens made with bare steel, the difference between the averages for the two types of strength was much smaller. Because of the high variability in individual test results, a formal analysis of variance indicates that there is an 8 % probability that the difference could be the result of randomness. Generally, if this probability is greater than 5 %, it can be concluded that the difference is not statistically significant. Thus for the case of good adhesion, the test results do not contradict the assumption that the adhesive strength and cohesive strength normal to the surface are equal. If this assumption is accepted, for the ¾ in. SFRM, the average of the adhesive and cohesive strengths is 409 psf, and for the 1½ in. SFRM, the average is 622 psf.

From the measured strength properties, estimates were made of the local accelerations required to damage or dislodge the SFRM, as described below.

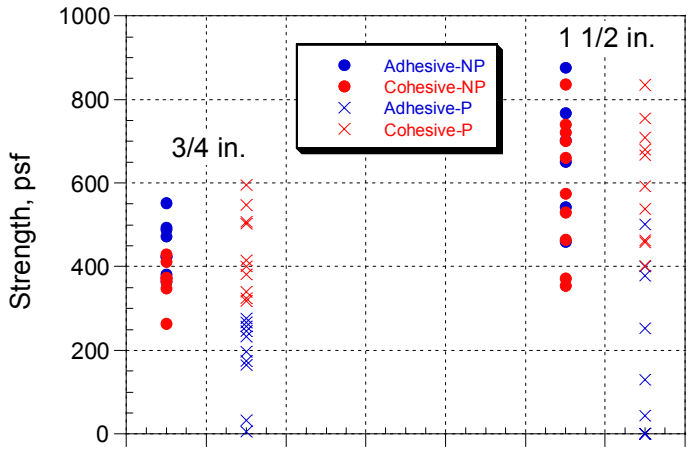


Figure 7–27. Comparison of adhesive strength with cohesive strength normal to surface (P = primed steel, NP = bare steel).

Table 7–9. Comparison of average adhesive strength and average cohesive strength normal to surface.

Primer	Nominal Thickness, in.	Average Adhesive Strength, psf	Standard Deviation, psf	Average Cohesive Strength, psf	Standard Deviation, psf
Yes	¾ in.	185	96	433	99
	1½ in.	171	196	610	142
No	¾ in.	450	63	367	79
	1½ in.	666	151	595	163

7.4 SIMPLIFIED APPROACH TO PREDICT DISLODGING OF SFRM

This section presents a simplified approach for estimating the acceleration required to dislodge SFRM from a structural element. When a member is subjected to an impact, it will undergo various modes of vibration. The vibrations result in local cyclic accelerations. These accelerations are transferred to the SFRM by forces applied at the interface between the steel and SFRM. Two limiting cases are considered:

- Case 1 is a planar element with SFRM applied to one face of the element. This would be representative of SFRM applied to large webs and flanges of beams and columns. In this case, adhesive strength or cohesive strength normal to the surface would be the controlling SFRM properties.

- Case 2 is a slender bar encased with SFRM. This would be representative of SFRM applied to elements of the floor trusses. In this case, in-plane tensile strength and bond strength are the controlling SFRM properties.

CASE 1: Planar Element

The simplified model considers the substrate and SFRM as rigid bodies. The SFRM would dislodge when the inertial force exceeds the smaller of the adhesive bond strength or cohesive strength normal to the surface. Figure 7-28, shows the free body of the thermal insulation being acted upon by its inertial force and the adhesive force. The acceleration to dislodge the SFRM from the substrate is:

$$a = \frac{f_b}{\rho\, t} \tag{2}$$

where:

f_b = cohesive strength normal to surface or adhesive strength, whichever is smaller

t = thickness of SFRM

ρ = mass density of SFRM.

This equation shows that the acceleration to dislodge the SFRM from a planar surface is directly proportional to the smaller of adhesive or cohesive strength (normal to surface) and inversely proportional to the thickness and density.

To arrive at the ranges of accelerations that could be expected to dislodge SFRM from a planar surface, the following plausible ranges of values were assumed:

- SFRM thickness: 0.75 in and 2.25 in.;
- SFRM density: 15 and 25 pcf[13];
- SFRM bond strength: 100 and 500 psf

Table 7-10 shows the resulting accelerations expressed as a multiple of g, which is the gravitational acceleration. For the combination of low thickness, low density, and high bond strength, the required acceleration is about 530 g. For the other extreme combination of high thickness, high density, and low strength, the required acceleration is about 20 g. This simplified model thus gives an approximate range of the amplitude of accelerations required to dislodge the SFRM from a planar surface, depending on the actual values of the key parameters. For example, using the average values of in-place measurements for CAFCO BLAZE-SHIELD II summarized in Section 7.1, for SFRM with a thickness of 2.5 in., a density of 19 pcf, and an adhesive strength of 300 psf, the SFRM would dislodge from a planar surface at an acceleration of about 80 *g*.

[13] These numbers need to be converted to units of mass by dividing by the gravitational acceleration.

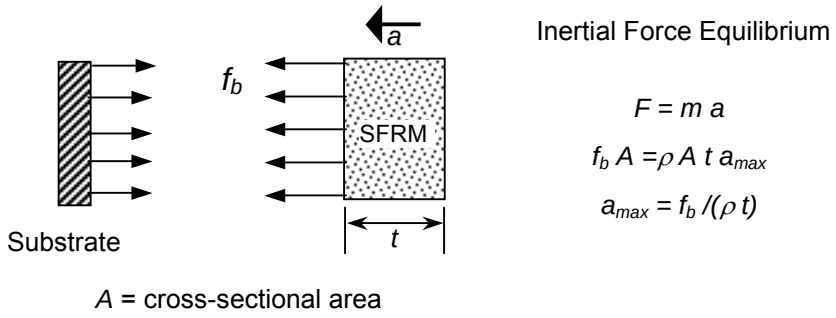


Figure 7–28. Derivation of acceleration to dislodge SFRM from planar substrate.

Table 7–10. Acceleration required to dislodge SFRM from planar surface for different values of density, thickness and bond strength (adhesive or cohesive).

Density, pcf	Bond Strength, psf	Thickness, in.	Acceleration/g
15	100	0.75	107
15	100	2.25	32
15	500	0.75	533
15	500	2.25	160
25	100	0.75	64
25	100	2.25	19
25	500	0.75	320
25	500	2.25	96
19	300	2.5	76

Case 2: Encased Bar

The second case is representative of slender elements that would be surrounded by SFRM, such as the chords and diagonals of the floor trusses. In this case, adhesive strength is of minor importance and the in-plane cohesive strength is of major importance. Figure 7–29 shows the derivation for the relationship between material strengths and acceleration to dislodge the SFRM from a round bar. The required acceleration is as follows:

$$a = \frac{4 f_t (d_0 + (\alpha - 1) d_i)}{(d_0^2 - d_i^2) \rho \pi} \tag{3}$$

where:

f_t = in-plane cohesive strength of SFRM

d_0 = outside diameter of SFRM

d_i = steel bar diameter

α = ratio of adhesive strength to in-plane cohesive strength of SFRM

ρ = density of SFRM

Inertial Force Equilibrium

$$\text{Mass} = m = \pi \frac{(d_o^2 - d_i^2)}{4} \rho$$

$$F = f_t(d_o - d_i) + f_b d_i$$

Let $f_b = \alpha\ f_t$

$$F = f_t(d_o + (\alpha - 1)d_i) = \pi \frac{(d_o^2 - d_i^2)}{4} \rho\ a$$

$$a = \frac{4 f_t(d_o + (\alpha - 1)d_i)}{(d_o^2 - d_i^2)\rho\pi}$$

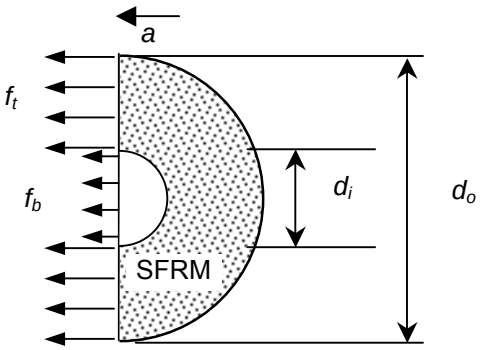


Figure 7–29. Derivation of acceleration to dislodge SFRM surrounding a round bar.

To arrive at the ranges of accelerations that could be expected to dislodge SFRM from a round bar, the following ranges of values were assumed:

- Bar diameter: 0.9 in. and 1.2 in;
- Thickness [$(d_0 - d_i)/2$]: 0.75 in and 2.5 in.;
- Density: 15 and 25 pcf;
- In-plane cohesive strength: 500 and 2000 psf; and
- Strength ratio (α): 0 and 0.3.

Table 7-11 shows the results of using these limiting values in Eq. (3). The smallest required acceleration is about 40g, which corresponds to a large bar having a thick layer of the higher density SFRM with low strength. At the other extreme, the required acceleration is about 730g. For a 1.2 in. diameter bar with 2.5 in. thickness of SFRM and density of 19 pcf, the acceleration required to dislodge the SFRM would vary from 55*g* to 230*g*, depending on the strength characteristics within the assumed ranges given above.

These simplified models are intended to provide insight into the important variables that affect the magnitude of the disturbance (that is, acceleration) required to dislodge SFRM from different kinds of structural members. These models do not consider the fact that the applied acceleration in an actual structure subjected to impact would vary with time. Also these models apply to members not directly impacted by debris. As discussed in NCSTAR 1-3C, there was photographic evidence to suggest that thermal insulation was dislodged from exterior columns in regions not likely to have been impacted directly by debris.

Table 7–11. Acceleration required to dislodge SFRM from encased bar for different values of bar diameter, SFRM thickness, SFRM in-plane cohesive strength, and strength ratio (alpha).

Bar Diameter, in	Outer Diameter, in.	Density, pcf	Cohesive Strength, psf	Alpha	Acceleration/g
0.9	2.4	15	500	0	154
				0.3	182
			2000	0	617
				0.3	728
		25	500	0	93
				0.3	109
			2000	0	370
				0.3	437
	5.9	15	500	0	75
				0.3	79
			2000	0	300
				0.3	316
		25	500	0	45
				0.3	47
			2000	0	186
				0.3	189
1.2	2.7	15	500	0	131
				0.3	162
			2000	0	522
				0.3	648
		25	500	0	78
				0.3	97
			2000	0	313
				0.3	389
	6.2	15	500	0	69
				0.3	74
			2000	0	275
				0.3	295
		25	500	0	41
				0.3	44
			2000	0	165
				0.3	177

Chapter 8
SUMMARY

This report focused on the passive fire protection used in the WTC towers. Specifically it sought to establish the likely characteristic of the sprayed fire-resistive materials applied to the structural system. This information was required for calculating the thermal histories of structural members in a conventional building fire and during the fires after aircraft impact.

To provide context, a brief review of code provisions related to structural fire protection wasprovided. An effort was made to document key decisions and actions related to passive fire protection during the design, construction, and subsequent occupancy of the towers. Copies of documents that support the findings are provided in Appendix A.

The NIST investigation sought available information on the in-place condition of the SFRM in the WTC towers. Some information was provided by the Port Authority in the form of thickness, density, and bond strength measurements on floor trusses taken at various times during the 1990s. Additional information was obtained from photographs of floor trusses provided to NIST. Analyses of the data indicated that fire-resistive material thickness was variable, as would be expected for application to floor truss members with small cross sections.

Results of simplified finite-element simulations of heat transfer under fire conditions showed that variability in thickness of SFRM reduced the effectiveness of the insulation so that protection is less than implied by the average thickness of the SFRM. A procedure was developed for estimating the equivalent uniform thickness of the variable thickness SFRM.

Tests were done on samples of SFRMs to establish the temperature dependencies of key thermophysical properties that were needed for calculating the thermal-structural response of the towers.

Tests were also done to establish basic tensile strength properties of SFRM, which are necessary to estimate the extent of dislodgement due to aircraft impact. Photographic evidence, documented in another phase of the investigations (see NCSTAR 1-3C), suggested that thermal insulation was dislodged from visible portions of the exterior columns of WTC 1 and 2 that were not impacted directly by debris.

8.1 FINDINGS

The following are the key findings based on the information discussed in this report.

- The reviewed documents appear to indicate that the initial design of the towers was based on the 1938 New York City Building Code and predicated on a Class 1A classification, which required a 4 h fire rating for columns and 3 h for the floor system. The WTC towers were classified subsequently as Class 1B, as defined by the 1968 New York City Building Code. This required a 3 h fire rating for columns and 2 h for the floor system. A condition assessment conducted in 2000 reported that the WTC towers were classified as Class-1B—noncombustible, fire-protected, retrofitted with sprinklers in accordance with Local Law 5/1973.

- The use of sprayed fire protection for floor trusses was innovative at the time of the design of the WTC and not consistent with prevailing practice, which used enclosures of fire-resistive materials to surround the floor trusses. Trial applications were performed to demonstrate that is was feasible and practicable to use this fire protection method for the composite floor truss system. Correspondence revealed that adhesion problems were encountered during application of the SFRM to the exterior columns.

- The 1968 New York City Building Code required testing of assemblies to establish that their fire rating conformed to Code requirements. The manufacturer of the floor trusses, the Architect of Record, and the Structural Engineer of Record recognized the need for such fire endurance testing of the composite floor system. There were no records of a fire endurance test of the WTC floor system.

- Fire protection of the exterior columns was the responsibility of Alcoa, which sub-contracted the work to Mario & Di Bono Plastering Co. The sprayed fire protection of the floor trusses and core members was performed under a separate contract awarded to Mario & Di Bono. The project specifications for sprayed fire protection of the interior portions of the towers did not specify the type of material or thickness to be applied. Correspondence in 1969, from the construction manager to Mario and Di Bono, stated that those portions of the floor system requiring thermal protection were "to have a ½ in. covering of 'Cafco.'" The product known as "Cafco" was CAFCO BLAZE-SHIELD Type D supplied by U. S. Mineral Products Co., and was composed of asbestos fibers with a portland cement binder. No evidence was available to provide the technical basis for the value of ½ in. thickness indicated in the correspondence. Correspondence and other documents indicated that economics was an important factor in the Port Authority's decisions related to passive fire protection.

- Because of the asbestos fibers, the use of CAFCO BLAZE-SHIELD Type D, was discontinued in 1970 at the 38th floor of WTC 1. The existing thermal insulation was encapsulated with a coating to contain the asbestos fibers. CAFCO BLAZE-SHIELD Type DC/F was used as its replacement. This material contained mineral fibers instead of asbestos. Tests conducted by Underwriters Laboratories in 1970 indicated that CAFCO BLAZE-SHIELD Type DC/F was "..as least as good…" and "…may even be slightly better…" than CAFCO BLAZE-SHIELD Type D "…in regard to fire resistance."

- In 1975, the Structural Engineer of Record reported that in March of 1975 he was made aware of a fire endurance test of a floor assembly consisting of composite floor trusses with a normal weight concrete slab on a corrugated steel deck. The trusses were protected with "Mono-Kote," which was described as a "cementitious spray-applied fireproofing." The members of the trusses were coated with 1½ in. of the insulation and the sheet metal deck had ½ in. The results of the fire endurance test assigned a 3 h rating to the floor system. It is noted that this test was not related in any way to the floor system in the WTC towers. The Structural Engineer of Record used this test result "with many simplifying assumptions" to demonstrate that ½ in. of CAFCO BLAZE-SHIELD would provide the same 3 h rating when applied to 1 in. web bars. The calculations were said to be based on the differences in the room temperature thermal conductivity of the two insulation materials, with the Mono-Kote product having about twice the thermal conductivity of the CAFCO product. He noted: "however, that theoretical extrapolations

of fire endurance tests must the viewed with caution." He stated further that: "Without benefit of a full-scale fire test we cannot establish a rating for the floor assembly."

- In 1975, the Structural Engineer of Record reported that certain elements of the floor system did not require fire protection because those elements were not critical in supporting gravity loads. These included the bridging trusses and the top chords in the one-way portion of the floor system.

- Based on data provided by the Port Authority of insulation thickness on 16 trusses on each of floors 23 and 24 of WTC 1, the average thickness of the original thermal insulation on the floor trusses was estimated to be 0.75 in. with a standard deviation of 0.3 in. (coefficient of variation = 0.40). The reported average thicknesses ranged from 0.52 to 1.17 in.

- In 1995, the Port Authority performed a study to establish the thickness of fire protection to be applied to the floor trusses during major tenant renovations. On the basis of Design G805 listed in the UL *Fire Resistance Directory*, the thickness to achieve a 2 h fire rating was estimated to be 1½ in. At the time of the WTC disaster, fire protection had been upgraded on floors affected by the aircraft impact. According to information provided by the Port Authority, upgrading had occurred on floors 92 through 100 and 102 of WTC 1 and on floors 77, 78, 88, 89, 92, 96 and 97 of WTC 2.

- Based on analyses of insulation thickness data contained in Construction Audit Reports provided by the Port Authority, the average thickness of the upgraded thermal insulation (CAFCO BLAZE-SHEILD II) on the floor trusses was estimated to be 2.5 in. with a standard deviation of 0.6 in. (coefficient of variation = 0.24). The reported average thicknesses ranged from 1.7 in. to 4.3 in.

- Based on finite-element simulations of a 1 in. round bar covered with SFRM having lognormal distributions for thickness that were consistent with the average values and standard deviations noted above, it was concluded that the original thermal protection on the floor trusses was equivalent to a uniform thickness of 0.6 in. and that the upgraded insulation was equivalent to a uniform thickness of 2.2 in.

- No information is available on in-place conditions of the thermal protection on the exterior columns and spandrel beams, and little information is available on the conditions of fire-resistive material on core beams and columns. For thermal analyses of the towers, the thermal protection on these elements was taken to have uniform thicknesses equal to the specified values. This assumption is justified by the offsetting factors of measured average thicknesses tending to be greater than specified thicknesses and the reduced effectiveness of a given average thickness of SFRM due to thickness variability. These were ½ in. for beams and spandrels, 2 1/16 in. for columns lighter than 14WF228, and 1 3/16 in. for columns heavier than 14WF228.

- Data provided by the Port Authority on the thickness and density of the upgraded thermal insulation for floor trusses indicated that the average thicknesses exceed the design thickness of 1½ in. and the bond strength measured according to ASTM E 736 exceeded 150 psf, which was stated to be the "standard performance" of CAFCO BLAZE-SHIELD II.

- Results of NIST tests indicated that the thermal conductivity of SFRMs increased significantly at higher temperatures.

- Results of NIST tests indicated that the presence of primer paint caused significant reductions in the adhesive strength of CAFCO BLAZE-SHIELD DC/F. Good adhesion was found with bare steel, in which case there was not statistically significant difference between adhesive strength and cohesive strength normal to the surface.

- Results of NIST tests indicated that the in-plane cohesive strength of CAFCO BLAZE-SHIELD DC/F was almost three times the cohesive strength normal to the surface.

- The density of CAFCO BLAZE-SHIELD DC/F in the NIST tests for strength properties was greater than the densities in the Port Authority reports or in the manufacturer's catalogs. This may have accounted for the higher strength values obtained by NIST compared with the manufacturer's published values.

- Based on simplified models, the acceleration required to dislodge SFRM from planar surfaces might range from 20 *g* to 530 *g*, depending on the in-place density, thickness and bond strength. For density of 19 pcf, thickness of 2.5, and bond strength of 300 psf, which are representative of the upgraded insulation on the floor trusses, an acceleration of about 40 g would dislodge the SFRM from a planar surface. For a round bar encased in SFRM, the estimates are 40 *g* to 730 *g*, depending on the bar diameter, insulation thickness, in-plane cohesive strength, and adhesive strength. For a 1.2 in. diameter bar, with 2.5 in. thickness of insulation having a density of 19 pcf, the acceleration required to dislodge the SFRM was estimated to be between 55 *g* and 230 *g*, depending on the strength characteristics of the SFRM. These models provide insight into the factors that affect SFRM dislodgment due impact-induced vibration.

Chapter 9
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Appendix A
REFERENCED DOCUMENTS

R40-1

6211 - A1

THE PORT OF NEW YORK AUTHORITY

111 Eighth Avenue-at 15th Street New York 11 NY

ALGONQUIN 5-1000

WORLD TRADE CENTER

Malcolm P. Levy
CHIEF, PLANNING DIVISION

Richard C. Sullivan
DIRECTOR

A. SCHREIER
RECEIVED
MAY 17 1963

May 16, 1963

Mr. Minoru Yamasaki
Minoru Yamasaki & Associates
1025 East Maple Road
Birmingham, Michigan

Dear Yama:

At a recent meeting with Mr. John Kyle, Chief Engineer, the subject of New York City Code compliance was further amended as follows:

"All consulting engineers and architects working on the World Trade Center have been instructed to comply with the Code in preparing their designs. Questions have arisen, however, in areas where the Code is not explicit. It was agreed that in such cases and, where technological advances make portions of the Code obsolete, the consultants may propose designs based on acceptable engineering practice. All such instances will be called to the attention of The World Trade Center Planning Division. 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".

Sincerely,

Malcolm P. Levy
Chief, Planning Division

LF:db
cc: Mr. J. Roth (ERS)

Figure A–1. Port Authority letter instructing consultants to follow New York City Building Code (3-P).

6211
R 110-4

THE PORT OF NEW YORK AUTHORITY

111 Eighth Avenue at 15th Street New York NY 10011 — 9E R 40-1

620-8233

WORLD TRADE CENTER

Malcolm P. Levy
CHIEF, PLANNING DIVISION

Richard C. Sullivan
DIRECTOR

September 29, 1965

Mr. Minoru Yamasaki
Minoru Yamasaki & Associates
1025 East Maple Road
Birmingham, Michigan 48011

Dear Yama:

We have decided to adopt the new Building Code presently existing in second and third draft form for The World Trade Center.

The Roth office is requested to revise floor plans as quickly as possible and on an accelerated basis to comply with the provisions of this code. It is my understanding that the present drawings have been prepared to permit rapid conversion to the new code. Generally the tower core should be redesigned to eliminate the fire towers and to take advantage of the more lenient provisions regarding exit stairs. No other major change to the core should be undertaken without review by this office.

The structural consultants are instructed, by copy of this letter, to revise structural design in accordance with the more realistic criteria for partition weight allowance. The majority of interior partitions, as noted in a previous letter, will consist of reinforced gypsum plank.

The Roth office is requested to provide me with the dates on which we can expect revised floor plans and also to indicate any changes in design schedule caused by these instructions.

Sincerely,

Malcolm P. Levy

cc: R. Baum (JBB), J. Loring (JRLA), J. Roth (ERS), J. Skilling and L. Robertson (WSHJ)

Similar letter sent to Mr. Julian Roth (ERS)

Figure A–2. Port Authority letter instructing consultant to follow New York City Building Code under development (3-P).

MEMORANDUM OF UNDERSTANDING BETWEEN THE NEW YORK CITY DEPARTMENT OF BUILDINGS AND THE PORT AUTHORITY OF NEW YORK AND NEW JERSEY

This Memorandum shall govern the relationship between the New York City Department of Buildings (the "Department") and the Port Authority of New York and New Jersey (the "Port Authority"), both parties entering into this agreement with the intention to establish procedures to be followed by the Port Authority for any building construction project ("Project"), to be undertaken by the Port Authority or any of its tenants at buildings owned or operated by the Port Authority and located in the City of New York (the "City), to assure conformance of Projects at such buildings with the standards set forth in the New York City Building Code (the "Code").

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 long-standing 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.

Accordingly, the Department and the Port Authority hereby agree as follows:

1. Port Authority Review. To assure conformance with the building standards set forth in the Code at the time of the design and construction of any Project, the Port Authority shall, in the case of each Project, thoroughly review and examine all plans in connection with such Project for conformance with the building standards set forth in the Code. Plans prepared for Projects to be undertaken by Port Authority tenants shall be prepared and sealed by a New York State licensed professional engineer or architect retained or employed by tenant; plans prepared for Projects to be undertaken by the Port Authority shall be prepared by a New York State licensed professional engineer or architect employed or retained by the Port Authority. The Port Authority's examination of plans shall be conducted by New York State licensed architects and engineers retained or employed by the Port Authority. The Port Authority engineer or architect approving the plans for any Project from the standpoint of Code conformance shall be a New York State licensed architect or engineer who shall not have assisted in the actual preparation of such plans.

2. Project File. The Port Authority shall maintain a file (the Project File") for each Project which file shall at all times contain the most recently

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Figure A–3. 1993 Memorandum of Understanding between Port Authority and New York City Department of Buildings (113-P).

prepared drawings, plans and any other documents required in connection with the review of the Project from the standpoint of Code conformance. In the case of any Project being effectuated by a tenant of the Port Authority (a "Tenant Project") such file shall also include the Tenant Alteration Application prepared by the Tenant. In the case of any project administered by a line department of the Port Authority, such file shall include any construction application prepared in connection with such Project. The Line Departments of the Port Authority are currently its World Trade, Aviation, Interstate Transportation, Port, and Regional Development Departments.

3. Project Certification. For each Tenant Project, the Port Authority shall require the Tenant to obtain the certification of a New York State licensed architect or engineer that such Project was constructed in accordance with the approved plans and specifications for such Project. For any Project effectuated by the Port Authority, the Chief Engineer or his successor in duties shall certify that the Project was constructed in accordance with the approved plans and specifications for the Project. Certifications for each Project shall be maintained in the Project File.

4. Copies of Project File. The Department may at any time request the Port Authority to provide it with a copy of any Project File and the Port Authority shall promptly provide a copy of the Project File to it.

5. Variances. The Port Authority shall promptly advise the Department of any Project approved by the Chief Engineer of the Port Authority which involves, in the judgment of the Chief Engineer of the Port Authority or his successor in duties, a variance from the clear requirements of the Code. In the event that the Department disagrees with the manner in which questions of Code conformance have been or are proposed to be dealt with in connection with such Project, it may so advise the Authority. The Port Authority shall seek expeditiously to resolve the matter. Any matter of Code conformance in connection with such Project which the Department believes involves an unacceptable variance from the requirements of the Code shall be subject to the further review of the Port Authority Board of Commissioners. The Commissioners shall be advised of the Department's views on the matter.

6. Inspections and Surveys. The Port Authority shall continue to conduct or cause to be conducted all building inspections, during both construction and post-construction periods, required under the Code. In addition, the Port Authority will continue to perform structural integrity inspections on a cyclical basis for all of its structures located in the City.

7. Port Authority Responsibility. As indicated above, the purpose of this Agreement is to set forth certain basic understandings between the Department and the Port Authority. It is understood, however, that the Port Authority with its tenants shall continue to bear the responsibility for life safety in buildings at its facilities and nothing in this Agreement is intended to impose any obligations of inspection or review on the Department. The Department shall refer back to the Chief Engineer of the Port Authority any requests for

2

Figure A–3 (Contd.). 1993 Memorandum of Understanding between Port Authority and New York City Department of Buildings (113-P).

information or interpretation which it may receive from tenants of the Port Authority with respect to any Project.

8. No Personal Liability. No Commissioner, officer, agent or employee of the Port Authority or the Department shall be held personally liable under any provision of this Agreement or because of its execution or attempted execution or because of any breach or alleged breach thereof.

IN WITNESS WHEREOF, the parties hereto have caused this instrument to be signed, sealed and attested.

ATTEST:

Secretary

DATE: 11/3/93

THE PORT AUTHORITY OF NEW YORK AND NEW JERSEY

By: Stanley Brezenoff
Executive Director

ATTEST:

FRANK M. SCHWARTZ
Notary Public, State of New York
No. 41-4632586
Qualified in Queens County
Commission Expires January 31, 19 95

DATE: 10/28/93

THE NEW YORK CITY DEPARTMENT BUILDINGS

By: Stewart D. O'Brien
Acting Commissioner

3

Figure A–3 (Contd.). 1993 Memorandum of Understanding between Port Authority and New York City Department of Buildings (113-P).

THE PORT AUTHORITY OF NY & NJ

One World Trade Center
New York, N.Y. 10048

William H. Goldstein
Deputy Executive Director/
Capital Programs
(212) 435-8415
(201) 961-6000 x8415

September 15, 1995

Honorable Joel A. Miele, Sr., Commissioner
Department of Buildings
City of New York
60 Hudson Street
New York, New York 10013

Dear Commissioner Miele:

As you know, the Port Authority of New York and New Jersey (the "Port Authority") and the New York City Department of Buildings (the "Department") recently executed a supplement (the "Supplement") to the Memorandum of Understanding between the Department and the Port Authority to provide that the Port Authority's tenant at the World Trade Center could, in lieu of any review by the Port Authority, use New York State licensed architects or engineers meeting qualifications to be established by the Port Authority to: (A) prepare and review such tenant's plans for the construction of any project and certify that such plans conform with the building standards set forth in the New York City Building Code and (B) certify that such project has been constructed in accordance with the approved plans and specifications for such project.

As you also know, the Supplement provides that the person or firm performing the review and certification described in (A) above shall not be the same person or firm providing the certification described in (B) above. A copy of the Supplement is attached.

This letter will-confirm the agreement of the Port Authority and the Department that, notwithstanding the last sentence of paragraph 1 of the Supplement, a single licensed consultant may make both certifications described in (A) and (B) of such paragraph, except where the alteration would change the character of the occupancy group under paragraph 27-237 of the New York City Building Code which would have been applicable to such space had such space been located in a privately owned building.

If the foregoing meets with your approval, please be good enough to sign this letter on behalf of the Department where indicated below and return one of the originals to me. In light of the fact that three originals of the Supplement were furnished to the Department, we have, for your record purposes, executed in total four originals of this letter.

Very truly yours,

William H. Goldstein
Deputy Executive Director
Capital Programs

THE NEW YORK CITY DEPARTMENT OF BUILDINGS

AGREED

BY: _____
Commissioner

Figure A–4. 1995 Supplement to Memorandum of Understanding between Port Authority and New York City Department of Buildings (113-P).

SUPPLEMENT TO MEMORANDUM OF UNDERSTANDING
BETWEEN THE NEW YORK CITY DEPARTMENT OF
BUILDINGS AND THE PORT AUTHORITY OF NEW
YORK AND NEW JERSEY

In November, 1993 the New York City Department of Buildings (the "Department") and the Port Authority of New York and New Jersey (the "Port Authority") entered into the attached Memorandum of Understanding (the "Memorandum") establishing certain procedures for the purpose of helping to assure conformance of construction projects to be undertaken at buildings owned or operated by the Port Authority in New York City with the standards set forth in the New York City Building Code.

Recently, the Department implemented its own optional plan review system providing for professional certifications of applications and plans and subsequent construction work falling under its jurisdiction.

The purpose of this Supplement to the Memorandum is to provide under the Memorandum for the adoption by the Port Authority of a procedure under which any Port Authority tenants at the World Trade Center may utilize New York State licensed architects or engineers to certify, in lieu of any review by the Port Authority, that (i) the tenant's construction plans are in conformance with the standards set forth in the New York City Building Code, and (ii) construction has been performed in accordance with such plans, it being understood that the persons making the certifications described in (i) and (ii) shall not be the same.

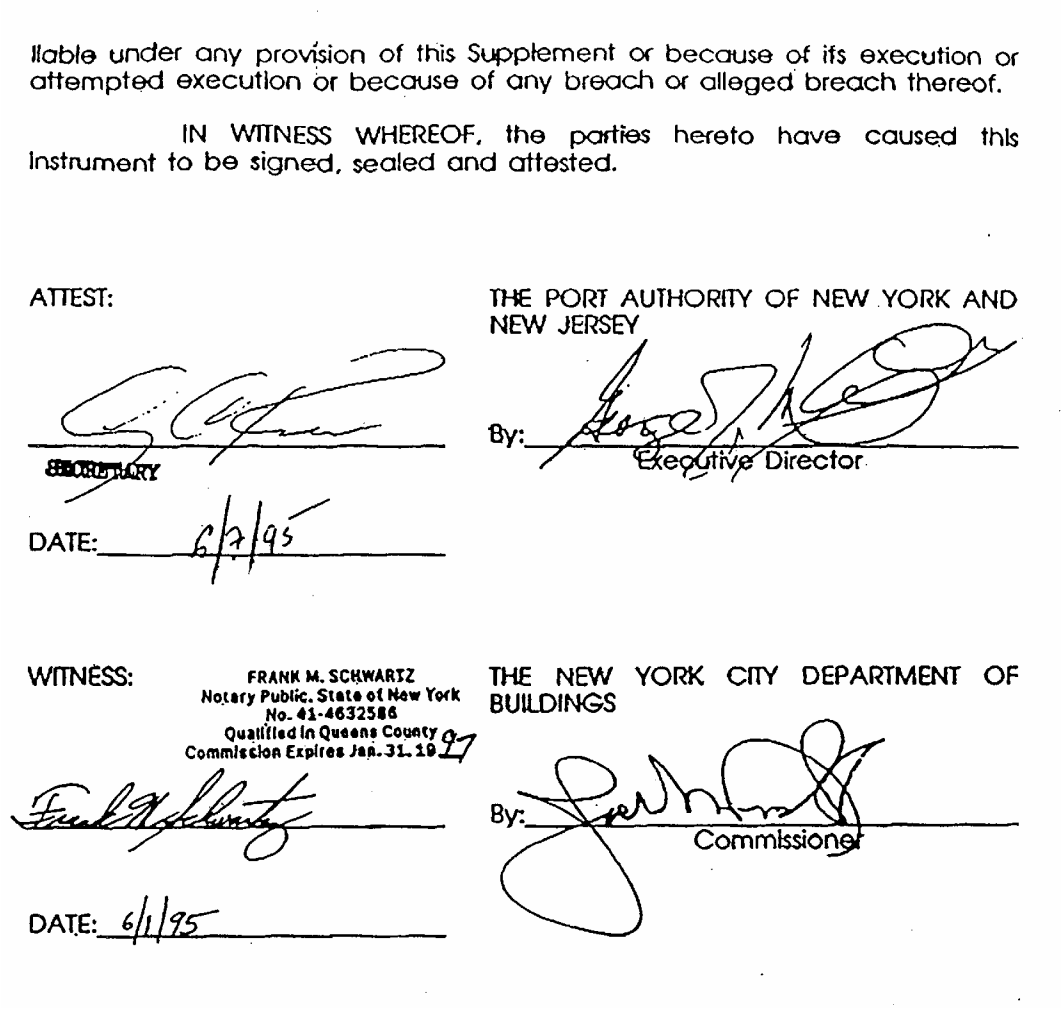
Accordingly, the Department and the Port Authority hereby agree that the Memorandum is amended as follows:

1. Professional Certification. Notwithstanding anything to the contrary in the Memorandum, the Port Authority may, in lieu of any reviews or certifications by the Port Authority provided for in the Memorandum, provide procedures pursuant to which its tenants at the World Trade Center may utilize New York State licensed architects or engineers meeting qualifications to be established by the Port Authority to (A) prepare and review such tenant's plans for the construction of any project and certify that such plans conform with the building standards set forth in the New York City Building Code and (B) certify that such project has been constructed in accordance with the approved plans and specifications for such project. The person or firm performing the review and certification described in (A) above shall not be the same person or firm providing the certification described in (B) above.

2. Other Provisions. Except as provided herein, all the terms and conditions of the Memorandum shall remain in full force and effect.

3. No Personal Liability. No Commissioner, officer, agent or employee of the Port Authority or the Department shall be held personally

Figure A–4 (Contd.). 1995 Supplement to Memorandum of Understanding between Port Authority and New York City Department of Buildings (113-P).



liable under any provision of this Supplement or because of its execution or attempted execution or because of any breach or alleged breach thereof.

IN WITNESS WHEREOF, the parties hereto have caused this instrument to be signed, sealed and attested.

