Comments on NIST—NCSTAR Federal Building and Fire Safety Investigation of the World Trade Center Disaster, Especially NIST NCSTAR Reports 1 and 1-7

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The NIST website (http://wtc.nist.gov/comments_submission.htm) contains the following instructions:

> To ensure that your comments are properly considered, it is important that they be submitted in the appropriate format to facilitate review and disposition by the report authors. NIST will prepare a public summary of the comments received and their disposition in September when the final report is issued.

The website goes on to stipulate:

> Comments not submitted through the web site should contain the following information:
> Name: (Optional)
> Affiliation: (Optional)
> Contact: Phone number or e-mail address where you can be contacted in case of questions. (Optional)
> Report Number: (e.g., NCSTAR 1-1)
> Page Number:
> Paragraph/Sentence: (e.g., paragraph 2/sentences 2-4)
> Comment:
> Reason for Comment:
> Suggestion for Revision:

Information Not Found Easily Or At All

General comment on comment process: it is ironic that NIST stipulates that comments be very specifically targeted when some topics are not addressed in an easily located, specific fashion in the reports. Also, as illustrated in the second topic area below, "Activity in Exit Stairwell," if something was missed in the study, exactly where in the reports does one reference that deficiency?

If NIST wanted to have a well-organized, easily perused set of comments, it should have provided a well-organized, easily perused set of reports. Report NIST NCSTAR 1-7 does not provide this. Alternatively, if commenters are expected to do so much work to compensate for deficiencies in the reports, NIST should be prepared to compensate the major effort required.

Important Baseline Information. For example, baseline information on the means of egress for the buildings is not all located at one logical place in the reports or even in the individual reports for specific projects (such as Chapter 2 of Report NIST NCSTAR 1-7).

Exit Stairway Step Geometry. Specifically, if one wants to find out what was the actual step geometry of the exit stairways, one has to resort to a word search of the PDF files and, even after this time-consuming process, one never does find out what the step geometry actually was, *only what it was supposed to be relative to code requirements.* Moreover, rather than being in a section on baseline information (such as Chapter 2), some of the means of egress information is buried well on in the occupant behavior report (NIST NCSTAR 1-7) in Appendix D on egress modeling. Also, only at this point (specifically page 240 of this report in Section D.3) is mention made of the number of stair risers between floors—18 to 26—with 19 risers per floor being present for floors 45-49 (according to Section D.4.1 on page 247). A bit further on in this appendix, the step geometry is reported as being "7.5 in by 9.5 in riser tread configuration" which is the NYC Building Code limit for stairs used for assembly occupancy (7.5 inches *maximum* riser height for assembly occupancy; 7.75 inches *maximum* for others) but which is not consistent with the result of a simple calculation dividing the reported (but well buried) typical floor-to-floor height of 12 feet by a typical office floor's 19 risers for a riser height of 7.58 inches. Does this mean—due to the assembly occupancies at the top of the towers—that the exit stair geometry, with the 7.58-inch risers, did not strictly comply with NYC Code requirements?

Even harder to figure out—if the tread depth (run) dimension is questionable also—is what the actual, as opposed to required, (minimum) tread depth (run) dimension was. When I worked in the WTC in 1993 I managed to take one, relatively crude, spot measurement at the 67th floor of Tower 1, which suggested the riser-tread geometry was approximately 7.5 by 9.5 inches.

Landing Geometry. Also, nowhere in the reports do I find a treatment of the size of landings for the exit stairways. Landing size is a key to the capability of the means of egress system to provide rest areas for the many people who reported they stopped occasionally to rest. Does this mean that the NIST team did not examine sufficient construction documents to determine landing geometry or does it mean the team did not consider this important to report?

Also apparently missing from the reports was information on the following building characteristics.

Overall Exit Stairway Area (available for evacuee occupancy). Total area of the stairway system including stair flights, landings and transfer corridors was not found.

