QUESTIONS ON THE WTC INVESTIGATION

WTC QUESTIONS

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Abstract - A critique of the World Trade Center investigation with respect to the cause of the collapse of towers 1 and 2 is presented. The official investigation conducted by the National Institute of Standards and Technology (NIST) concluded that the collapse was due to the fires heating the core columns that were stripped of insulation by the aircraft impacts. An alternative cause is considered that puts the cause on insufficient insulation of the steel truss floor members. Evidence for the latter is supported by NIST analysis of a truss member, Underwriter Laboratory furnace tests of the floor assembly, and engineering calculations and scale model tests conducted at the University of Maryland. The presentation is couched in terms of 10 questions for NIST.

Keywords: collapse cause, fire, investigation, WTC.

1. Introduction

Many questions could be asked of the NIST World Trade Center investigation. The investigation was convened nearly a year after the event when Congress passed a special act to give NIST authority to investigate catastrophes related to the built environment, and funded it with $ 16 million. They investigated many aspects of the event related to the fire and collapse of the twin towers including the egress of people, the fire service response, the detection system, and of course the fire and structural

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collapse. NIST actually began an investigation activity shortly after 911 with an inquiry into the fire behavior through the acquisition of photographs and video from the news media. I assisted in this acquisition as I had begun to speak out on things that bothered me about the investigation, or lack thereof. As I spoke out, I came in contact with two women, Sally Regenhard and Monica Gabrielle, who were members of the "911 families", losing a son and husband, respectively. They were determined to have an investigation on the collapse of the buildings, and formed the Skyscraper Safety Campaign, a non-profit organization. Their '"in-your-face" actions got the attention of Congress, who listened, and launched the NIST investigation. At the time, I told them NIST was the best organization to do the job. Little did I realize that the NIST heart was not in it, and its efforts would not be proactive, but reclusive. While NIST had public hearings during the course of discharging their findings, they were limited to 5-minute presentations by the public, and no response to submitted questions or comments. There was no transparency of their effort, and even their Advisory Board did not know when they would finally release conclusions until October of 2004. The conclusion was formally contained in a report consisting of a 10,000-page document that defies reading and analysis. Although Sally and Monica were updated in bi-weekly conference calls mandated by Congress from NIST, they very early became discouraged and concerned with the NIST progress and style. I participated in all of the NIST hearings, and the related Congressional hearings, and in that way followed the NIST progress. In October of 2004 their conclusions on the cause of the building collapse was a surprise to me. While I can find issues with their investigation of the event in assembling information through the lack of calling witnesses, issuing subpoenas, and applying normal proactive legal processes, I will primarily focus on the issues related to the fire and the collapse of WTC 1 & 2.

Specifically I will demonstrate why I believe the NIST conclusion is deficient and I will offer an alternative conclusion. The significance of these two conclusions is significant, as it bears on the responsibility for the collapse of the towers. The NIST conclusion essentially puts the primary cause on the impact of the aircraft, while the alternative conclusion lays it at the feet of fire safety design. The correct answer bears on the practice of fire safety.

Let us recall the events of 911. WTC 1, the North tower, was struck first at about the 96th floor. The South tower, WTC 2, was struck about 20 minutes later at about the 81st floor. We would then see the South tower fall first in 56 minutes, followed by the North in nearly twice the time, 102 minutes. WTC 7, not struck by any aircraft, fell after 7 hours of unchallenged fires. A curious aspect of the failure times for WTC 1 and 2

is that the insulation of the steel floor truss system had about twice the thickness in WTC 1 than 2. This coincidence will be the basis of the "alternative hypothesis" for the collapse.

Figure1. Impact of WTC 1, North tower

Figure 2. Impact of WTC 2

Figure 3. Collapse of the South tower

1.1. MY INVOLVEMENT

I became involved in the WTC investigations as an observer and a fire scientist. I followed the NIST activities throughout. In late September I was invited to be part of the American Society of Civil Engineering team of experts that were to attempt to investigate the scene. I was asked to be on a backup team and began to receive emails on activities of the ASCE team at the WTC site. The ASCE did not get easy access, and were initially concerned about the pending and later actual sale of the steel debris from the scene. This is where I began to speak out as the loss of the primary steel

elements that were coded according to location could provide vital information about the temperatures achieved. Metallurgical analysis could yield the temperatures and help to pinpoint the role of the fire in the structural collapse. Needless to say, most all the steel was sold off, and only little remained as a result of voluntary efforts of the Civil Engineers of New York (CEONY). Subsequently, I never became part of the ASCE team.

My involvement during the course of the investigation is summarized below. I was not a paid consultant, nor did I have any research contracts to support my work.

- September 2001: presented seminar to NIST for conducting a scale model simulation of the impact and fire
- Nov 2001: spoke out against sale of steel in news media, NY officials
- Dec 2001: affiliated with the Skyscraper Safety Campaign (SSC)
- Feb 2002: assisted NIST in accessing NY Times photo archives
- Attended all NIST public hearings, submitted extensive comments and questions
- Attended all Congressional Hearings on WTC
- Published and presented papers on WTC in peer-reviewed venues 2002-2005[1-3]
- Conducted tests on insulation in cooperation with Isolatek
- Co-led student project to simulate floor fire of WTC 1
- Investigated fuel load on Marsh & McLennan floors of WTC 1

1.2. WHY QUESTIONS?

The NIST investigation was done in virtual secrecy with periodic hearings to give progress. It was not until October in 2004 did NIST present a conclusion. Up until that time, it was not clear what they would conclude. NIST has not responded to written questions, but has accepted comments and posted some on their website. A dialogue has not been conducted between the public, press and NIST. In addition, litigation related to the civil suit between the WTC lease holder and the insurance companies never would be made public. Conspiracy theorists have dominated the web pages and received strong recognition in the media. Yet responsible criticism has been minimal. A quietly written book by Arthur Scheuermann, a NYC retired fire chief with a knowledge of building structure, presents an balanced qualitative analysis of the WTC collapse.[4] This book should be referred to for an objective report of the background on the WTC construction and the events of 911. Other excellent books on

the history of the WTC and on the accounts of those trapped in the twin towers on 911 have been written by NY Times correspondents: Glanz and Lipton[5], and Dwyer and Flynn[6], respectively.