ATTEST:

SECRETARY

DATE: 6/7/95

THE PORT AUTHORITY OF NEW YORK AND NEW JERSEY

By: _____
Executive Director

WITNESS:

FRANK M. SCHWARTZ
Notary Public, State of New York
No. 41-4632586
Qualified in Queens County
Commission Expires Jan. 31, 19 97

DATE: 6/1/95

THE NEW YORK CITY DEPARTMENT OF BUILDINGS

By: _____
Commissioner

Figure A–4(Contd.). 1995 Supplement to Memorandum of Understanding between Port Authority and New York City Department of Buildings (113-P).

MEMORANDUM OF UNDERSTANDING BETWEEN THE FIRE DEPARTMENT
OF THE CITY OF NEW YORK AND THE PORT AUTHORITY OF NEW YORK AND NEW JERSEY
EXECUTED AS OF DECEMBER 30, 1993

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.

Specifically, the Fire Department of the City of New York ("FDNY") and the Port Authority hereby agree as follows:

1. FDNY, acting through its Bureau of Fire Prevention ("BFP"), shall have the right to conduct fire safety inspections at any Port Authority facility located in the City of New York. These inspections will generally be coordinated with the Port Authority's General Manager of Risk Management operations, but the BFP, at its option, may conduct inspections without prior notice to the Port Authority.

2. BFP will issue a letterhead report of its fire safety findings and recommendations for corrective action with respect to any deficiencies forming a part of such findings addressed to the Port Authority's General Manager of Risk Management operations. The Port Authority will promptly undertake the implementation of such findings (including undertaking corrective action with respect to any deficiencies) and shall notify BFP of the actions taken to implement such findings. BFP may at any time conduct follow-up inspections with respect to any matters recommended to the Port Authority for corrective action.

3. Prior to the introduction of a new fire safety system or the introduction of modifications to an existing fire safety system at any building located at a Port Authority facility in the City of New York, the Port Authority shall provide BFP with copies of the drawings and specifications or other appropriate description of such system or modification for review and approval. The Port Authority policy is and will continue to be to assure that such new or modified fire safety systems are in compliance with local codes and regulations. When circumstances or conditions are unusual, the Port Authority shall have the right to petition the Bureau of Fire Prevention for a variance in specific cases.

Figure A–5. 1993 Memorandum of Understanding between Port Authority and the Fire Department of New York City and 1995 amendment (160-P).

4. The Port Authority and BFP will seek to expeditiously resolve any issues arising out of matters covered by this Memorandum of Understanding.

5. Nothing in this Memorandum of Understanding is intended to limit or modify in any way any arrangements which the Port Authority currently has with local fire companies in New York City regarding either facility inspections or joint training exercises or any other matters.

6. The Port Authority shall continue to be exempt from all inspection and permit fees for FDNY inspections at its facilities.

7. No Commissioner, officer, agent or employee of the Port Authority or FDNY shall be held personally liable under any provision of this Memorandum or because of its execution or attempted execution or because of any breach or alleged breach thereof.

IN WITNESS WHEREOF, the parties hereto have caused this instrument to be signed and sealed by duly authorized officers thereof.

THE PORT AUTHORITY OF NEW YORK AND NEW JERSEY

By: Stanley Brezenoff
Stanley Brezenoff
Executive Director

FIRE DEPARTMENT - CITY OF NEW YORK

By: William M. Feehan
William M. Feehan
Fire Commissioner
City of New York

Figure A–5 (Contd.). 1993 Memorandum of Understanding between Port Authority and the Fire Department of New York City and 1995 amendment (160-P).

FIRST AMENDMENT TO MEMORANDUM OF UNDERSTANDING BETWEEN THE FIRE DEPARTMENT OF THE CITY OF NEW YORK AND THE PORT AUTHORITY OF NEW YORK AND NEW JERSEY EXECUTED AS OF DECEMBER 30, 1993

On December 30, 1993, the Port Authority of New York and New Jersey (the "Port Authority") and the Fire Department of the City of New York ("FDNY") entered into a Memorandum of Understanding ("MOU") with respect to certain matters relating to the implementation of the policy adopted by the Port Authority on April 15, 1993 regarding the maintenance and enhancement of fire safety at Port Authority facilities.

Under paragraph 3 of the MOU, the FDNY, acting through its Bureau of Fire Prevention ("BFP") was to receive copies of the drawings and specifications of proposed new or modified fire safety systems for BFP's review and approval. FDNY has requested, and the Port Authority is agreeable, to the following changes to paragraph 3 of the MOU. Accordingly, effective January 1, 1995, FDNY and the Port Authority agree that paragraph 3 of the MOU shall be amended to read as follows:

3. The Port Authority shall notify the BFP in writing prior to the introduction of a new fire safety system or the introduction of modifications to an existing fire safety system at any building located at a Port Authority facility in the City of New York.

a. Port Authority Review: To assure conformance with the standards set forth in local codes and regulations at the time of the design and construction of any new or modified fire safety system, the Port Authority shall, in the case of each system, thoroughly review and examine all plans in connection with such system for conformance with the standards set forth in all applicable local codes and regulations. Plans prepared for new or modified systems to be undertaken by Port Authority tenants shall be prepared and sealed by a New York State licensed professional engineer or architect retained or employed by tenant; plans prepared for new or modified systems to be undertaken by the Port Authority shall be prepared by a New York State licensed professional engineer or architect employed or retained by the Port Authority. The Port Authority's examination of plans shall be conducted by New York State licensed architects and engineers retained or employed by the Port Authority. The Port Authority engineer or architect approving the plans for any new or modified system from the standpoint of Code conformance shall be a New York State licensed architect or engineer who shall not have assisted in the actual preparation of such plans.

b. New and/or Modified Fire Safety System File: The Port Authority shall maintain a file for each new or modified system which file shall at all times contain the most recently prepared drawings, plans and any other documents required in connection with the review of the systems from the standpoint of Code conformance. In the case of any new or modified system being effectuated by a tenant of the Port Authority, such file shall also include the Tenant Alteration Application prepared by the tenant. In the case of any new or modified system administered by a line department of the Port Authority, such file shall include any application prepared in connection with such new or modified system. The Line Departments of the Port Authority are currently its World Trade, Aviation, Interstate Transportation, Port and Regional Development Departments.

Figure A–5 (Contd.). 1993 Memorandum of Understanding between Port Authority and the Fire Department of New York City and 1995 amendment (160-P).

c. Fire Safety System Certification: For each Tenant System, the Port Authority shall require the Tenant to obtain the certification of a New York State licensed architect or engineer that such system was constructed in accordance with the approved plans and specifications. For any system effectuated by the Port Authority, Risk Management shall certify that the system was constructed in accordance with the approved plans and specifications. Certifications for each System shall be maintained in the New and/or Modified Fire Safety System File.

d. Copies of New and/or Modified Fire Safety System File: The BFP may at any time request the Port Authority to provide it with a copy of any Fire Safety System File and the Port Authority shall promptly provide a copy of the File as requested. The BFP reserves the right to audit any new or modified fire safety system to assure conformance with the standards set forth in local codes and regulations.

e. Variance: The Port Authority policy is and will continue to be to assure that such new or modified fire safety systems are in conformance with the local codes and regulations. When circumstances or conditions are unusual, the Port Authority shall have the right to petition the BFP for a variance in specific cases.

IN WITNESS WHEREOF, the Port Authority and FDNY have caused this First Amendment to the MOU to be signed by duly authorized officers thereof.

THE PORT AUTHORITY OF NEW YORK AND NEW JERSEY

Dated: 2/2/95 By: _____
Stanley Brezenoff,
Executive Director

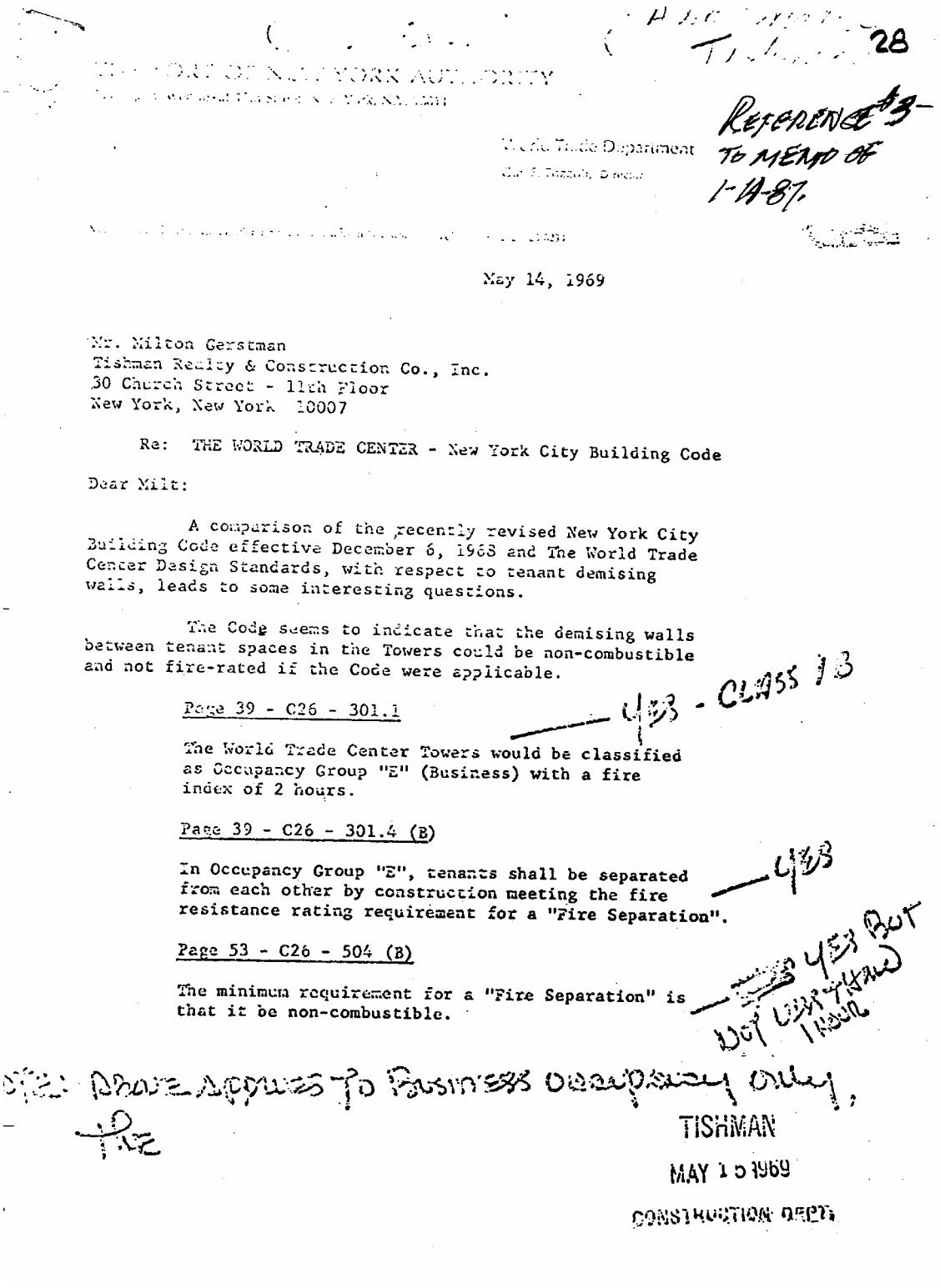
Approved As To Form

Approved As To Terms

FIRE DEPARTMENT - CITY OF NEW YORK

Dated: 1/27/95 By: _____
Howard Safir
Fire Commissioner
City of New York

Figure A–5 (Contd.). 1993 Memorandum of Understanding between Port Authority and the Fire Department of New York City and 1995 amendment (160-P).



PORT OF NEW YORK AUTHORITY

World Trade Department

28

REFERENCE #3 TO MEMO OF 1-14-87.

May 14, 1969

Mr. Milton Gerstman
Tishman Realty & Construction Co., Inc.
30 Church Street - 11th Floor
New York, New York 10007

Re: THE WORLD TRADE CENTER - New York City Building Code

Dear Milt:

A comparison of the recently revised New York City Building Code effective December 6, 1968 and The World Trade Center Design Standards, with respect to tenant demising walls, leads to some interesting questions.

The Code seems to indicate that the demising walls between tenant spaces in the Towers could be non-combustible and not fire-rated if the Code were applicable.

Page 39 - C26 - 301.1

4B3 - CLASS 1B

The World Trade Center Towers would be classified as Occupancy Group "E" (Business) with a fire index of 2 hours.

Page 39 - C26 - 301.4 (B)

4B3

In Occupancy Group "E", tenants shall be separated from each other by construction meeting the fire resistance rating requirement for a "Fire Separation".

Page 53 - C26 - 504 (B)

4B3 BUT DEF CONTAINED 1 HOUR

The minimum requirement for a "Fire Separation" is that it be non-combustible.

NOTE: ABOVE APPLIES TO BUSINESS OCCUPANCY ONLY.

TISHMAN

MAY 15 1969

CONSTRUCTION DEPT.

Figure A–6. Letter from Port Authority to Tishman Realty & Construction Co. regarding Occupancy Group for WTC towers (3-P).

29

Mr. M. Gerstman - 2 - May 14, 1969

If we apply these interpretations to the World Trade Center, there would be savings in construction costs with respect to the following items:

a. Ordinary non-combustible partitions could be used in lieu of the one-hour rated tenant demising walls.

b. Standard non-combustible ceiling system could be used in lieu of the one-hour rated acoustical tile ceiling.

c. The deletion of all insulating batt fire protection at all air handling lighting fixtures in ceilings as well as the deletion of damper equipped return air troffers. These are presently proposed for fixtures within 10'-0" of a demising partition.

We would appreciate your opinion as to whether it would be appropriate to make the changes to the design noted in paragraphs a, b and c. By copy of this letter, the office of Emery Roth & Sons is also requested to comment.

Sincerely,

Malcolm P. Levy

cc: Mr. Joseph Solomon (ER&S)

Figure A–6 (Contd.). Letter from Port Authority to Tishman Realty and Construction Co. regarding Occupancy Group for WTC towers (3-P).

PORT AUTHORITY OF NY & NJ
OFFICE OF CHIEF ENGINEER OF DESIGN
INFRASTRUCTURE

M E M O R A N D U M

RECEIVED

TO: Robert J. Linn, Deputy Director for Physical Facilities, WTD
FROM: Lester S. Feld
DATE: January 15, 1987

NOTED:
REFERRED TO:

SUBJECT: THE WORLD TRADE CENTER - TOWERS & PLAZA BUILDINGS FIRE RATING PER NYC BUILDING CODE REVISION EFFECTIVE 12-6-68.

REFERENCE:
(1) - Memo - M. Levy to File - dated 4-20-65
(2) - Letter - L. Robertson (WSHJ) to M. Levy - dated 4-26-65
(3) - Letter - M. Levy to M. Gerstman (TRCC) - dated 5-14-69
(4) - Office Memo - W. Bracco (TRCC) to J. Endler (TRCC) - dated 5-26-69
(5) - UL Fire Test Report from T. P. Feit - dated 7-26-69
(6) - Letter - A. F. Abbasi (UL) to T. P. Feit (Zonolite) - dated 3-26-70
(7) - Buckslip - V. Dovletian to D. Bais - dated 1-9-87
(8) - Page 4 - Item 1C of Issue A entitled "Office Space Design Guide"

COPY TO: D. Bais, J. Carlock, A. Cracchiolo, V. Dovletian, P. Martinez (ER&S)
D. Montalbano, A. Preschle, J. Pugh (LERA), L. Robertson (LERA)
A. Vaccaro - All w/Reference 1 - 8 attached.

1/28 Please advise me. Thanks.

COPY TO
AGC
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1. On January 13, 1987 I contacted Richard Roth, Jr. (ER&S) regarding the subject fire ratings, normally established by the Architect. Mr. Roth referred me to Phil Martinez for the required information.

2. Phil's recollection (since ER&S had given all their WTC tracings to our Planning Division) was as follows:

   A. The egress requirement and fire ratings used to design the WTC Towers & Plaza Buildings were in accordance with the provisions of the planned NYC Building Code revisions effective December 8, 1968. Normally fire ratings are not shown on the Architectural Working Drawings or in the General Notes. The fire ratings are given only on the application forms filed with the plans for NYC Building Department Approval. Since the Port Authority is not subject to the NYC Building Code Requirements, no plans or forms were filed.

   B. For office buildings there is no economic advantage in using Class 1A Construction, and ER&S used Class 1B Construction for the WTC Towers and Plaza Buildings which are Occupancy Group "E" (Business) with a fire index of 2 hours. As such, columns must have 3 hour fire rating and floor construction with a 2 hour rating.

3. Please note that Reference #3 by Mal Levy was concurred in by W. Bracco (TRCC) in Reference #4, with regard to Class 1-B Construction cited by Mr. Martinez. In addition, References #1 & #2 (written in 1965) are superseded by References #3 & #4 (written in 1969).

Figure A–7. Port Authority memorandum indicating that WTC towers were classified as Class 1B Construction (3-P).

4. For your information and use I have also attached References #5 & #6 on the UL Test of floor construction showing a 3 hour rating. Please note that the UL Test is based on the use of 1½" thick Monokote Fireproofing on joists and ½" thick Monokote on steel deck. Actually - Cafco - Type "D" spray-on was used at the WTC on joists only, in lieu of Monokote. In addition, the UL Test used stone-concrete slab with a thickness of 2' 3/4" over top of corrugated deck, as compared to the 4" lightweight concrete slab used at the WTC.

5. With regard to Reference #7, no joists were used in the floor construction of 3 WTC, 4 WTC, or 5 WTC - rolled beam are used in all Plaza Buildings. Mr. Martinez (ER&S) Mal Levy (Reference #3) & TRCC (Reference #4) all concur that the Plaza Buildings are Class 1B Construction.

6. In addition, Issue "A" of the "Tower Office Space Design Guide" prepared by the WTC Planning and Construction Division (with Errata Sheet #1 to Issue A - dated March 23, 1970) - Page 4 - Item C1 (attached as Reference #8) verifies that the towers are class 1B Construction.

Lester S. Feld
Chief Structural Engineer
World Trade Department

Figure A–7 (Contd.). Port Authority memorandum indicating that WTC towers were classified as Class 1B Construction (3-P).

COPY

EMERY ROTH & SONS
850 THIRD AVENUE
NEW YORK, N. Y. 10022

February 11, 1969

Mr. Joseph A. Schwartzman
The Port of New York Authority
111 Eighth Avenue
New York, N. Y. 10011

RE: WORLD TRADE CENTER
TOWERS "A" and "B"
SPRAY-ON FIREPROOFING

Dear Joe:

In checking out your printed copy of the "Spray-On Fireproofing" specification, it has been noticed that someone in your office has taken the liberty of rewriting the original specification, making it almost totally unrecognizable. In the process of rewriting the specification, a key paragraph seems to have been omitted in its entirety, reading as follows:

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

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

Very truly yours,

EMERY ROTH & SONS

BY
DOUGLAS FERNANDEZ

DF:srf

Figure A–8. Letter from Emery Roth & Sons to Port Authority regarding specification for sprayed thermal insulation (3-P).

ATTACHMENT A PAGE 3

Standpipe Hose Stations

6. Several standpipe and auxiliary hose stations do not provide coverage of all portions of all floor areas within the required 145 feet of any given hose's effective reach. Further, some hose racks are equipped with 150 feet of hose in lieu of the standard 125 feet, and provide coverage for 170 feet.

It is recommended that the Port Authority establish a program to survey all tenanted floors to identify areas inadequately covered, and to remediate such inadequacies as quickly as possible.

Also, it is recommended that approval be obtained from the New York City Fire Department for the existing 150 foot long hoses.

Standpipe Telephone Jacks

7. **The requirement that permanent telephone jacks be installed on each floor near standpipe risers has been addressed.** Permanent standpipe telephone jacks have been installed and activated on each floor level of all fire stairways in both towers.

Smoke Vents

8. All closed shafts having a cross-section area exceeding four (4) square feet are required to be equipped with a smoke vent. Although the return air shafts currently have the means to exhaust smoke-laden air directly to the outside by mechanical means, **it is recommended that the Port Authority investigate methods by which this overall requirement maybe satisfied.**

Sprinkler Protection

9. Of At this writing, only four (4) tenanted floors (all in 1 WTC) have not been sprinklered. those floors, the sprinklerization of floors 17, 30, and 33 will be completed by the end of this year (*1997*). 1997

Additionally, as referenced in Item ! above, plans will be made to sprinkler the MER's and the skylobbies in both towers.

All four (4) floors noted above (floor 19 was not mentioned by Mr. Coty of Rolf Jensen) have been completed at this time. Also, the Sky Lobbies sprinklerization are currently underway. PA update 1999

Return Air Smoke Detectors

10. Although smoke detectors or combination smoke/heat detectors are required at each inlet to a return air shaft on each floor, our survey indicated that such detectors may not have been installed at all required locations.

This has been addressed via a Port Authority contract which will be handling new, addressable smoke detectors at each return air intake above the suspended ceilings beginning July 1997 and completed by December 1999.

Figure A–9. Excerpt from 1999 code compliance evaluation indicating progress since a similar 1997 evaluation (161-P).

M&H

One World Trade Center

World Trade Center
New York, New York

The ADA sets forth "recommended priorities for public accommodations" to be accessible to the disabled. In general, the three priorities are as follows:

1. Access from public sidewalks, parking, or public transportation to a building entrance;
2. Access to any areas of goods and services that are made available to the public; and,
3. Access to rest room facilities.

During our tour of the project, we noted the following:

The building's primary entrance is from West Street into the Tower lobby through automatic power operated entrance doors. The path to the elevators is accessible. The Concourse entrance also has 2 sets of automatic doors.

The Plaza Level main entrance has 2 sets of swing doors, without automatic door opening hardware. Provide door-opening hardware on 1 set of swing doors to make the entrance accessible.

The banks of local elevators and mid-zone express elevators are equipped with car control panels that comply substantially with ADAAG. Two upper zone elevators (19 and 19) are not equipped with complying car controls.

Some (approximately 25%) toilet rooms have had upgrades for ADA requirements, but in most rooms observed, there were noncompliant items such as lack of full size ADA toilet stalls, and ADA compliant urinals. ADA compliance on most full tenant floors is reportedly the responsibility of the tenant under terms of the lease.

12. Code Compliance

Applicable Code	1968 NYC Building Code as Administered by the Port Authority of New York and New Jersey
Building Construction Classification	Class1-B - noncombustible, fire-protected, retrofitted with sprinklers in accordance with Local Law 5/1973
Occupancy Type	Group E - Business

December 6, 2000 20-251E - Section V-1 - Page 24

Figure A–10. Excerpt from 2000 property condition assessment of the WTC towers indicating construction classification (7-P).

Truss Fireproofing Systems

Early discussions for fireproofing systems for the floor truss work covered nearly every conceivable method. Port Authority staff as well as the architectural and structural consultants sought efficient and economical systems; the structural steel industry proposed alternative methods.

In early 1963 project estimates carried an allowance for a "demountable ceiling" providing the needed fire protection for the steel floor trusses. The problems of fire dampers for such a ceiling were discussed at length.

By late 1964 a series of alternate contact fireproofing systems had been investigated with some cost data assembled.

By late 1965 the use of a spray-on material similar to Cafco or Mono-Kote appears to have been selected. The ERS letters of December 14 and 23, 1965 are clear on this point. Only the required thickness appears to have been in doubt. (see pages 5.1 and 5.2).

"Demonstrations" of fireproofing systems were carried out by various vendors. For example, on Aug. 7 and 8, 1967, the application on Laclede trusses Mono-Kote fireproofing was demonstrated to Mr. Feld and others (1"thickness). In September of 1967 Messrs. Monti and Solomon appear to have wittnessed spray tests making use of U.S. Mineral Products Co. "Cafco".

Figure A–11. Excerpt from 1975 post-fire report prepared by Skilling, Helle, Christiansen, Robertson (3-P).

CC: W. M. Akin
P. B. Akin
H. R. Kilpatrick
A. C. Weber
R. D. Bay
J. R. Paul

August 10, 1967

OFFICE MEMORANDUM

BLOWN ON FIREPROOFING
LACLEDE STEEL JOISTS

During the past week two test applications of blown on fireproofing on Laclede joists and trusses have been accomplished by the U. S. Gypsum Company and the Zonolite Division of W. R. Grace and Company.

This testing, primarily concerned with the floor trusses of the World Trade Center, has been necessary to provide information to the Port of New York Authority engineers on the amount of loss they might expect from a spraying operation on open web structures.

The U. S. Gypsum Company materials, primarily a gypsum and asbestos combination of fibrous material, was applied at the Cupples Company plant of the Aluminum Company of America on Hanley Road on the wall structure that is currently being tested for wind and temperature variations.

The Zonolite Company material made up primarily of vermiculite and gypsum plaster is a much harder cementaecous coating that seems to apply better than the so-called Cafco (U. S. Gypsum material).

A set of 24H8 joists electro coated in the same fashion that the World Trade Center joists will be painted were set up at Madison and with 1/2" and 3/8" nozzles, the Leroy Thompson Plaster Company of Belleville, Illinois coated six joists, two of them with only a single coat to demonstrate the material adherence.

It is apparent that a single coating or scratch coat can be applied as quickly as a man can pass across web and chord sections of the joists leaving a thickness of 3/8" to 1/2" completely incasing all metal.

With a one to two day drying time, depending on the humidity, a second and final coat to a 1" thickness can be easily applied, and according to figures from the Zonolite engineers, a remarkably low percentage of material loss results. Less than 15% material was shot through the joists and lost. With this low material loss it has been pointed out that the use of material is far less than would be required for solid section beams previously considered for spray insulation and is no more than would be experienced with angle and flat section trusses.

Figure A–12. Intra-office correspondence at Laclede Steel Co. regarding 1967 demonstration of sprayed application of thermal insulation to floor trusses (70-I).

- 2 -

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

It is anticipated that the U. S. Gypsum Company will be doing further testing on small web trusses at their plant in Stanhope, New Jersey since Ray Monti the general superintendent of the World Trade Center called yesterday to ask if we would provide joists similar to those used by Zonolite for U. S. Gypsum. A New York plastering contractor that is normally the applicator for U. S. Gypsum products in New York, Mario DeBono, is the contractor with whom we would be working if U. S. Gypsum material would be specified.

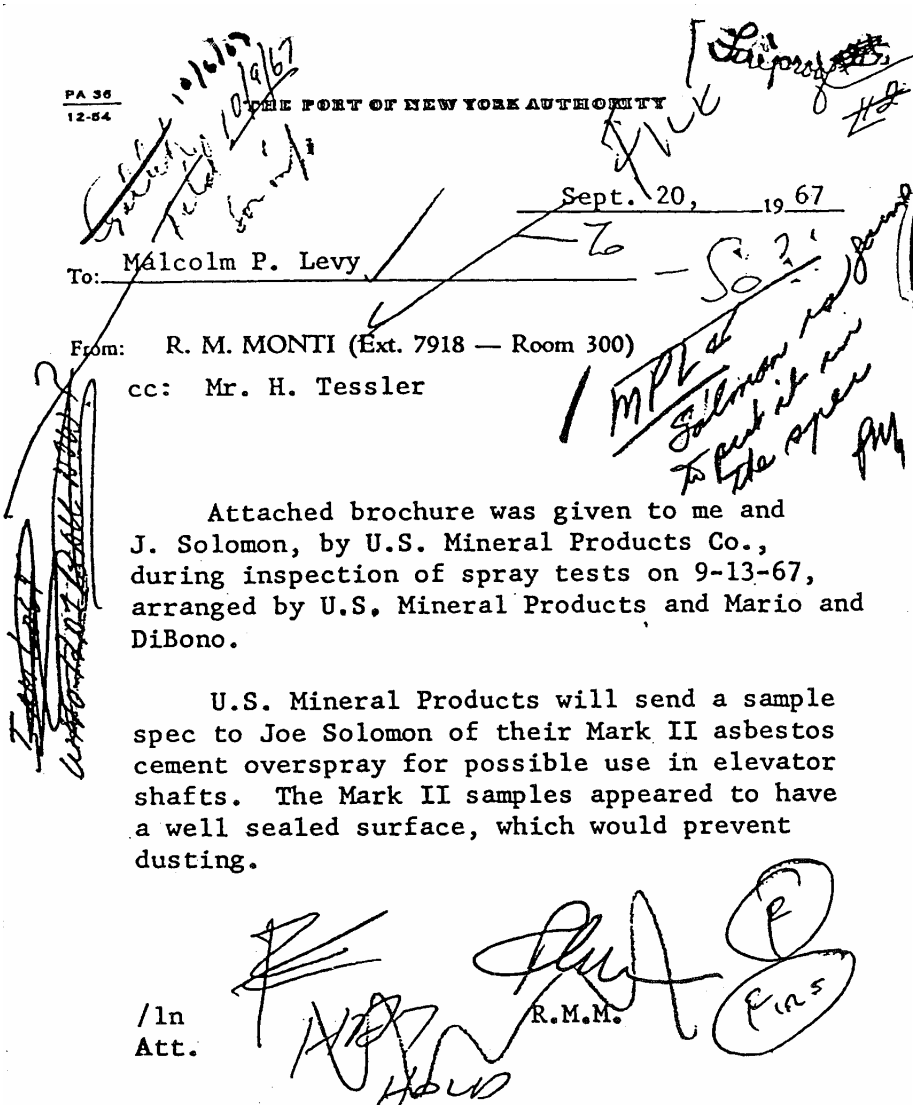
Mr. DeBono is to call us with an order for electro coated 24" trusses, and according to the Port Authority, will be paying for them since this is a research that U. S. Gypsum is intending to perform without others observing the results. From what I gather, various types of surrounding nozzles are proposed by the DeBono people and they are not anxious to have their competitors learn of their application plans.

In any event, the fireproofing of joists seems to be a problem now solved, and in the World Trade Center as well as in other steel joist structures, we may be sure that an economical fireproofing can be effected in the field without the expense of a heavy ceiling construction.

A. C. Weber

ACW:pjz

Figure A–12 (Contd.). Intra-office correspondence at Laclede Steel Co. regarding 1967 demonstration of sprayed application of thermal insulation to floor trusses (70-l).



PA 36
12-54

THE PORT OF NEW YORK AUTHORITY

Sept. 20, 1967

To: Malcolm P. Levy

From: R. M. MONTI (Ext. 7918 — Room 300)

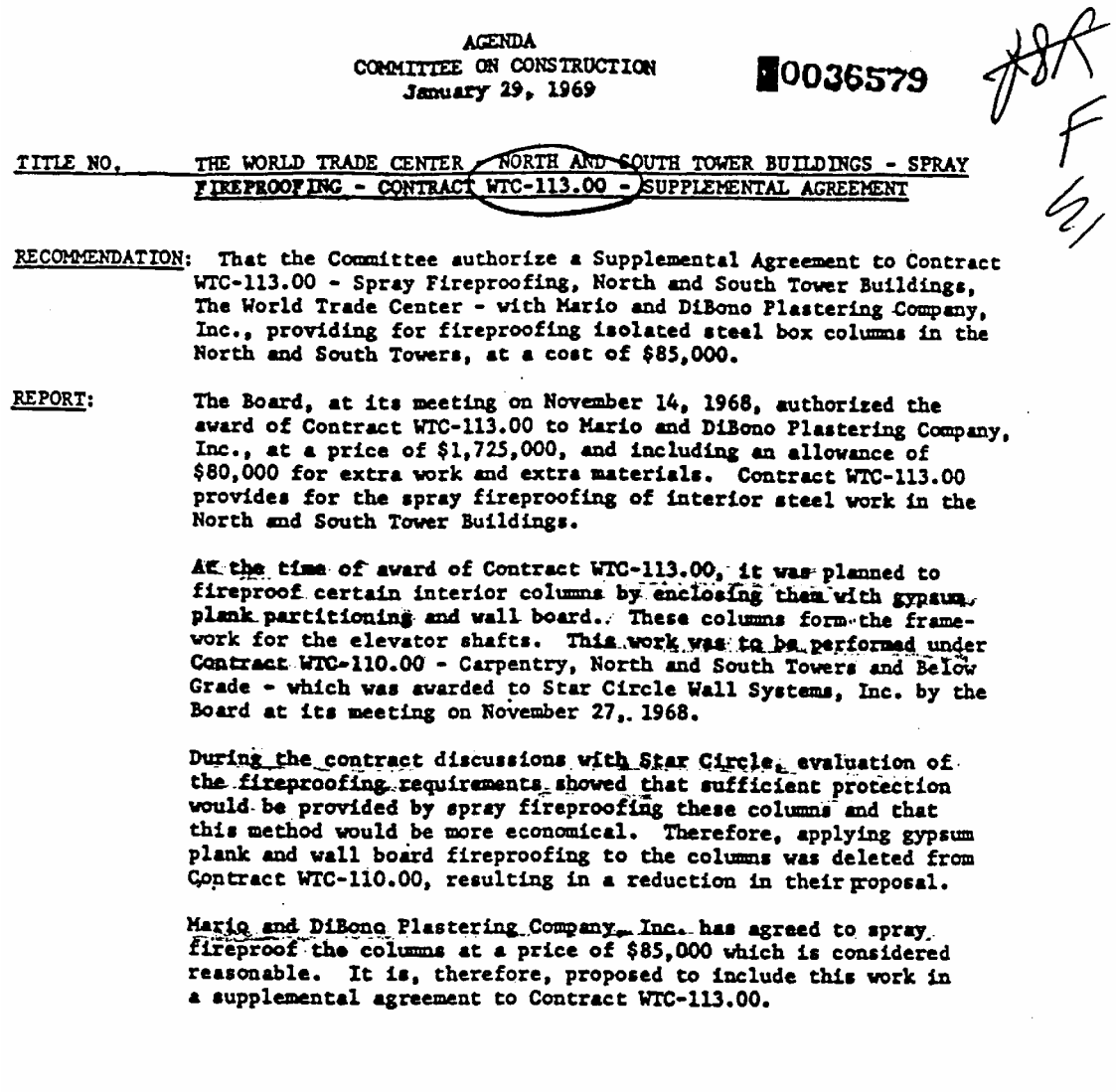
cc: Mr. H. Tessler

Attached brochure was given to me and J. Solomon, by U.S. Mineral Products Co., during inspection of spray tests on 9-13-67, arranged by U.S. Mineral Products and Mario and DiBono.

U.S. Mineral Products will send a sample spec to Joe Solomon of their Mark II asbestos cement overspray for possible use in elevator shafts. The Mark II samples appeared to have a well sealed surface, which would prevent dusting.

/ln R.M.M.
Att.

Figure A–13. Port Authority intra-office memorandum indicating demonstration of the application of thermal insulation from U.S. Mineral Products Co. was completed in August 1967 (176-ITK).



AGENDA
COMMITTEE ON CONSTRUCTION
January 29, 1969

0036579

TITLE NO. THE WORLD TRADE CENTER - NORTH AND SOUTH TOWER BUILDINGS - SPRAY FIREPROOFING - CONTRACT WTC-113.00 - SUPPLEMENTAL AGREEMENT

RECOMMENDATION: That the Committee authorize a Supplemental Agreement to Contract WTC-113.00 - Spray Fireproofing, North and South Tower Buildings, The World Trade Center - with Mario and DiBono Plastering Company, Inc., providing for fireproofing isolated steel box columns in the North and South Towers, at a cost of $85,000.

REPORT: The Board, at its meeting on November 14, 1968, authorized the award of Contract WTC-113.00 to Mario and DiBono Plastering Company, Inc., at a price of $1,725,000, and including an allowance of $80,000 for extra work and extra materials. Contract WTC-113.00 provides for the spray fireproofing of interior steel work in the North and South Tower Buildings.