Stairway Handrails. Information on the stairway handrails cannot be found anywhere in the NIST report. However, I do have some information. For example, handrail height (at my measurement site on the 67th floor of Tower 1) was about 33 to 34 inches above step nosings with a handrail section size of 1.5 inches diameter with 1.5 inches clearance to the adjacent wall. Also, as was typical with handrails of 1960s vintage, the wall mounted handrails did not extend past the point directly above the lowest step nosing so that some users, for example descending in darkness in 1993 or 2001 evacuations

—accustomed to handrails extending at least one tread depth past the lowest nosing—might not be aware of the lowest step of each flight if they were walking on the wall side of the stairs. Here it should be noted that evacuees walking on the inner side of the exit stairs would have inconsistent handrail extensions with some shorter ones at end-of-flight newel posts. The report does not address the propensity of most evacuees to descend on the wall side of the stairs nor does the report describe the stairs as either turning left or right (relative to a descending person). The former appears to be the case for the two sets of stair photos I have for the 67th floor of Tower 1 but the plan I attach in Appendix 1 to these comments shows both configurations. Without such detail about the handrails, it is not possible to do a full assessment of important ergonomics issues facing evacuees and affecting their egress performance plus safety generally.

Ground-level Egress Activity. Finally, in terms of major omissions, the issue of ground-level egress activity was apparently missed in the investigation/study and the report. Given the nature and scale of the multi-building disaster, it is important to understand what happed to the evacuees once they reached the WTC concourse. Which exits were used from the concourse and how was that process managed by authorities? How did this interface with evacuation from the underground transit stations? What happened to evacuees at ground level after collapse of WTC 2? And what about evacuees from nearby buildings? Over 15,000 evacuees from the two towers alone went somewhere. Where and how? Approximately how many were able to evacuate from the towers only to die at ground level due to the towers' collapses. Generally, urban neighborhood issues need to be addressed when dealing with large, high-occupancy buildings such as in the WTC and surrounding developments such as World Financial Center.

General Criticism about Inadequate Attention to Activity in Exit Stairwells

Relative Emphasis on Evacuation Delay Contrasted with Stairwell Activity. Generally, the arrangement, sizing and—*especially*—the utilization of the exit stairwell system in the towers got short shrift in the NIST study. Contrast, for example, the many questions asked in the telephone interviews about the delay in starting egress down the stairs to the one *single* question related to the difficulties experienced in the extensive behavior of evacuees and others in the exits (described in the interview script, page 201, and reported in Table 10-1, page 151, of NIST NCSTAR 1-7). The one or two questions on difficult conditions during stairway use ("Time Period: 3" having, overall, about a dozen questions) can be contrasted with the two dozen or so questions about delays in initiating egress ("Time Period: 2"). Certainly, pre-evacuation behavior is important (and apparently a pet subject with some of the researchers on the NIST team) but it does not impact means of egress design and codes/standards/regulations deliberations the way that behavior in the exit stairwells does.

Moreover, the fact that both towers provided a rare opportunity to compare evacuation in two different stairway widths—*at a time when this continues to be a "hot" code-change issue* (see next section)—makes the apparent emphasis on pre-evacuation behavior even more questionable. As a well-known researcher on evacuation of a range of

buildings—located a mere half-hour drive from NIST—who took the effort to have several NIST staff meet in my office in January 2004 to discuss research needs and opportunities, it is especially galling to see the NIST investigation/study give the stairwell-related activity such relative short shrift.

Information Relevance to Codes. NIST staff knew—or should have known—that the whole topic of exit stair design, especially minimum width in relation to counterflow and other evacuation movement, was a major one within the NFPA process for the Life Safety Code (NFPA 101) and Building Construction and Safety Code (NFPA 5000). They also knew that, unlike in most tall office buildings, there were two significantly different exit stair widths, nominally 44 and 56 inches—the very exit widths being debated in the NFPA standards/codes change process. Why then did NIST not adequately address what happened in the exits?

Difficulties Experienced in the Stairwells. For the especially important question about difficulties in the stairwell, "Did any of the following make your evacuation more difficult while you were in the buildings?" only three of seven options dealt with key pedestrian movement issues—coherent flow (everyone moving more or less as a unified mass with similar descent speeds), counterflow and overtaking movement (what the NIST report refers to as "superflow")—as follows:

> "Crowded stairways"
> "Firefighters or Police moving up stairwell"
> "Disabled or injured people being taken down stairwell."

The coding for these questions was only "Yes," "No," "DK," and "RF." Thus detail on so much important behavior in the exits was not even systematically elicited in the telephone interviews.