What is lacking from NIST is a clear account of the logic they used in explaining the collapse mechanisms. It is one thing to state the cause and imply their computation by computer codes; it is another to clearly illustrate the physics behind the collapse mechanisms. Perhaps that is the reason for so many conspiracy theories. A contrast can be made to the investigation of the Columbia shuttle accident that occurred after 911 and whose investigation concluded before the NIST final report. The NASA team clearly identified the cause by using the photographic evidence, analysis and clear testing done at Southwest Research Institute. No conspiracy theories here.

Let's examine the evidence and let me try to lay out the basis of alternative to the NIST conclusions. In doing so, I will try to explain the logic in the simplest way possible, yet try to keep true to the physics of the problem.

1.3. THE NIST CONCLUSIONS

The NIST work is a tome to read. It is made up of several lengthy progress reports that then were melded into a final report of approximately 10,000 pages. Each investigator wrote their separate analyses; as I learned there was not a full integration of the work as each passed their work on to the other. A spiritual leader of the investigation never emerged. Because of the lengthy reports it is difficult for me to explicitly document all of my NIST sources, but I will do the best I can. I list the reports that I used.

December 2003, Public Update on the Federal Building and Fire Safety Investigation of the world Trade Center Disaster, NIST Spec. Pub. 1000-4, NIST, DoC.[7]

Reports of the Federal Building and Fire Safety Investigation of the world Trade Center Disaster, Drafts for Public comment, NIST, DoC , June 23, 2005.[8]

Final Report of the Federal Building and Fire Safety Investigation of the world Trade Center Disaster, Drafts for Public comment, NIST, DoC , September 2005.[9]

The NIST findings state (pp xliii-xlviii)[9]:

"In WTC 1, the fires weakened the core columns and caused the floors on the south side of the building to sag. …The time from the aircraft impact to collapse was largely determined by how long it took for the fires to weaken the building

> core and reach the south side of the building and weaken the perimeter columns and floors."
>
> In WTC 2, the collapse is based on similar reasoning but the core was more severely damaged in the southeast corner.
>
> "The WTC towers likely would not have collapsed under the combined effects of the aircraft damage and the extensive, multifloor fires if the thermal insulation had not been widely dislodged or had been only minimally dislodged by the aircraft impact."…On September 11, 2001, the minimum specified thickness of the insulation [0.5 inches] was adequate to delay heating of the trusses…"

In other sections of the reporting, NIST concluded that the core columns, heated from lack of insulation, " softened and shortened" which led to pulling in the exterior columns and then collapse. The lack of insulation on the core columns removed by the aircraft impact is their main basis of the root cause of the collapse. The originally specified insulation thickness on the truss floor system of 0.5 inches was declared sufficient for the fire conditions, and therefore not the root cause of the collapse.

1.4. OTHER COLLAPSE SCENARIOS

Other collapse scenarios have been suggested in the literature. This is how I interpret them.

The Weidlinger investigators[10, 11] were part of the civil case brought by the leaseholder against the insurance companies, but did publish some of their work. They did the work mainly in 2002 and concluded all of the insulation in the path of the aircraft was stripped off. Their work is shown in Figure 4. But they admit that the structural collapse calculation have issues of accuracy as in their computations, the south tower WTC 2 collapses on immediate impact of the aircraft. As that did not happen they needed to make adjustments. The core columns are completely stripped of insulation in their work.

Other collapse scenarios are based on the floor truss systems as the cause. These are based on the trusses being heated between 400 - 600ºC and failing. They are done with structural models at these temperatures, and do not consider the needed fire conditions that would cause these temperatures. Usmani et al.[12] show that the heating of the trusses would cause the instability of the external columns due to sagging of the trusses. Burgess[13] and his team indicate that the trusses can fail at their connections. Indeed, the NIST group arrives at a similar conclusion, but apparently does not believe the fire can achieve the needed temperatures.[9] [p.96]. Figure 5 shows the NIST result. They find the following consequences if the truss achieved these temperatures:

- 340 ºC diagonals buckle
- 400 ºC knuckles fail
- 510 ºC Interior seat bolt shears
- 650 ºC Truss walks off seat.

If trusses are heated to 500 - 600 ºC, the floor can fail.

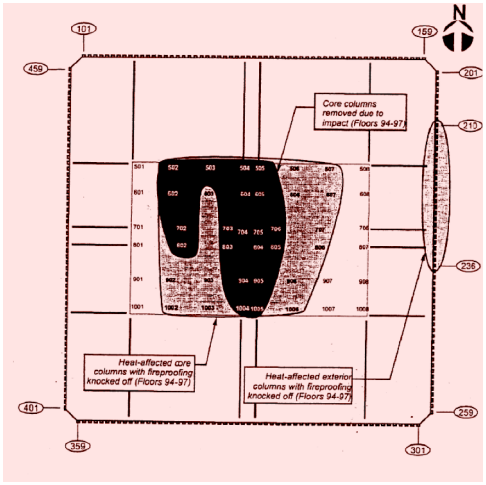

Figure 4. Damage computed by the Weidlinger group[10]

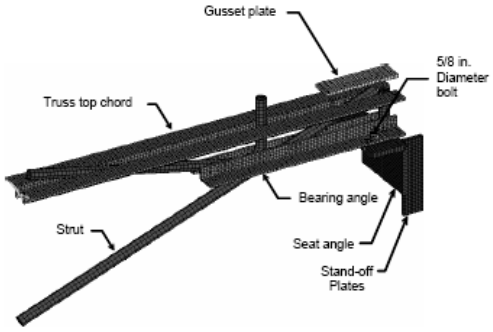

Figure 6–10. Finite element model of an exterior truss seat.