At the time of award of Contract WTC-113.00, it was planned to fireproof certain interior columns by enclosing them with gypsum plank partitioning and wall board. These columns form the framework for the elevator shafts. This work was to be performed under Contract WTC-110.00 - Carpentry, North and South Towers and Below Grade - which was awarded to Star Circle Wall Systems, Inc. by the Board at its meeting on November 27, 1968.

During the contract discussions with Star Circle, evaluation of the fireproofing requirements showed that sufficient protection would be provided by spray fireproofing these columns and that this method would be more economical. Therefore, applying gypsum plank and wall board fireproofing to the columns was deleted from Contract WTC-110.00, resulting in a reduction in their proposal.

Mario and DiBono Plastering Company, Inc. has agreed to spray fireproof the columns at a price of $85,000 which is considered reasonable. It is, therefore, proposed to include this work in a supplemental agreement to Contract WTC-113.00.

Figure A–14. Agenda item for January 29, 1969 meeting of Committee on Construction regarding modification to sprayed fire protection contract (120-ITK).

7. The World Trade Center - North and South Tower Buildings - Spray Fireproofing - Contract WTC-113.00

It was reported to the Committee that Contract WTC-113.00 requires the contractor to spray the structural steel of the North and South Tower Buildings of The World Trade Center with a mixture of asbestos, cement and water, which, when hardened, will provide the necessary fire protection for the structure.

The Board, at its meeting on January 12, 1967, authorized the award of Contract WTC-400.00 - North and South Tower Buildings, Curtain Wall, The World Trade Center - to Aluminum Company of America. Under this contract, Alcoa will provide spray-on fireproofing and plastering to the exterior columns of the North and South Tower Buildings. Alcoa sub-contracted this work to Mario and DiBono Plastering Company, Inc., who performed extensive tests of various methods of providing fireproofing which would meet specifications.

The fireproofing mixture will be applied to the erected steel on each floor and must be completed before any other work on a floor can proceed. In view of this, it was evident that the interior and exterior fireproofing applications would have to be closely coordinated. Staff determined that contract administration problems would be minimized and coordination between the fireproofing work on the interior structural steel and the exterior columns would be facilitated if a single contractor were to perform such work. Therefore, discussions were held with Mario and Di Bono on the interior fireproofing work and resulted in the submission of a proposal of $1,725,000, including $925,000 for work and $800,000 for sale.

The Project Estimate for Contract WTC-113.00 is $1,625,000, exclusive of an allowance of 5% for extra work and extra materials.

Mario and DiBono Plastering Company, Inc., is qualified to perform the work under Contract WTC-113.00. In the past, they have provided all interior finish plastering, exterior cement plastering and interior and exterior fireproofing for such projects as the International Arrivals Building at Kennedy International Airport; Madison Square Garden; Two Penn Plaza; Rochdale Village, Jamaica, Long Island, consisting of twenty 14-story buildings; and Co-op City in the Bronx, New York.

Recommendation was made that the Committee recommend to the Board that the Board authorize the award of Contract WTC-113.00 - Spray Fireproofing, North and South Tower Buildings, The World Trade Center - to Mario and DiBono Plastering Company, Inc., at a price of $1,725,000 and an allowance of $80,000 for extra work and extra materials.

Approved and recommended to the Board.

Figure A–15. Excerpt from October 30, 1968 minutes of the Committee on Construction regarding the sprayed fire protection contract (123-ITK).

TISHMAN REALTY & CONSTRUCTION CO., INC.
666 FIFTH AVENUE
NEW YORK, N.Y. 10019

OWNERS AND BUILDERS SINCE 1898

JUDSON 2-6700

THE PORT OF NEW YORK AUTHORITY
RECEIVED
APR 1 1966
WORLD TRADE DEPARTMENT
WORLD TRADE CENTER
PLANNING DIVISION

MARCH 30, 1966

PORT OF NEW YORK AUTHORITY
111 EIGHTH AVENUE
NEW YORK, NEW YORK 10011

ATTENTION: MR. R. M. MONTI, RES. ENGINEER - WORLD TRADE CENTER

RE: FIREPROOFING COST COMPARISON
WORLD TRADE CENTER

DEAR RAY:

WE ARE TRANSMITTING HEREWITH OUR COST COMPARISON AND RECOMMENDATIONS FOR SPRAYED FIREPROOFING. THIS ANALYSIS COMPARES THE COSTS AND MERITS OF VONCO 2, CAFCO TYPE D, SPRAY-CRAFT, FIRECODE V AND MONOCOAT SPRAY MATERIALS. WE HAVE SELECTED FOR COMPARISON, ONLY THOSE SYSTEMS FOR WHICH UNDERWRITERS' LABORATORIES INC. AND/OR NEW YORK BOARD OF STANDARDS AND APPEALS APPROVALS ALREADY EXIST OR ARE IMMINENTLY EXPECTED.

THE ANALYSIS SHOWS AUTHORITY, STRUCTURAL MEMBER SIZE AND FUNCTIONAL FIREPROOFING THICKNESS REQUIRED, FIRE RATING IN HOURS, AS WELL AS COST PER SQUARE FOOT FOR MATERIAL AND LABOR AT THE INDICATED THICKNESS. WE HAVE ALSO INTERJECTED BY NOTE, INFORMATION WHICH WE FEEL IS PERTINENT TO PERFORMANCE AS WELL AS POSSIBLE, HIDDEN ECONOMIES OR EXPENSES.

VERY TRULY YOURS,

TISHMAN REALTY & CONSTRUCTION CO., INC.

JAMES R. ENDLER
ASSISTANT VICE PRESIDENT

ENCL.
DU

USM-002657

DEFENDANT'S EXHIBIT DX 282

Figure A–16. Correspondence related to study of alternative thermal insulation materials (432-P).

WORLD TRADE CENTER - FIREPROOFING ANALYSIS

RECOMMENDATIONS

PRESENTLY, IT APPEARS THAT THE SPRAYED FIBER MATERIALS (CAFCO AND SPRAY CRAFT) ENJOY A SLIGHTLY MORE ECONOMICAL APPLIED COST PER SQUARE FOOT THAN THE SPRAYED CEMENTITIOUS (FIRECODE V AND MONOCOAT) MATERIALS BUT NOT ENOUGH TO PRECLUDE KEEPING BOTH IN COMPETITION UNTIL A FINAL BUY IS MADE. NOTE THAT THE FIBER SUPPLIERS HAVE NOT CONDUCTED AS EXTENSIVE A FIRE TESTING PROGRAM AS HAVE THE CEMENTITIOUS MATERIAL MANUFACTURERS. SINCE MORE DATA IS AVAILABLE IN THE LATTER INSTANCE, MORE ACCURATE INTERPOLATION IS POSSIBLE HERE WITHOUT EXPENSIVE ADDITIONAL TESTING.

THE REMOVAL OF BOTH THE TAMPING AND ADHESIVE REQUIREMENTS (BY ACTUAL U.L.I. AUTHORITY) FROM THE FIBER APPLICATIONS, THE APPARENT ABILITY TO SPRAY FIBER WITH ACCURACY FROM THE FLOOR USING THE NEWLY DEVELOPED POLE-FIBER-GUN AND THE RELATIVE EASE OF CLEAN-UP WITHOUT SCRAPING OF OVER SPRAYED MATERIAL, GENERALLY CONTRIBUTES TO THE EDGE IN ECONOMY OF THE FIBER MATERIALS.

THE POSSIBLE REQUIREMENT (ASSUMING THAT AN EXTERIOR GYPSUM BOARD ASSEMBLY PROVES ITSELF) OF CONFINED SPRAYING BETWEEN THE CURTAIN WALL AND EXTERIOR BOX COLUMNS AS WELL AS BETWEEN THE CURTAIN WALL AND EXTERIOR SPANDREL MEMBERS, COULD GIVE THE FIBER MATERIAL AN ADDED ADVANTAGE OVER CEMENTITIOUS, SINCE FIBER EQUIPMENT APPEARS MORE VERSATILE AND EASILY ADAPTABLE TO FAN SPRAYS, NOZZLE MIXING OR SLURRY MIXING (GROUT), SIMPLY BY CHANGING EXISTING SPRAY HEADS OR ADAPTING NEW HEAD CONFIGURATIONS IF EXISTING EQUIPMENT CANNOT BE SATISFACTORILY CONTROLLED.

THE ABILITY OF THE CEMENTITIOUS MATERIAL TO HARDEN OR CRUST AFTER APPLICATION IS A PLUS FOR THIS MATERIAL SINCE DUCT WORK GENERALLY IS SCHEDULED FOR INSTALLATION (BETWEEN TRUSSES) AFTER THE FIREPROOFING OF STEEL, WITH RESULTING DAMAGE TO FIREPROOFING BEING MINIMIZED. MATERIAL COSTS HAVE BEEN DROPPING AND MAY NOT HAVE REACHED BOTTOM.

IT IS RECOMMENDED THAT BOTH SPRAYED FIBER AND SPRAYED CEMENTITIOUS SUBCONTRACTORS BE PLACED IN A COMPETITION WITH EACH OTHER WITH INSTRUCTIONS FOR LOGICAL INTERPOLATION OF REQUIRED THICKNESS OF THEIR RESPECTIVE MATERIALS BASED ON ACTUAL OR UNPUBLISHED UNDERWRITERS' LABORATORIES APPROVALS.

WE ARE IN THE PROCESS OF EVALUATING THE ECONOMICS OF VONCO MAGNESIUM SPRAY VERSUS A SPECIAL WATERPROOFED LAMINATED ASSEMBLY OF GYPSUM BOARD SHEETS FOR THE EXTERIOR OF THE COLUMNS AND SPANDRELS ONLY (WHERE MOISTURE OR TEMPERATURE PRECLUDES OTHER MATERIALS, IN OUR OPINION, WITHOUT EXCESSIVE RE-WORK).

VONCO IS TOO COSTLY FOR FURTHER CONSIDERATION FOR INTERIOR FIREPROOFING APPLICATION.

WHEN THIS ANALYSIS IS COMPLETE, WE WILL RECOMMEND THE MOST ECONOMICAL APPROACH TO THE PROJECT'S EXTERIOR FIREPROOFING REQUIREMENTS. AT THIS TIME, THERE APPEARS JUSTIFICATION TO PURSUE THE INVESTIGATION OF THIS PREFABRICATED LAMINATED ASSEMBLY OF EITHER THE STANDARD 5/8" FIRECODE GYPSUM BOARD OR A SPECIAL BOARD MADE OF FIRECODE V MATERIAL WHICH CONCEIVABLY WILL PERMIT A 4 HOUR RATING WITH A SINGLE 1 1/8" THICK BOARD (U.L.I. 31-4 REVISED) FOR APPLICATION TO THE EXTERIOR FACE OF THE EXTERIOR BOX COLUMNS, PERMITTING THE ERECTION OF CURTAIN WALL AND THE CLOSING IN OF THE TOWER STRUCTURE PRIOR TO APPLICATION OF THE INTERIOR SPRAYED

USM-002661

Figure A–16 (Contd.). Correspondence related to study of alternative thermal insulation materials (432-P).

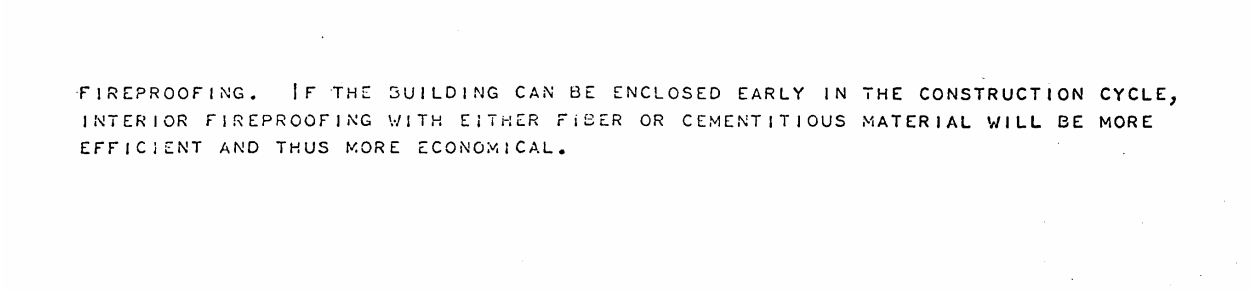

FIREPROOFING. IF THE BUILDING CAN BE ENCLOSED EARLY IN THE CONSTRUCTION CYCLE, INTERIOR FIREPROOFING WITH EITHER FIBER OR CEMENTITIOUS MATERIAL WILL BE MORE EFFICIENT AND THUS MORE ECONOMICAL.

Figure A–16 (Contd.). Correspondence related to study of alternative thermal insulation materials (432-P).

WORLD TRADE CENTER

EXTERIOR WALL, SPANDRELS AND EXTERIOR COLUMN INSULATIONS

THERMAL CONDUCTIVITY AND HEAT TRANSMISSION COEFFICIENTS

Value Based on Wall & Column Design As of 5/5/66
Drawing A-A-314

Fireproofing Material	Conductivity (k) BTU HR-SF-8F-IN	"U" - Coefficient Transmission - BTU/HR-SF-OF At Sides of Column		At Outside Face of Column (W/Air Space)		
		With 1 5/8" F. P.& Air Space	1 5/8" F. P.+ 3/8" Urethane No Air Space	With 1 5/8" F. P.	1 5/8" F. P.+ 3/8" Urethane	With 2" F.P. and 3/8" Polyurethane
1. Sprayed Mineral Fiber (Spraycraft)	.26	0.135	0.116	.136	.104	.092
2. Sprayed (Cementitious) Vermiculite (Monokote)	.75	0.302	.221	.302	.182	0.167
3. Laminated Gypsum Board (U.S.G. FireCode)	1.11	0.385	.261	.385	.209	.195
4. Concrete (L.W. 100 PCF)	3.57	0.630	.353	.625	.264	.256
5. Vonco	.38	0.185	.151	.185	.131	0.116
6. Cafco	.27	0.140	.119	.140	0.107	0.093

192-99

Notes:
1. Fireproofing for inside face of column is assumed to be 1 3/8" gupsum plaster having conductivity of 1.56 and the overall transmission coeff. of .396 between the room and column steel.
2. Inside still air film resistance is taken as .68
3. Outside air film resistance is taken as .17
4. Air space resistance is taken as .97
5. Conductivity of polyurethane is taken as .17

NC:rt,dd,fk

Figure A–17. Thermal conductivity and heat transfer coefficients of candidate thermal insulation materials for exterior columns (437-P).

THERMAL INSULATION

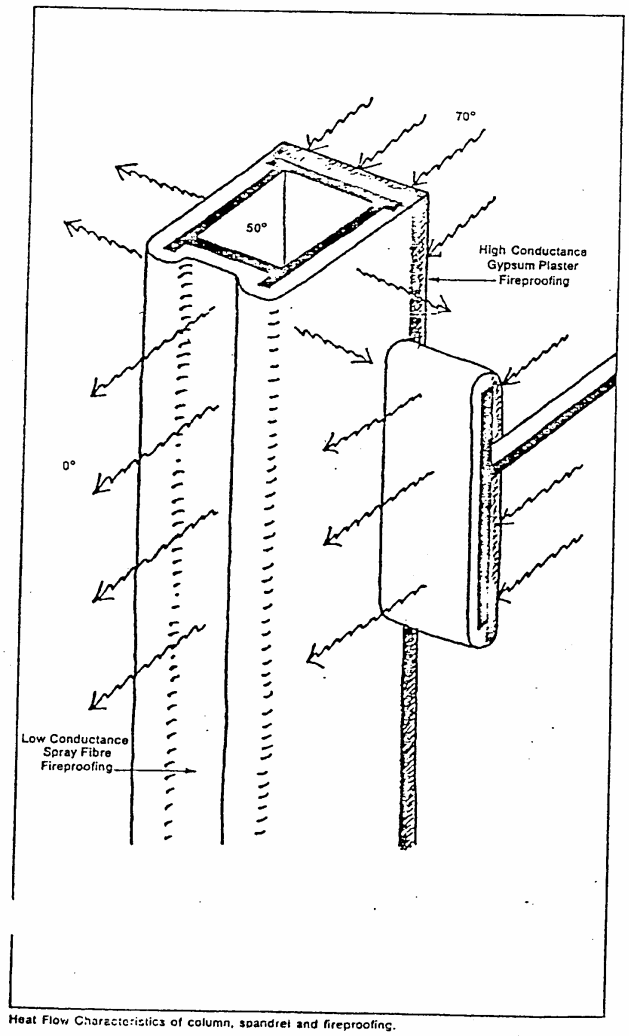
The insulation materials applied to the structural steel components of the wall (columns and spandrels) must serve to control column temperature to a minimum of 50° with 70° inside and 0° outside, provide fireproofing to meet a four hour test on a heavy column, and minimize heat loss and gain to satisfy HVAC requirements. After extensive testing of many insulating and fireproofing materials, a sprayed mineral fibre has been selected to meet all requirements of the three purposes above. It will be used on the three exterior sides of the column and both sides of the spandrel plate. The *room* side of the column will be covered with gypsum plaster to meet fireproofing requirements with a relatively high "K" value to permit heat migration to the steel. This migration is necessary to hold steel temperatures above specified minimum during extreme and prolonged cold periods.

Thermal Testing

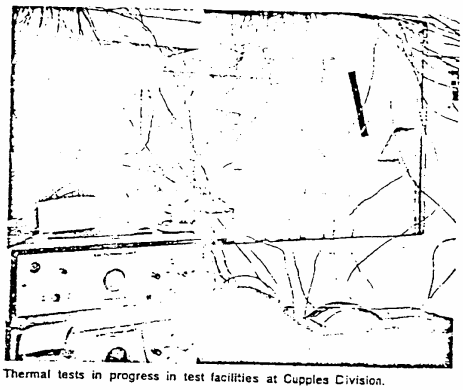
The minimum column steel temperatures of 50°F requires strategic use of both high "K" and low "K" fireproofing. Since the required thermal balance results from a combination of many factors, calculations can be only a rough guide to design and true performance can be determined only by actual test.

Such tests have been performed at Cupples on three 5' sections of columns completed in full detail typical of the 100th floor. Two units were assembled in a dividing partition of the thermal chamber at Cupples with thermocouples mounted on the steel, top and bottom and inside to outside. "Outside" temperature on one side of the partition was reduced to 0°F and "Inside" temperature was controlled at 70°F until steel had reached thermal balance when results were recorded. A third unit was tested similarly at Pennsylvania State University in the thermal chambers of the Institute for Building Research.

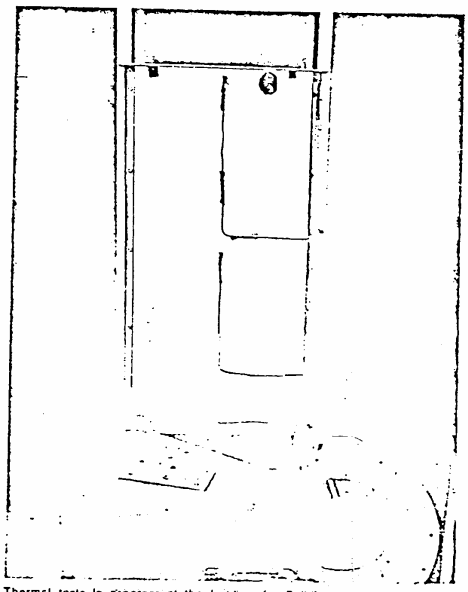
Complete details of tests and results are included in the pocket at the back of this book.



Heat Flow Characteristics of column, spandrel and fireproofing.



Thermal tests in progress in test facilities at Cupples Division.



Thermal tests in progress at the Institute for Building Research, Pennsylvania State University.

Figure A–18. Excerpts from Alcoa proposal for exterior wall of WTC (448-P).

Hoisting—All hoisting would be done after regular working hours from 4 P.M. to approximately 8 P.M. Assuming the inside dimension of the hoist platform to be 7'4" x 13'3", each lift will include one mobile cart carrying two 1800# packages.

Distribution and Floor Storage—On the designated floor the mobile carts would be moved to storage areas allotted for the purpose. A minimum of six and as many as ten floors of material would be so stored ahead of the actual erection. Glass would be handled on the inside job hoist in cases weighing 3,600 lb. The cases would be handled, moved and stored on the floors in the same manner as the metal components.

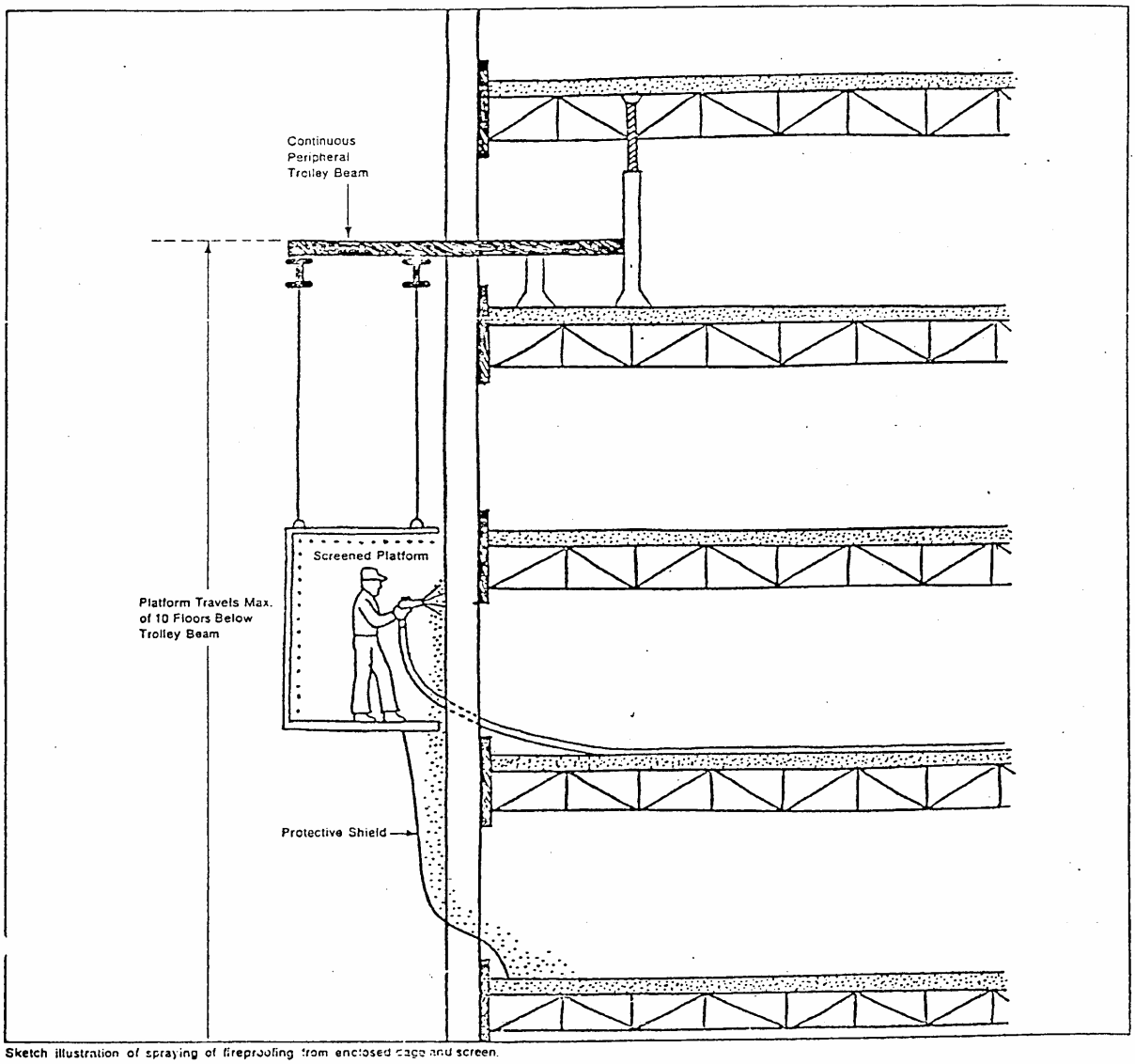
FIREPROOFING

Sprayed fiber material as manufactured by CAFCO and of a type described in Underwriters Laboratories report R 3749-10 will be applied to three sides of the exterior columns thick enough to provide four hour fire protection and to maintain the proper thermal insulations. The required thicknesses to meet fireproofing requirements are 1 1/16" for exterior columns and ½" for spandrels. As space permits, the thickness can be increased to obtain the required thermal characteristics.

On the inner side of the columns, a high "K" value material will be applied to provide fireproofing while also permitting heat migration from room air to column steel.

The sprayed fiber will resist the elements during construction of the curtain wall, remain firm to the touch and will not reduce in thickness with time. (See copy of CAFCO Bulletin C-940 in pocket at rear of book). Application would be accomplished with a special nozzle and a transportable cage to safely project the applicator to the exterior of the building. Adjustable vertically, the cage would permit complete coverage of the outer faces of columns and spandrel beams. A screen would be provided around the spray zone to prevent the "blow-by" of fiber material to the exterior of the building and the street below.

Fireproofing in progress would be approximately ten floors above the aluminum wall,



Sketch illustration of spraying of fireproofing from enclosed cage and screen.

Figure A–18 (Contd.). Excerpts from Alcoa proposal for exterior wall of WTC (448-P).

PA 90-A
5-63

MEMORANDUM

0011788

REFER TO	DATE	NOTED BY	DATE
RETURN TO		FILE	

TO: Mr. R. M. Monti
FROM: A. J. Calabrese
DATE: August 8, 1967
SUBJECT: COLUMN AND SPANDREL FIREPROOFING OBSERVED AT ALCOA PLANT

REFERENCE:

COPY TO:

I went to Alcoa-Cupples plant in St. Louis on August 3, 1967 on an inspection of column and spandrel fireproofing of mock-up.

Mario and D'Bono - plasterer - contractor representative was a Mr. Louis D'Bono and Cafco representative was a Mr. A. Bessemer.

The above mentioned and I were present when columns and spandrels were sprayed with Cafco Blaze Shield Fireproofing Type "D" on August 3 and 4, 1967.

It is my opinion that the method of applying was done in a workmanship like manner. It is also my opinion that the method of applying was done with ease and very little spillage.

A. J. Calabrese

AJC/eam

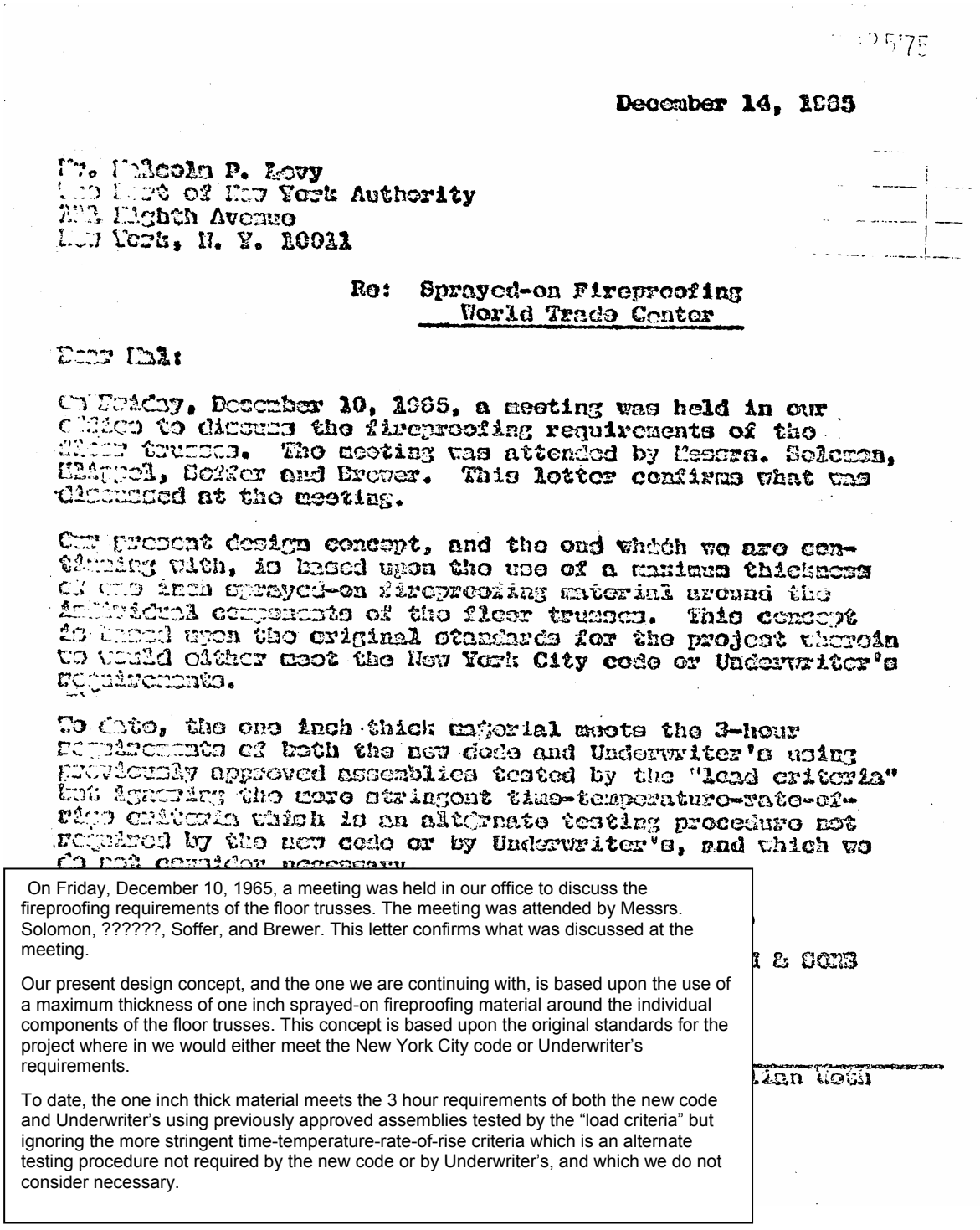
THE PORT OF NEW YORK AUTHORITY
RECEIVED
AUG 8 1967
WORLD TRADE DEPARTMENT
WORLD TRADE CENTER
PLANNING DIVISION

PLAINTIFF'S EXHIBIT
PX-470

A-B-C-F
1-4-5F-5G
5J-5K-6-7-8
9-10B-10C
II1-II3-II4 II2

(19)

Figure A–19. Port Authority correspondence related to demonstration of application of CAFCO BLAZE-SHIELD to mockup of exterior columns and spandrels (384-P).



December 14, 1965

Mr. Lincoln P. Levy
Port of New York Authority
111 Eighth Avenue
New York, N. Y. 10011

Re: Sprayed-on Fireproofing
World Trade Center

Dear Sir:

On Friday, December 10, 1965, a meeting was held in our office to discuss the fireproofing requirements of the floor trusses. The meeting was attended by Messrs. Solomon, Schaper, Soffer and Brewer. This letter confirms what was discussed at the meeting.

Our present design concept, and the one we are continuing with, is based upon the use of a maximum thickness of one inch sprayed-on fireproofing material around the individual components of the floor trusses. This concept is based upon the original standards for the project wherein we would either meet the New York City code or Underwriter's requirements.

To date, the one inch thick material meets the 3-hour requirements of both the new code and Underwriter's using previously approved assemblies tested by the "load criteria" but ignoring the more stringent time-temperature-rate-of-rise criteria which is an alternate testing procedure not required by the new code or by Underwriter's, and which we do not consider necessary.

On Friday, December 10, 1965, a meeting was held in our office to discuss the fireproofing requirements of the floor trusses. The meeting was attended by Messrs. Solomon, ??????, Soffer, and Brewer. This letter confirms what was discussed at the meeting.

Our present design concept, and the one we are continuing with, is based upon the use of a maximum thickness of one inch sprayed-on fireproofing material around the individual components of the floor trusses. This concept is based upon the original standards for the project where in we would either meet the New York City code or Underwriter's requirements.

To date, the one inch thick material meets the 3 hour requirements of both the new code and Underwriter's using previously approved assemblies tested by the "load criteria" but ignoring the more stringent time-temperature-rate-of-rise criteria which is an alternate testing procedure not required by the new code or by Underwriter's, and which we do not consider necessary.

Figure A–20. Correspondence from Emery Roth & Sons to Port Authority related to thickness of thermal insulation for floor trusses (text in box was typed by NIST since copy of document is of poor quality) (3-P).

COPY

EMERY ROTH & SONS, ARCHITECTS
850 THIRD AVENUE
NEW YORK 22, N. Y.

December 23, 1965

Mr. Malcolm F. Levy
The Port of New York Authority
111 Eighth Avenue
New York, N.Y. 10011

Re: Sprayed-on Fireproofing
World Trade Center

Dear Mal:

This supplements my December 14th letter to you.

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

By informational copy of this letter, all consultants are requested to review their designs and drawings, and to make all necessary changes to meet this new criteria.

Sincerely,

EMERY ROTH & SONS

BY: _____
JULIAN ROTH

JR:ml
cc: Leslie Robert
Aaron Schreib
Joseph R. Lor
Jaros, Baum &
J. Solomon

This supplements my December 14th letter to you.

Although the one-inch thick sprayed fireproofing meets the 3 hour requirements of the proposed building code and Underwriters, advance information form the manufacturers indicates that if the truss were required to be fire-tested, the two inches of material would be required for the light angle members. We are therefore revising our working drawings to indicate a one-inch thickness of sprayed-on fireproofing around the top and bottom chords of the trusses, and a two-inch thickness for all other members of the trusses.

By informational copy of this letter, all consultants are requested to review their designs and drawings, and to make all necessary changes to meet his new criteria.

(5.2)

Figure A–21. Correspondence from Emery Roth & Sons. to Port Authority on thickness of thermal insulation for floor trusses (text in box was typed by NIST since copy of document is of poor quality) (3-P).

732-5222-3-4

Mario & Di Bono

Plastering Co., Inc.

136 LIBERTY STREET NEW YORK, N. Y. 10006

September 15, 1969

Mr. Milt Gerstman
Tishman Realty & Construction Co., Inc.
30 Church Street
New York, New York

RE: Fireproofing thickness' to be sprayed on steel

Dear Mr. Gerstman:

This list is being submitted for your approval.

1. Beams throughout buildings - 1/2 inch. No tamping or shaping of Cafco type D.

2. Columns 1 3/16 inches. No tamping or shaping of Cafco type D.

3. Elevator columns - 1 inch total including overspray. No tamping or shaping of Cafco type D.

4. Bar joist - 1 inch overall thickness. No tamping or shaping of Cafco type D.

Very truly yours,

MARIO & DI BONO PLASTERING CO., INC.

Louis Di Bono

LD/cz

TISHMAN REALTY & CONST. CO., INC.

SEP 15 1969

DEFENDANT'S EXHIBIT DX 434

USM-002883

Figure A–22. Correspondence from thermal insulation contractor to Tishman Realty & Construction Co. related to insulation thickness (XX-ITK).

732-5222-3-4

Mario & Di Bono
Plastering Co., Inc.
136 LIBERTY STREET NEW YORK, N. Y. 10006

September 18, 1969

A-49

Mr. Milt Gerstman
Tishman Realty & Construction Co., Inc.
30 Church Street
New York, New York

RE: Fireproofing thickness' to be sprayed on steel

Dear Mr. Gerstman:

In regard to our letter dated September 15, 1969 concerning the thickness of fireproofing material, please add the following paragraph:

5. All beams in MER rooms and utility rooms will be 1/2 inch thickness with overspray. No tamping or shaping of Cafco type D.

Very truly yours,

MARIO & DI BONO PLASTERING CO., INC.