Counterflow. Also troubling is the apparent effort by the study team to play down the importance of counterflow, for example, claiming that it was of little importance—*on the basis of an arcane statistical analysis!* If the reasonably detailed questions are not even asked—and responses not coded in detail, no amount of statistical analysis is going to compensate for the deficiency and produce useful, meaningful findings! By way of revision suggestion, instead of trying to misrepresent the findings, it would be better if NIST simply admitted that the appropriate line of inquiry was not used to address the counterflow issue and other evacuee movement issues related to the exit stairways.

Study Constraints. There is some admission of inadequacies with the telephone interview process found on page 138 of NIST NCSTAR 1-7.

> While the multivariate regression analysis of the telephone data has extraordinary power to distill the telephone interview data to the salient features, the analysis was necessarily limited by the constraints of the number and type of questions contained in the telephone interviews. Face-to-face interviews and focus groups provided a more detailed understanding than can be achieved by exclusive use of the telephone interviews.

Questionable Conclusion on Counterflow. Highly questionable as a result is the statement on pages 167-168 of NIST NCSTAR 1-7.

> Contrary to the perceptions of the occupants, counterflow in WTC 1 was determined by causal modeling analysis not to be a significant predictor of increased total evacuation time while in the stairwells when compared to other factors, including evacuation interruption and environmental cues.

Who Influenced Study? In the discussion about "Predicting Normalized Stairwell Evacuation Time In WTC 1 on September 11, 2001," on page 229 of NIST NCSTAR 1-7, there is a note:

> A group of individuals selected for the expertise on human evacuation during high rise fires was assembled. The individual experts developed the final list of variables, and the relationships between them, to use to specify the model used in this analysis.
>
> Second, preliminary statistical analyses were performed to determine which variables thought to be important predictors of normalized stairwell evacuation time by the team of experts had and did not have predictive salience in WTC 1. Those that had no significant impact on normalized stairwell evacuation time were excluded from further consideration. The factors that had salient impacts on normalized stairwell evacuation time were carried forward into the model used in this analysis.

Later, on page 229, after describing the "Causal Modeling," the report states:

> This model is parsimonious, consistent with the input received from high rise fire evacuation experts, and it well-represented the positive findings of our preliminary analyses of the many variables that could have impacted normalized stairwell evacuation time.

Who were these people?

Statistical Manipulations. On page 230, is a potential partial explanation for the relatively good statistical results that are claimed; certain responses were coded to the mean.

> Finally, normalized stairwell evacuation time (X7) was measured by asking respondents how much time passed between the moment they first began their evacuation until they exited the tower. Answers were coded on an interval scale; "don't know" and "refused to answer" responses were coded to the mean. These raw numbers were then normalized. The hydraulic model of people movement dominates the average evacuation time per floor, so it had to be removed from normalized stairwell evacuation time so as to fully explain the fluctuations (denoted by a prime) in reported evacuation time. This was accomplished by a least squares analysis of reported evacuation time against floor for each tower, with statistical outliers removed.

After a few pages of very arcane discussion of statistics, the authors concluded, "All of the equations in the model were statistically significant at the .001 level or better."

There is some truth to the statement about statistics: they tend to conceal more than they reveal. Appendix C is a good example of the misuse of statistics and statistical jargon; here apparently used in an attempt to hide the fact that NIST's interview process was seriously flawed in not probing sufficiently into what happened in the exit stairwells during the evacuation.

"Straightforward and Clear" Process? The stated conclusions of Appendix C are only slightly more illuminating and less arcane than the explanation preceding it (page 235 of NIST NCSTAR 1-7):

> Although each of the aforementioned findings are interesting in and of their own right, the most important findings that we can offer are those that emerged when all of the above findings are brought together and viewed at the same time in the context of the model as a whole (see Figure 1). What doing so revealed was that, based on this analysis, the main process that led to increased normalized stairwell evacuation time in the evacuation of World Trade Center WTC 1 on September 11, 2001, was straightforward and clear. It can be described as follows.
>
> Floor (increased distance to safety) substantially increased the odds that people would encounter environmental cues. Floor also increased delay in starting evacuation, which, in turn, also increased the chances that people would encounter environmental cues. But it was encountering environmental cues (which likely blocked egress) that had a large and direct effect on increasing the amount of time that people spent, on average, to traverse their evacuation stairwell. In addition to this multi-step process with environmental cues as the key predicting variable, interrupting the process of evacuation for any reason also increased the amount of time, on average, that people used to descend their evacuation stairwell.