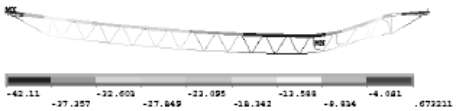

Figure 6–11. Vertical displacement at 700 °C.

Figure 5. NIST truss computations

There are two likely collapse scenarios:

1. Core columns fail as stripped of insulation and heated by fire: as contended by NIST in their findings, or
2. Trusses fail as heated by fire (with insulation intact) as due to the instability of the external columns according to Usmani et al.[12], or the trusses fail at the connections according to Burgess et al.[13] and the NIST truss computations[9].

It will be shown that the second conclusion can be supported by calculations, scale model tests, and the standard furnace test results of the truss floor assemblies conducted by NIST. The stripping of the core column insulation is critical to the NIST conclusion, and without it they cannot get the buildings to collapse. Although NIST did not mention this stripping until they presented their conclusions in October 19, 2004, I first heard it in early 2003 at a local ASME Washington meeting as presented by NIST scientist, T. McAllister. No scientific justification was give for the stripping except that it was in the path of the aircraft. I thought at the time it was influenced by the Weidlinger results[10]. Indeed, Kevin McGrattan, in a recorded conference presentation to the Nuclear Regulatory Commission on September 11, 2006 states: "that [insulation removal] will become a pivotal part in the explanation of why these buildings fell down." "It will carry on through the rest of all the modeling." He attributes it to the work of Terri McAllister. The NIST area on insulation removal is depicted in Figure 6.

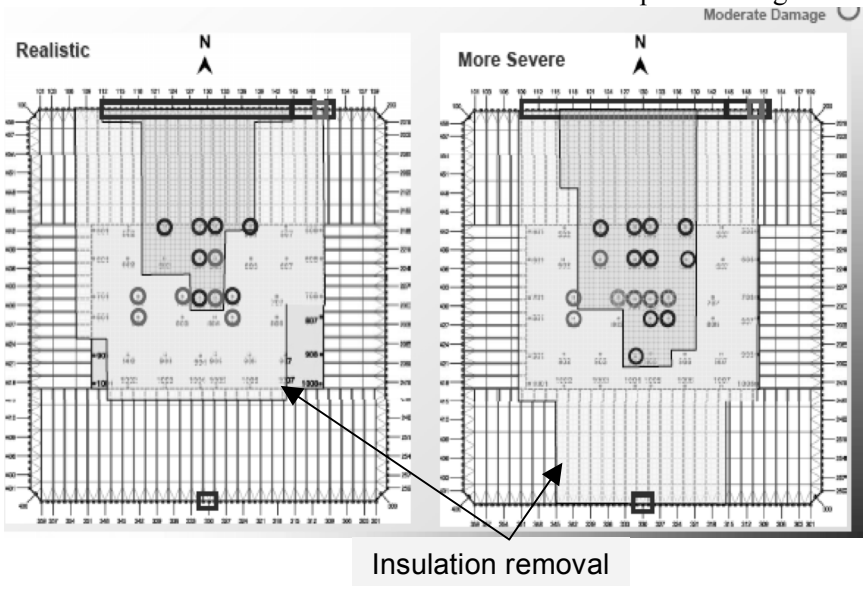

Figure 6. Illustration of the NIST impact damage and the area of insulation removal

The damage computed by various investigators has differed widely, and in a recent analysis, a group at Purdue[14] states that, "Objective evaluations of the simulation results indicated that identification of the number and distribution of columns damaged immediately by the impact was quite sensitive to the input parameters." In a press release last June 2007, the Purdue group stated that their results confirm NIST. They go on to say that, "It is evident from observation and our simulations that the debris of the aircraft went through the WTC structure at stories 94 through 97. Much of the fire insulation would have been scoured off leaving the steel elements unprotected during the immediately following fire event." But there is no analysis or data to support the effect of aircraft debris with the removal of the insulation. They conclude that, "For both the intact and plausible compromised core states considered, it is estimated that a core collapse mechanism could have been initiated in WTC-1 if the tower core column temperatures were elevated to approximately 700ºC." How results of the damage calculations lead to the removal of insulation is a key point in Scenario 1, and needs more justification in my opinion.

2. Ten Questions for NIST

I will pose ten key questions to NIST on their findings, and by doing so will elaborate, and indicate the basis for the second hypothesis: insufficient insulation on the trusses.

2.1. QUESTION 1: WHY AND HOW WAS INSULATION STRIPPED?

In the NIST modeling it was *assumed* that the insulation was stripped if debris is sufficient to break gypsum board. NIST did conduct experiments to determine the adhesive strength of the insulation to the steel, but never related those results to any analysis. They also conducted what appears to have been an ad hoc experiment in which 0.3-inch diameter pellets @ 350 mph stripped the insulation on 1-inch diameter steel bars.[9] [p117]. No discussion of the rationale of this experiment is given. If the removal of the insulation is such a necessary condition for the core steel to be heated, then more evidence to support this assumption is needed.

2.2. QUESTION 2: WHY WAS THE DEBRIS STEEL SOLD? COULD IT HAVE PROVED NIST CORRECT?

All of the primary structural steel was coded, and the steel from the fire floors could have been segregated for analysis. If NIST had the steel they claim got hot and shortened, it could prove their case.