Louis DiBono

LD/cz

DEFENDANT'S EXHIBIT DX 438

TISHMAN REALTY & CONST. CO., INC.
SEP 22 1969

USM-002884

Figure A–22 (Contd.). Correspondence from thermal insulation contractor to Tishman Realty & Construction Co. related to insulation thickness (XX-ITK).

October 30, 1969

Mr. Louis DiBono
Mario & DiBono Plastering Co., Inc.
370 Northern Boulevard
Great Neck, Long Island, New York 11021

Re: THE WORLD TRADE CENTER - Contract WTC 113.00-
Spray-On Fireproofing - Towers A & B

Dear Lou:

As a result of your meeting with Mr. Levy on October 21, 1969 I am enclosing a list of Tower "A" columns that are less than 14WF328 which will require 2 3/16" thick of "Cafco Glaze-Shield 'TypeD'" spray-on fireproofing. All Tower columns equal to or greater than 14WF328 will require 1 3/16" of fireproofing. Both of the above thicknesses develop the required 4-hour rating.

All Tower beams, spandrels and bar joists requiring spray-on fireproofing are to have a ½" 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.

Sincerely,

Robert J. Linn
Manager, Project Planning
The World Trade Center

cc: Messrs. M. Gerstman (TRCC), J. Solomon (ER&S)

Figure A–23. Correspondence from World Trade Center Department to the thermal insulation contractor specifying the required insulation thickness (3-P).

BLAZE-SHIELD fireproofing STANDARD

is a mill quality control blend of virgin asbestos fiber, highly refined white mineral fiber and proprietary binders. Tested and listed by Underwriters' Laboratories, Inc. (ULI) and Underwriters' Laboratories of Canada (ULC) for fireproofing applications, code acceptance has been registered by major municipal building departments throughout the United States and Canada and in many countries overseas.

PRODUCT FEATURES

— An improved BLAZE-SHIELD STANDARD formulation eliminates application dustiness generally associated with conventional sprayed fiber products. Respiratory hazards, clean-up time and expenses are minimized.

— BLAZE-SHIELD STANDARD out-performed other fireproofing media when exposed to severe fire temperatures on major high-rise structures. CAFCO applications have been credited with restricting fire spread and preventing serious damage.

— Tested in accordance with ASTM B-117 and Federal Specification MIL-E-5272A, CAFCO protected, shop painted steel evidenced no corrosion under severe exposure conditions. Rust preventive properties are superior to the combination of shop and field painting; costly field painting may be eliminated.

— CAFCO treated spandrels, roof decks and floor units reduce heating and air conditioning costs; ...d insulation at roof set backs may be eliminated. BLAZE-...ELD STANDARD provides a thermal conductivity (k) value ...of 0.27.

...S

ALL-WEATHER APPLICATION

REDUCTION IN DEAD LOAD

PERMANENCE OF PROTECTION

ACOUSTICAL ABSORPTION

ARCHITECTURAL SPECIFICATIONS
BLAZE-SHIELD STANDARD

GENERAL

... — See BLAZE-SHIELD Type D specification

... — See BLAZE-SHIELD Type D specification

... — See BLAZE-SHIELD Type D specification

MATERIALS

— Bonding adhesive, where required, shall be a milky white, latex-type water emulsion which shall be unaffected by water, water vapor, condensation, aging or freezing once it has set. Shall be CAFCO ADHESIVE as supplied by the United States Mineral Products Company (Canadian subsidiary—Columbia Acoustics & Fireproofing Co. (Canada) Ltd.), or approved equal.

— The fiber shall be a factory quality controlled and formulated mix consisting of 100% inorganic virgin Crysolite asbestos fiber and small pellet, white mineral fiber, combined with 100% inorganic binders. Fibers shall be CAFCO BLAZE-SHIELD STANDARD as manufactured by United States Mineral Products Company (Canadian subsidiary—Columbia Acoustics & Fireproofing Company (Canada) Ltd.), or approved equal, and shall be supplied to the job site in sealed bags, properly marked and labeled to show the inspection of Underwriters' Laboratories, Inc. or Underwriters' Laboratories of Canada for the application specified.

— Overspray, where required, shall be transparent and unaffected by moisture; shall be CAFCO SEALER as supplied by United States Mineral Products Company (Canadian subsidiary—Columbia Acoustics & Fireproofing Company (Canada) Ltd.), or approved equal.

WORK OF OTHER SECTIONS

... — See BLAZE-SHIELD Type D specification

... — See BLAZE-SHIELD Type D specification

... — See BLAZE-SHIELD Type D specification

INSTALLATION

... — See BLAZE-SHIELD Type D specification

... — See BLAZE-SHIELD Type D specification

— All surfaces to be treated shall be primed with CAFCO ADHESIVE. Fibers shall be applied and tamped to required thickness and oversprayed, where required, with CAFCO SEALER.

... — See BLAZE-SHIELD Type D specification

BEAMS — GIRDERS — SPANDRELS

SYSTEM	HOURS	THICKNESS	AUTHORITY	BLAZE-SHIELD Type D	BLAZE-SHIELD Standard	CONSTRUCTION
BEAMS, GIRDERS, SPANDRELS	2	½"	ULI=R3749-6		X	
	3	⅜"	ULI=R3789-2		X	
	4	½"	ULI=R3749-13 N605	X		
WRAPPED BEAMS, GIRDERS, SPANDRELS, JOISTS	3	15/16"	ULI=R3749-18	X		
	4	1"	ULC=60197	X	X	

COLUMNS

COLUMNS AND COLUMN CAPS	3	1⅛"	ULI=R3749-10† X807	X		
	4	1 1/16"	ULI=R3749-9† X807	X		
	2	1¼"	ULI=R3749-19 X818	X	X	
	3	1¾"	ULI=R3749-19 X818	X	X	
	4	2 5/16"	ULI=R3749-19 X801	X	X	

WALLS

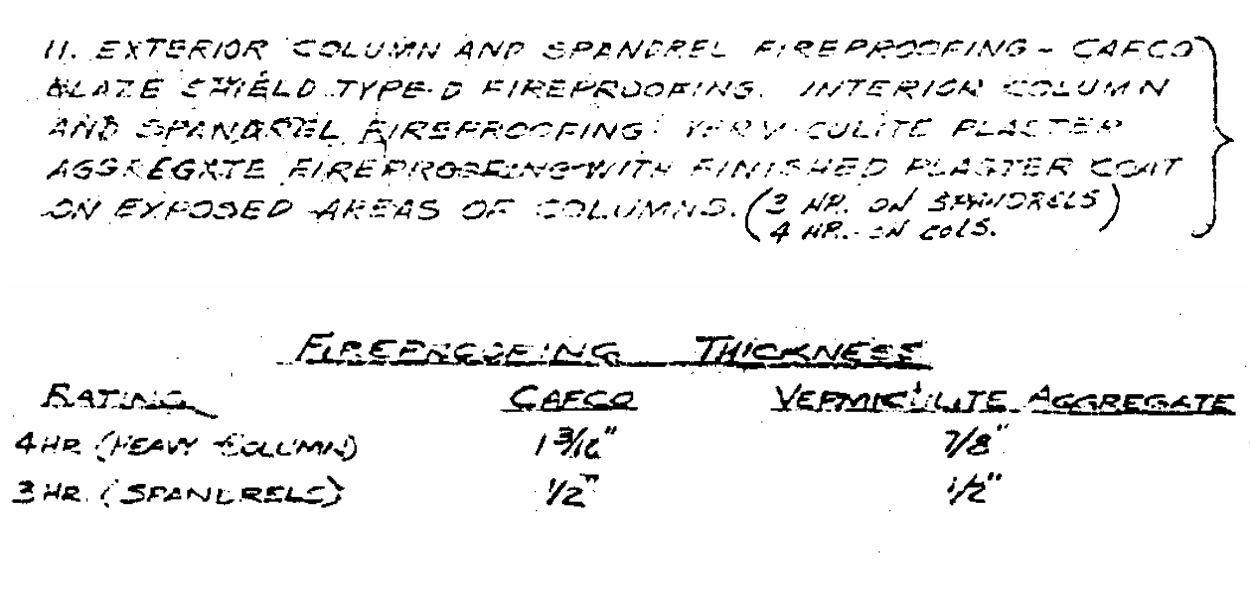
WALLS	4	4"	ULI=R3749-21	X		

† For application to columns 14WF228 or greater

ULC — Underwriters' Laboratories of Canada / ULI — Underwriters' Laboratories, Inc.

All tests conducted in accordance with ASTM E-119

Figure A–24. Excerpt from 1966-67 U.S. Mineral Products Co. catalog for CAFCO BLAZE-SHIELD indicating thermal insulation thickness for various applications (3-P).



11. EXTERIOR COLUMN AND SPANDREL FIREPROOFING - CAFCO BLAZE SHIELD TYPE-D FIREPROOFING. INTERIOR COLUMN AND SPANDREL FIREPROOFING: VERMICULITE PLASTER AGGREGATE FIREPROOFING WITH FINISHED PLASTER COAT ON EXPOSED AREAS OF COLUMNS. (3 HR. ON SPANDRELS, 4 HR. ON COLS.)

FIREPROOFING THICKNESS

RATING	CAFCO	VERMICULITE AGGREGATE
4 HR (HEAVY COLUMNS)	1 3/16"	7/8"
3 HR (SPANDRELS)	1/2"	1/2"

Figure A–25. Note 11 from the "General Notes" page of the Alcoa drawings indicating the thermal insulation thickness for the exterior columns and spandrels (116-LERA).

COPY

EMERY ROTH & SONS, ARCHITECTS
850 THIRD AVENUE
NEW YORK 22, N. Y.

6211
R40-2

July 25, 1966

Mr. Malcolm P. Levy
The Port of New York Authority
111 Eighth Avenue
New York, New York 10011

Re: World Trade Center

Dear Mal:

In accordance with your requirement that we inform you of any proposed installation that might not conform to the New York City Building Code, I would like to call yourattention to the floor construction in the tower buildings.

As you know, we propose to pour a 4" concrete slab over a metal deck which serves only as a form and will have no structural value but will remain in place at completion. Since the deck is non-structural it will not be fire proofed.

The electrical contract drawings show 3" header ducts buried in the slab with 1" concrete over the duct and removable metal covers at the intersections of raceway cells. Spray fireproofing will be applied to the under side of the deck in strips where headers occur.

The headers, in turn, feed into electric and telephone raceways which are 6'-8" on centers having floor inserts 3'-4" o.c. and knock-outs for lighting below spaced alternately. The deck under the raceways will not be fireproofed.

Obviously with so many penetrations of the floor system the fire rating of the floor construction is of an indeterminate value unless tested. It is doubtful if it will meet a 3-hour test. However, I believe that this is still much better than the "punch-through" system currently prevalent in many newly constructed buildings in New York City.

If there is concern for fire rating perhaps spraying the under s of the entire deck may be a solution. I would like to have your thoughts on this.

Very truly yours,

EMERY ROTH & SONS

CC Aaron Schreier/MYA
Dick Humenn/JRLA

BY
HARRY J. HARMAN

HJH:mlk

Figure A–26. Letter from Emery Roth & Sons to Port Authority regarding the application of thermal insulation to the bottom of the concrete floor slabs (3-P).

THE PORT AUTHORITY OF NY & NJ

One World Trade Center
New York, N.Y. 10048
(212) 466-7000
(201) 622-6600

PORT AUTHORITY OF N. Y. & N. J.
RECEIVED
MAR 17 1983
WORLD TRADE DEPARTMENT
DEP. DIR. PHYS. FAC.

March 14, 1983

Mr. Jerry Silecchia
National Cleaning Contractors, Inc.
60 Madison Avenue
New York, New York 10010

Dear Jerry:

As you know, during the construction of the World Trade Center the use of asbestos fireproofing was discontinued at the 38th floor of the World Trade Center. Those areas were subsequently encapsulated with a spray-on hardening material. The Port Authority has, on occasion, reviewed the asbestos fiber count above the ceiling in these areas and found these counts to be well below the OSHA standards.

However, in the interest of safety for all, you should direct your employees to use OSHA approved dust filter masks, provided by the Port Authority, when working above the ceilings in these areas.

Kindly advise your employees as needed.

Sincerely,

Daniel J. Censullo
Manager, WTC Operations
The World Trade Center

bcc: T. Cancelliere, J. Grismer, R. Linn, A. Rhome, J. Ritter, J. Verbist

Writer's direct dial telephone: 466-3585

Figure A–27. Correspondence indicating that use of CAFCO BLAZE-SHIELD Type D was discontinued at the 38th floor of WTC 1 (229-ITK).

MEMORANDUM

PA 90-A
5-63

REFER		NOTED	
TO	DATE	BY	DATE
RETURN TO			

TO: File
FROM: R. M. Monti
DATE: May 15, 1970
SUBJECT: THE WORLD TRADE CENTER - SPRAY FIREPROOFING - CONTRACTS WTC 400.00, WTC 113.00, WTC 120.00
REFERENCE:

COPY TO: Messrs. Levy, Tozzoli, Falvey, Werneke, Raiola, DeConzo (All W/Ref.)

At the present time there are two contracts involved in spray fireproofing: 1) WTC 400.00 with ALCOA, and 2) Port Authority Contract WTC 113.00 for fireproofing of floor trusses in the towers, core column in the towers, below grade areas of the bathtub area, and the Northeast Plaza Building. In the immediate future there will be a third subcontract (WTC 120.00) for fireproofing the Customs building.

ALCOA Contract WTC 400.00

From the inception of studies on this contract ALCOA proposed the use of Cafco type D spray fireproofing which conforms to the fire requirements, but more important to ALCOA, conforms to the required K factor for thermal conductivity. ALCOA is a performance type contract and they proposed to use this material which met their performance requirements and contained asbestos fibers. On all other contracts the Port Authority likewise specified Cafco type D spray fireproofing which contained asbestos fibers.

For the last six months there has been a certain amount of interest developed in the New York City area on the potential health problems caused by asbestos fibers. This study was conducted primarily by Dr. I. Selikoff of Mt. Sinai School of Medicine in conjunction with the New York City Air Pollution Department. Early in April, New York City promulgated a set of emergency instructions regarding the application and use of spray fireproofing containing asbestos fibers (Enclosure 1 is a copy of said regulations). On the World Trade Center, the Port Authority complied to the best of its ability and was praised as the best job in the city in conforming with the regulations for the application of this material. However, item No. 10 of Enclosure 1 indicates potential problems of exposed fireproofing containing asbestos which is installed in return air plenum ceilings. It was maintained by Dr. Selikoff that studies performed by his staff indicated that exposure over a considerable number of years of people sitting in an office, where the return air passed by exposed spray fireproofing containing asbestos, could cause health problems. Item No. 10 of Enclosure 1 specifies that such asbestos products in return plenums should be sealed with an appropriate sealant to prevent dusting of asbestos particles. At this point the Port Authority started studying possible sealants that could be applied, should it be decided to proceed in this matter. Enclosure 2 is a letter from Mario & DiBono Plastering Company, listing the components of a possible sealant manufactured by U. S. Mineral Products for areas already sprayed with asbestos. Enclosure 3 is a letter from R. M. Monti to Dr. Selikoff regarding the possible use of a sealant and asking that he advise us of his opinion before we proceed further.

DEFENDANT'S EXHIBIT DX 589

Figure A–28. Port Authority memorandum summarizing the factors considered in choosing CAFCO BLAZE-SHIELD Type DC/F as a replacement for the asbestos-fiber containing Type D (185-ITK).

File - 2 - May 15, 1970

Enclosure 4 is a letter from Dr. Selikoff, Mt. Sinai School of Medicine, to R. M. Monti, dated April 16, 1970, indicating that our proposal to use a sealant on areas sprayed with mineral fireproofing containing asbestos is the best technical means available at this time to prevent dusting, and it has his concurrence.

On April 17, 1970 the spray fireproof contractor, Mario & DiBono Plastering Co. who is a subcontractor to ALCOA under WTC 400.00 and also the Port Authority's contractor under WTC 113.00, was served with five summonses, one for each day of the week of April 13th. These summonses stated that he was in violation of the regulations listed in Enclosure 1. On April 17th, Mario & DiBono also received a Show Cause order returnable before the Commissioner of the Department of Air Resources on April 24th in connection with the fireproofing work being performed at the World Trade Center, as to why the job should not be sealed off. On April 20, 1970 I was advised by Mario & DiBono that he had received said Show Cause order and asked my advice. I immediately contacted Pat Falvey, Assistant General Counsel of the Port Authority, and discussed it with him. A meeting regarding this Show Cause order was held with Pat Falvey on April 21, 1970, at which time Mr. Falvey called Mr. Fabricant, General Counsel of the New York City Environmental Protection Administration, and requested that said Show Cause order be indefinitely postponed. Mr. Fabricant agreed, providing he received said request in writing from Mr. Falvey. Enclosure 5 is a copy of Mr. Falvey's letter to Mr. Fabricant requesting said adjournment. This letter states that should we resume spraying with asbestos we would give the City a two day notice, and should we resume spraying with non-asbestos material we would give them a one day notice of our intentions.

As of April 20, 1970 all spray fireproofing operations at the World Trade Center site were suspended.

On April 20, 1970 I also went to the office of U. S. Mineral Products Company in Stanhope, New Jersey where I observed a test demonstration on Cafco type D which had been sealed with a sealant to prevent its dusting. Enclosure 6 is a copy of results of tests conducted on mineral fiber fireproofing in accordance with GSA specifications regarding dusting. I was advised by the Research Director of U. S. Mineral Products that the application of a sealant on top of the Cafco type D would reduce the dusting to a negligible amount. Tests on Cafco type D for dusting, due to air velocity without a sealant, have been conducted and documented as listed in Enclosure 6. These tests indicated that the amount of asbestos particles dusting off due to air velocity are well within the standards set by the Environmental Health Department of the United States and also the British standard. It is also concluded and concurred in by Dr. Selikoff as indicated in the aforementioned Enclosure 4, that the use of a sealant is the best way to control dusting for work already installed that contains asbestos.

While at Stanhope, New Jersey, I also inquired into their research of an asbestos free material which would perform the same functions as Cafco-D. I was advised that they have such a material which had passed

Figure A–28 (Contd.). Port Authority memorandum summarizing the factors considered in choosing CAFCO BLAZE-SHIELD Type DC/F as a replacement for the asbestos-fiber containing Type D (185-ITK).

File - 3 - May 15, 1970

preliminary tests and which they were working on final tests for all the requirements. The tests that are required for approval of this material are as follows:

1. A fire rating test.
2. An adhesion under fire test.
3. A K factor or thermal conductivity test.
4. A bonding strength test.
5. Confirmation regarding the components of the material that could possibly be alleged to have health hazards.

Cafco research lab advised me that they had performed all of the above tests in their own laboratory, and that their material without asbestos, known as Cafco type D-CF, was equivalent to their previous Cafco type D with asbestos in all aspects. I advised Cafco representatives that I could not accept only the findings of their own laboratory but must have independent laboratory tests. They said they would arrange for all such tests and send reports directly to me. On April 23, 1970 Cafco called me and advised me that the fire rating tests being conducted by Underwriters Laboratory in Chicago had passed all the requirements. I requested that this be put in writing. On April 24, 1970 I received a telephone call from an engineer in Underwriters Laboratory, Inc., Mr. S. Bell, who advised me that the fire resistance tests on Cafco type D-CF were at least equivalent and probably 5% better than Cafco type D. I requested confirmation in writing. Attached is Enclosure 7 from Underwriters Laboratory attesting to this finding.

Enclosure 8 is a letter from U. S. Mineral Products dated April 30, 1970 attaching a copy of a test made by Dynatech of Cambridge, Massachusetts on the thermal conductivity of type D-CF. The test indicates that type D-CF is equivalent or better to regular type D.

Cafco also advised that they had performed bonding tests on type D-CF and these were successful. However, I requested independent laboratory tests. Enclosure 9 is a report from International Testing Laboratories, Inc. of Newark, New Jersey which reports the tensile strength in pounds per square foot of type D-CF to be within a range of 19.9 to 22.40. This tensile strength indicates that type D-CF is able to support its own weight approximately 20 times. Regular type D Cafco is advertised to support its own weight 10 to 12 times. Therefore, type D-CF results indicated it to be better than regular type D for bond strength.

I had previously been advised by Cafco representatives that two samples of type D-CF had been sent to Dr. Selikoff at Mt. Sinai for his examination. On April 23, 1970 I called Dr. Selikoff and asked him if he ever had examined Type D-CF. He advised me that he had not, but he had examined some similar material and he had found it to contain certain particles of asbestos. He advised that if I were to deliver to him a sample of this type, which I had taken personally out of a bag, he would re-examine same. I had a bag of type D-CF delivered to my office and one of my inspectors removed from the bag a one gallon canister of this material with rubber gloves, sealed it and delivered it to Mt. Sinai Hospital.
:losure 10 is a memorandum to file from my inspector, R. Kalenborn,
ıfirming said delivery.

Figure A–28 (Contd.). Port Authority memorandum summarizing the factors considered in choosing CAFCO BLAZE-SHIELD Type DC/F as a replacement for the asbestos-fiber containing Type D (185-ITK).

File - 4 - May 15, 1970

On the afternoon of April 24, 1970 Dr. Nicholson, assistant to Dr. Selikoff at Mt. Sinai Hospital, called me and advised me that a preliminary analysis of the material indicated that it was free of asbestos fibers except for possibly a few fibers that could have been picked up in the production line of the previous type D material. Dr. Nicholson gave me a good report on the material and further stated that it appeared to be much better in all respects to type D. I asked Dr. Nicholson if he would put this in writing to me. He said he would and he further stated that in his opinion this material did not present a health hazard due to asbestos, but of course we should maintain tarpaulins during installation and thorough cleanup as you would do with any material. He even said that it would not be necessary to comply with the City regulations listed in Enclosure 1 for this material. Dr. Nicholson did say that he would do further analysis of the material to check for its other constituent parts. I received a letter dated April 29, 1970 from Dr. Nicholson, Enclosure 11 hereto, regarding the examination of this material, which indicates the material is free from asbestos and excellent in other respects. However, Dr. Nicholson stated that "while no direct evidence exists linking mineral wool fibers to disease its extensive use has not been of sufficient duration to say that there could not be such disease." This statement merely allows Mt. Sinai to keep the door open on research of this material.

I have also received other preliminary verbal reports on extensive previous research performed by independent outside agencies on any deleterious health problems due to the mineral wool fibers in Cafco D-CF. These reports, to date, are very encouraging in that they are all negative. When written reports are received, copies will be sent to all interested parties.

On April 27, 1970 Mr. Sorrell and Mr. Roby of ALCOA requested my acquiescence to allow them to resume spraying and/or patching on floors 16 to 19 with type D-CF to permit continued erection of aluminum column covers. At this time all the required test reports indicated above had not been received by me and therefore I merely indicated my acquiescence to their request to proceed with the understanding that this change in material for these floors or for any subsequent change for their material under their performance type contract would not entail any additional costs to the Port Authority. Mr. Sorrell agreed to no cost for floors 16 to 19 but said "let's not talk about the rest." I repeated my statement that there would be no consideration of additional costs under their performance type contract for changing the materials. Enclosure 12 hereto is a copy of my letter to ALCOA dated April 27, 1970, confirming the aforementioned discussions and restating the Port Authority's position on no additional compensation for change in material, should ALCOA desire to do so. Enclosure 12 was reviewed by Tony Raiola and Pat Falvey of the Port Authority Law Department prior to its issuance.

Enclosure 13 attached hereto is a copy of a letter from ALCOA to Mr. Tozzoli, dated April 23, 1970, requesting consideration of additional compensation of $173,000 for their corporate decision to change the material to type D-CF. This letter was received in Mr. Tozzoli's office on April 27. This is an attempt by ALCOA, as I discussed with Mr. Tozzoli, to see if one letter they can possibly get consideration of $173,000. I understand that ALCOA has made a corporate decision to change this material on

Figure A—28 (Contd.). Port Authority memorandum summarizing the factors considered in choosing CAFCO BLAZE-SHIELD Type DC/F as a replacement for the asbestos-fiber containing Type D (185-ITK).

File - 5 - May 15, 1970

on their own, regardless of the fact whether they get additional compensation, because they do not want to get involved with the bad public relations that would be associated with their continuing the two towers with an asbestos material, even if they were able to continue, by conforming to the regulations in Enclosure 1. It is interesting to note that since April 20 all jobs in New York City using asbestos material have been stopped, and to the best of my knowledge, as of this date have not resumed spraying. Enclosure 14 is a reply by Mr. Tozzoli to ALCOA dated May 8 substantiating the Port Authority's position as stated in Mr. Monti's letter to Mr. Sorrell of ALCOA, dated April 27, 1970, in that the Port Authority does not accept any responsibility for any additional costs ALCOA may incur due to their performance type contract. On May 1, 1970 Mr. Sorrell of ALCOA hand delivered to me a letter dated May 1, 1970 requesting Port Authority approval to use type D-CF in lieu of type D for the entire project. This is Enclosure 15 hereto. Since on May 1, 1970 I did not have in my hands all complete reports listed above, I annotated said ALCOA letter and gave verbal approval to proceed with type D-CF only for Tower "A" floors 20 through 25 inclusive, pending receipt of final reports. Mr. Sorrell concurred with this and advised that by the time he reached the 25th floor, maybe all reports would be in and we could give him an unqualified proceed for the entire two towers.

In the interim Tishman Realty & Construction Co., Inc. proceeded on a separate course of investigating other sources of spray material which would be free from asbestos. Enclosure 16 is a copy of a letter from Tishman to ALCOA dated May 1, 1970, reporting on their investigations with W. R. Grace Company on a material called Monacote and coming to the conclusions that the K factor of the material that they investigated did not meet the requirements and therefore concluded that Monacote would not be considered any further for application.

Contract WTC 113.00

Mario & DiBono Plasterinc Company includes the spraying for Towers "A" & "B" and below grade. This contract was awarded specifying asbestos spray materials (Cafco type D) for floor trusses, columns and beams. Certain specific columns in the elevator shafts are required, under the original contract, to be coated with Cafco Mark II hard finish coating due to the high velocity of air caused by the elevators. Thus, if we continued spraying with Cafco type D, the elevator shafts specified to be hard finished are already sealed and would not require a sealant on top of same. All other areas which were to be sprayed with type D asbestos material would require a sealant.

During the week of April 13, 1970, I started discussions with the contractor regarding the possibility of applying a sealant to all areas of both Towers "A" & "B" and below grade which are not required to have Cafco Mark II hard finish coating. The contractor originally indicated that the going price for sealants per square foot would result in a total compensation of approximately $605,000 for sealing the entire project. The contractor
'icated, however, he was willing to cooperate. Using an estimated cost
9 en to me by Dr. Neuman of Tishman Realty & Construction Co., Inc. of

Figure A–28 (Contd.). Port Authority memorandum summarizing the factors considered in choosing CAFCO BLAZE-SHIELD Type DC/F as a replacement for the asbestos-fiber containing Type D (185-ITK).

File - 6 - May 15, 1970

3½ cents per square foot as an equitable price, I was able to convince the contractor to agree at a lump sum proposal of $350,000 for sealing all areas of Towers "A" & "B" and below grade. The contractor also agreed that he would release the Port Authority of his existing claim for excessive rust scaling on steel, which is outside of the scope of his contract, and was estimated by him to run $160,000. My staff indicated to me that based on T&M slips submitted to date that this item of removing excessive rust could run as high as $200,000.

Subsequent to the above discussions, the problem of continued use of asbestos material arose; therefore, I proceeded to discuss costs of substituting type D-CF fireproofing and only sealing the areas that had previously been sprayed with the asbestos material, plus continued release of the claims for excessive rusting of the steel. The contractor's proposal for this work, including changing the material on the U. S. Customs Building and the Northeast Building, amounted to $442,425. I offered the contractor $296,500. After further review with the contractor and a review of the numbers with Mr. Tozzoli, I made a final offer to the contractor of $320,000. The contractor accepted same. This cost covers the following items of work in Towers "A" & "B" and below grade, the Norhteast Plaza Building and the U. S. Customs Building:

1. From the times that we allow him to proceed to resume spray operations he will use asbestos free Cafco type D-CF in all spray work.

2. He will apply a sealant to all areas that have previously been sprayed with asbestos material, except for those areas which receive Cafco Mark II hard finish, in both Tower "A" and below grade, and should any be done in Tower "B", in that area also.

3. He releases the Port Authority by signed release from any further claim regarding removal of excessive rusting from the steel. Clause 13.03 subparagraph 2 on page 123 of Contract WTC 113.00 must be amended or deleted so that no further recourse to said statements can be made by the contractor.

R. M. Monti
Construction Manager
The World Trade Center

RMM:rd

Figure A–28 (Contd.). Port Authority memorandum summarizing the factors considered in choosing CAFCO BLAZE-SHIELD Type DC/F as a replacement for the asbestos-fiber containing Type D (185-ITK).

UNDERWRITERS' LABORATORIES, INC.
an independent, not-for-profit organization testing for public safety

April 24, 1970

L3749

Port of New York Authority
111 8th Avenue, Room 300
New York, New York

Attention: Mr. R. Monti, Construction Manager
World Trade Center

Subject: Fire Resistance Evaluation of Cafco CF Type "D" vs Cafco Type "D"

Gentlemen:

Confirming our telephone conversation of April 23, the Subject investigation is approximately 80 per cent completed. All of our test results to date indicate that Cafco CF Type "D" sprayed fiber is at least as good as Cafco Type "D" in regard to fire resistance. The CF Type "D" may even be slightly better from this standpoint.

Although our test results to date are not 100 per cent conclusive, the indications are that Cafco CF Type "D" will be approved for all of the Floor and Ceiling Designs for which Cafco Type "D" is currently Listed, particularly those incorporating a 1 to 1 blend of cellular and fluted steel deck units and normal weight concrete.

If you should have any further questions regarding this investigation, we would be happy to try to answer them for you so long as we have the permission of United States Mineral Products Company to release our testing information.

Very truly yours,

S. W. BELL
Assistant Engineer
Fire Protection Department

SWB/klr

cc: Mr. Frank M. Stumpf

USM-007234

Figure A–29. Correspondence indicating CAFCO BLAZE-SHIELD Type DC/F as a suitable replacement for Type D (180-ITK).

SKILLING, HELLE, CHRISTIANSEN, ROBERTSON

Consulting Structural and Civil Engineers · 230 Park Avenue, New York, N. Y. 10017 · MU. 9-8874

John B. Skilling · Helge J. Helle · John V. Christiansen · Leslie E. Robertson

Manager
Wayne A. Brewer

April 1, 1975
File: WTC-Fire

Mr. Malcolm P. Levy
Chief, Planning and Construction
Port Authority of New York & New Jersey
1 World Trade Center - 63rd floor
New York, New York 10048

Dear Mal:

Attached to this letter is a report dealing with the fire safety of specific facets of the twin towers of the World Trade Center.

The report deals with the general topic of the fire resistivity of the floor system. Questions of structural integrity and of heat transmission through the floor are examined. The report is intended to provide background to the reader as to the development of the fire-resistive standards for World Trade Center and looks also at the adequacy of the existing systems.

In preparing these documents, SHCR holds itself out as a reporter of facts--as they are presented in communications gleaned from the files of Port Authority, ERS, MYA and SHCR. It does not purport to have any special expertise not commonly held by other structural engineers. No new literature search or research was accomplished for purposes of this report.

Finally, the data contained in the report is based on logic and analysis and, as such, is not definitive or conclusive. The only way to assure the existence of the fire safety of floor systems is to be found through the participation of a fire safety engineer and/or fire testing.

Please feel free to call on us should you have any questions.

Very truly yours,

SKILLING, HELLE, CHRISTIANSEN, ROBERTSON

Leslie E. Robertson
Enclosure
LER/amh
c.c. Mr. Julian Roth, ERS (Encl)
Mr. M. Yamasaki, MYA (Encl)

Figure A–30. Excerpts from 1975 post-fire report prepared by Skilling, Helle, Christiansen, Robertson (3-P).

MANUFACTURERS CATALOGUES

The fireproofing contract was accepted on the basis of the Mario and DiBono Plastering Co., Inc. proposal dated March 17, 1969. While SHCR is not privy to the contents of that proposal, it is likely that it contains only finanical and catalogue information.

The only Cafco catalogue available to SHCR (excluding current issues of 1975) is the one supplied by Mr. Monti to Mr. Levy in September 20, 1967 (see -appendix). The catalogue cites ULI #R3749-6, ULI R3789-2 and ULI #R3749-13 for the spray fireproofing of beams. From the catalogue one can determine that:

(1) The product has been subject to extensive ULI testing; and
(2) for "beams, girders and spandrels", a thickness of 1/2 inch of Blaze-Shield Type D (the product used in World Trade Center) provides a 4 hour rating.

The catalogue does not report on fireproofing of trusses.

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SKILLING, HELLE, CHRISTIANSEN, ROBERTSON

Figure A–30 (Contd.). Excerpts from 1975 post-fire report prepared by Skilling, Helle, Christiansen, Robertson (3-P).

LACLEDE COMPOSITE FLOOR TRUSSES

FIRE RESISTIVITY - TOP CHORD

Introduction

The Laclede trusses used in the construction of The World Trade Center are a standard product manufactured from specially-rolled angles used in conjunction with round-bar webs. To achieve composite action the webs extend into the concrete slab so as to effect the required shear transfer.

In The World Trade Center the top chords are not spray fireproofed for selected areas of the work. Specifically, for the most of the one-way span areas directly out from the service core, the top chords are not always spray fireproofed. Also bridging trusses are not spray fireproofed.

This paper addresses itself to reasons of structural engineering as to why spray fireproofing may not be required.

Structural System - Top Chord

First, a discussion of the role of the steel top chord in the overall structural system:

1) Construction Period:

   a) Acting in conjunction with the bottom chord and the web, the steel top chord completes the trusswork providing primary structural support for the concrete slab until such time as the slab has achieved design strength.

      Fireproofing of the steel top chord is not required for reasons of construction loading.

   b) Acting as a beam, spanning from truss panel point to truss panel point, the top chord supports a small amount of concrete until such time as the concrete has attained design strength.

      Fireproofing of the steel top chord is not required for reasons of construction loading.

2) Supporting Gravity Loads:

   a) Once concrete strength has been achieved, the capabilities cited under 1) are modified. The concrete slab becomes the dominant element of the top chord. So long as the shear knuckle is maintained, the structural integrity of the steel top chord is not required.

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SKILLING, HELLE, CHRISTIANSEN, ROBERTSON

Figure A–30 (Contd.). Excerpts from 1975 post-fire report prepared by Skilling, Helle, Christiansen, Robertson (3-P).

Since the top chord may be cut without loss of structural integrity, we concur that fireproofing of the steel top chord is not required for this purpose.

b) Where a given shear knuckle is not adequate to transfer panel point loads directly into the slab, then an increment of the load must be taken down the steel top chord to the next knuckle. This condition exists only in the corner, two-way portion of the floor. We concur that fireproofing of the steel top chord is required and is provided for this purpose.

3) Assisting in Diaphragm Strength:

a) The concrete slab, with its mesh and bar reinforcing provides for diaphragm strength within the building. As structure sway under wind load increases, the need for diaphragm strength increases. Structural steel top chords provide a kind of reinforcing steel and add to diaphragm strength. While diaphragm strength is not required by Code, we know it to be essential to the proper behavior of the structural system. We do not believe it to be proper to design for the combined circumstance of an extreme wind and an extreme fire with the same factor of safety as that associated with the single event alone.

Since the structural steel top chord provides only a small increment in the diaphragm strength, we concur that fireproofing may be omitted for this purpose.