The foregoing, as well as Appendix C generally, should be edited or rewritten for clarity. What are the authors trying to say? What are they trying not to reveal?

Normalized Stairwell Evacuation Time. So what was the "Normalized Stairwell Evacuation Time" in WTC1? A search for all uses of the phrase in the PDF file for NIST NCSTAR 1-7 revealed it appeared 38 times, *but never in close proximity to the result stated in meaningful form!* So where is the information? Section 10.1.2, "Time and Average Travel Speed in the Stairwells, WTC 1," and Figure 10-4 appear to present the answers (possibly reported by a different writer than the one seemingly infatuated with arcane statistics and the phrase "Normalized Stairwell Evacuation Time" which appears nowhere in Section 10.1.2). The results:

> The reported time spent in the stairwells for occupants of floor 10 to floor 91 in WTC 1, based on the NIST telephone interviews (n=368), yielded a mean normalized travel speed of 1.3 floors per minute. Normalized travel speed is defined as the total time from entering the stairwell until leaving the building, divided by the number of floor that had to be descended. According to Figure 10–4, 25 percent of the occupants traveled faster than 1.5 floors per minute, while 25 percent of the occupants traveled more slowly than 0.9 floors per minute. The median normalized travel speed was 1.2 floors per minute.

The phrase, "According to Figure 10–4," appears in error as the graph shows only 25 data points—not 368—with 7 (28 percent) below 0.9 floors per minute and 12 (48 percent) above 1.5 floors per minute; indeed the median for the data points presented on the graph is 1.5, not 1.3 floors per minute. So even a relatively straightforward presentation of data ends up being confusing.

Stairway Descent Speeds. The report authors go on translate the "floors per minute" to a more standard measure of stairway speed, measured in feet or meters along the stair slope and along the landings, which they estimate at 33 ft (10 m) per floor, "assuming an average floor height of 3.7 m (12 ft)." (The authors' estimate of average travel distance per floor is within a couple of feet of my estimate, based on methods I first used in my high-rise building evacuation studies of 35 years ago in Canada.) They go on to compare their results with the estimates of speed reported in the "published scientific literature" which, logically, should include book chapters, papers and handbook chapters I produced although none of these is referenced in the report. For example, in Figure 14.11 of my chapter, "Building Evacuation: Research findings and recommendations," (D. Canter, editor, Fires and Human Behaviour, Wiley, 1980), a median speed of about 0.65 m/s is shown—representing many samples of speed taken while evacuees were actually moving down stairs, not averages based on an evacuee's entire descent which—depending on building height and population, plus other factors—could include delays where speed was very low if not zero. Thus, the NIST team is comparing apples and oranges when, on page 129, it reports the WTC's estimated speed of 0.2 m/s is "on the slow end of published scientific literature values for stairwell descent speeds."

Key Stairwell Activity Not Addressed. What NIST should have done, among many things that were missed in the WTC study, is to examine exit stairwell activity in much more detail—especially to document where, when and why there were stoppages and other disruptions to movement. Such stoppages are more likely at lower levels of the building but, if the populations were larger—as would be the case at times other than the early morning conditions of 9/11, stoppages would be expected over most of the stairwell height. For example, with 20,000 occupants per tower and a full evacuation of all floors, people on the highest floors could expect to be queuing on the exit stairways or even outside the exits for about one half of the total time taken to descend about 110 stories. This assumes normally observed deference behavior with lower floor occupants

allowed into the exits ahead of those already in the exits from upper floors. (Observed deference behavior on 9/11 was apparently not even addressed in the NIST study despite its major implications for specific issues such as average speed and clearance of certain levels preferentially.) Notably, the technical background referred to in the preceding sentences was included prominently in my major presentations during 2002 and 2003. Although some NIST staff attended those presentations, as far as NIST is apparently concerned, these presentations either did not occur or did not matter. A word search of NIST NCSTAC 1-7 found no usage of the relevant terms, "mixing," "merging," "deference" or "precedence" that describe key concepts of exit stairwell use in high-population tall office buildings where evacuees on the stair interact with evacuees desiring to enter the exits from lower floors.

The bottom line is that normal deference behavior and associated queuing alone can account for a potential reduction of average speed down stairways by a factor of two for a building such as the WTC. NIST's reported reductions are factors of about two to three. One of the most important things that NIST could have done in reporting the speed data would be to present speed estimates in relation to where and when the speed occurred.