This is an excerpt of a letter I wrote, when I became an advocate for the investigation. The letter was never answered, along with many telephone calls pleading for the preservation of the steel.

November 27, 2001

Michael Burton, P.E
Executive Deputy Commissioner of DDC
30-30 Thomson Avenue
Long Island City, NY 11101

> …. The **steel members are coded** and they could be segmented by floor so that analysis could indicate the basis of failure. … When we live in times that an aircraft that crashed in the sea can be put back together, it is not beyond expectations that similar action can be taken here. ….

The steel that was saved is due to the voluntary efforts of the Civil Engineers of New York (CEONY) who went to the dumpsite. It was not done in the best systematic way and much of the critical pieces from the fire floors were not saved. NIST did not acquire the steel until mid-2002, and only received about 1 % of the core steel of the fire floors. "None of the recovered [core] steel samples showed evidence of exposure to temperatures above 600 ºC for as long as 15 minutes. This was based on NIST annealing studies that established the set of time and temperature conditions necessary to alter the steel microstructure. These results provide some confirmation of the thermal modeling of the structures, since none of the samples were from zones where such heating was predicted." [9] [p. 176]. It would have proven far better if steel were found that confirmed the needed temperatures. These annealing studies of the steel were done by NIST late in their investigation, as they appeared to not initially realize the benefit of metallurgical studies of steel grain size analysis to assess attained temperature. Moreover, they do not fault the removal of the steel as an error by the investigators on the scene.

The steel could have served as a thermometer that indicated the maximum temperature achieved in a given location. Having that mapping

of the fire conditions could have proved invaluable. Losing it is spoliation of a the fire scene.

2.3. QUESTION 3: DID NIST USE THE CORRECT FUEL LOAD?

I believe the fuel loading used by NIST is in error and was too low. This, I believe, led to short fires that were insufficient to heat the steel to failure unless the insulation of the core was missing. Note that most of the floor truss insulation was consider intact by NIST except for the immediate impact areas. These short fires could not heat the insulated trusses to failure in the NIST fire computation, in my opinion.

NIST used 4 lb/ft^2 (19.5 kg/m^2) in their analysis of WTC 1, and presumably did the same for WTC 2. Typical office fuel loads range from 24 to 100 kg kg/m^2 [wood equivalent] and average roughly 60 kg/m^2.[15] The NIST value is low over this range. Based on an analysis of the same floors audited by NIST, we obtained a different value for the fuel load of the Marsh & McLennan 96th floor.[16] For the same fuel items that NIST used, we obtained about 135,000 lbs, giving us an estimate of the NIST load of 4.3 psf. This agrees with the NIST computed load of 4.0 psf, and gives a check on our accounting methodology for the same furniture. When we included the additional storage items and the 50 % load in the common files that NIST had omitted, we reached about 300,000 lbs. or 9.7 psf [44 kg/m^2]. We think this difference in fuel load needs an explanation from NIST.

By the way, access to the furniture information was obtained through the connections of the Skyscraper Safety Campaign by reaching out to the 911 families. A family member from the supplier of the furniture gave me access to the auto-cad drawings of the furnishings. Kate Stewart discovered and accounted for the central file cabinets ignored by NIST (170 4-drawer), and also made estimates for the movable load brought in by the occupants. In talking to people who had access to the Marsh & McLennan floors, I was told that they were “paper hogs” and had piles of paper on the windowsills. The architectural drawings of the furniture layout on the Marsh & McLennan floors clearly show a ring of central file cabinets. For NIST to have missed the files is a gross error.

After communicating our results to NIST, some scientists from NIST remarked to me that paper in file cabinets does not fully burn. Not finding any information on this subject in the literature, I conducted my own experiments. Two file drawers in a cabinet loaded at 50 % and to full capacity were subjected to furnace conditions of 600 to 800 ºC for 2 hours. Figure 7 shows the results of the tests. Approximately 60 % of the paper was vaporized with the remainder consisting of char and ash. This is not an

uncommon distribution for cellulosic material in a fire. Hence, the file paper would follow the behavior of wood in a fire.

Using a low fuel load would reduce the heating time of the fire, and that is the primary factor in the heating of the structure. Figure 9 illustrates the typical floor conditions as depicted by NIST.[9] The trading-floor was indicative of WTC 2. NIST modeled its fires by reconstructing facsimiles to the Marsh office workstations. We think our conservatively low estimate of 44 kg/m^2 compared to 19.5 used by NIST needs to be addressed.

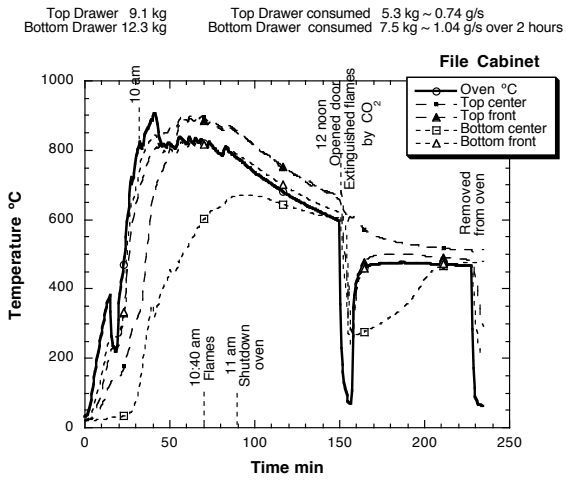

Figure 7. Burning of paper in file drawers of a metal cabinet

Figure 8. Actual WTC occupancies according to NIST

2.4. IS THE NIST FIRE MODEL ACCURATE?

The NIST computed fires only last about 20 minutes (Figure 9) in any give location on a floor, but the flames move about the floor. NIST validated their model by comparing with the photographic evidence of the window flames. As the smoke in these fires at the windows have a visibility of about 1 m, it is not possible to observe the nature of the flames within the building. The NIST validation strategy may be lacking as they cannot see the internal fires.