Structural System - Bridging

The bridging system is used only to provide for the reduction in floor "tremor" and to reduce the effects of differential deflections associated with heavy gravity loads.

Since it is not required as a part of the structural system, we concur that fireproofing may be omitted for these members.

Conclusions

Fireproofing of the top chords of floor trusses is required and is provided in the two-way portions of the floor systems.

A logical analysis indicates that fireproofing of the structural steel top chord and of the bridging is not required so long as the risk of the joint occurrence of an extreme value wind storm and a fire is accepted. Over much of the two buildings, fireproofing has been provided.

Figure A–30 (Contd.). Excerpts from 1975 post-fire report prepared by Skilling, Helle, Christiansen, Robertson (3-P).

PERFORMANCE IN SERVICE

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

The SHCR report of fire damage, including all repairs, is attached in the appendix.

As requeste by Port Authority Engineering Department and by SHCR, shores were placed in the vicinity of repairwork. This was done, not because of concern for damaged structure, but as a matter of prudence to avoid the accidental destruction of needed structure by over-zealous steel workers.

It is likely that this fire did not provide the ultimate test of fire-resistivity. More severe fires will likely strike the project. However, since only non-essential, non-fireproofed elements of the floor assembly were damaged, some optimism can be expressed.

SKILLING, HELLE, CHRISTIANSEN, ROBERTSON

Figure A–30 (Contd.). Excerpts from 1975 post-fire report prepared by Skilling, Helle, Christiansen, Robertson (3-P).

March 7, 2003

John L. Gross, Ph.D., P.E.
Leader, Structures Group
National Institute of Standards and Technology
100 Bureau Drive, Stop 8611
Gaithersburg, MD 20899-8611

Re: Confidential and Pre-decisional Communication – Questions on Fire Resistance of the WTC Floor System

Dear John:

Following are the Port Authority (PA) responses to your questions:

Questions to the Port Authority of New York & New Jersey, February 26, 2003

1. In a letter from ERS (Julian Roth) to PoNYA (Malcolm Levy) dated December 14, 1965, it had apparently been decided that the fire protection of the WTC floor system would involve "the use of a maximum thickness of one inch spray-on fireproofing material around the individual components of the floor trusses." It was further stated that "one inch material meets the 3-hour requirements of both the new code (New York City Building Code under revision in 1965 and ultimately published in 1968) and Underwriter's (Underwriter Laboratories, Inc.) using previously approved assemblies tested by the 'load criteria' method but ignoring the more stringent time-temperature-rate-of-rise criteria which is an alternate testing procedure not required by the new code or by Underwriter's, and which we do not consider necessary."

   In a follow-up letter from ERS (Julian Roth) to PoNYA (Malcolm Levy) dated December 22, 1965, the PA is advised that "advance information from manufacturers indicates that if the truss were required to be fire-tested, then two inches of material would be required for light angle members."

   In a letter from ERS (Harry Harman) to PoNYA (Malcolm Levy) dated July 25, 1966, it is stated "Obviously, with so many penetrations of the floor system [4" concrete slab over a metal deck] the fire rating of the floor construction is of an indeterminate value unless tested."

   1) Were tests performed on the fire resistance of the composite floor system during the design or construction phase of the project?

   PA Response: There are no test records in our files.

Figure A–31. Response from Port Authority regarding the applied thermal insulation (XX-I).

2. In a letter dated October 30, 1969, from PoNYA (Robert Linn) to Mario & DiBono Plastering Co., Inc, the contractor is directed as follows: "bar joists requiring spray-on fireproofing are to have 1/2" covering of 'Cafco'."

   2) Was ½ inch of Cafco Type-D fireproofing specified for the floor trusses requiring spray-on fireproofing?

   PA Response: Thickness was not specified on the drawings. PA is still trying to locate the original specifications, which NIST is aware of. The letters you reference and quote in your questions are snapshots in time. The culmination of these written exchanges led to what was finally called for in the original specifications that were part of the contract documents. In the absence of the original specifications, we must rely on the actual measured thickness of the fireproofing. Over the years, this has been documented to be a nominal ¾ inches.

   It should be kept in mind that the fireproofing determinations were made in the context of buildings that were to be constructed without a sprinkler system. Following the enactment of Local Law 5 in New York City, a complete sprinkler system was added to the towers over a period of years, thus reducing the overall reliance on the truss joist fireproofing for fire protection.

3. In a report by SHCR prepared for the PANYNJ dealing with "the fire safety of specific facets of the twin towers of the World Trade Center" following the 1975 fire, it is stated that the 4 inch slab exceeds the commonly used (and therefore accepted by the NYC Building Dept.) 3-1/4 inch slab on metal deck without fireproofing.

   3) Was the underside of the floor slab (metal deck) fireproofed?

   PA Response: No.

4. In this same report by SHCR prepared for the PANYNJ, it is stated that, fireproofing of the top chord of the floor trusses is not necessary (except for the two-way portion of the floor). Additionally, it is stated that fireproofing of the bridging system is not required.

   4a) In the one-way portions of the floor system, were the top chords of the composite floor trusses fireproofed?

   PA Response: Yes.

   4b) In the one-way portions of the floor system, were the bridging trusses fireproofed?

Figure A–31 (Contd.). Response from Port Authority regarding the applied thermal insulation.

PA Response: **Yes.**

5. It is our understanding that initially the spray-on fireproofing contained asbestos. We also understand that, at some point, asbestos was not permitted and a Cafco product that contained mineral wool instead of asbestos was substituted.

   5a) Is the situation stated here correct?

   PA Response: **Yes.**

   If so,

   5b) What floors of which towers were fireproofed with the asbestos-containing product?

   PA Response: **For the tower floor system, only steel trusses in Zone 1(44th floor and below) in Tower 1 were fireproofed with asbestos containing product.**

   5c) Was the asbestos-containing "fireproofing" removed?

   PA Response: **Yes.**

I hope these responses are helpful. If you have any further questions please send them to us.

Sincerely,

o/s/b

Joseph M. Englot, P.E.
Asst. Chief Engineer/Design

CC: F. Lombardi

Figure A–31 (Contd.). Response from Port Authority regarding the applied thermal insulation.

.O: B. Weinstien, Project Manager (TRCC) DATE: March 25, 1970
FROM: D. L. Brown
SUBJECT: THE WORLD TRADE CENTER CONTRACT 113.00 - MARIO DIBONO PLASTERING CO. SPRAY ON FIREPROOFING - TOWER A & B - INSPECTION
REFERENCE:

COPIES: P. Balduzzi, R. Linn, M. Levy, R. Monti, T. Calabrese, F. Werneke

During a routine inspection trip on March 19, 1970, I had occasion to discuss with Frank Tartamella, superintendent, the status of work under the subject contract. In the course of this conversation I reminded Frank Tartamella that Mario DiBono still had to complete the core columns spray-on fireproofing of Tower A core columns up to the 28th floor as these columns are unsatisfactory having only ½" to 3/4" of fireproofing not the 1 3/16 inches required. He stated that I should direct this matter to his office as he did not plan to do any further work on these members. Please again remind the contractor that this work is not acceptable to this office, also that they are to fireproof the under side of the electrical header ducts.

DLB:mb

D. L. Brown
Supervising Engineer
The World Trade Center

Figure A–32. Correspondence indicating that thickness of thermal insulation was being checked during construction (XX-ITK).

K-127

(212) 964-8691

Tishman Realty & Construction Co., Inc.

AS AGENTS FOR THE PORT OF NEW YORK AUTHORITY
WORLD TRADE CENTER
30 CHURCH STREET, NEW YORK, N.Y. 10007

MARCH 30, 1970

4/6/70 Ltr to D. Brown

MARIO & DIBONO PLASTERING
136 LIBERTY STREET
NEW YORK, NEW YORK 10006

ATTENTION: MR. F. TARTAMELLO

RE: WTC/113.00 9
INSUFFICIENT THICKNESS

GENTLEMEN:

REFERENCE IS MADE TO OUR LETTER DATED JANUARY 9, 1970 WITH FOLLOW-UP COPIES SENT DATED JANUARY 19TH AND FEBRUARY 6TH, IN ADDITION TO PHONE CALLS ON THE SUBJECT, ADVISING YOU OF THE INSUFFICIENT THICKNESS OF SPRAY-ON FIREPROOFING ON CORE COLUMNS.

WE ARE NOW IN RECEIPT OF A COMMUNICATION FROM THE PORT OF NEW YORK AUTHORITY REITERATING THE SAME ITEM.

BE ADVISED THAT TO CONTINUE TO IGNORE THESE COMMUNICATIONS WILL REQUIRE US TO ADVISE THE PORT OF NEW YORK AUTHORITY TO SEEK COMPENSATION AMOUNTS FROM YOUR CONTRACT PRICE, COMMENSURATE WITH THE WORK WHICH IS INCOMPLETE PLUS ANY COSTS INVOLVED IN REMOVING AND REPLACING WORK BY OTHERS WHICH MAY, DUE TO THIS LONG DELAY, COVER YOUR WORK.

VERY TRULY YOURS,

TISHMAN REALTY & CONSTRUCTION CO., INC.

BERT WEINSTEIN
PROJECT MANAGER

BW/BMS

CC: MESSRS. MONTI, WERNEKE, P/A

Figure A–32 (Contd.). Correspondence indicating that thickness of thermal insulation was being checked during construction (XX-ITK).

ORIGINAL

Port Authority of N.Y and N.J.
Litigation Sampling Program

JOB NUMBER 115-245

Sample Area Data Sheet

Facility: One World Trade Center Building: Tower Building One

Building No: 1 Floor: 29th Floor Sample Size Vial, 40z.

Description of Sampling Area: 29th Floor

Sample Numbers: Additional Sample #'s on the following page →

LL-389-WTC-A,B,C	LL-395-WTC-A,B,C	LL-401-WTC-A,B,C	LL-
LL-390-WTC-V,A,B,C	LL-396-WTC-A,B,C	LL-402-WTC-V,A,B,C	LL-
LL-391-WTC-A,B,C	LL-397-WTC-A,B,C	LL-403-WTC-A,B,C	LL-
LL-392-WTC-A,B,C	LL-398-WTC-A,B,C	LL-404-WTC-A,B,C	LL-
LL-393-WTC-V,A,B,C	LL-399-WTC-V,A,B,C	LL-	LL-
LL-394-WTC-A,B,C	LL-400-WTC-A,B,C	LL-	LL-

Form of Asbestos Material	Location of Asbestos Material
✓ Sprayed-On	✓ Support Beams/Columns
✓ Troweled-On/Cementitious	✓ Concrete Slab/Metal Decking
___ Plaster	___ Cable
___ Acoustical Plaster	___ Duct/Breeching
___ Air Cell	___ Floors
___ Molded Sections/Pads	___ Heating/Cooling Equiptment
___ VAT	___ Ceilings
___ Ceiling Tile	___ Piping/Fittings
___ Other:	✓ Other: Troweled on wall support Be

Comments: (Indicate any unique characteristics of the material which may help identify the manufacturer.)

Sample taken by: Frantz Dambreville, Frank Pergola Date: 03/12/90.

Persons Present Frantz Dambreville, Frank Pergola, Charles Kondakjia

Photographs Taken By: Frantz Dambreville, Frank Pergola

1 1 D 0 [signature] Frank Pergola 03/14/90

Figure A–33. Example of "Sample Area Data Sheet" used to record condition of sprayed thermal insulation (212 ITK).

ORIGINAL

Job Number 115 • 245

COMMENTS

South West quadrant → fluffy spray-on fireproofing coating the support Beams, joists, and deck above the ceiling. the thickness of the material on the Beams and joists was consistently about ½". Regarding the deck it ranged from very Sparce in areas to ¼" in other areas. The Areas we Sampled were coated with a Light green encapsulant.

NorthWEST quadrant → Fluffy Spray-on Fireproofing. The Beams and joists were coated with about ½" of material. the deck ranged from ¼" to Barely notting. this Section was also coated with a Light green encapsulant.

North East quadrant → Fluffy Spray-on fire proofing the Beams and joists were coated with @ ½" of material the deck was coated with @ ¼" of material in this section. the Light green encapsulant was presEnt in' this area.

South East quadrant → fluffy spray-on fire proofing. Beams and Joists were coated with @ ½" of material the deck was coated with ¼" of material. Sample area was coated with encapsulant. One Sample from a Vertical Support Beam on the outermost wall, was a grayish cementitious material @ ¼" thick.

* the only Samples that were free From the encapsulant were those taken from the top of the Support Beam. (LL-395-WTC LL-397-WTC)

Figure A–33 (Contd.). Example of "Sample Area Data Sheet" used to record condition of sprayed thermal insulation (212 ITK).

THE PORT AUTHORITY OF NEW YORK & NEW JERSEY

MEMORANDUM

TO: Peter Sweeney, Engineering Program Manager
FROM: Joseph M. Englot
DATE: August 18, 1995
SUBJECT: **STEEL JOIST SPRAY-ON REQUIREMENTS FOR NEW CONSTRUCTION IN WORLD TRADE CENTER TOWERS**

COPY TO: R. Davidson, J. Lin, F. Lombardi, E. Ramabhushanam, O. Suros

Attached is a white paper summarizing a study to determine the spray-on thickness required to achieve the required two hour rating for steel joist trusses in the towers of the World Trade Center. This is intended for any new construction for which the Engineering Department is engineer-of-record. It concludes that 1-1/2 inches of spray-on mineral fiber is sufficient when applied directly to chords and web members.

Joseph M. Englot, P.E.
Chief Structural Engineer

JME:ng

Attachment

Figure A–34. Results of 1995 study of thermal insulation for floor trusses during new construction when tenants vacated spaces (3-P).

FIREPROOFING REQUIREMENTS FOR WORLD TRADE CENTER TENANT FLOOR JOIST CONSTRUCTION THAT REQUIRES INSTALLATION DUE TO ASBESTOS REMOVAL OR LOCAL REMOVAL TO FACILITATE CONSTRUCTION

This serves as a basis for determining the minimum requirements for installing sprayed mineral fiber fireproofing on the steel floor joist trusses supporting typical tenant floor areas within the towers of the World Trade Center. Its purpose is to establish requirements for new construction that meet local codes and ordinances.

The technical basis for the fireproofing requirement is Design No. G805 in the Fire Resistance Directory (BXRH) Published by Underwriters Laboratories. This UL design is based upon fire tests conducted as per ASTM E-119 which is a basic Reference Standard (No. RS5-2) in the New York City Building Code for structural members and assemblies. Reference standard RS5-1F, "Methods of Analytical Determination of Fire Resistance of Load Bearing Steel Truss Assemblies", is not applied since it is intended for large trusses (i.e., deep trusses), too large to fit in the fire test compartments. Since there is a wealth of fire tests on steel joists which approximate the ones used in the World Trade Center, joist test results are interpreted to arrive at an appropriate spray-on protection thickness.

There are various parameters in the G805 design which have to be interpreted or approximated in the case of World Trade Center construction. Each parameter will be discussed individually.

Joist Spacing

G805: 48 inch and 66 inch spacing.
Actual: Double joist system - average joist spacing is 40 inches (spacing alternates between 8 inches and 72 inches). Conservatively, use values for 66 inches since actual spacing is not uniform.

Metal Deck Protection

G805: Values tabulated with or without spray-on applied to bottom of metal deck.
Actual: Use values without spray-on applied to deck. Spray-on is only used in the World Trade Center below trench headers. Follow design values without protected deck.

Concrete Topping

G805: Values tabulated for lightweight concrete, 117 pcf unit weight, 3500 psi compressive strength and a thickness of topping over the metal deck of 3-7/8 inches to achieve a 2 hour rating.
Actual: Lightweight concrete, 110 pcf unit weight, 3000 psi compressive strength and a thickness of topping over the metal deck of 4 inches. The actual is judged equivalent to the G805 design for 2 hour rating.

Wire Mesh Location

G805: Provides a thickness of concrete from the top plane of the metal deck to the wire fabric of 1-1/4 inches for a 2 hour rating with 1-5/16 inch deep steel form unit.
Actual: Has two layers of wire mesh. Thickness from top plane of 1-1/2 inch metal deck to center of wire mesh layers is 1.22 inches. Where rebar is used instead of wire mesh, 1-1/4 inch thickness

Figure A–34 (Contd.). Results of 1995 study of thermal insulation for floor trusses during new construction when tenants vacated spaces (3-P).

is provided. This is judged to be equivalent to the G805 design for 2 hour rating.

Steel Joist Parameters

G805: Composite steel joist with a minimum area of steel (double angles) for top and bottom chords (each) of 0.708 sq. inches and minimum steel area of web members of 0.442 sq. inches in conjunction with the "thinner" layer of spray-on (1-1/2 inches) applied directly to the joist without lath.
Actual: Minimum area of chords is 0.813 sq. inches and the minimum area of web steel is 0.665 sq. inches with composite behavior. 1-1/2 inches applied directly to the joist steel yields a two hour assembly rating whether restrained or unrestrained.

Ceiling

G805: A ceiling is not relied upon for fire protection in the design.
Actual: All occupied areas in the World Trade Center have ceilings and they will add to the fire rating of the floor system, however, a stringent study of what rating values could be achieved for existing types of ceilings is beyond the scope of this study.

Conclusion

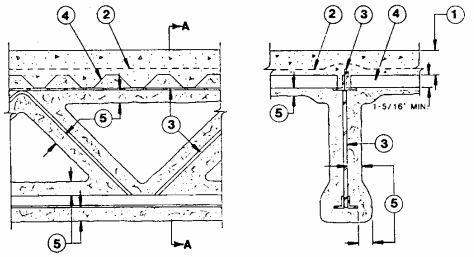
It is concluded that a two hour fire rating for the steel floor joist trusses can be achieved by applying a 1-1/2 inch thickness of spray-on mineral fiber fire protection material directly to the steel truss chords and webs. The value of the ceiling as a fire protection element is not relied upon to achieve this fire rating.
Attachments:

1. Excerpted pages from N.Y.C. Building Code.
2. G805 Design from U.L. Directory

Figure A–34 (Contd.). Results of 1995 study of thermal insulation for floor trusses during new construction when tenants vacated spaces (3-P).

Design No. G805

Restrained Assembly Ratings — 1, 1-1/2, 2 or 3 Hr (See Items 1, 4 and 5)
Unrestrained Assembly Ratings — 1, 1-1/2 or 2 Hr (See Items 1, 4 and 5)
Unrestrained Beam Ratings — 1, 1-1/2 or 2 Hr (See Item 5)



SECTION A-A

1. **Normal-Weight Or Lightweight Aggregate Concrete —** Normal weight concrete carbonate or siliceous aggregate, 150 pcf unit weight, 3500 psi compressive strength, vibrated. Lightweight concrete, expanded shale, clay or slate aggregate by rotary-kiln method, 117 pcf unit weight 3500 psi compressive strength, vibrated, 2 oz air entrainment per bag of cement. The thickness of concrete topping over the top plane of the steel deck varies according to the spacing of the structural steel members, the hourly ratings and whether or not the steel deck is protected. When no Spray-Applied Fire Resistive Materials protection is used on the steel deck, the thickness of concrete topping over the top plane of the steel deck shall be as specified in the following table:

Restrained or Unrestrained Assembly Rating Hr	Normal Weight Concrete Topping Thk In		Lightweight Concrete Topping Thk In		Min Thk of Concrete From Top Plane of Steel Deck to Bottom of Reinforcement In.
	Joist Spacing 48 In. OC Max	Joist Spacing 66 In. OC Max	Joist Spacing 48 In. OC Max	Joist Spacing 66 In. OC Max	
1 h	3-1/8	3-7/8	2-3/8	3-7/8	1
1-1/2 h	3-7/8	3-7/8	2-7/8	3-7/8	1-1/8
2 h	4-5/8	4-5/8	3-3/8	3-7/8	1-1/4

When the steel deck is protected with the Spray-Applied Fire Resistive Materials, the min thickness of normal weight or lightweight concrete topping above the top plane of the steel deck, and the min thickness of concrete from the top plane of steel deck to the wire fabric, shall be as follows:

Restrained or Unrestrained Assembly Rating Hr	Min Concrete Topping Thk In		Min Thk of Concrete From Top Plane of Steel Deck to Bottom of Reinforcement In.
	Joist Spacing 48 In. OC Max	Joist Spacing 66 In. OC Max	
2 h or less	2-3/8	2-3/8	1-1/8
3 h	2-3/8	3-7/8	1-1/4

2. **Welded Wire Fabric/Reinforcing Bars —** As required, to develop the structural capacity of the floor in accordance with the applicable ACI specifications.
3. **Structural Steel Members* —** Composite joists with vertical leg of top chord angles embedded in concrete slab. Min area of steel angles for the top and bottom chord members shall be 0.708 sq in. each, and the min area of web members shall be 0.442 sq in. when the sprayed material is applied directly to the joists. Min area of steel angles for the top and bottom chord members may be reduced to 0.560 sq in. each, and the min area of web members to 0.299 sq in. when the joists are protected with greater thickness of Spray-Applied Fire Resistive Materials with or without the metal lath or the nonmetallic fabric, as covered in the Table under Item 5. Max joist spacing is 48 or 66 in. O. C. depending on the thickness and type of concrete topping, the hourly ratings, and the thickness of Spray-Applied Fire Resistive Materials applied to the steel deck (see Items 1 and 5).

VESCOM STRUCTURAL SYSTEMS INC —Type V.

3A. **Steel Joists — (Not Shown) —** As alternate to Item 3, Min size 16K6 or heavier K-Series joist with min 3/4 in. diam or larger cross sectional area web members.

3B. **Horizontal Bridging — (Not Shown) —** Min 1-1/4 by 1-1/4 by 1/8 in. thick steel angles for use with steel joists (Item 3A). Size and spacing per Steel Joist Institute specifications. Welded to top and bottom chords of each joist. Min thickness of Spray-Applied Fire Resistive Materials on bridging angles is 1-1/2 in.

4. **Steel Floor and Form Units —** For max 2 h ratings, nom 1-5/16 in. deep uncoated or galv corrugated steel form units. For 3 h ratings, composite or noncomposite, min 1-1/2 in. deep, 22 gauge uncoated or galv fluted steel floor units. The steel floor and form units are not considered in calculating the load carrying capacity of the floor.
5. **Spray-Applied Fire Resistive Materials* —** All surfaces to which material is applied must be free of dirt, loose scale and oil before spraying. Applied by mixing with water and spraying in more than one coat to the required thickness on the joists and the steel form units as tabulated below:

Min Area of Joist Chord Sq In.	Min Area of Joist Web Sq In.	Thk of Spray Applied Fire Resistive Mtl In. on Steel Deck: Normal Weight Concrete Topping	Thk of Spray Applied Fire Resistive Mtl In. on Steel Deck: Lightweight Concrete Topping	on Joist	Hr Rating: Restrained Assembly Rating Hr	Hr Rating: Unrestrained Assembly Rating Hr	Hr Rating: Unrestrained Beam Rating Hr
0.708	0.442	3/8	—	1-1/2	1	1	1
0.708	0.442	3/4*	3/8	1-1/2	2	2*	2*
0.708	0.442	1-1/4	1	1-1/2	3	2	2
0.560	0.299	3/8	—	2-1/2**	1	1	1
0.560	0.299	3/4	3/8	2-1/2**	2	2	2

Min avg and min ind density of 13/11 pcf, respectively for Types II or DC/F. Min avg and min ind densities of 22 and 19 pcf, respectively, for Type HP. For method of density determination, see Design Information Section, Sprayed Materials.

*The 3/4 in. thickness may be reduced to 1/2 in. when (a) the joist spacing does not exceed 48 in. O. C. or (b) the Unrestrained Assembly and Beam ratings are reduced from 2 to 1-1/2 h.

**The 2-1/2 in. thickness of Spray-Applied Fire Resistive Materials shown may be reduced to 2 in. when the metal lath or the nonmetallic fabric mesh is used.

ISOLATEK INTERNATIONAL —Type D-C/F, HP or Type II, Type EBS or Type X adhesive/sealer optional.

6. **Metal Lath —** (Optional, not shown) — Metal lath may be used to facilitate the spray application of Spray-Applied Fire Resistive Materials to steel bar joists. The diamond mesh, 3/8 in. expanded steel lath, 1.7 to 3.4 lbs per sq yd should be secured to one side of each steel joist with 18 SWG galv steel wire at joist web and bottom chord members, spaced 15 in. O. C. max. When used, the metal lath is to be fully covered with Spray-Applied Fire Resistive Materials with no min thickness requirements.
7. **Non-Metallic Fabric Mesh —** (Optional, not shown) — As an alternate to metal lath, glass fiber fabric mesh — weighing approximately 2.5 oz per sq yd, polypropylene fabric mesh — weighing approximately 1.25 oz per sq yd, or equivalent, may be used to facilitate the spray application. The mesh should be secured to each joist web member and/or the chords to hold the mesh and the Spray-Applied Fire Resistive Materials material in place during application. One method for attaching the mesh is by embedding it in 1/4 in. long beads of hot melted glue spaced a max of 12 in. O. C. along the top chord of the bar joist. Another method is by using 1-1/4 in. long by 1/2 in. wide hairpin clips formed from 18 SWG or heavier steel wire.

*Bearing the UL Classification Mark

Figure A–35. Underwriters Laboratories Design No. G805 used as the basis for Port Authority determination of retrofit thermal insulation thickness for floor trusses (XX-I).

THE PORT AUTHORITY OF NEW YORK AND NEW JERSEY

CHIEF ENGINEER'S OFFICE
P.A. OF N.Y. & N.J.
RECEIVED

1999 MAR 25 PM 3: 28

BUCKSLIP

TO: John Castaldo, Kent Piatt
FROM: Alan L. Reiss
DATE: March 24, 1999
SUBJECT: **World Trade Center Fireproofing Guidelines For Tenant Spaces**

COPY TO: E. McGinley, T. Kobel, F. Lombardi J. Richardson, J. Napolitano, R. Rafferty, L. Menno, E. Moscovitz, C. Nanninga, N. Seliga, T. Stam

In order to establish clear and consistent guidelines regarding fireproofing repairs, replacement, and upgrades at the World Trade Center Towers, the following guidelines have been established with the concurrence of the Chief Engineer.

1) Full floors being demolished for new construction or renovation shall have the fireproofing on trusses checked and upgraded if it has not already been done to the attached 1995 Engineering Department Engineered Solutions Standard. Adequate time must be allowed in any schedule to accommodate this work, typically two weeks. This work may be performed by either the tenant or us but is a landlord obligation and reimbursable to the tenant (typically $5/sq. ft.) if the work is performed by the tenant. Refireproofing requires removal of existing material to insure adequate bonding and is subject to a controlled inspection.

2) Tenant spaces that are less than a full floor, undergoing either new construction or renovation, need only meet the original construction standard. Fireproofing shall be inspected and patched as required to the greater of ¾" or to match existing (it may already have been upgraded to the Engineered Solutions Standard.)

3) On a new lease, trusses requiring patching at the time of tender of the space are a landlord obligation, however, we normally will reimburse fair and reasonable costs if performed by the tenant after authorization. For existing tenant space being renovated, careful judgement should be used to determine if the need for the work arose as a result of a tenant action, i.e. previous construction work, or our obligation because of our work over the years in the ceiling. Any recommendation should be discussed with project and property management prior to being discussed with the tenant.

AT	AF	BF	CJL	RP	SB	
	MAR 26 1999					MA
						RS
FILE	Att: JOHN LIN MANAGER Q.A.D.					IR
POST						RTN

Alan L. Reiss
Director
World Trade Department

Figure A–36. Port Authority 1999 guidelines for thermal insulation on floor trusses (3-P).

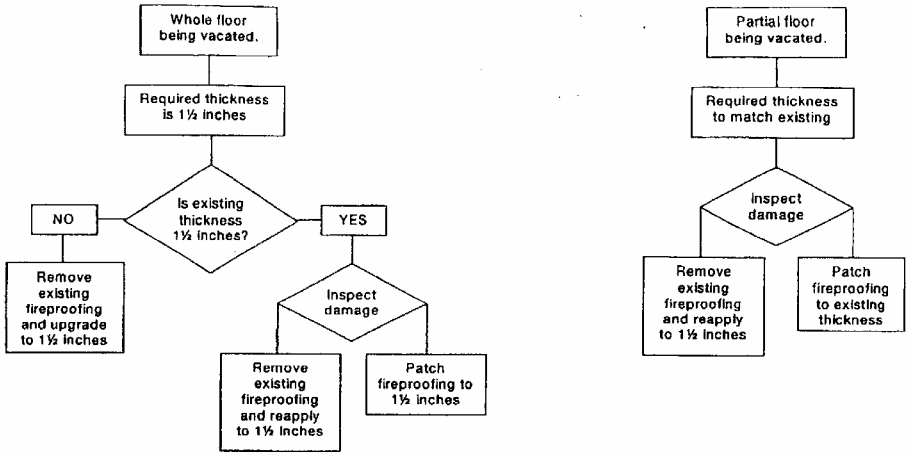


Figure 1: Fireproofing assessment process

Damage of existing fireproofing

Significant amounts of damage to the existing fireproofing occur during demolition after tenants move out. The product used in the past can be easily dislodged as ductwork, partitions, hangers, etc. are removed. Additional damage that happened during tenant fit-out or later modifications that may not have been repaired at the time.

As we understand it, in the majority of cases, the existing fireproofing requires so much patching that it is more cost-effective to replace it.

Repairs

If the damaged fireproofing is to be patched rather than replaced, the cementitious Monokote product is generally used regardless of what the in situ fireproofing material is. This can result in joists that are fireproofed by a combination of materials. This patching is generally done by hand rather than spray application. Repairs are made such that a constant thickness of fireproofing is provided to all joist members.

Removal

The Cafco Blaze-Shield fireproofing is readily removed using a high-powered water jet. The water from the jet is soaked up by the fireproofing which falls to the floor in a damp state. Usually all the water is absorbed by the fire proofing, however, on occasion water does leak onto the floor below. The floor is covered with protective sheets. The fireproofing is collected from these sheets and transported in waste buckets to a waste disposal area.

Any portions of fireproofing that are not removed by the jet are scraped away by hand. This often happens if there are sections of Monokote fireproofing and in the troughs that are formed at the bottom flange of the joist by the back-to-back angles. If the Monokote cannot be removed by hand, it is assumed to be fixed in place and is covered by the new fireproofing applications.

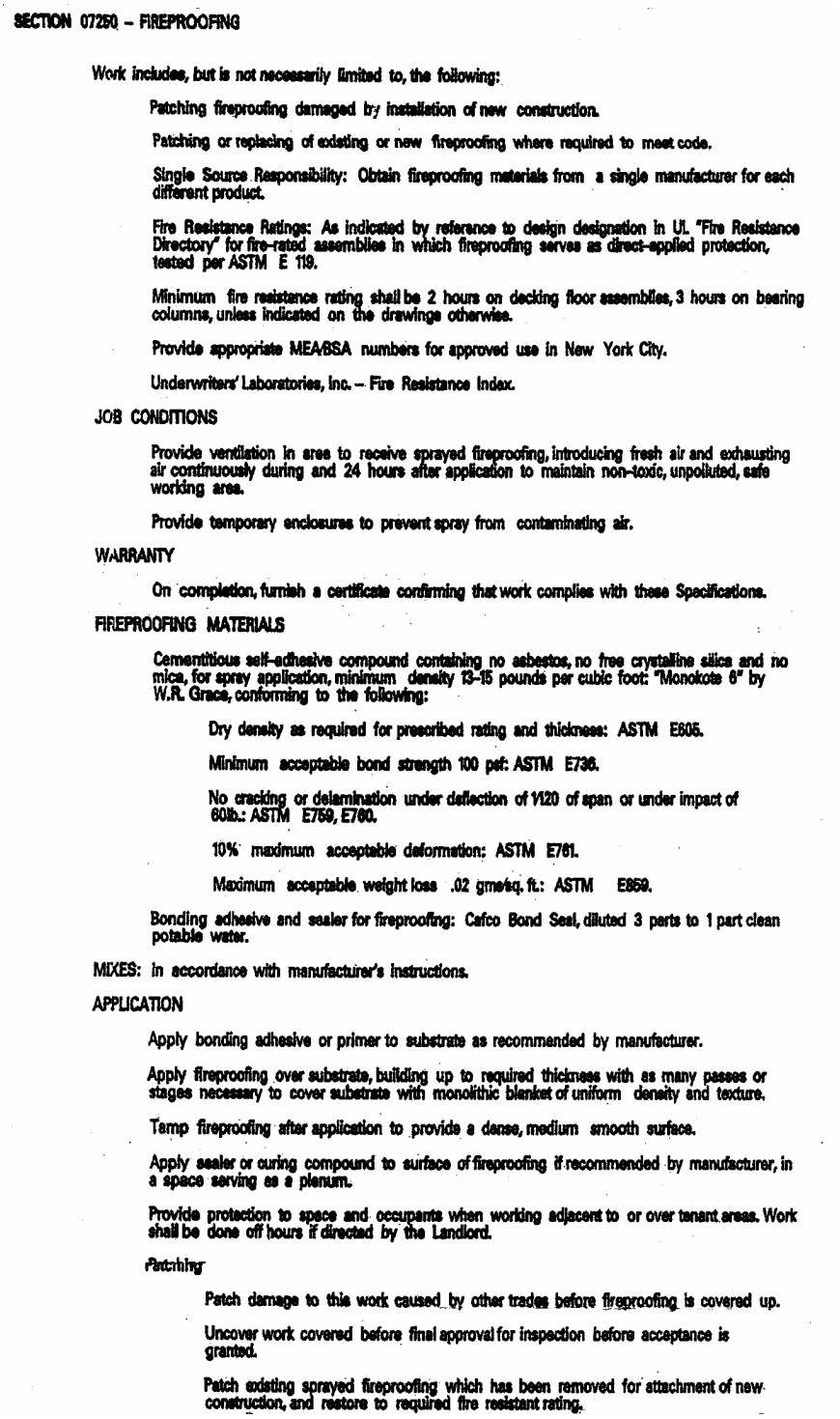
Application

When the fireproofing needs replacing, new fireproofing is applied to a thickness of 1½ inches. While equivalent products are permitted, Cafco Blaze-Shield mineral fiber spray is generally used as the replacement fireproofing.

It is estimated that 60-70% of the material is lost to overspray.

It can take 2-3 passes to apply 1½ inches. If it is done in fewer passes, the fireproofing tends to fail the adhesion tests that are conducted after application. Sometimes ten feet fall off at once when tested.

Figure A–37. Excerpt from draft report on the assessment of thermal protection of steel in WTC ((73-LERA).



SECTION 07250 – FIREPROOFING

Work includes, but is not necessarily limited to, the following:

Patching fireproofing damaged by installation of new construction.

Patching or replacing of existing or new fireproofing where required to meet code.

Single Source Responsibility: Obtain fireproofing materials from a single manufacturer for each different product.

Fire Resistance Ratings: As indicated by reference to design designation in UL "Fire Resistance Directory" for fire-rated assemblies in which fireproofing serves as direct-applied protection, tested per ASTM E 119.

Minimum fire resistance rating shall be 2 hours on decking floor assemblies, 3 hours on bearing columns, unless indicated on the drawings otherwise.

Provide appropriate MEA/BSA numbers for approved use in New York City.

Underwriters' Laboratories, Inc. – Fire Resistance Index.

JOB CONDITIONS

Provide ventilation in area to receive sprayed fireproofing, introducing fresh air and exhausting air continuously during and 24 hours after application to maintain non-toxic, unpolluted, safe working area.

Provide temporary enclosures to prevent spray from contaminating air.

WARRANTY

On completion, furnish a certificate confirming that work complies with these Specifications.