Failure to Communicate Evacuation Process Effectively. In this regard, one of the huge disappointments I have with NIST's study is the failure to report data in the very effective forms I have been using for 35 years. (See for example Figures 3-13-11 through 3-13-14 of the SFPE Handbook of Fire Protection Engineering, Third Edition, chapter, "Movement of People: The Evacuation Timing," which have been in that handbook since its first edition in 1988—when I was the author.) This involves plotting traces of individual people's movement on a chart with building height on the vertical scale and time on the horizontal scale. Even with the relatively crude, incomplete data collection done by NIST, the researchers could have prepared some of these charts and these would have quickly shown where and when evacuees were experiencing major delays and slowdowns and, by virtue of crossing traces depicting emergency responder counterflow, where and when counterflow occurred. In this regard it is insightful to compare the clarity and informative content of such charts with the dense, arcane discussion of "Normalized Stairwell Evacuation Time" presented in NIST NCSTAC 1-7, particularly on pages 229-235.

Opportunity at NIST WTC Conference. An effort will be made during my intended presentation at the NIST conference in mid September 2005 to compare NIST's presentation of stairway evacuation findings with the much more informative methods I have been advocating for decades. Hopefully NIST conference organizers will permit, indeed welcome, such a different approach to consideration of the WTC evacuation on 9/11. This raises a larger question; will NIST preserve the occupant survey data in the most original form (without divulging names of particular survey respondents) so that other researchers can present the data in more meaningful fashion?

Expert Guidance on High-Rise Evacuation? Generally, this high rise building evacuation expert (indeed likely the most experienced one still active today) has serious heartburn over the study approach and findings presentation for NIST's investigation of occupant behavior and egress in the WTC. Thus I am especially intrigued by the statement on page 229 of NIST NCSTAC 1-7.

> A group of individuals selected for the expertise on human evacuation during high-rise fires was assembled. The individual experts developed the final list of variables, and the relationships between them, to use to specify the model used in this analysis.

Who was in this group of experts? Who on this group of experts had extensive knowledge about, and long experience with, technical bases of requirements for means of egress in model codes and standards—the prime focus for NIST recommendations based on the WTC investigation? Also, why does the NIST NCSTAR 1-7 report not reference the most relevant technical literature about the technical bases for exit stair requirements and about performance of exit stairs in full and phased evacuations?

Inadequate Reference to Evacuation Literature. One final example related to this inadequacy; pages 162-163 of the report describe prediction of total evacuation time including a graph, Figure 10-9, estimating or predicting (minimum) full building evacuation times for various population conditions. No mention is made here of research-based literature I have produced in recent decades on this topic. Especially notable are the office building evacuation time prediction graphs and formulas included in the *SFPE Handbook of Fire Protection Engineering* chapter on Movement of People included in the 1988, 1995 and 2002 editions. Equation 9, in the third edition of the Handbook, offered a simplified formula for estimating minimum total evacuation time by stairs. For 20,000 actual occupants, the predicted time is 98 minutes which should be compared with the roughly 110 minutes shown for 19,800 occupants in Figure 10-9 of the NIST NCSTAR 1-7 report. Even closer was the correspondence between the Figure's linear graph slope—5.2 minutes per 1000 additional occupants or, alternatively stated as 192 persons per minute—and the SFPE Handbook's Table 3-13.5. This Table suggests a value of 216 persons per minute—for "optimum" flow—and 168 persons per minute—for "moderate" flow. In both cases these represent total flow for the combined 12-ft nominal width for all three WTC exit stairwells. Notably, the average of 216 and 168 is 192, the total flow in terms of persons per minute (or 3.2 persons pre second) for the three stairwells combined.

Fruin Levels of Service. Also, although the report references Fruin's classic book, *Pedestrian Planning and Design*, it does not relate estimated WTC stair movement conditions with the "levels of service" described by Fruin. For example, for flow down stairs, using the average flow assumed for Figure 10-9, this assumes a Fruin level of service E, based on a flow of 16 persons per minute per foot of nominal stairway width. This level of service is associated with stairway areas of 4-7 sq ft per person (1.5 to 2.7 persons/m^2) and speeds of about 100 ft/min (0.5 m/sec)—3 stories per min for the WTC stairways (with speed measured along the stair flight slope).