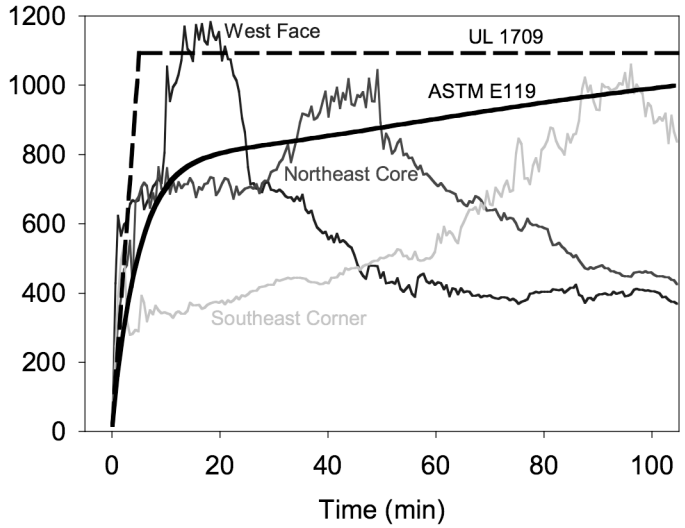

Figure 9. Average temperatures predicted for WTC 1, 97th floor [from McGrattan]

There are several factors that influence the accuracy of the NIST fire model. It is a large eddy based fluid flow model. There is no direct accounting for the local scale of turbulence or the small-scale combustion phenomenon. Some factors contributing to its uncertainty are listed here:

- Grid size for computations = 0.4 m
- Scale of combustion ~ 1 mm
- No validation for predicting temperatures in a fire plume
- Model has never validated for a large fire in a compartment
- Large fire measurements suggest higher flame temperatures than predicted >1300 ºC.

Both the fire and the structural models used in the prediction of the WTC have never been used for such computations. NIST admits they have stretched their application. In view of such uncertainty, it is disappointing that alternative approaches were not invoked.

Alternative computations are available and have been based on experimental data. Formulas have existed for decades and have served as

the basis for design estimates. Recently the SFPE has produced a guide on such formulas. Figure 10 shows results for temperature and its duration based a formula established by the extensive CIB data base.[2] Here is an example of applying the CIB correlations to the WTC fires with a fuel loading of 7.5 psf (34 kg/m2). It is compared to NIST temperature for 4 psf loading at a given floor location. The results also show the standard fire temperature furnace curve and the temperature suggested by Beyler et al. [11]. The CIB fire is longer than the NIST local fire prediction, and indicates fire heating beyond the collapse times of each building. These CIB-estimated results will be used later to compute the steel temperature in the trusses.

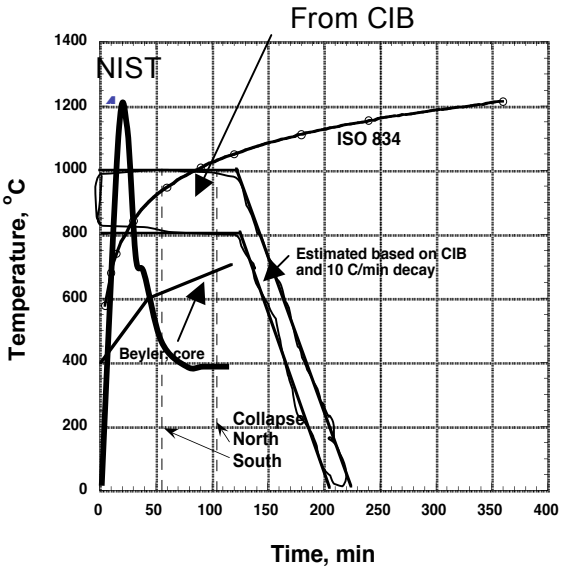

Figure 10. Estimates of the fire temperature

2.5. QUESTION 5: NIST SAYS THE ORIGINALLY SPECIFIED INSULATION THICKNESS WAS ADEQUATE. IS THIS CORRECT?

There is a long history concerning the insulation of the trusses in the WTC towers.[5] NIST concludes that the insulation as used in both buildings would have been adequate to keep the buildings from falling had there been no loss of insulation in the core. The history of this insulation thickness from its design in 1965 of ½-inch to an upgrade initiation of 1-1/2 inches in 1994 is a story that fire protection engineers need to understand. The

Table 1. Insulation Thicknesses (taken from NIST[9] [p70])

Component	Specified	Installed	Used in Calculations
Truss			
WTC 2: Original	1/2	3/4	0.6
WTC 1: Upgrade	1.5	2.5+/-0.6	2.2
Core Columns			
WF Light	2 3/16	?	2.2
WF Heavy	1 3/16	?	1.2
Box Light	?	?	2.2
Box Heavy	?	?	1.2

process of the insulation design is fraught with non-transparency and needs clarification.

Table 1 shows the insulation thicknesses and its history. It is striking the NIST did not have full data on all of the elements. But the most striking is the change made to the trusses. These changes are a portrayal of the insulation design process. NIST's lack of probing in this area through subpoenas and testimony is remiss. The basis for the original design, and the change in 1994 should be a lesson learned. The stated "installed" insulation thickness of the WTC 1 upgrade should be questioned, as its source is a NYNJ Port Authority audit report with no photographic evidence. It should be realized that the installer was requested to upgrade the thickness on the Marsh floors of WTC 1 from ½ (or measured as ¾ inches) to 1.5, but instead put on 2.5 inches on average. On a 1-inch diameter steel truss rod, that would make the overall diameter 6 inches, instead of 4. This is an unlikely application of insulation in my opinion, and is subject to question.