FIREPROOFING MATERIALS

Cementitious self-adhesive compound containing no asbestos, no free crystalline silica and no mica, for spray application, minimum density 13-15 pounds per cubic foot: "Monokote 6" by W.R. Grace, conforming to the following:

Dry density as required for prescribed rating and thickness: ASTM E605.

Minimum acceptable bond strength 100 psf: ASTM E736.

No cracking or delamination under deflection of 1/120 of span or under impact of 60lb.: ASTM E759, E760.

10% maximum acceptable deformation: ASTM E761.

Maximum acceptable weight loss .02 gms/sq. ft.: ASTM E859.

Bonding adhesive and sealer for fireproofing: Cafco Bond Seal, diluted 3 parts to 1 part clean potable water.

MIXES: In accordance with manufacturer's instructions.

APPLICATION

Apply bonding adhesive or primer to substrate as recommended by manufacturer.

Apply fireproofing over substrate, building up to required thickness with as many passes or stages necessary to cover substrate with monolithic blanket of uniform density and texture.

Tamp fireproofing after application to provide a dense, medium smooth surface.

Apply sealer or curing compound to surface of fireproofing if recommended by manufacturer, in a space serving as a plenum.

Provide protection to space and occupants when working adjacent to or over tenant areas. Work shall be done off hours if directed by the Landlord.

Patching

Patch damage to this work caused by other trades before fireproofing is covered up.

Uncover work covered before final approval for inspection before acceptance is granted.

Patch existing sprayed fireproofing which has been removed for attachment of new construction, and restore to required fire resistant rating.

Fig A–38. Excerpt from 1998 specification related to SFRM for upgrade of public corridors and bathrooms on 15th, 18th, and 22nd floors of WTC 2 (3-P).

SECTION 07250 – FIREPROOFING

SUMMARY
1. Patch fireproofing disturbed by remodeling operations.

PRODUCTS
1. Fire Performance: ASTM E 119, and local regulations. Cementitious Type for Concealed Use: 15 pounds per cubic foot dry density,
2. ASTM E 605.
3. Mineral Fiber Type for Concealed Use: 15 pounds per cubic foot dry density, ASTM E 605.
4. Exposed Sprayed–On Fireproofing: Match existing.

INSTALLATION
1. Inspect existing and new structural members for proper fireproofing prior to close–in of ceilings and walls.
2. Provide material thicknesses necessary to provide fire–resistance ratings indicated or required by authorities having jurisdiction.

SECTION 07270 – FIRESTOPPING SUMMARY

1. Provide Firestopping at the Following Locations: Penetrations through fire–resistance–rated floor and roof construction; Penetrations through fire–resistance–rated walls and partitions; Penetrations through smoke barriers and construction enclosing compartmentalized areas; Sealant joints in fire–resistance–rated construction.

PRODUCTS
1. Fire Performance: ASTM E 119, ASTM E 814, and local regulations.
2. Through–Penetration Firestop Systems: Ceramic–Fiber and Mastic Coating; Endothermic, Latex Compounds; Intumescent Latex Sealant; Intumescent Putty.
3. Fire–Resistive Elastomeric Joint Sealants: Single–component, neutral–curing, silicone sealant; Multicomponent, nonsag, urethane sealant; Single–component, nonsag, urethane sealant.

INSTALLATION
1. Inspect existing and new work for proper firestopping prior to close–in of ceilings and walls.
2. Provide material thicknesses necessary to provide fire–resistance ratings indicated or required by authorities having jurisdiction.

Fig A–39. Excerpt from 2001 specification related to SFRM for upgrade on 48th floor of WTC 2 (3-P).

Executive Summary

The development of fire safety engineering and in particular the performance of structure during fire has been developing rapidly over the last 5 years. Buro Happold has identified the value and benefits of this work to many of our global clients. This has required major investment in research and development, involvement with the development of new codes, working with government and the employment of staff as part of a technology transfer from the universities carrying out this research. The ultimate aim is to ensure that the research and development is used in practical way for real buildings in a short but realistic time scale. The extent to which fire safety engineering can be used in this respect has to be based on the local code development, the attitude of the client and the authorities having jurisdiction.

The USA has been party to this development and now has its own performance based design codes. Historically fire safety engineering in the USA has only been done on special or difficult projects. However as the benefits are understood and are more widely accepted the quantity of performance based design is likely to increase significantly. This work on the World Trade Centre is significant and well contained example of what is possible now as a relatively low risk early development.

The components of this global development that have been most important from the point of view of the World Trade Centre are.

1. Better understanding and the analysis of natural fires.
2. Analysis of structures at high temperatures during fire.
3. Improving relationship and understanding between the supplier and the designer
4. More data relating to the performance of materials.
5. The development of the fire safety engineering discipline and the risk assessment process.

On the basis of the current calculations and the risk assessment whilst taking a reasonably conservative view the following conclusions can be drawn for the open web joists on the tenant floors of World Trade Center Towers 1 and 2.

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

Figure A–40. Excerpts from 2000 report on thermal protection of floor trusses (3-P).

7 Recommendations

The calculations, the reliability of information, the conservative assumptions, and the risk assessment have been carefully judged to determine a reasonable compromise between the following: -

- Compliance with the defined performance criteria and a reasonable level of safety.
- Value engineering to reduce costs or improve performance. Performance can be based on long term durability and robustness, reduction in fibre content, insulation of steelwork during fire and ease of application.
- The need for margins of safety to ensure that the decision making and the approvals process are more straightforward. This in combination with the sensitivity tests covers the fact that the calculations and predictions for the phenomena of fire can never be exact.

If the most optimistic assumptions are made the thickness of the fire protection can be as low as 30% of the current thickness. However taking into account the variables, the following recommendations can be made.

7.1 Thickness

For the existing material, there is some uncertainty about the performance of this material due to lack of available data. If the material performs to the insulation standard defined at ambient temperature in the manufacturers data a thickness of 0.5 inches can be used whilst still maintaining a reasonable margin of safety. If however the material does degrade to some extent as suggested by the UL listings then a greater thickness of up to 1.3 inches is recommended. Further tests or test data would be required to achieve the lower thicknesses. The issues of reduced fibre content and long term durability have not been addressed with this selection. It is likely that only a single coat will be required for the 0.5 inch case.

7.2 Choice of System

The true cost of a system can only be accurately determined following a market test. The long term costs are a complex and are a function of the following:

- Material cost
- Required thickness
- Maximum thickness per application
- Time before the next layer can be applied
- Volume of dry material required
- Volume of water required in spraying procedure
- Overspray and other wastage
- Durability
- Etc.

An assessment of a variety of materials has been carried out in this report and judging from the results alternative materials should be considered for use in the World Trade Center. For example, the Carboline Pyrocrete 239 could be applied to a thickness of 0.75 inches, subject to receipt of confirmatory test data. This product is significantly more durable than the current product and therefore could reduce the overall life-cycle costs of the fireproofing system.

Figure A–40 (Contd.). Excerpts from 2000 report on thermal protection of floor trusses (3-P).

M&H

Executive Summary

World Trade Center
New York, New York

Structural

The building structures appear to be in adequate overall condition. Major structural repairs following the 1993 bomb blast were successfully completed and signed-off by a Permit to Occupy or Use issued by the Port Authority Office of the Chief Engineer on October 10, 1997. The repairs appear to have been properly engineered and executed. Following the bombing incident, stringent security measures were implemented at the vehicular entrances to the Plaza and subgrade facilities.

In the buildings we observed only minor cracking in some slabs, partitions or in stairwells of the buildings. Some minor slab cracks have been noted which should be monitored by the PA's structural consultant. The slabs at the truck dock and delivery area on level B-1 have deteriorated due to ice-melting salts that enter the building on vehicles during the winter. A slab replacement program is ongoing and should be continued until all of the damaged slabs are replaced. The monitoring of the visco-elastic movement dampers in the two Towers is an essential program that has been strongly recommended for continuation by the PA's outside structural consultant. Building movement is monitored by analysis of measurements taken and recorded by devices located in the 108th floor of 1 WTC. Analysis of these records is done by the Port Authority's independent engineer (LERA) and should continue in the future. In addition, physical sampling and analysis of the condition of the visco-elastic dampers is reportedly continuing on a 5-year cycle, with the next sampling to be done in 2001. The slurry wall that surrounds and contains the subgrade levels of the complex has some seepage that is contained by curbing and leaders, and is discharged by sump pumps in the lowest levels.

The slurry wall and the adjacent floor slabs that brace the wall are inspected on an ongoing basis to ensure that unsafe conditions do not develop. Structural Integrity Inspection (SII) Report I-38, dated April 3, 1998, provided in the Data Room, found the conditions to be acceptable. These periodic inspections should continue.

The rating of the structural fireproofing in the Towers and subgrade has been judged to be an adequate 1-hour rating considering the fact that all Tower floors are now sprinklered. An ongoing program of re-fireproofing the structural steel to the full thickness for 2-hour rating is in place. This work is done on a lease rollover basis whenever there is a full floor of space being built out for new occupancy. To date approximately 30 floors have been completed in the two towers. The PA will require this program to continue. The presence of asbestos containing

December 6, 2000

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Figure A–41. Excerpt from 2000 report on condition assessment of the World Trade Center (7-P).

cc: A. C. WEBER
J. R. PAUL

August 10, 1967

Mr. M. Malter
Zonolite Division
W. R. Grace & Company
135 South LaSalle Street
Chicago, Illinois 60603

Dear Marty:

It was nice to get together with you and your good associates this week at Madison to see the spraying of your fireproofing on steel joists.

I think the people from the Port Authority were impressed with the good job you did on our joists, and I hope that you are successful in your effort with the Authority and the plastering contractors in New York.

Mr. Ray Monti, the general superintendent of the World Trade Center towers, called yesterday to ask if we could furnish some trusses similar to those you had used in the spray application, so I presume there will be considerable activity regarding the spray-on material in the next few weeks.

If there is anything further we can be doing for you, do not hesitate to call upon us. I know Jim Paul is expecting a call from you concerning what effort might be made to run some fire tests on the coated trusses and joists. Give us a call the next time you are in town.

Best personal regards.

Yours very truly,

LACLEDE STEEL COMPANY

A. Carl Weber
Vice President

ACW:pjz

Figure A–42. Example of correspondence referring to fire endurance testing of coated floor trusses (70-I).

FIRE TESTING

While not advocating the omission of fire testing, it is clear that numerous examples of non-tested assemblies are incorporated into major buildings--under the watchful eye of responsible building officials and with the full knowledge of designers, builders and constructors. Obvious examples include:

(1) The floor assembly of the Sears Tower; and
(2) Typical composite beams supporting composite deck construction, with unsprayed steel deck.

The latter is an example of industry "standard" construction, accepted on a nationwide basis, but not supported by fire testing.

Reasons for this lack of testing of special construction (such as Sears and World Trade Center floors) is not to be found on account of a lack of desire on the part of designers or builders. The problem is quite straightforward:

(1) It is not possible to test all products and all combinations of products prior to contract award. For example, Leclede trusses were accepted on October 4, 1967 and Cafco fireproofing on March 26, 1969.
(2) Proper testing of the one-way World Trade Center floors would have required a floor furnace capable of testing an assembly 60'x15'.
(3) Proper testing of the two-way World Trade Center floors would have required a floor furnace capable of testing an assembly 60'x80'.
(4) With the limited availability of such furnaces, it is nearly impossible to schedule a test program in time to meet construction requirements.

These special floor assemblies would best be fire tested--since actual testing is the only known, reliable method known to assure compliance with fire resisting requirements. At the same time the writer knows of no example wherein testing has been accomplished--the problems of time and scheduling appear to preclude such testing.

-10-

SKILLING, HELLE, CHRISTIANSEN, ROBERTSON

Figure A–43. Excerpts from 1975 post fire report indicating need for fire endurance testing to establish a fire rating for the floor system (3-P).

Early drafts of the revised Code required the 3-hour rating. Later drafts and the final version of the Code allow a 2-hour rating.

It is unlikely that a fire test of the 4-inch World Trade Center slab, making use of materials actually incorporated into the work, will pass a 3-hour test. It will almost surely pass a 2-hour test and would not be challenged on this account.

The World Trade Center construction of 4-inch reinforced concrete slab atop 1 1/2 inch steel deck formwork is more fire-resistive then the most commonly used construction of today (1975)--a 3 1/4 inch slab atop 1 1/2 inch composite steel deck without benefit of spray fireproofing.

Available Fire Rating

The fire resistive requirements for the project were subjected to continuous modification as a result of the development of the new Building Code.

The decision to provide for 1/2 inch of Cafco was made in full realization that:

(1) the floor slab provided only a 2-hour rating; and
(2) the new Code provided for a 2-hour rating.

We presume, but do not know, that the Cafco decision was based on the need for a 2-hour rating. Even without benefit of full scale testing we do know that a 3-hour rating cannot be achieved by the floor slab. We know also that the basic World Trade Center floor slab is superior to construction provided commonly throughout the country and does exceed a 2-hour requirement. Without benefit of a full-scale fire test we cannot establish a rating for the floor assembly.

Fire Performance

The construction performed as expected during the fire of February, 1975. While some reports indicated that the fire was very hot, no evidence of temperatures reached is available to the writer. In any event, at the very least, it can be said that the February fire provided no evidence that the construction was not satisfactory for its intended purpose.

- -

We hope that this report will provide some insight into the fire-

SKILLING, HELLE, CHRISTIANSEN, ROBERTSON

Figure A–43 (Contd.). Excerpts from 1975 post fire report indicating need for fire endurance testing to establish a fire rating for the floor system (3-P).

Fire Testing

While it is difficult to document through the media of project correspondence, the question of full scale fire testing occupied the minds of the planners and designers of The World Trade Center.

In March of 1964 Mr. C. H. Yuill, Manager Fire Research Section, Southwest Research Institute wrote to SHCR in response to its inquiry. The tone of the letter reflects a little the many problems associated with such tests; size of furnace, non-standard test procedures, long waiting time and the like (see page 8.1 and 8.2).

In June 2, 1965, SHCR transmitted truss loads for use in a fire test by U.S. Mineral Products Co. Designs of that era assumed conventional trusses--not the Laclede variety actually incorporated into the work. While not privy to the results of the test we understand(from discussions with Mr. Soffer of Port Authority) that another test program was carried out in small scale using Mono-Kote spray-on materials.

The Underwriters' Laboratories, Inc., test of July 26, 1969 (Fire TEst R4374; 68NK2435) makes use of Mono-Kote materials and Laclede trusses and provides a 3-hour rating. A copy of that report is attached (appendex). The test is not completely representative of World Trade Center trusses in that the members are lighter, the span is shorter (16'-10") and the trusses are shallower. (see page 8.3). It should be noted also that the test was conducted subsequent to the contracting for World Trade Center fireproofing. There is no evidence of when the report came to the attention of Port Authority; it was given to SHCR on March 24, 1975.

Figure A–44. Excerpt from 1975 post-fire report referring to fire endurance test of floor truss system with sprayed thermal insulation (3-P).

GRACE
ZONOLITE
ONSTRUCTION PRODUCTS DIVISION

G E N E R A L

The subject of this report is a 3-hour fire endurance rated assembly composed of Laclede Composite Joists supporting a concrete slab over corrugated steel centering, protected with Mono-Kote cementitious fireproofing spray-applied directly to the surfaces of the joists and to the underside of the steel centering.

The object of the investigation was to establish a 3-hour fire resistance classification for the assembly, constructed with the materials and in the manner as herein described, by means of the Fire Test of Building Construction and Materials, ASTM E-119 (UL 263).

D E S C R I P T I O N

MATERIALS:

The following materials were used in the test assembly.

Laclede Composite Joists - Type 10H5C, spaced 3 ft. 6 in. on center with a 16 ft. 10 in. clear span.

Corrugated Centering - No. 28 gauge steel attached to joists with welding washers.

Concrete - Average 28 day strength of 4290 psi, ready-mixed concrete, poured to a thickness of 2-3/4" as measured over the crests of the corrugated centering.

Temperature Reinforcement - No. 8 SWG, 6 in. by 6 in. wire mesh.

Mono-Kote Cementitious Spray-Applied Fireproofing - Applied directly to the surfaces of the joists to a thickness of 1-1/2" and to the underside of the centering to a thickness of 1/2", following the contours of the joists and the corrugated centering. Bags of Mono-Kote contained the UL label for "Cementitious Mixture."

Figure A–45. Reports of 1970 fire endurance test of floor truss system with sprayed thermal insulation (3-P).

GRACE
ZONOLITE
)NSTRUCTION PRODUCTS DIVISION

ERECTION OF TEST ASSEMBLY:

The assembly was constructed at the Northbrook, Illinois, testing facility of Underwriters' Laboratories, Inc. in accordance with the attached construction drawing Nos. UL 100-1 and -2, dated 2/27/70, under the observation of members of the staff of Underwriters' Laboratories, Inc.

FIRE ENDURANCE TEST:

The test was conducted in accordance with the Fire Test of Building Construction and Materials, ASTM E-119 (UL 263 test method).

The assembly was loaded to provide a uniformly distributed live load of 126 psf or a combined live and dead load of 169 psf, producing a maximum stress of 30,000 psi in the joists.

R E S U L T S

Observations of the Exposed Surface - All of the Mono-Kote cementitious fireproofing remained in place throughout the 3 hour 13 minute test duration.

Temperatures of the Assembly - The initial average temperatures of the unexposed surface was 69F. Based, therefore, on a maximum average temperature rise of 250F and a maximum individual temperature rise of 325F, the average limiting temperature was 319F and the individual maximum limiting temperature was 394F. At 180 minutes (3-hours), the average limiting temperature of 319F was reached. At this time the maximum individual temperature was 352F.

Figure A–45 (Contd.). Reports of 1970 fire endurance test of floor truss system with sprayed thermal insulation (3-P).

GRACE
ZONOLITE
NSTRUCTION PRODUCTS DIVISION

Deflection of the Assembly

Time	Deflection
60 min	2 "
90 min	2-1/2"
120 min	3 "
150 min	3-3/8"
180 min	4-3/4"

Temperatures of the Joists -

Time	Top Chord	Diagonal Web	Bottom Chord	Average
60 min	235F	485F	485F	301F
90 min	395F	915F	1,150F	814F
120 min	486F	972F	1,243F	900F
150 min	550F	1,200F	1,543F	1,095F
180 min	622F	1,280F	1,580F	1,160F

C O N C L U S I O N S

The assembly achieved a 3-hour fire endurance rating in accordance with ASTM E-119 and as verified by the attached letter dated March 26, 1970, from A. F. Abbasi of Underwriters' Laboratories, Inc.

Submitted by:
Thomas P. Feit
Thomas P. Feit - Manager
Technical Services

TPF/jac

Figure A–45 (Contd.). Reports of 1970 fire endurance test of floor truss system with sprayed thermal insulation (3-P).

UNDERWRITERS' LABORATORIES, INC.
333 PFINGSTEN ROAD · NORTHBROOK, ILLINOIS 60062
an independent, not-for-profit organization testing for public safety

AIR MAIL March 26, 1970

in reply, please refer to
R4374
68NK2453

CAMBRIDGE

Zonolite Construction Products Div.
W. R. Grace & Co.
62 Whittemore Ave.
Cambridge, Massachusetts 02140

Subject: Fire Endurance Test of Composite Bar Joist and Concrete Deck

Attention: Mr. T. P. Feit

Gentlemen:

This letter summarizes the results of the fire endurance test of floor assembly of the subject matter.

The floor assembly was constructed according to Drawing No. LS101UL dated July 26, 1969 of Laclede Steel Company. It consisted of 3 bar joists type 10H5C with 3 ft 6 in. spacing on centers and 16 ft 10 in. clear span, supporting concrete deck over corrugated centering. The thickness of concrete was 2 3/4 in. over the crests and 3 1/4 in. over the valleys, and was reinforced with 6 by 6 in. No. 8/8 wire mesh. The bar joists and the corrugated centering were sprayed with Mono-Kote MK of the following thicknesses:

1. Bar Joists - An average of 1 1/2 in. thick directly applied over all the exposed surfaces of bottom and top chords and webs.
2. Corrugated Centering - An average of 1/2 in. thick following the contours of the exposed surface of the corrugations.

The average strength of concrete at 28 days was 4290 psi. The equivalent uniform live load of 126 p. s. f. was applied on the assembly. The total live and dead load was 169 p. s. f. which produced a maximum stress of 30,000 psi in the bottom chord of the bar joist.

Figure A–45 (Contd.). Reports of 1970 fire endurance test of floor truss system with sprayed thermal insulation (3-P).

UNDERWRITERS' LABORATORIES, INC.

- 2 - March 26, 1970

The floor assembly was tested on February 27, 1970, and the test was continued for 3 hours 13 minutes and 10 seconds. The structural performance of the floor assembly during the test was considered satisfactory. The average temperature of the unexposed surface before the fire test was 69F. At 3 hours of test time the average temperature of the unexposed surface reached 319 F and the maximum individual temperature was 352 F. The maximum deflection of the unexposed surface at 3 hours was 4.76 in.

The assembly was further loaded with an additional live load of 126 p. s. f. on March 2, 1970 which increased the maximum deflection by 0.35 in. without any apparent structural damage.

We shall be preparing a formal report which will contain details of the test.

Very truly yours,

A. F. ABBASI
Fire Protection Department

AFA:ck

Figure A–45 (Contd.). Reports of 1970 fire endurance test of floor truss system with sprayed thermal insulation (3-P).

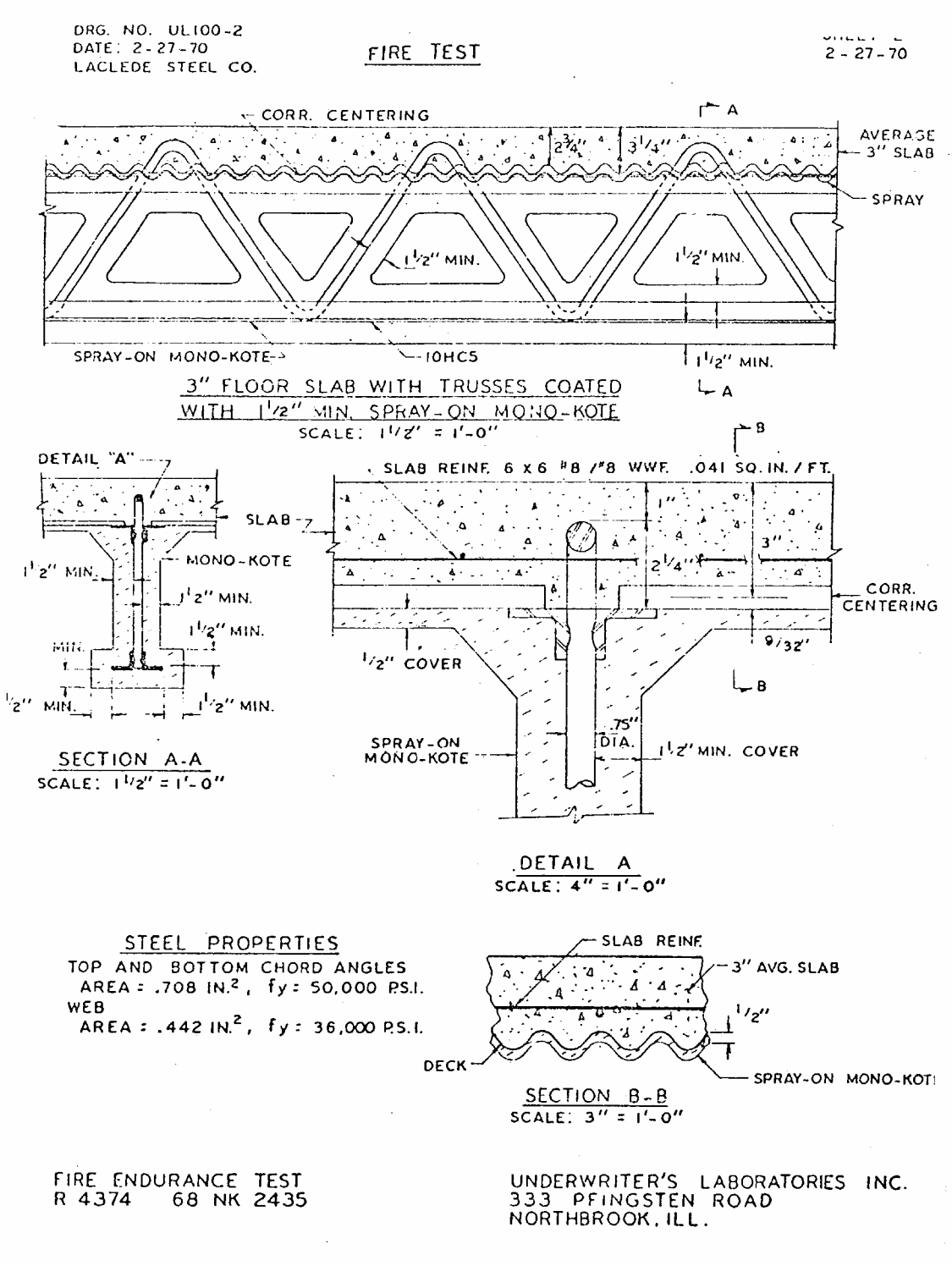


Figure A–45 (Contd.). Reports of 1970 fire endurance test of floor truss system with sprayed thermal insulation (3-P).

THEORETICAL CONSIDERATIONS

Port Authority specified in a letter dated October 30, 1969, to Mario & DiBono Plastering Co., Inc., 0.50 inch thickness of Cafco Blaze-Shield Type D for the steel beams, spandrels and bar joists. In the ULI report of July 26, 1969, for 3-Hour Fire Endurance Assembly with Mono-Kote Spray-applied Cementitious Fireproofing and Laclede Composite Joists, the test assembly achieved a 3-hour fire endurance rating in accordance with ASTM E-119.

In the test assembly the Mono-Kote fireproofing was 0.50" on the steel deck formwork and 1.50" on the surfaces of the joists with 0.75" diam. webs and 1.50" x 1.25" x 0.135" chord angles.

With many simplifying assumptions, the required thickness of Cafco Blaze-Shield for the WTC floor trusses the same 3-hour fire rating may be extrapolated in a very approximate way on the basis of the thermal conductivity of the two materials.

The thermal conductivity in units of BTU/HR-FT^2-1°F/IN, is 0.27 for Cafco Blaze-Shield and 0.61 for Mono-Kote. The required thickness of Cafco Blaze-Shield is computed to be 0.50" for the Laclede trusses with 1"Ø webs and chord angles thicker than 3/16"; 5/8 "thickness would be needed for 3/4Ø web members. It must be emphasized, however, that theoretical extrapolation of fire endurance tests must be viewed with caution.

-12-
SKILLING, HELLE, CHRISTIANSEN, ROBERTSON

Figure A–46. Excerpt from 1975 post-fire report indicating interpretation of 1970 fire endurance test of truss floor system with sprayed thermal insulation (3-P).

REV. | LERA LESLIE E. ROBERTSON ASSOCIATES CONSULTING STRUCTURAL ENGINEERS | P 1003114 | DRAWING NO.

WTC - REFIREPROOF ELEVATOR SHAFTS 12 & 13 | DRAFT | 1/37

INTRODUCTION | DESIGN WPM | 12/9/92 | CHECK

PURPOSE: THE PURPOSE OF THIS CALCULATION IS TO DETERMINE THE THICKNESS OF FIREPROOFING REQUIRED FOR THE EXPOSED BEAMS AND COLUMNS IN THE WORLD TRADE CENTER ELEVATOR SHAFTS PE 12 AND PE 13.

RESULTS: VARIOUS THICKNESSES OF FIREPROOFING ARE REQUIRED. THE VARIABILITY IS DUE TO THE USE OF THREE DIFFERENT MATERIALS AND THE CHANGES IN BEAM AND COLUMN SIZES FROM FLOOR TO FLOOR. THE THICKNESSES ARE NOT LISTED HERE IN ORDER TO SAVE SPACE AND MAY BE FOUND IN THE BODY OF THE CALCULATION.

DISCUSSION: REFIREPROOFING OF BEAMS AND COLUMNS IN SHAFTS PE12 AND PE 13 MAY BE PERFORMED WITH ANY OF THE 3 MATERIALS LISTED BELOW:

1. MONOKOTE TYPE Z-106, MANUFACTURED BY W.R. GRACE & Co.
2. CAFCO 560, MANUFACTURED BY ISOLATEK INDUSTRIES
3. ALBI DURASPRAY OR ALBI DURASPRAY 30 MANUFACTURED BY STAN CHEM, INC. (NOTE: THESE ARE TWO DIFFERENT MATERIALS WITH DIFFERENT THICKNESSES REQUIRED FOR EACH.)

THE CALCULATIONS WERE PERFORMED USING THE UNDERWRITERS LABORATORY FIRE RESISTANCE DIRECTORY, REFERENCE (A). THE REFERENCE (E) AND (H) AISI PUBLICATIONS ARE ALSO VERY HELPFUL.

Figure A–47. Excerpts from 1992 report on thermal insulation thickness for repair of missing insulation (240-LERA).

REV. | LERA LESLIE E. ROBERTSON ASSOCIATES CONSULTING STRUCTURAL ENGINEERS | P 1003114 | DRAWING NO.

WTC - REFIREPROOF ELEVATOR SHAFTS 12+13 | DRAFT | 2/37

INTRODUCTION | DESIGN WPM | CHECK 12/9/92

DISCUSSION (CONTINUED)

A REVIEW OF THE APPROPRIATE DRAWINGS, REFERENCES (B), (D), (F) AND (G) IDENTIFIED WHICH BEAMS AND COLUMNS WERE ACCESSABLE FROM INSIDE THE ELEVATOR SHAFTS. BEAMS SEPARATING SHAFTS PE12 & PE 13 ARE NOT FIREPROOFED.

ASSUMPTIONS: THE FOLLOWING ASSUMPTIONS WERE USED IN THIS CALCULATION:

- THE FIREPROOFING THICKNESS FOR COLUMNS WAS CALCULATED FOR GROUPS OF FLOORS IN ORDER TO SAVE TIME. THE GROUPS WERE DETERMINED BY LUMPING TOGETHER ALL COLUMNS WITH PLATE THICKNESSES WITHIN 1/2" OF EACH OTHER. BECAUSE FIREPROOFING THICKNESS INCREASES WITH SMALLER CROSS-SECTIONS, THE SMALLEST CROSS SECTION IN EACH GROUP WAS USED.
- SOME BEAMS HAD ADDITIONAL STIFFENING PLATES AND MOUNTING BRACKETS WELDED TO A PORTION OF THEIR SPAN. THIS EXTRA MATERIAL WAS NOT INCLUDED IN THE CALCULATION. AGAIN, THIS WAS DONE TO SAVE TIME AND IT SHOULD BE NOTED THAT THE ADDITION OF THESE PLATES WOULD TEND TO INCREASE THE BEAM'S CROSS SECTION AND THEREBY REDUCE THE THICKNESS OF FIREPROOFING REQUIRED.
- A 2 HOUR RATING FOR BEAMS IS REQUIRED. BEAMS ARE RESTRAINED AGAINST THERMAL EXPANSION.
- A 3 HOUR RATING FOR COLUMNS IS REQUIRED.

Figure A–47 (Contd.). Excerpts from 1992 report on thermal insulation thickness for repair of missing insulation (240-LERA).

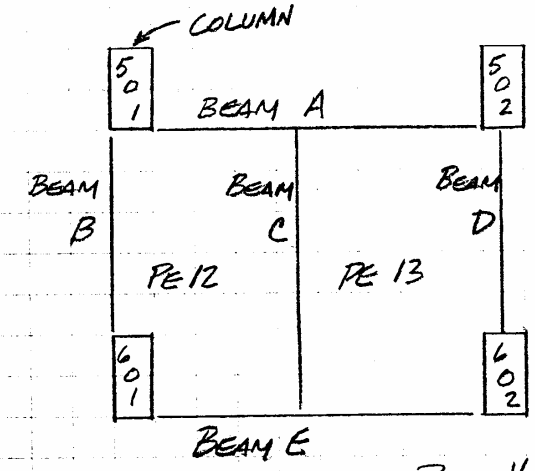
REV. | LERA LESLIE E. ROBERTSON ASSOCIATES CONSULTING STRUCTURAL ENGINEERS | P/003114 | DRAWING NO.

WTC - REFIREPROOF ELEVATOR SHAFTS 12413 | DRAFT | 4/37

BEAMS | DESIGN WPM | CHECK | 12/3/92

BEAMS

THE FOLLOWING CALCULATIONS WILL DETERMINE THE THICKNESS OF FIREPROOFING REQUIRED FOR BEAMS EXPOSED IN ELEVATOR SHAFTS PE12 & PE 13. FROM THE SKETCH BELOW, THERE ARE 5 BEAMS EXPOSED IN THE SHAFTS. BEAMS A AND E ARE NORMALLY ENCLOSED IN CONCRETE AND DO NOT REQUIRE SPRAY ON FIREPROOFING. BEAM C SEPARATES THE ELEVATOR SHAFTS AND IS NOT FIREPROOFED. ONLY BEAMS B AND D REQUIRE SPRAY ON FIREPROOFING.



PLAN VIEW

SEE REFERENCE (D) FOR EXTENT OF FIREPROOFING ON BEAMS.

A 2 HOUR RATING FOR BEAMS (RESTRAINED) IS DESIRED.

SEE REFERENCES (F) AND (G) FOR BEAM DETAILS.

Figure A–47 (Contd.). Excerpts from 1992 report on thermal insulation thickness for repair of missing insulation (240-LERA).

REV. | LERA LESLIE E. ROBERTSON ASSOCIATES CONSULTING STRUCTURAL ENGINEERS | P/003114 | DRAWING NO.

WTC-RG FIREPROOF ELEVATOR SHAFTS 12+13 | DRAFT | 5/37

BEAMS | DESIGN WPM | 12/3/92 | CHECK

BEAM B

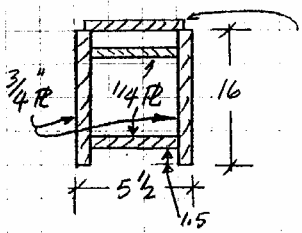
THERE ARE SEVERAL CROSS-SECTIONS USED IN THIS LOCATION. ACCORDING TO THE REFERENCE (E) PROCEDURE FOR DETERMINING FIREPROOFING THICKNESS, THE W/D RATIO FOR THESE DIFFERENT CROSS-SECTIONS IS REQUIRED. AFTER THIS RATIO IS COMPARED TO THE W/D RATIO FOR THE BEAM USED IN THE REFERENCE(A) FIRE TEST, THE REFERENCE(A) FIREPROOFING THICKNESS MAY BE ADJUSTED UP OR DOWN.

W/D RATIOS

- W12x72 USED AT ELEV 294'
  $W/D = 1.2$ (REFERENCE E)

- 24 I 79.9 USED AT ELEV 310' AND FLOOR 7
  SIMILAR TO S24x80
  $W = 80\ lb/ft$
  $D = 3b_f + 2d - 2t_w = 3(7) + 2(24 - .5) = 68$
  $W/D = 80/68 = 1.18$

- 16x5 1/2 TUBE USED AT INTERMEDIATE LEVEL
  FABRICATED SECTION, SEE REFERENCE (F)



THIS PL ONLY 2' LONG. DON'T INCLUDE IN CALCULATION.

$$W = \left[2(16)(.75) + 2(4)(.25)\right] \times 12\ in/ft \times \frac{490}{1728} = 88.5\ lb/ft$$

$D = 16(2) + 5.5 + 2(1.5) = 40.5$

$$W/D = \frac{88.5}{40.5} = 2.18$$

Figure A–47 (Contd.). Excerpts from 1992 report on thermal insulation thickness for repair of missing insulation (240-LERA).

REV.	LERA LESLIE E. ROBERTSON ASSOCIATES CONSULTING STRUCTURAL ENGINEERS	P 1003114	DRAWING NO.
	WTC - REFIREPROOF ELEVATOR SHAFTS 12+13	DRAFT	8/37
	BEAM B	DESIGN WPM	
		CHECK	12/3/92

NOW, DETERMINE THE THICKNESS OF FIREPROOFING FOR EACH OF THE THREE MATERIALS.

MONOKOTE TYPE Z-106 BEAM B

UL DESIGN (REFERENCE (A)) N720

2HOUR RESTRAINED TEST BEAM W8X28, $W/D = .80$

ALL BEAMS WITH W/D GREATER THAN .80 MAY USE THE N720 SPECIFIED THICKNESS OF $15/16$".

ALTERNATIVELY, THIS THICKNESS MAY BE REDUCED BY USING THE REFERENCE (A) BEAM SUBSTITUTION EQUATION:

$$h_1 = \left[\frac{W_2/D_2 + 0.6}{W_1/D_1 + 0.6}\right] h_2$$

WHERE:
h = THICKNESS OF FIREPROOFING
SUBSCRIPT 1 = SUBSTITUTE BEAM VALUES
SUBSCRIPT 2 = UL DESIGN BEAM VALUES

NOTE:
FOR BEAMS WITH A W/D RATIO LESS THAN 0.8, THE ABOVE EQUATION MUST BE USED TO INCREASE THE FIREPROOFING THICKNESS.

FLOOR	W/D	REVISED THICKNESS – BEAM SUBSTITUTION EQUATION USED.
ELEV 294'	1.2	3/4"
ELEV 310'	1.18	3/4"
INTERMEDIATE	2.18	1/2"
2	1.28	3/4"
3-6	1.78	9/16"

Figure A–47 (Contd.). Excerpts from 1992 report on thermal insulation thickness for repair of missing insulation (240-LERA).

REV.	LERA LESLIE E. ROBERTSON ASSOCIATES CONSULTING STRUCTURAL ENGINEERS	P 1003114	DRAWING NO.
	WTC - REFIREPROOF ELEVATOR SHAFTS 12413	DRAFT	10/37
	BEAM B	DESIGN WPM	
		CHECK	12/4/92

BEAM B, CAFCO 560 MATERIAL

UL DESIGN N714

2 HOUR RESTRAINED TEST BEAM W 8X28, $^{W}/_{D}$ = .80

AS BEFORE, ALL FLOORS EXCEPT THE 8TH MAY USE DESIGN N714 THICKNESS OF 7/8".

FLOOR 8 REQUIRES AN INCREASE IN THICKNESS AND THE REMAINING FLOORS MAY BE REDUCED, ALL BY USING THE BEAM SUBSTITUTION EQUATION.

REVISED THICKNESSES (USE THE BEAM SUBSTITUTION EQUATION)

FLOOR	W/D	THICKNESS	FLOOR	W/D	THICKNESS
ELEV 294'	1.2	11/16"	41, 43, 44	1.03	13/16"
ELEV 310'	1.18	3/4"	42	.85	NO CHANGE 7/8"
INTER.	2.18	1/2"	45-66	1.01	13/16"
2	1.28	11/16"	67	1.26	11/16"
3-6	1.78	9/16"	68-74	1.01	13/16"
7	1.18	3/4"	75	1.28	11/16"
8	.57	1 1/16" REQ'D	76	.85	NO CHANGE 7/8"
9	1.13	3/4"	77	1.28	11/16"
10-39	1.26	11/16"	78	1.65	9/16"
40	1.01	13/16"	79	1.43	5/8"

Figure A–47 (Contd.). Excerpts from 1992 report on thermal insulation thickness for repair of missing insulation (240-LERA).

REV. | LERA LESLIE E. ROBERTSON ASSOCIATES CONSULTING STRUCTURAL ENGINEERS | P 1003114 | DRAWING NO.

WTC - REFIREPROOF ELEVATOR SHAFTS 12+13 | DRAFT | 11/37

BEAM B | DESIGN WPM | CHECK | 12/4/92

BEAM B ALBI DURASPRAY

UL DESIGN N711

2 HOUR RESTRAINED TEST BEAM W8X28 W/D = .80

SIMILAR TO THE TWO PREVIOUS CASES, ALL FLOORS EXCEPT 8TH MAY USE THE N711 DESIGN THICKNESS OF 1". FLOOR 8 REQUIRES AN INCREASED THICKNESS.
THE REVISED THICKNESSES AND THE REQUIREMENT FOR FLOOR 8 ARE BELOW.

REVISED THICKNESSES (USE THE BEAM SUBSTITUTION EQUATION)

FLOOR	W/D	THICKNESS	FLOOR	W/D	THICKNESS
ELEV 294'	1.2	13/16"	42	.85	NO CHANGE 1"
ELEV 310'	1.18	13/16"	45-66	1.01	7/8"
INTER	2.18	1/2"	67	1.26	13/16"
2	1.28	3/4"	68-74	1.01	7/8"
3-6	1.78	5/8"	75	1.28	3/4"
7	1.18	13/16"	76	.85	NO CHANGE 1"
8	.57	1 1/4" REQ'D	77	1.28	3/4"
9	1.13	13/16"	78	1.65	5/8"
10-39	1.26	13/16"	79	1.43	3/4"
40	1.01	7/8"			
41,43,44	1.03	7/8"			

Figure A–47 (Contd.). Excerpts from 1992 report on thermal insulation thickness for repair of missing insulation (240-LERA).

REV. | LERA LESLIE E. ROBERTSON ASSOCIATES CONSULTING STRUCTURAL ENGINEERS | P 1003114 | DRAWING NO.

WTC - REFIREPROOF ELEVATOR SHAFTS 12+13 | DRAFT | 19/37

COLUMN 601 | DESIGN WPM | CHECK 12/8/92

COLUMNS

THE FOLLOWING CALCULATIONS WILL DETERMINE THE THICKNESS OF FIREPROOFING REQUIRED FOR COLUMNS 601, 602, 501 AND 502 FOR ALL 3 FIREPROOFING MATERIALS. COLUMN SIZES ARE FROM REFERENCE (B).

A) MONOKOTE TYPE Z-106, MANUFACTURED BY W.R. GRACE

COLUMN 601

UL DESIGN X738

THE UL DIRECTORY, REFERENCE (A), PROVIDES AN EQUATION FOR DETERMINING THE THICKNESS OF TYPE 106 MATERIAL REQUIRED. THIS EQUATION IS BASED ON THE W/D RATIO. BECAUSE THIS COLUMN'S CROSS SECTION CHANGES OVER ITS HEIGHT, SO WILL THE W/D RATIO.

IN AN ATTEMPT TO REDUCE THE NUMBER OF THICKNESS CHANGES, THE W/D RATIO WILL BE CALCULATED FOR GROUPS OF COLUMNS WHOSE PLATE THICKNESSES ARE WITHIN 1/2" OF EACH OTHER. BECAUSE FIREPROOFING THICKNESS INCREASES WITH SMALLER W/D RATIOS, THE LIGHTEST COLUMN IN EACH GROUP WILL BE USED.

ALTHOUGH DIFFERENT SIDES OF THE SAME COLUMN ARE EXPOSED AT DIFFERENT ELEVATIONS WITHIN THE SHAFT, THE CALCULATION WILL ASSUME A FIRE AROUND THE FULL PERIMETER OF THE COLUMN. THIS IS CONSERVATIVE AS IT WILL TEND TO LOWER THE W/D RATIO.

Figure A–47 (Contd.). Excerpts from 1992 report on thermal insulation thickness for repair of missing insulation (240-LERA).

REV. | LERA LESLIE E. ROBERTSON ASSOCIATES CONSULTING STRUCTURAL ENGINEERS | P 1003114 | DRAWING NO.

WTC - REFIREPROOF ELEVATOR SHAFTS 12413 | DRAFT | 20/37

COLUMN 601 | DESIGN WPM | CHECK | 12/8/92

THE UL EQUATION TO DETERMINE TYPE Z-106 FIRE-PROOFING IS:

$$h = \frac{R}{1.05(W/D) + .61}$$

WHERE:

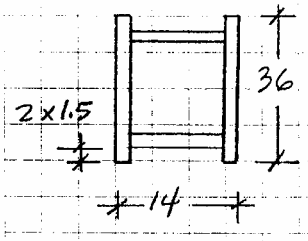
h = THICKNESS OF FIREPROOFING, INCHES

R = RESISTANCE TIME IN HOURS

W/D = WITHIN THE RANGE OF .33 TO 6.62

NOTE THAT THE USE OF THIS EQUATION IS NOT MANDATORY FOR W/D RATIOS GREATER THAN THOSE IN THE UL DESIGN. IT MUST BE USED FOR W/D RATIOS SMALLER THAN THOSE IN THE UL DESIGN.

FLOORS 69 → 79



ALL PL IS .8125" THICK

$W = [(36 \times 2) + (14 - .8125(2))2] .8125 \times 12 \times \frac{490}{1728} =$

268 lb/ft

$W/D = \frac{268}{(36 + 14 + 3)2} = 2.52$

THE UL DESIGN THICKNESS IS 15/16" ...

APPLYING THE EQUATION $h = .92$ USE 15/16"

Figure A–47 (Contd.). Excerpts from 1992 report on thermal insulation thickness for repair of missing insulation (240-LERA).

REV. | LERA LESLIE E. ROBERTSON ASSOCIATES CONSULTING STRUCTURAL ENGINEERS | P 1003114 | DRAWING NO.

WTC - REFIREPROOF ELEVATOR SHAFTS 12413 | DRAFT | 27/37

COLUMNS | DESIGN WPM | CHECK | 12/9/92

(B) CAFCO 560, MANUFACTURED BY ISOLATEK INTERNATIONAL

UL DESIGN X767

NO EQUATIONS ARE PROVIDED IN THE UL CODE, REFERENCE (A), FOR REDUCING THE THICKNESS SPECIFIED IN DESIGN X767. THE VENDOR ALSO STATED THAT THE FULL THICKNESS SPECIFIED IN THIS DESIGN SHOULD BE USED. FOR A 3 HOUR RATING, DESIGN X767 SPECIFIES A THICKNESS OF

$2\ ^{11}/_{16}$" FOR ALL COLUMNS.

CHECK W/D

THE TEST COLUMN IS A $4 \times 4 \times ^{3}/_{8}$ TUBE

$W/D = \frac{17.27}{4(4)} = 1.08$, THIS IS LESS THAN THE W/D FOR COLUMNS 501, 502, 601 & 602, SO THE TEST THICKNESS IS ACCEPTABLE.

Figure A–47 (Contd.). Excerpts from 1992 report on thermal insulation thickness for repair of missing insulation (240-LERA).

REV. | LERA LESLIE E. ROBERTSON ASSOCIATES CONSULTING STRUCTURAL ENGINEERS | P 1003114 | DRAWING NO.

WTC ~~REFERENCE~~ ELEVATOR SHAFTS 12+13 | DRAFT | 28/37

COLUMNS | DESIGN WPM

CHECK 12/9/92

c) ALBI DURA SPRAY AND DURASPRAY 30 UL DESIGN X-730 MANUFACTURED BY STANCHEM, INC

ALTHOUGH THIS DESIGN IS FOR A METAL LATH ENCLOSED W-SHAPE COLUMN, THE VENDOR RECOMMENDS THIS DESIGN FOR TUBE COLUMNS. FOR A 3 HOUR RATING, THE DESIGN SPECIFIED THICKNESS IS

1 "1/16" FOR ALL COLUMNS.

CHECK W/D

THE TEST COLUMN IS A W10x49, ENCLOSED IN A BOX. THIS SHAPE HAS A HEIGHT AND FLANGE WIDTH OF 10".

$W/D = \frac{49}{10(4)} = 1.23$, THIS IS LESS THAN THE W/D FOR COLUMNS 501, 502, 601 & 602, SO THE TEST THICKNESS IS ACCEPTABLE.

NO EQUATIONS ARE AVAILABLE FOR REDUCING THIS THICKNESS.

Figure A–47 (Contd.). Excerpts from 1992 report on thermal insulation thickness for repair of missing insulation (240-LERA).

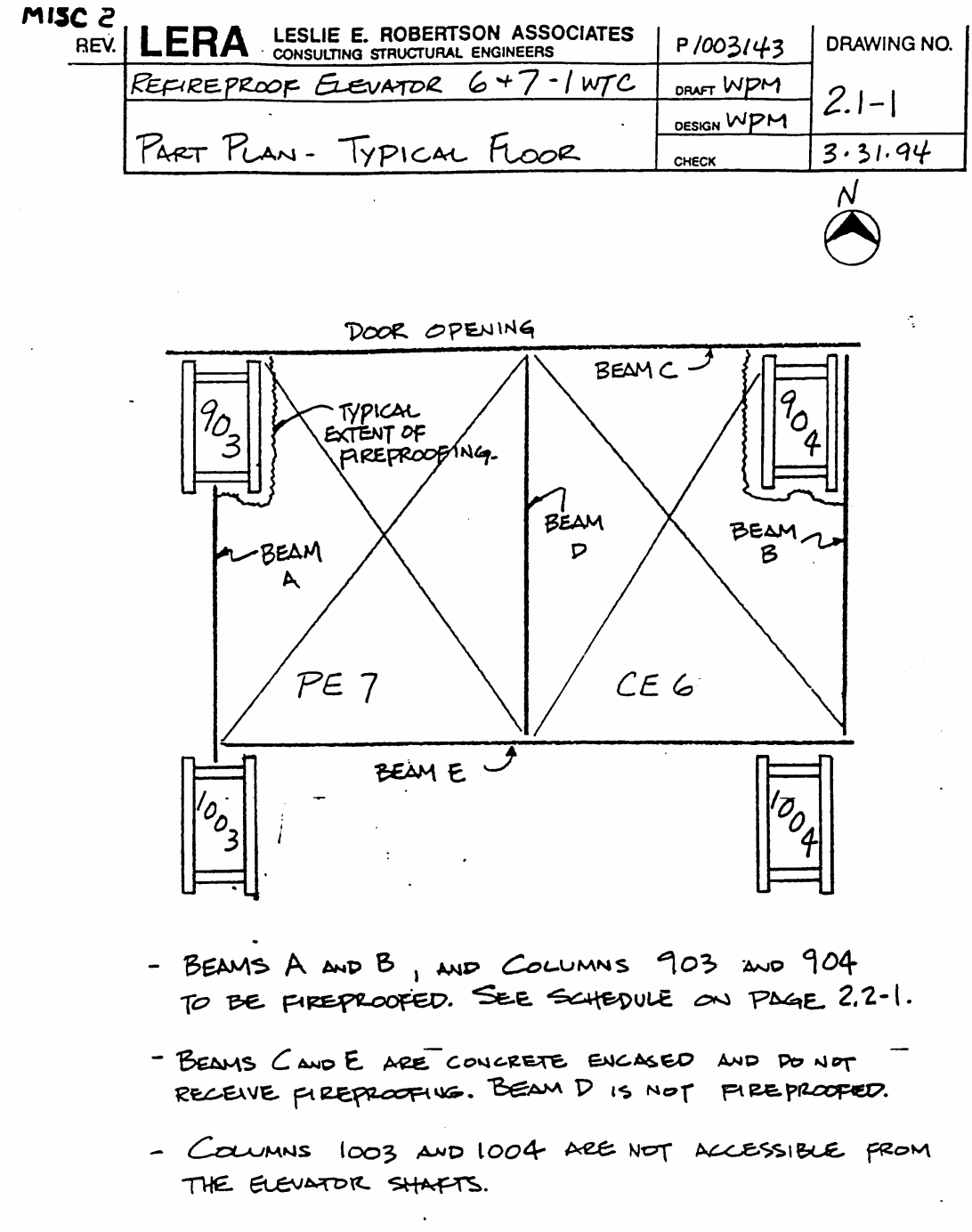


Figure A–48. Excerpt from 1994 design document related to reapplication of SFRM to accessible members in elevators shafts of WTC 1 (XX-I).

TO: M. Gerstman 9 DATE: April 12, 1973
FROM: E. J. Boland
SUBJECT: THE WORLD TRADE CENTER - CONTRACT WTC 320.00 - ELEVATORS AND CONTRACT WTC 113.00 - SPRAY-ON FIREPROOFING - TOWERS A & B
REFERENCE: Letter M. Gerstman to Otis - dated 3/22/72
COPIES: R. Belsky, R. Linn, C. A. Smith, F. H. Werneke; G. Hughes, B. Weinstein (TRCC); File

As reported to this office, the slack condition in compensating cables, especially on shuttle cars, is causing a chafing condition against finished spray-on fireproofing on structural steel within hoistways.

The chafing has caused extensive damage to the spray-on which has been patched at considerable expense in the past. However, the damage re-occurs.

As evidenced in the referenced letter, TRCC has previously pursued this slack condition problem with Otis but it has not been corrected to date.

Patching costs due to cable chafing should be backcharged to the Otis account. For hoistways where patching work has not been completed, the chafing area will not be done until this problem is resolved by Otis.

Any comeback costs for later repair work on spray-on fireproofing should also be for Otis' account.

E. J. Boland
Supervising Engineer
The World Trade Center

EJB/lp

Figure A–49. Correspondence indicating that slack cables within elevator shafts damaged the thermal insulation (XXX-ITK).

R. E. Schlemmer

F. M. Stumpf July 29, 1960

CAFCO Bond Strength

In our recent vibration tests we have noted some poor bond characteristics of our CAFCO BLAZE and HEAT-SHIELD. This was contrary to work which we had done in the past on laboratory mixes. Since this difference was noted several times in the past, we decided to see if there was any difference in bond strength between plant and lab mixed formulas. As will be seen in the attached data sheet, there is quite a difference and most of it is in favor of the lab mixed formulas. This is particularly true in the critical low density ranges of HEAT and BLAZE-SHIELD for both wet and dry conditions.

This low bond strength can be a very serious defect to our products since at 11 lbs. per square foot bond, reasonable vibration should shake the mass loose. At a wet strength of 3½ lbs. per square foot, installed CAFCO which becomes wet and is subject to moderate vibration should delaminate. All specimens were sprayed under ideal laboratory conditions which means they were given the proper amount of water, proper spraying angle, and proper tamping. In the field, most of these conditions are not met which would further indicate poor performance of the product. It just happens that CAFCO is usually applied in areas where there is not excessive vibration and its weight is below the 3 lbs. per square foot range.

Before we start determining the difference in mixing procedures, changing formulas, etc., this appears to be a good time to set a minimum bond strength standard of perhaps 20 lbs. per square foot and that this check be a part of the quality control procedure. Next, we can study the mixing which appears to be non-uniform as evidenced by previous difficulties with SOUND-SHIELD variations and with the research wood fiber formula which never resulted in the uniform blend. We think it is also mandatory to regulate the nodule size of wool entering the mixer rather than depending upon the mixer to do this. In the lab mixer, with its tumbling action, the wool asbestos and binders gently tumble which results in uniform coating. In the plant mixer the constant breaking up of the wool nodule is never permited to be coated with the asbestos fibers and binders. This may be a key to our problem.

Under Section B of the attached data sheet is data of bond tests run previously, namely an audit in July 1959 and the original audit in February 1956. We can not answer why the bond strengths for the 1956 audit were as good as they were except that in these days we were using steam blown wool.

FMS/ad
CC - J. F. Verhalen

F. M. Stumpf

PLAINTIFF'S EXHIBIT PX-24

Figure A–50. Correspondence indicating poor bond performance of sprayed thermal insulation during vibration testing (51-ITK).

MAR - 7 1968

MEMORANDUM

0011814

TO: Mr. R. M. Monti, Construction Manager
FROM: F. E. Werneke
DATE: March 6, 1968
SUBJECT: THE WORLD TRADE CENTER - FIELD TEST APPLICATION CAFCO TYPE "D" FIREPROOFING

REFERENCE:

COPY TO: Messrs. Levy w/att., Endler (TRCC) w/att.

The attached are letters dated March 1, 1968, from both United States Mineral Products Company and Mario & DiBono Plastering Company, plus a memorandum from Tony Calabrese, dated March 4, 1968, relative to an "on-the-job" application of Cafco spray-on insulating material. The comments of all are factual with no exaggeration. I was truly amazed at the ability of this material to adhere to the steel and to itself under adverse weather conditions. I examined the material again on this date and found it to be in tact.

In my opinion this material can be applied successfully to the exterior steel under adverse weather conditions and if we feel it necessary I can request a repeat test at a temperature of 20°±. Of course, the insulating value of this material will have to be determined at the mock-up test in St. Louis.

F. E. Werneke
Assistant Construction Manager
The World Trade Center

FEW/em

Figure A–51. Correspondence indicating acceptable performance of CAFCO BLAZE-SHIELD when applied under adverse weather conditions (250-P).

January 14, 1970

Mr. Joseph Ferro
Deputy Commissioner
The City of New York
Department of Buildings
2 Lafayette Street
New York, New York 10007

RE: THE WORLD TRADE CENTER - FIREPROOFING

My dear Commissioner:

Transmitted herewith is a record of a sprayed fireproofing test conducted by the Port Authority. The material was applied on January 29, 1968 under adverse weather conditions and was subsequently inspected on July 22, 1968 and found to be in good condition. There is also attached a report from the U. S. Mineral Products Company on the material and techniques used in the application. The material used was a cementacious asbestos fiber whose trade name is Cafco Type D. I am also enclosing a copy of the U. S. M. catalog. You will also note from the report that pictures were taken of the installation. I am obtaining copies and will forward them to you in the near future.

I hope this information will be useful to you. Any additional information we have is, of course, at your disposal.

Sincerely,

Malcolm P. Levy

Encl.

MPL:fg:jtm

bcc: Messrs. J. Kyle, R. Monti

Figure A–52. Correspondence sent to New York City Department of Buildings in 1970 providing information on the performance of CAFCO BLAZE-SHIELD Type D (92-ITK).

INTER-OFFICE MEMORANDUM

J.P. Verhulen

Harry Cropp

Date: Dec. 11, 1969

Last shipment of special Type D to World Trade Center

The last 800 bag shipment (20 tons) shipped to the World Trade Center was sprayed on Friday, Dec. 5th, Saturday, Dec. 6th and half of Sunday, Dec. 7th.

Of the 20 tons of material sprayed to the 10th floor exterior columns on this project, approximately 600-700 bags of the material washed off as clean as a whistle from the exterior columns on this job.

On reporting this experience to Frank Stumpf, he couldn't believe that this could happen. On Dec. 9th, 1969, Frank Stumpf and Siggy Sumski visited the World Trade Center in the company of Allen Bessemer to view this [illegible]. As Allen reports to me, he got the usual dribble of suggestions as to how to cure the problem. Such as, we are spraying too wet, we should change the disperser tip from a 60° to a 75° tip and there was too much hose on the floor.

As Allen knows, as I know, as you know, as Frank Stumpf knows, and as Bob Rath knows, none of those suggestions are going to cure what is the real problem of this material on the World Trade Center. Since we all know the problem, but unfortunately don't have the guts to tell each other in our own company. We know that the real problem is the lousy, poor, sub-standard product that we are trying to get our customers to accept and apply, and don't give me that the weather may have been cold, or the distance of the spray nozzle may be incorrect, or the amount of the blower pressure may be off, or the disperser tip may be the wrong one, because all of these things have been actually field tried on this job and we are headed for potential disaster - to put it very bluntly.

If this company doesn't realize now, that the product we are shipping to our customers is poor quality, inferior quality for which we are asking list prices or prices above what is asked for by our competitors, and for which we are asking our applicators to apply 20 to 30 per cent more material for, and for which we have no right or reason to ask a greater price for, no matter how you look at it, then we had better wake up very, very soon to this fact.

I can no longer accept that we are trying very hard to overcome our problems. Our customers really don't give a dam how hard a foreman or superintendent works in our plant. It doesn't mean two good dams to him that a superintendent is loading a truck. All he wants, and he has a perfect right to expect, since he is paying a premium and applying extra material over what our competitors do, is a product that does what we say it will do.

Whether we have the daily IBM inventory report, or whether we measure something on a slide rule really isn't pertinent to our real corporate problems. The sooner we begin to learn what our real problems are, then and only then will we be able to achieve profitable sales.

Figure A–53. Intra-office correspondence dealing with adhesion problems during spraying of exterior columns in WTC 1 (248-ITK).

- 2 -

For over one year, the Sales Department has lived with sub-standard, sub-par, below quality material products. My men, and myself, have overcome complaint upon complaint with very few contractors asking for compensation for experiences due to rocks, wire, nuts, bolts, lath, paper bags in the product. I feel we have come to the end of the line. Our contractors feel we have come to the end of the line. Please, no further ambiguous excuses. You want a company - then let's make the product.

Harry Gropp

cc: R. Rath
F. Stumpf
A. Bessemer
X & D File
WTC file
HSG

Figure A–53 (Contd.). Intra-office correspondence dealing with adhesion problems during spraying of exterior columns in WTC 1 (248-ITK).

MEMORANDUM

REFER TO	DATE	NOTED BY	DATE
RETURN TO			

TO: E. Boland
FROM: L. Guadagno
DATE: March 15, 1971
SUBJECT: THE WORLD TRADE CENTER - CONTRACT WTC-113.00 - TOWER A - ELEVATOR BANK C SHAFTS 39, 40 & 41
REFERENCE:
COPY TO: C.A. Smith, File

Spray-on fireproofing work was performed by Mario & DiBono in Shafts 39, 40 & 41 from 2/4/71 to 2/17/71. This work was done during extremely cold temperatures in an attempt to meet existing construction schedules.

During a recent inspection of these shafts, it was noted that the Cafco fireproofing treated with Mark II overspray has not cured or hardened according to specifications. The writer believes that this improper hardening was caused by the low temperatures during which the Mark II sealer was applied.

This inspector recommends that shafts 39, 40 & 41 be re-sprayed with Mark II sealer.

L. Guadagno
Construction Inspector IV
The World Trade Center

LG/mk

Figure A–54. Correspondence related to inadequate hardening of thermal insulation applied to core columns (XX-I).

A-34580

FILE: WTC 113.00

TO: D. Meyers
FROM: E. J. Boland
DATE: September 24, 1973
SUBJECT: THE WORLD TRADE CENTER - CONTRACT WTC 113.00 - TOWER "B" ELEVATOR SHAFTS #10 & #11 - LOOSE AND FALLING SPRAY-ON FIREPROOFING
REFERENCE: Photos attached, B-1, B-2, B-3, B-4

COPIES: R. Linn, C. A. Smith; B. Weinstein (TRCC); File

Our inspection of the above mentioned shafts indicates that the spray-on fireproofing has been improperly applied in several areas.

The fireproofing has come loose and fallen at floors 35, 40 and 43 in shaft #10 and at floor 31 in shaft #11. Also several small sections have come loose from perimeter box beams in both shafts.

We request that you direct the contractor Mario & DiBono, to re-spray the above mentioned areas as required under their Contract. Please refer to Chapter II, Page 123, Section 13.03 - Product Qualifications, "...the material shall resist the normal abuse resulting from the construction work of subsequent trades, shall not crack, craze, dust or disintegrate and shall adhere to the base surfaces with sufficient strength to insure against any loosing and falling off of applied material." And Page 126, Section 13.07 - Workmanship "4. The sprayed-on fireproofing and sprayed-on insulation, when completed, shall be free from seams, staging breaks, holes, spalls, cracks, flaking and dusting action, and other defects of any kind."

E. J. Boland
Supervising Engineer
The World Trade Center

RV/lp

cc: J.R. B.W. => ACTION F.C. FILE

[illegible] & CONST. CO., INC.

SEP 24 1973

Figure A–55. Correspondence related to dislodged thermal insulation within elevator shafts of WTC 2 (XX-I).

LERA

WORLD TRADE CENTER
Structural Integrity Inspection
Accessible Columns @ 1,2,4 and 5 WTC

P1103904 & 3927
29 January 1993
Page 1 of 9

EXECUTIVE SUMMARY

This report details the findings of the inspection of accessible columns in the elevator shafts of 1, 2 and 5 World Trade Center.

No structural deficiencies such as cracking or bowing were found in any of the columns inspected.

The most common irregularities observed were missing fireproofing and light surface rusting of exposed steel.

We recommend that fireproofing be repaired on all columns in the elevator shaft

Figure A–56. Excerpts from 1993 structural integrity inspection report related to condition of thermal protection on accessible columns (16-FEMA).

LERA

WORLD TRADE CENTER P1103904 & 3927
Structural Integrity Inspection 29 January 1993
Accessible Columns @ 1,2,4 and 5 WTC Page 5 of 9

PROCEDURE & LIST OF INSPECTED COLUMNS

The visual assessment of the accessible columns in the elevator shafts was carried out from top of the elevator cars. The elevator was operated by a field inspector from National Elevators.

The operator ran the elevator at a very slow speed from top to bottom and if any irregularity was noticed the car was stopped and the defect was duly noted and, at times, recorded using a 35mm camera.

A total of 10 elevator shafts were selected. This selection included 8 local elevators and 2 express elevators. Table A gives a listing of all the elevators and columns inspected during this survey.

Figure A–56 (Contd.). Excerpts from 1993 structural integrity inspection report related to condition of thermal protection on accessible columns (16-FEMA).

LERA

WORLD TRADE CENTER P1103904 & 3927
Structural Integrity Inspection 29 January 1993
Accessible Columns @ 1,2,4 and 5 WTC Page 6 of 9

TABLE A

Tower	Elevator Shaft Number	Floors Inspected	Adjacent Column Number	Face of Column Inspected
A (1 WTC)	21	4-78	606	East
		4-78	607	West
	36	1-32	701	East, South
		1-32	801	East, North
	63	45-67	701	East, South
		45-67	801	East, North
	73	43-74	703	North, West
		43-74	803	North, West
	83	78-93	701	East, South
		78-93	801	East, North
B (2 WTC)	15	4-78	602	North
		4-78	603	South, West
	29	1-16	707	South, East
		1-16	806	South, West
	56	45-54	707	South, East
		45-54	806	South, West
	78	78-86	707	South, East
		78-86	806	South, West
Northeast Plaza (5 WTC)	E-7 28	1-9	E-7 28	W

See Appendix A for the plan locations of the above columns.

Figure A–56 (Contd.). Excerpts from 1993 structural integrity inspection report related to condition of thermal protection on accessible columns (16-FEMA).

LERA

WORLD TRADE CENTER P1103904 & 3927
Structural Integrity Inspection 29 January 1993
Accessible Columns @ 1,2,4 and 5 WTC Page 7 of 9

OBSERVATION

Appendix B-2 shows the typical cross sections of columns used in elevator shafts. These columns are encased with sprayed on fireproofing. (Photo 1)

The most common irregularity in the express elevator shafts was spalling & missing fireproofing. The probable cause of this spalling may be attribute to:

- rubbing of the hoist cables against the face of column.
- air pressuresinduced due to high speed of the elevators moving up and down the shafts

Photograph 2 shows a patch of missing fireproofing at support brackets for conduits and elevator hardware. It appears that the fireproofing was removed when this bracket was installed.

Photograph 3,4 & 5 show typical patches of spalled fireproofing caused probably by rubbing of hoist cables against the girder and column faces.

Large areas of fireproofing were missing from the faces of column 606 and 607 in one World Trade Center.

The columns in local elevator shafts were generally well protected by fireproofing.

Isolated areas of spalling fireproofing were noticed on some of the columns in the local elevator shafts. (Photo 7,8,9)

Photograph 10 shows large areas of damaged and spalling fireproofing on column E-7/28 in the North East plaza building.

Light surface rusting was typically noticed in areas of exposed steel.

Figure A–56 (Contd.). Excerpts from 1993 structural integrity inspection report related to condition of thermal protection on accessible columns (16-FEMA).

LERA

One and Two World Trade Center
Strucural Integrity Inspection
Accessible Columns

14 April 1995
File: P1113903
Page 1 of 10

Executive Summary

Leslie E. Robertson, R.L.L.P., (LERA) carried out a survey of the accessible columns in the elevator shafts of One and Two World Trade Center as part of the ongoing structural integrity inspections. This survey was undertaken for the purpose of ascertaining the condition of the accessible columns in the elevator shafts in terms of the overall structural integrity of the accessible columns, for signs of rust or cracking, bowing, or deviation from plump, to identify specific locations of structural distress or damage, to identify locations of damage to the fireproofing envelopes, for lateral displacement or rotation of the column about a vertical axis where the column is braced directly on only one axis by connecting beams or abutting concrete slabs due to large beam offset dimensions, for signs of rust, or deformation of the slabs on ground surrounding each column at sub-level, and to provide recommendations for remedial work for both structural and fireproofing damage.

Most of the information presented in this report originates from on-site observations of selected columns within elevator shafts made by LERA during March 1995. The visual assessment of the accessible columns in the elevator shaft was carried out from the top of the elevator cars, by a field inspector. A total of 24(Twenty-four) elevator shafts and 56(Fifty-six) elevator pits were selected, this selection included 10 local elevators and 14 express elevators.

The accessible columns in the selected elevator shafts of One and Two World Trade Center are generally in good condition, no structural deficiencies such as cracking or bowing were found, the most common irregularities observed were missing fireproofing and light surface rusting of the exposed steel.

Based on our observation and our evaluations of the inspection, we believe that the structural integrity of the accessible columns within the selected elevator shafts are satisfactory. Areas of concern, in terms of remedial work to be taken, are the fireproofing envelopes and the corrosion of the exposed steel. We recommend that the fireproofing be repaired on all columns within the selected elevator shafts. We also recommend that the exposed areas of steel be cleaned prior to re-fireproofing.

Figure A–57. Excerpts from 1995 structural integrity inspection report dealing with accessible columns (17-FEMA).

LERA

One and Two World Trade Center
Strucural Integrity Inspection
Accessible Columns

14 April 1995
File: P1113903
Page 5 of 10

INSPECTION METHODOLOGY

Since the concurrent visual inspection of all the accessible columns or even a major portion of them is not a practical goal, a statistical approach is followed. This approach involves the sampling of those components and systems which are more important to structural integrity, and at locations with a relatively higher potential for occurrence of defects or problems. A visual inspection of the accessible columns located in the rectangular core (the elevator area) was made from the top of the elevator cars and from a walk-through of the elevator pits. The elevator car was operated by a field inspector from A.C.E. Elevator Co. The operator ran the elevator car at a very slow speed from the top of the car. Within the bounds of the suggested sampling procedure, the inspection frequency and the building layout, it was anticipated that the inspection work could be organized to proceed in a more or less linear sequence to minimize both wasted motion and duplication of effort, and to help assure that no important item was missed. The inspection team carried a set of reduced drawings, individual field notebook, a camera and a flashlight, methods and procedures were conformed strictly to the Port Authority safety regulations.

Visual inspection was supplemented by the use of simple hand tool such as a screw driver as needed. Where structural steel columns or the connecting beams were covered by spray-on fireproofing, removal of loose, cracked or rust-stained cover material was provided to examine the steel. A number of on-site visits were made to obtain the current condition of the accessible columns. No lifts were used for the inspection. The inspection findings were recorded on copies of architectural drawings. The accessible columns were not directly visible due to their fireproofing; therefore, the focus of the visual observations depended largely on the condition of the fireproofing. However, in several instances, the structural columns and the connecting beams were visible for inspection purposes or due to spalling of fireproofing.

Figure A–57 (Contd.). Excerpts from 1995 structural integrity inspection report dealing with accessible columns (17-FEMA).