My information on the history of the truss insulation is summarized below. I am making estimates on the basis for the original specification and changes.

- Basis of original specification:

1966 memo (Tishman, J. R. Enders: cost analysis)
Cafco D for ULI-86-3: 8 in. x 3/4 in. beam-floor assembly
1/2 in. Insulation ~ 4 hrs
1969 memo R. Linn to DiBono "beam cover should be 1/2 in."

- Basis of 1994 change: (Upgrade on re-evaluation)

UL G805:	1 1/2 in. ~ 2 hrs
(but UL N826 without deck insulation:	2 1/16 in.)

- 2001 Burro-Happold report to NYNJPA: "insulation adequate", recommends 1.3 in.

- Floor assembly never tested until done by NIST in 2003 at UL:

Rating ranges from 3/4 hr for 1/2 in. to 1 - 2 hrs for 3/4 in.
Tested at 17 and 35 ft spans, not longest 65 ft.
Rating based on collapse criterion, not on temperature achieved.

The ratings for the UL furnace tests were based on loaded assemblies, and therefore the failure time is based on structural collapse. Note the long span truss of 65-ft could not be tested. Normally the test assembly is not loaded and temperature is the criterion for the rating; in some areas of the world only the temperature criterion applies. By examining the temperatures achieved and by assuming the standard time-temperature curve represents a reasonable fire (See Figure 11), some conclusions on failure can be drawn. Especially since structural models indicate failure of the floors trusses at temperature of 400 – 600ºC. The UL tests of 17- (scaled) and 35-ft truss spans give temperatures indicative of failure, and consistent with the temperatures need to cause structural failure of the floors in times of 58 to 86 minutes. Note the following:

- Time to reach 593 ºC (average) - 66 to 86 min.
- Time to reach 704 ºC (max.) - 58 to 76 min.
- NIST computed truss "walks off seat at 650 ºC.

The variation in the UL times is due to three separate tests at 3/4 inch of insulation and one at 1/2 inch, indicative of WTC 2. One might question why there is a 28-minute variation in the results for simple thermocouple measurements in a standard time-temperature furnace test. But that is a question for the accuracy of the test, not these general results. For these times, of 58-86 minutes, are consistent with the failure time of 56 minutes for Tower 2. So the UL tests do support that fire conditions can fail the trusses in WTC 2.

Let us consider that a steel temperature of 600ºC is sufficient for causing failure of a WTC truss as structural calculations have borne out. Tests were done on facsimiles of the truss steel rods for various levels of insulation thickness in a furnace at 800ºC, representative of the WTC fires (See Figure 10). These were done with the Cafco insulation at the Isolatek laboratory in NJ. The details of these computations can be found in Quintiere[2]. Figure 11 shows the time to achieve 600ºC (failure) for the various structural elements in the twin towers. It also displays the effect of

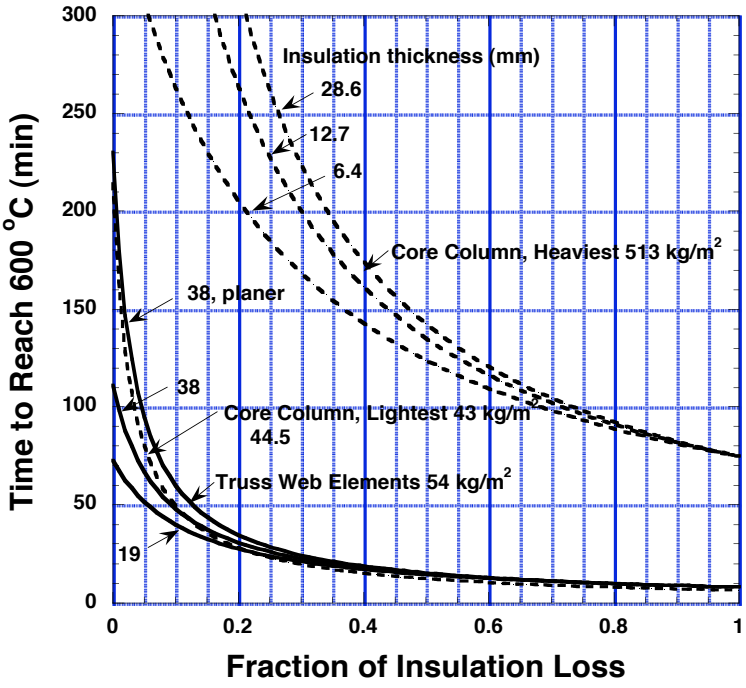

Figure 11. Steel time to reach 600ºC failure criterion

lost insulation as a fraction of that lost around the perimeter. The truss representations for WTC 1 are listed as 38 [mm] (1.5 inch insulation) and WTC 2, 19 [mm] (3/4 inch insulation). Failure times are 70 and 110 minutes for WTC 2 and 1, respectively, for no loss of insulation. A small loss in insulation reduces these times sharply, especially after 20 % is lost. This result suggests that the loss of insulation on the trusses was not likely, as collapse would have resulted much earlier than in reality. However, the loss of all insulation on the heavy core columns results in a failure time of about 75 minutes; this is not so inconsistent with the actual failure times of 56 and 102 minutes. But the correspondence to the truss computed times are a much better match. Moreover, more than 50 % of the insulation must be lost from the core heavy columns to yield failure times consistent with

the event. These computations support the trusses as the root cause of the collapse.