LERA

One and Two World Trade Center 14 April 1995
Strucural Integrity Inspection File: P1113903
Accessible Columns Page 7 of 10

DETAILED INSPECTION FINDINGS

This report details the findings of the inspection of the selected accessible columns within elevator shafts. Our inspection findings and our opinions concerning the findings and our recommendations for remedial action are summarized below. Detailed inspection findings can be found in Appendix E and F.

The inspection was undertaken to ascertain the condition of the columns in the elevator shafts in terms of the overall structural integrity. Columns were observed for signs of rust or cracking, bowing, or deviation from plump, to identify specific locations of structural distress or damage, to identify locations of damage to the fireproofing envelopes, for lateral displacement or rotation of the column about a vertical axis where the column is braced directly on only one axis by connecting beams or abutting concrete slabs due to large beam offset dimensions, for signs of rust, or deformation of the slab on ground surrounding each column at sub-level, and to provide recommendations for remedial work for both structural and fireproofing damage.

Most of the information originated from on-site observations of selected columns within elevator shafts made by LERA during March 1995. The visual assessment of the accessible columns in the elevator shafts was carried out from the top of the elevators cars, by a field inspector. A total of 24(Twenty-four) elevator shafts and 56(Fifty-six) elevator pits were selected, this selection included 10(Ten) local elevators and 14(Fourteen) express elevators.

The accessible columns in the selected elevator shafts of One and Two World Trade Center are generally in good condition, no structural deficiencies such as cracking or bowing were found, the most common irregularity in both the express and the local elevator shaft were spalling & missing of fireproofing, the probable cause of this spalling may be attribute to rubbing of the hoist cables against the face of column, or air pressure induced due to high speed of the elevator cars moving up and down the shaft, or due to testing purposes. The exposed steel revealed only light to moderate surface rust.

Figure A–57 (Contd.). Excerpts from 1995 structural integrity inspection report dealing with accessible columns (17-FEMA).

LERA

One and Two World Trade Center 14 April 1995
Strucural Integrity Inspection File: P1113903
Accessible Columns Page 9 of 10

CONCLUSIONS AND RECOMMENDATIONS

Our opinions concerning the findings and our recommendations for remedial action are summarized below. Detailed suggested remedial action can be found in Appendix B, E and F.

Based on the survey data we collected and our evaluations of this data, we believe that the structural integrity of the accessible column in the selected elevator shafts is satisfactory. We recommend that remedial action to be taken where spray fireproofing is damaged, deteriorated or missing and where there is corrosion of the column base due to water leaks in the elevator pits.

The following are our specific recommendations for the structural and fireproofing damage we observed.

Spalling, Missing and Damaged Fireproofing

We recommend that the exposed areas of steel be properly cleaned and then protected with fireproofing. The existing spray fireproofing may contain asbestos, therefore, adequate measures need be undertaken to ascertain the presence of asbestos and to ensure both the protection of personnel and the proper handling of the material.

Water Leaks, Corrosion and Accumulation of Debris in Elevator Pits

At express and local elevator pits of both 1 WTC and 2 WTC, where evidence of past or present water leaks has occurred, we recommend that the following action be taken:

- areas of current water leaks be drained;
- where steel has been corroded, chip away the floor concrete surrounding corroded steel to a depth where corrosion no longer exists;
- clean and inspect all the steel, welds and bolts at these locations to determine the extent of corrosion;
- repair steel, welds and bolts as required; and
- prior to re-fireproofing steel, paint with a zinc-rich paint.

We also recommend that the accumulation of debris in elevator pits be removed and a maintenance program involving cleaning be provided.

Figure A–57 (Contd.). Excerpts from 1995 structural integrity inspection report dealing with accessible columns (17-FEMA).

THE PORT AUTHORITY OF NY AND NJ MEMORANDUM

TO: E. Ramabhushanam
FROM: S.M. Solomon
DATE: March 17. 1994
SUBJECT: WTC Existing Fireproofing

REFERENCE:

COPY TO: V. Berndt, C. Bognacki, Eng. Files

As requested, the Chemical Division performed numerous thickness measurements on existing fireproofing located on the 23rd and 24th floors of the WTC North.

Damaged and/or absent fireproofed areas on the 23rd Floor were repaired with patch material; These areas were not measured. Truss members located adjacent to the outside walls (within 3 feet) are devoid of fireproofing material. Visual inspection of the truss members on the 24th floor was not possible, as this area still has a lowered ceiling in place. Tests were taken through areas where ceiling tiles were removed. Thickness readings were taken on 16 random truss members on each floor. Measurements were taken from both flanges and webs of the truss member.

At each of these locations, a total of six individual measurements were made and averaged. These mini averages are listed on the attached table along with a total average, standard deviation, high value and low value for each floor.

S.M. Solomon
Chief of Chemical/
Environmental Testing

RG

Figure A–58. Correspondence related to 1994 measurement of thermal insulation thickness on floor trusses for 23rd and 24th floors in (3-P).

Lombardi, Frank

From: Lombardi, Frank
Sent: Tuesday, February 12, 2002 3:03 PM
To: 'edepaola@severud.com'
Subject: WTC - 1 1/2" SPRAY-ON FIREPROOFING UPGRADE

Fireproofing Upgrade

The 1½" spray-on fireproofing was established in 1995, to address any new construction for which the PA's Engineering Department was the Engineer-of-Record and to acknowledge that 1½" of spray-on mineral fiber was sufficient when applied directly to chord and web members of the floor trusses to provide the 2-hour fire rating for the floor.

It was required on all full floors being demolished for new construction or renovation either by the tenant or the PA. Because it was a landlord obligation, reimbursement was made to the tenant if the work was performed by the tenant.

Tenant spaces that were less than a full floor, undergoing either new construction or renovation, needed only to meet the original construction standard. Fireproofing had to be inspected and patched as required to the greater of ¾" or to match existing (it may already have been upgraded to the 1½").

The PA was also responsible to test the application of the sprayed-on fireproofing for conformance with ASTM E-605, "Thickness and Density" and ASTM E-736, "Adhesion/Cohesion". The tests were also in conformance with the NYC Building Code.

Here's the information about the 1½" upgrade in the upper third zone of both Towers (77th floor and above).

Based on our records, a total of 18 floors in Tower 1 and 13 in Tower 2 were upgraded with 1½" spray-on fireproofing.

The entire impact zone for Tower 1 (92-99) was upgraded with the 1½" spray-on fireproofing. Only the 78th floor was upgraded with the 1½" spray-on fireproofing within the impact zone in Tower 2 (78-84).

We're still working on the population and should have it to you shortly.

Figure A–59. Port Authority correspondence indicating number of floors where thermal insulation on floor trusses was upgraded to 1½ in. (73-LERA).

THE PORT AUTHORITY OF NY AND NJ MEMORANDUM

TO: Eli Moscovitz
FROM: Dorian Bailey
DATE: September 28, 1999
SUBJECT: World Trade Center: Test of Fire Resistive Material
Contract WTC - 697.00 W.O. #4682 Charge #W02-857090
COPY TO: C. Bognacki, J. Bullard, P. Ortiz, J. Shanahan, M.Young, E.F.

As requested, the Materials Engineering Division has tested the application of the sprayed-on fireproofing, CAFCO Blaze-Shield II for conformance to Port Authority specifications. The material was applied at the 102nd floor of WTC #1.

The tests were performed in accordance with ASTM E-605, "Thickness and Density" and ASTM E-736 "Adhesion/Cohesion" of Sprayed Fire Resistive Materials Applied to Structural Steel Members".

The results are as follows:

	Density lb./cu. ft.	Adhesion/ Cohesion lb./sq. ft.	Thickness Inches
Minimum Requirements	***15.00***	***150***	***1.50***
TEST AREA #1 1WTC 102nd Floor Truss 131 North Bottom of truss	16.47	333	3.25
TEST AREA #2 1WTC 102nd Floor Truss 231 East Bottom of truss	16.87	333	3.25
TEST AREA #3 1WTC 102nd Floor Truss 313 South Bottom of truss	15.93	315	2.11

Figure A–60. Example of test report on upgraded thermal insulation for floor trusses (3-P).

The test results indicate that the applied fireproof material, CAFCO Blaze-Shield II meets Port Authority specifications. Therefore the Materials Engineering Division recommends the acceptance of the fireproofing material.

Dorian Bailey
Staff Services Engineer

Figure A–60 (Contd.). Example of test report on upgraded thermal insulation for floor trusses (3-P).

Physical Performance*

	ASTM Method	BLAZE-SHIELD DC/F	BLAZE-SHIELD II	BLAZE-SHIELD HP
Surface Burning	CAN/ULC-S102 E84	Flame: 0 Smoke: 0	Flame: 0 Smoke: 0	Flame: 0 Smoke: 0
Combustibility	CAN4-S114 E136	Noncombustible	Noncombustible	Noncombustible
Density	E605	13 pcf (208 kg/m³)	16.0 pcf (256 kg/m³)	26.2 pcf (419.2 kg/m³)
Cohesion/Adhesion	E736	295 psf (14.2 kPa)	360 psf (17.2 kPa)	1,421 psf (68 kPa)
Deflection	E759	No Cracks or Delaminations	No Cracks or Delaminations	No Cracks or Delaminations
Bond Impact	E760	No Cracks or Delaminations	No Cracks or Delaminations	No Cracks or Delaminations
Compressive Strength	E761	828 psf (39.6 kPa)	2,380 psf (113.9 kPa)	7,980 psf (382 kPa)
Air Erosion Resistance	E859	0.000 g/ft² (0.000 g/m²)	0.000 g/ft² (0.000 g/m²)	0.000 g/ft² (0.000 g/m²)
Corrosion Resistance	E937 or Mil Std 810	Does Not Promote Corrosion of Steel	Does Not Promote Corrosion of Steel	Does Not Promote Corrosion of Steel
Sound Absorption	C423	0.85 NRC 1/2" (12.7 mm) onto deck & beam	0.75 NRC 1/2" (12.7 mm) onto deck & beam	0.85 NRC 1/2" (12.7 mm) onto deck & beam
Thermal Conductivity	C518	3.45 R Value	3.33 R Value	2.43 R Value

* Values represent independent laboratory tests under controlled conditions. Refer to individual product brochures for standard values which indicate average performance to be specified.

Figure A–61. Excerpt from manufacturer's product catalog showing properties of BLAZE-SHIELD DC/F obtained from independent testing under controlled conditions (Source: www.buildcore.com/c0cafco.htm).

THE PORT AUTHORITY OF NY & NJ

FRANCIS J. LOMBARDI, P.E.
CHIEF ENGINEER
225 PARK AVENUE SOUTH, 18TH FLOOR
NEW YORK, NY 10003
(212) 435-7449
(212) 435-6689 FAX
flombard@panynj.gov

April 14, 2004

John L. Gross, Ph.D., P.E.
Leader, Structures Group
United States Department of Commerce
National Institute of Standards and Technology
Gaithersburg, MD 20899-0001

Dear Dr. Gross:

Following are responses to your questions in your letter to Joe Englot dated April 5, 2004, which are repeated here in bold italics.

By this letter, I am requesting information from The Port Authority on fireproofing of the interior and exterior columns of the World Trade Center towers. Specifically, please provide the following:

1) ***Fireproofing material and thicknesses for the exterior columns as follows:***
- ***Plates 1 and 2 (these plates face the outside of the building and were covered by the aluminum column panels)***
- ***Plate 3 (interior plate within the occupied space)***
- ***Plate 4 (spandrel), both interior and exterior surfaces***

2) ***Fireproofing material and thicknesses for the core area box columns.***

3) ***Confirmation that the wide flange column sections were specified to be fireproofed as follows using Cafco Type DC/F:***
- ***Columns smaller than 14WF228 – 2-3/16 in***
- ***Columns greater than or equal to 14WF228 – 1-3/16 in.***

In response to your first three questions, Mr. Englot inquired throughout the Port Authority and was not able to find any information related to these questions other than that information already turned over to NIST.

4) ***Any information the Port Authority has regarding measurements of the in-place fireproofing material thickness.***

We have no records in our Materials Division of ever repairing or replacing fireproofing on exterior columns due to their inaccessibility and, therefore, have no recent thickness measurements of any re-applied fireproofing.

Figure A–62. Correspondence from Port Authority dealing with thermal insulation on WTC columns (XX-I).

THE PORT AUTHORITY OF NY & NJ

John L. Gross, Ph.D., P.E.
National Institute of Standards and Technology
April 14, 2004
Page two

We have no records in our Materials Division of ever repairing or replacing fireproofing on core columns due to their inaccessibility (other than columns which are accessible within the elevator shafts) and, therefore, have no recent thickness measurements of any re-applied fireproofing for core columns.

The only records of thickness measurements we could find were for the columns that are accessible within the elevator shafts. The Port Authority Materials Engineering Division took them and they correspond to World Trade Center Tower 1 elevator shafts. Discrete readings were taken at shaft 10/11 from the basement to the 45th Floor in Tower 1 in a report dated 4/7/1999. Mean thickness values were found for shaft 14/15 from the basement to the 80th Floor in Tower 1 in a report dated 8/4/1997. These measurements cover the full extent of these two elevator shafts. One was an express from the concourse lobby to 44 with a machine room on 47 and the other was express from the concourse to 78 with an EMR on 81. The readings for both of these shafts are attached (Excel file).

Discussions with Engineering Department staff and former World Trade Department staff indicate that these two shafts had asbestos abatement and were re-fireproofed. The measurements also show a "Minimum Thickness Required" of fireproofing. Staff members recall that there was a schedule of replacement fireproofing thickness that was prepared by the firm Leslie E. Robertson Associates (LERA). One staff member located a copy of one schedule, which will be forwarded under separate cover as a sample. We have contacted William Faschan of LERA and it appears that the "Minimum Thickness Required" is the thickness called for in a schedule that appeared in documents for the work that was prepared by LERA. The sample schedule indicates that the fireproofing applied was "Type Z-106". We will try to locate the specification book for this material. This information may be among the documents that LERA assembled for NIST at the Port Authority's 225 Park Avenue South office. We will continue to search for more complete sets of this information.

In the meantime, I hope this answers your questions. Please call or reply otherwise if you need further information.

Very truly yours,

Francis J. Lombardi, PE
Chief Engineer

Att.

Figure A–62 (Contd.). Correspondence from Port Authority dealing with thermal insulation on WTC columns (XX-I).

Pacific Car and Foundry Company

March 5, 1968 PCF #D666-69

THE PORT OF NEW YORK AUTHORITY
Office of the Construction Manager
30 Church Street - Room 1119
New York, New York 10007

Attention: Mr. R.M. Monti
Construction Manager

Reference: World Trade Center
Contract WTC-214.00
Project D679

Gentlemen:

Please find enclosed 2 copies of PCF painting specifications for Contract WTC-214.00.

A copy of this letter and specifications has been forwarded directly to Mr. J. White (SHCR).

Please note particularly Clause 5.3 which we believe satisfies the erector's requirements for these panels.

We are about to paint our first production panels and request your early approval of this specification.

Yours very truly,

PACIFIC CAR & FOUNDRY COMPANY

R.C. Symes, Project Engineer
Structural Steel Division

RCS/dv
Encl.
cc: J. White (SHCR)
J. Endler/A. Guttentag (TRCC)

Figure A–63. Letter from Pacific Car and Foundry regarding painting specification and excerpt from that specification.

5.0 PAINT, INHIBITORS AND PRESERVATIVES

5.1 Tnemec 99 Red Metal Primer is the only paint approved for use on this project.

5.2 Milled surfaces and bevels for field welds shall be treated with one coat Texaco #LB rust proofing compound.

5.3 All panels shall be stencilled, showing full engineering panel number and weight of panel in tons, thus:

$$103\text{-}22\text{-}19(12^{T})$$

Weight shall be taken to nearest ton above actual weight. Stencilled marks shall be placed on Plate 3, center column of panel, directly above the bottom hand-hole. Tnemec 99-G Green Metal Primer shall be used for all stencilled marks and letters and numbers shall be 3" high.

Figure A–63 (Contd.). Letter from Pacific Car and Foundry regarding painting specification and excerpt from that specification.

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Appendix B
THERMOPHYSICAL PROPERTIES TEST DATA

Table B–1. Specific heat capacity results of the three SFRMs from TPRL DSC.

	Specific heat capacity (J/kg K)		
Temperature (^{o}C)	**BLAZE-SHIELD DC/F**	**BLAZE-SHIELD II**	**Monokote MK-5**
35	--------	--------	1204
40	939	1009	1243
45	972	1047	1276
50	1004	1087	1302
55	1034	1134	1325
60	1064	1186	1355
65	1094	1237	1391
70	1130	1295	1423
75	1175	1355	1415
80	1227	1417	1348
85	1284	1479	1279
90	1369	1546	1253
95	1491	1623	1236
100	1663	1755	1183
105	1892	1945	1122
110	2187	2199	1100
115	2495	2528	1290
120	2740	2908	1851
125	2756	3298	3094
130	2074	3672	5117
135	1658	3293	7488
140	1785	2235	8589
145	2050	1937	6528
150	2062	2038	4713
155	1763	1934	5146
160	1536	1796	4459
165	1437	1700	1629
170	1375	1637	1244
175	1328	1587	1162
180	1289	1546	1152
185	1254	1506	1161
190	1220	1466	1174

	Specific heat capacity (J/kg K)		
Temperature (°C)	**BLAZE-SHIELD DC/F**	**BLAZE-SHIELD II**	**Monokote MK-5**
195	1190	1414	1196
200	1167	1368	1226
205	1145	1320	1251
210	1125	1284	1266
215	1110	1248	1283
220	1094	1217	1309
225	1077	1183	1332
230	1063	1149	1364
235	1050	1112	1393
240	1035	1082	1428
245	1022	1053	1460
250	1006	1025	1492
255	991	996	1521
260	977	961	1544
265	965	926	1567
270	958	891	1590
275	956	857	1622
280	945	807	1636
285	936	765	1656
290	924	729	1669
295	911	701	1673
300	899	675	1665
305	888	649	1651
310	878	627	1625
315	876	613	1578
320	877	610	1512
325	880	620	1400
330	893	642	1245
335	911	682	1042
340	932	734	892
345	955	789	940
350	975	857	1042

Table B–2. Specific heat capacity of Firecode Core Type X 5/8 in. gypsum.

Temperature (°C)	Cp (J/kg K)		Temperature (°C)	Cp (J/kg K)
50	1248		192	3569
100	1416		196	5020
125	1608		200	8087
135	2155		202	9200
140	3118		204	9356
142	3890		206	8816
144	5210		208	7948
146	7428		210	6497
148	11148		212	4496
150	15341		214	2771
152	18490		216	2010
154	19671		218	1695
156	19648		220	1550
158	18822		225	1389
160	17476		250	1156
162	15728		300	1094
164	13734		350	1089
166	11553		400	1046
168	9436		415	890
170	7034		430	453
172	5107		445	506
174	3501		460	808
176	2768		475	966
178	2417		500	1104
180	2297		550	1192
184	2544		600	1245
188	2923			

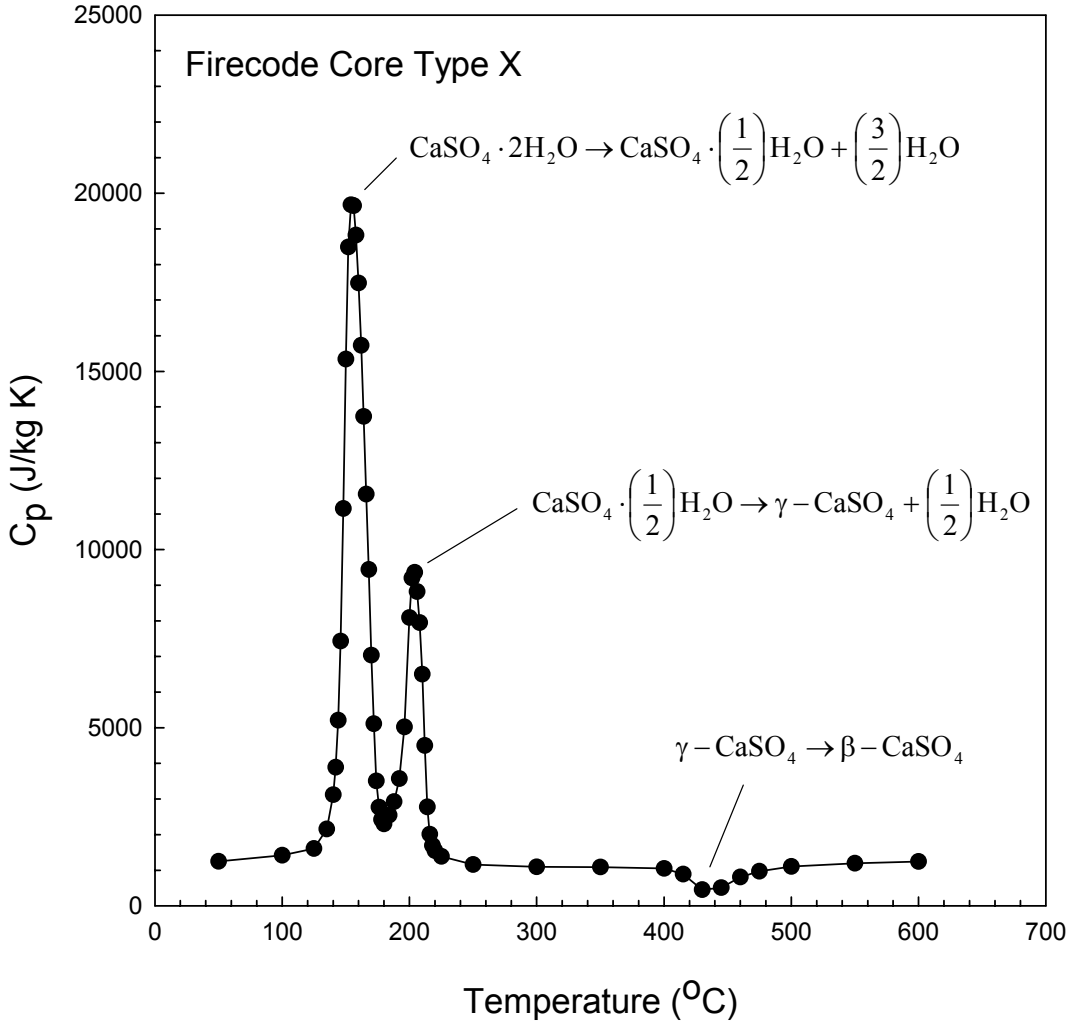

Figure B–1. Specific heat capacity of Firecode CoreType X 5/8 in. gypsum.

Table B–3. Specific heat capacity of Firecode C Core ½ in. gypsum.

Temperature (°C)	Cp (J/kg K)		Temperature (°C)	Cp (J/kg K)
50	1325		192	3693
100	1544		196	4957
125	1764		200	7730
135	2457		202	8774
140	3801		204	9088
142	4769		206	8644
144	6418		208	7693
146	8787		210	6364
148	12015		212	4487
150	15429		214	2888
152	17532		216	2090
154	18399		218	1828
156	18349		220	1672
158	17769		225	1495
160	16776		250	1278
162	15564		300	1185
164	13895		350	1188
166	12124		400	1159
168	10357		415	1015
170	8263		430	667
172	6180		445	642
174	4459		460	930
176	3383		475	1091
178	2768		500	1235
180	2545		550	1350
184	2632		600	1416
188	3006			

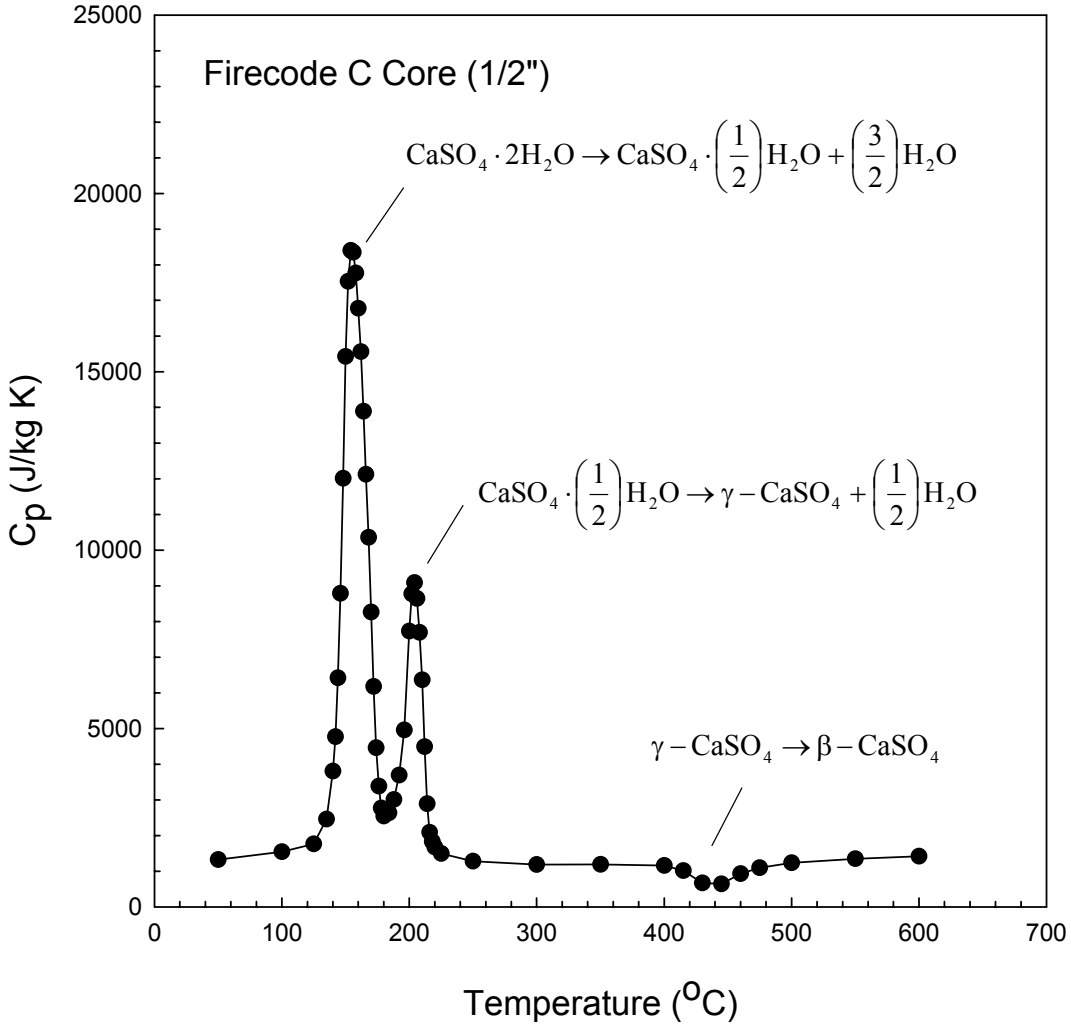

Figure B–2. Specific heat capacity of Firecode C Core 1/2 in. gypsum.

Table B–4. Specific heat capacity of Firecode C Core (5/8”) gypsum.

Temperature (°C)	Cp (J/kg K)		Temperature (°C)	Cp (J/kg K)
50	1250		192	3624
100	1507		196	4886
125	1711		200	7769
135	2486		202	8848
140	3966		204	9102
142	5001		206	8727
144	6728		208	7705
146	9142		210	6210
148	12341		212	4342
150	15681		214	2775
152	17740		216	2052
154	18550		218	1770
156	18374		220	1621
158	17667		225	1451
160	16401		250	1233
162	14914		300	1148
164	13190		350	1168
166	11251		400	1130
168	9096		415	984
170	7108		430	568
172	5091		445	646
174	3658		460	930
176	2814		475	1084
178	2516		500	1232
180	2364		550	1347
184	2567		600	1432
188	2936			

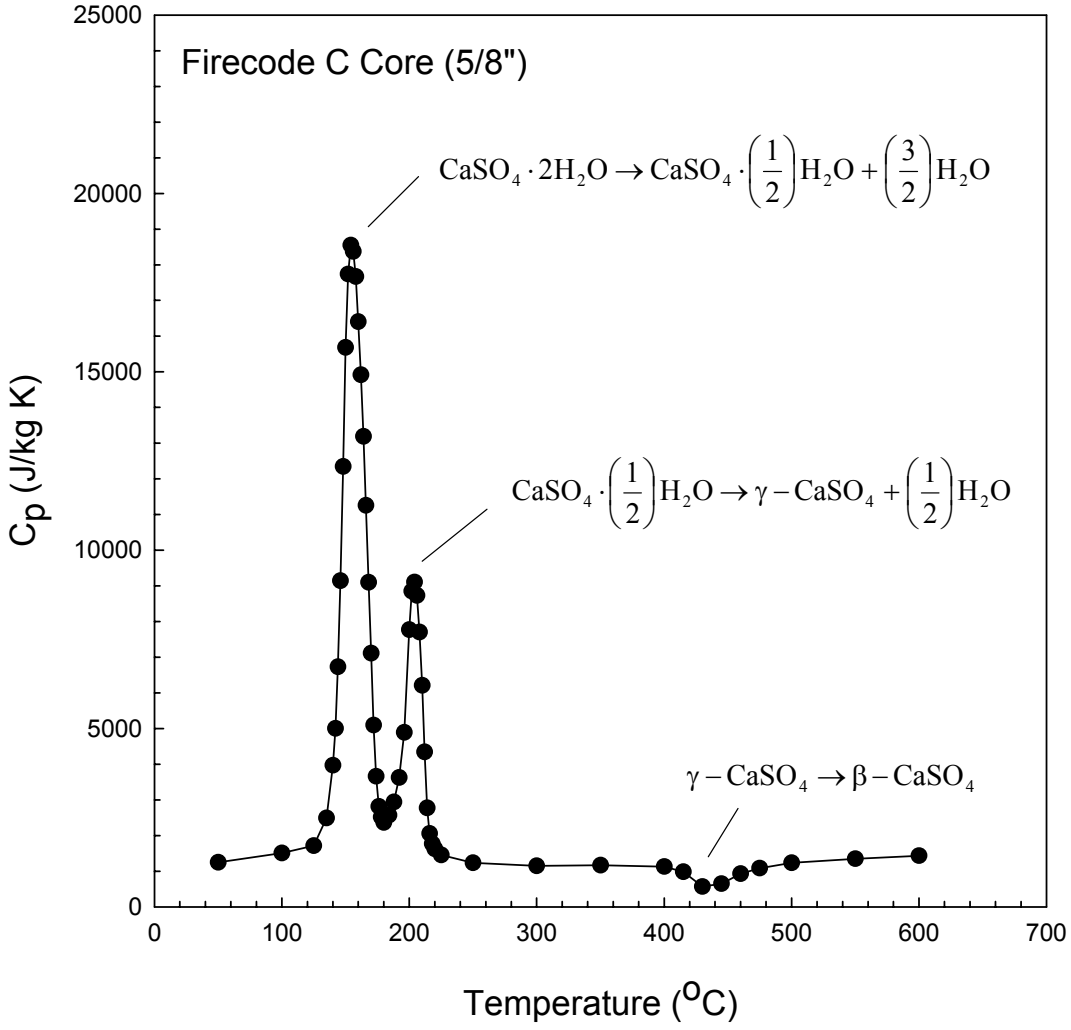

Figure B–3. Specific heat capacity of Firecode C Core 5/8 in. gypsum.

Table B–5. Specific heat capacity of 1 in. gypsum liner panel.

Temperature (°C)	Cp (J/kg K)		Temperature (°C)	Cp (J/kg K)
50	1192		192	3583
100	1495		196	4876
125	2293		200	7346
135	3766		202	8360
140	5548		204	8872
142	6987		206	8787
144	8876		208	8164
146	11092		210	6847
148	13303		212	5256
150	15076		214	3305
152	15999		216	2260
154	16160		218	1787
156	15787		220	1597
158	14949		225	1408
160	13925		250	1192
162	12577		300	1137
164	10840		350	1146
166	8755		400	1060
168	6481		415	822
170	4676		430	609
172	3296		445	794
174	2685		460	971
176	2369		475	1079
178	2252		500	1200
180	2288		550	1306
184	2577		600	1378
188	2959			

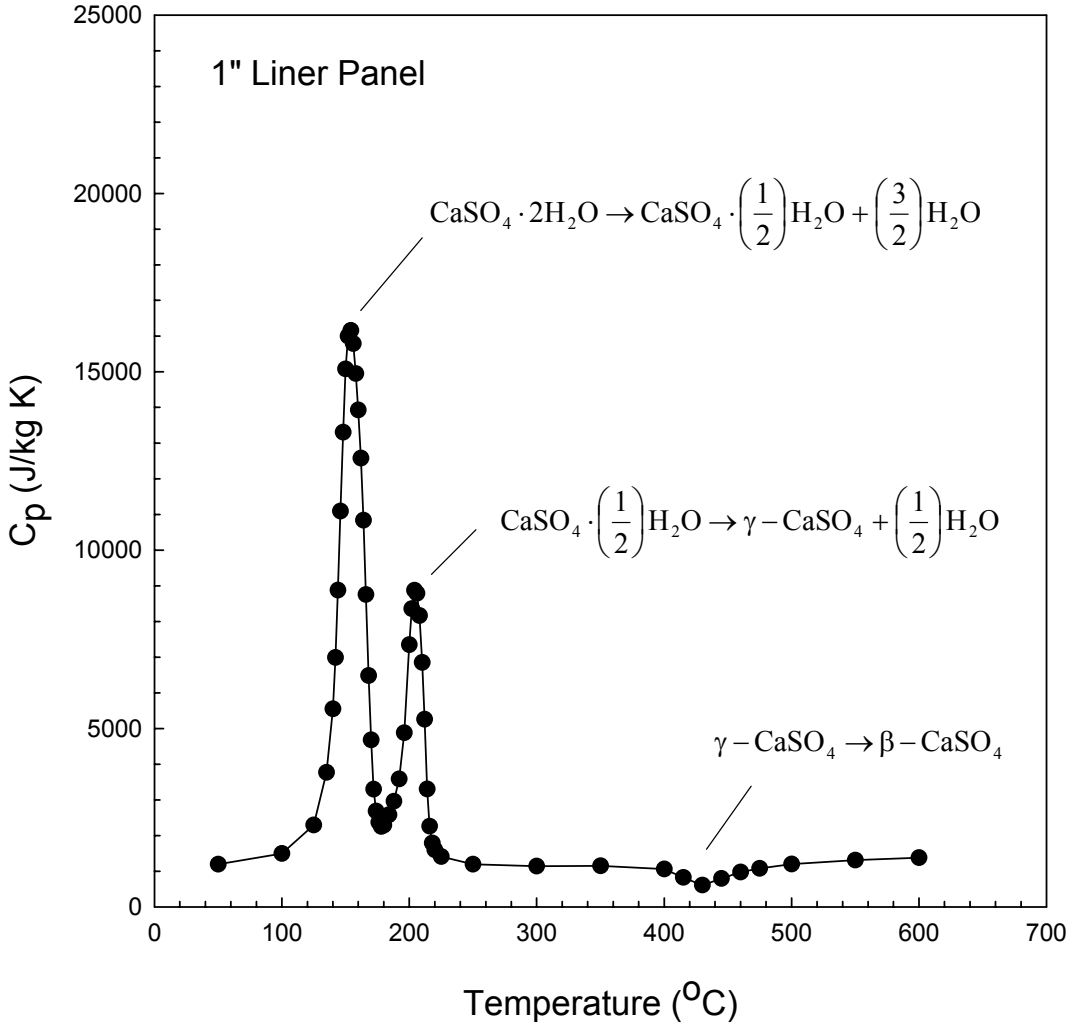

Figure B–4. Specific heat capacity of gypsum 1 in. liner panel.