2.6. QUESTION 6: ARE COMPUTER MODELS SOLELY SUFFICIENT?

NIST admits to stretching the envelope on computer models, never used before on such a complex fire. Damage predictions vary extensively. The models cannot fully resolve turbulent combustion, and small details of construction as represented by the insulation and connections. So how can NIST accurately compute the fire, and the removal of the insulation by the aircraft?

Alternatives to computer modeling exist. First, computations based on formulas and correlations have been used for analysis and design in engineering. When done, these provide a transparent view of the computational process, as opposed to hidden aspects of computer codes. Second, scale-modeling approaches have been used for design and accident investigation in both fire and structures. This approach not only provides a relatively inexpensive view of the phenomena, but also a measurement workbench upon which to compare computer models. Third, there is always the complete reproduction of the event at its scale. In this case, the reconstruction of a full floor (or quadrant) would have been extremely useful, and within the $16 million budget for this investigation.

2.7. WHY NO FULL-SCALE TEST?

NIST conducted tests involving several workstations representative of the Marsh & McLennan floors. These included some of the steel truss assemblies. But as stated earlier, it believed to be sorely deficient in fuel load. The tests were used to tune the fire model to better represent the workstation fuel load, and are responsible for the 20-minute fire durations in any given location. A much more representative reconstruction could have been constructed and tested. As the WTC floor plans were fairly symmetric, a quadrant of one floor could have been a good starting point. A more comprehensive reconstruction of the fuel load should have been assembled, validated and tested. The truss and core temperature could have been measured for various insulation thicknesses. The effect of fire scale on turbulent flame temperature would have been determined from these tests. Then, computer modeling could have been tested.

It was stated an alternative to a full-scale test is physical scale modeling. We conducted such an exercise for the 96th floor of WTC 1 as a senior undergraduate class semester project. [18] The project was funded internally, and cost about $2000 in materials and equipment.

In scale modeling, some compromise must be made in satisfying the key dimensionless groups, but the phenomena of turbulence and combustion function according to their natural scales. Scaling rules are displayed in Table 2.[3]

Table 2. Scale rules

Phenomena	Modeling: Scale: $s = l_m / l_p$
Geometry, coordinates Time	Length ~ s^1 Time ~ $s^{1/2}$
Fire dynamics	Power ~ $s^{5/2}$, Flame height ~ s^1
Fluid mechanics	Re ~ $s^{3/2}$ *(make large enough)*, Velocity ~ $s^{1/2}$
Thermal effects	Temperature ~ s^0, Radiation flux ~ s^0, Convection flux ~ $s^{1/5}$
Structural mechanics (Fracture and buckling)	Stress ~ s^0, Strain ~ s^0

Students considered the office fuel load and the aircraft fuel. Wood cribs simulated a 10-psf (45 kg/m^3) office fuel load. The construction of the structure was based on the heat transfer scaling and required relatively low density material. Measurements included temperature, heat flux, fuel mass loss, and smoke obscuration. Several external columns and insulated trusses (unloaded) were included according to the scaling laws. The insulation on the scale model is based on heat transfer consideration, and is not based on geometric scale. Consequently, the insulation thickness was applied to the complete truss, not the individual components. Photographs of the assembly and fire are show in Figures 12 and 13. Figure 14 shows the results of the scale model in terms of the temperatures. In comparison to the NIST computations for comparable temperatures on the 97th floor, the NIST upper layer temperatures are only about 800 ºC for about 20 minutes, while the model results show a given region is in excess of 800 ºC for about 45 minutes. This is a more severe fire condition. Moreover, the scale model is likely to give lower flame temperatures due the scale effect on radiation. Thus, the scale model shows a similar movement of the fire about the floor as the NIST computations, but more significantly shows a

longer duration of the flames. Indeed, the scale model shows in Figure 16 that the steel trusses in the model, with scaled insulation thicknesses of 1 and 2 inches, respectively, indicate failure in 80 to 90 minutes compared to an actual failure in WTC 1 of 102 minutes. We feel this gives some credibility of the scale model result, and supports the hypothesis that the trusses are at the root cause.

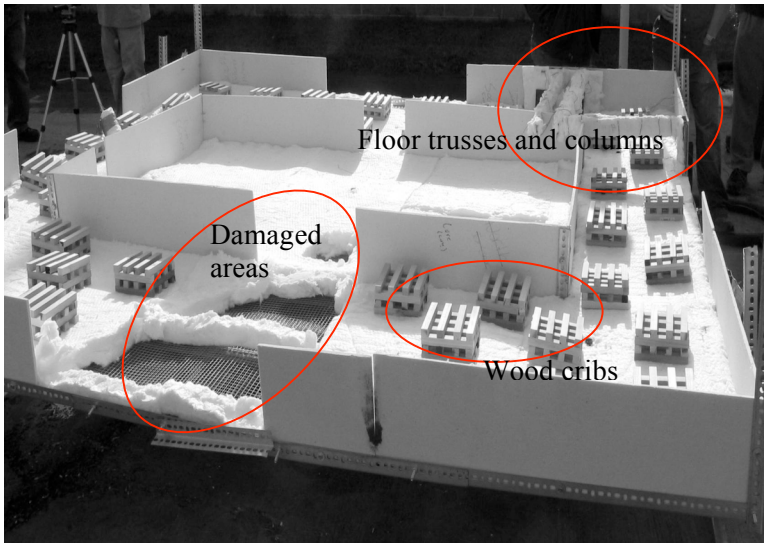

Figure 12. Scale model floor with no ceiling

Figure 13. Scale model test in progress

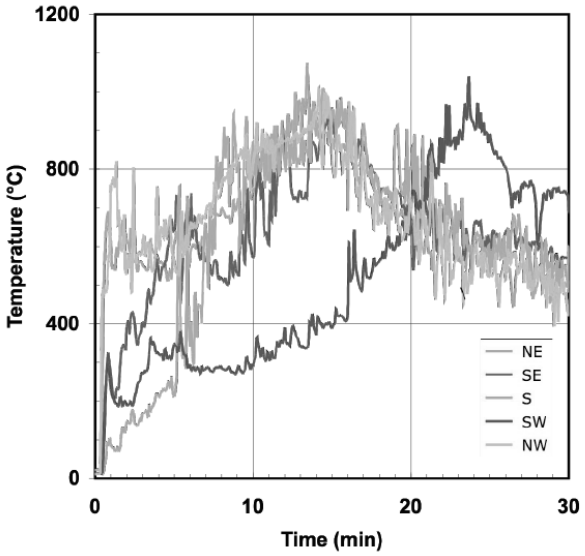

Figure 14. Scale model upper layer gas temperatures for 96th floor, WTC 1. Time is in model time, and WTC full-scale time is $(20)^{1/2}$ x [model time], e.g. 20 minutes is 89 minutes WTC time.

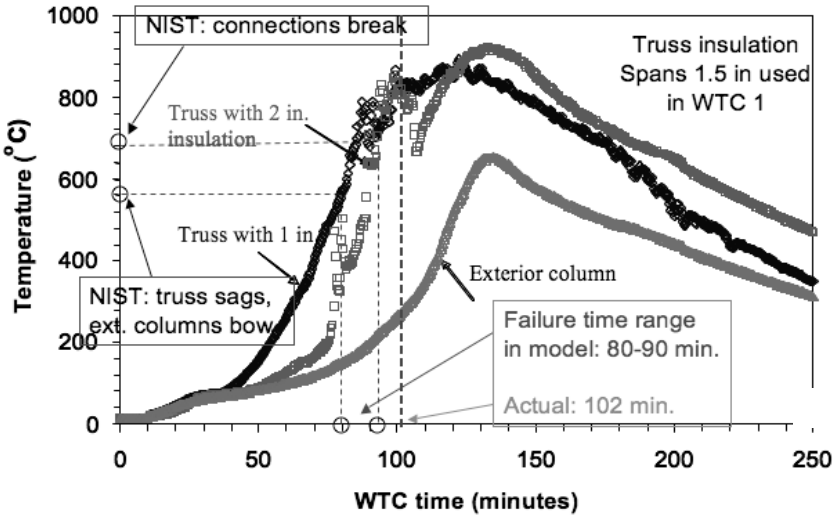

Figure 15. Scale model truss temperatures

2.8. QUESTION 8: WHY NO ACCOUNTABILITY?

Perhaps it was not the job of NIST to hold people or practices accountable. But the style of their report should have had the sharpness of focus to indicate where the faults were. Instead, NIST has produced a long list of recommendations, most of which do not tie to the root cause of the disaster. Let me list some of the more notable issues that needed sharpness of focus to bring appropriate accountability and corrective actions:

- Loss of the steel as evidence of temperature
- Documentation and analysis of the process for the fire resistance design
- Radio communication of the fire service.

NIST had subpoena authority that was not used, and had the ability to hold hearings under oath that was not invoked. This lack of authority should have been a vital part of the investigation.

2.9. QUESTION 9: WHY NOT OFFER SEVERAL HYPOTHESES ON COLLAPSE AS NIST INITIALLY SAID?

From the start of the investigation NIST continually stated that the end point of the process would be to present hypotheses according to their probability of occurrence.[7] NIST orriginal objectives stated:

- What is the most probable collapse sequence?
- What is the probability of the possible collapse sequences?

Instead, NIST lists one cause without equivocation. What happened to their original plan?

2.10. QUESTION 10: WHAT ABOUT WTC 7?

As we know WTC 7 collapsed many hours later. It was hit by falling debris from the towers, and that caused damage and fires to occur. NIST has yet to produce a report on the cause of its collapse. Little has been reported. At the NIST NSTAR Advisory Board meeting I attended in December of 2005, discussion centered on whether it was worthwhile for NIST even to pursue WTC 7. As I understand, the report is still a work in progress, 6 years after the event. As the removal of insulation by the impact of the aircraft would not be an issue here, it is imperative to find the cause of the WTC 7 collapse that was solely due to its fires. Some believe diesel oil tanks within the building fed the fires. I contend that these tanks would have played the same role as the aircraft jet fuel that ignited the contents of WTC 1 and 2. This jet fuel burned quickly, and the building contents were the primary source of the fires. The same would apply to

WTC 7. Hence, an ordinary building fire, unattended by the fire service, led to a collapse. The design of fire resistance in a building is supposed to prevent the heating of the structure to failure over the expected duration of a fire. This apparently was not the case. Do we have a design flaw?

3. Conclusions

I contend that the NIST analysis used a fuel load that was too low and their fire durations are consequently too short. Only these short fires could then heat the bare core columns as NIST reports. The fires were too short to heat the insulated trusses to failure. The NIST analysis has flaws, is incomplete, and has led to an unsupported conclusion on the cause of the collapse.

An alternative hypothesis with the insulated trusses at the root cause appears to have more support. Heat transfer analyses, a scale model, and the UL furnace tests all indicate that the steel trusses can attain temperatures corresponding to failure based on structural analyses. This hypothesis puts the blame on the insufficiency of the truss insulation. Something NIST says was not an issue.

The two different hypotheses lead to very different consequences with respect to recommendations and remedial action. I think the evidence is strong enough to take a harder look at the current conclusions. I would recommend that all records of the investigation be archived, that the NIST study be subject to a peer review, and that consideration be given to re-opening this investigation to assure no lost fire safety issues.

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