Confusion between Flight and Floor. Incidentally, a word search should be done by authors of the NIST report to find and correct instances where time per flight is noted rather than time per floor (story); typical office floors of the WTC towers had two flights and two landings per floor in a "dog-leg" or "switchback" configuration. (As noted elsewhere in my comments, the authors should also specify the direction of turn to give a complete description of such stairs.)

Key Pedestrian Movement Characteristics Confused. On the topic of Fruin's classic book, *Pedestrian Planning and Design*, the NIST report authors betray a lack of experience in dealing with the key pedestrian movement characteristics, density, speed and flow. On pages 129-130, they state the following (with my underlining added for purposes of my post-quote comment).

> A "rule-of-thumb" for calculating evacuation speed is to assume that a standard size door at the bottom of the stairwell is capable of discharging approximately one person per second. (Fruin 1987)[59] By that logic, with three stairwells, the WTC system would have been capable of moving approximately three people per second from the occupied floors to the Mezzanine or Concourse. In WTC 1, where elevators were not operational for the duration of the evacuation, approximately 7,500 occupants used the stairwells over a 100 minute period, yielding an exit rate of 1.3 people per second from the occupied floors. Even discounting the final 27 minutes (after the collapse of WTC 2 when the evacuation rate dropped significantly), the discharge rate was 1.5 people per second (or 0.5 people per second per door), or about one-half the "rule-of-thumb" discharge rate. This is consistent with the previous observation that the stairwell movement speed was slower than the published literature values would have predicted and that the slower rate was to be expected given the number of obstacles to egress encountered by the evacuees and the total travel distance required.

This discussion confuses "speed" and "flow." The quoted discussion should be referring consistently to "flow" instead of (in sequence as shown underlined in the quote): speed, exit rate, evacuation rate and (twice) discharge rate. Use of "rate" in the last sentence is ambiguous; it apparently refers here to speed but it should be noted that all three of the key movement characteristics are rates.

Confusion about Door Widths. On page 18 of the Report we learn that doors leading to stairs were to be designed at a 3-ft width. However, on page 45 we learn "The 44 in. stairwells were served by doors on each floor measuring 34 in. (1 m) (sic), while the 56 in. stairwell was served on each floor by a door measuring 44 in." Then, on page 46, we learn, "Each stairwell would be required to have a door at least 0.9 m (36 in.) wide" to comply with the 1968 NYC Building Code. Erroneously, at pages 46 and 47 respectively, the report authors state International Building Code and NFPA 101 and 5000 requirements for "door width" as 0.8 m; both actually refer to a minimum clear width of 813 mm (32 in) for the door opening, not the door width. In the egress modeling portion of the report there are a few references to "door width into and out of the stairwell" but, nowhere in the entire report do we authoritatively learn what were the actual door widths (or clear door opening widths) for entry into or discharge from the

three exit stairs. Should we assume, in absence of such information in the report, that doors into and from the narrower exit stairs (A and C) were nominally 36 in (32-34 in clear opening) and doors into and from the wider stair (B) were nominally 44 in (about 42 in clear opening) or what? And what are we to assume about doors located at transfer corridors of the exit stairwell system? Errors and omissions in the report on this matter of door width and code requirements should be corrected as a matter of high priority.

Information Lacking about Exit Discharge Doors. Frankly, I was looking not only to a thorough and readily located collection of information on the detailed geometry of the key means of egress components but also for a detailed treatment of how they were utilized by evacuees and emergency responders. For example, how did the exit stairwell discharge doors at plaza and concourse levels serve during periods of counterflow? These are matters of direct relevance to the creation of suggested revisions to codes and standards for means of egress as well as to emergency operations procedures for emergency responders and for occupants.

Study Formulation and Funding. Generally, I am even increasingly convinced that the occupant behavior and egress portion of NIST's investigation was badly under funded and inadequately staffed given the importance of the findings and the great extent of "people committing data" to use the colorful yet apt expression first heard from my late peer, John Archea, then with NIST's predecessor organization, NBS, in the 1970s. At a House Science Committee hearing NIST staff asked for a total of $16 million for the investigation before they were (apparently) convinced by a non-NIST testifier (Prof. Glen Corbett) and the Families to include occupant behavior and egress in the scope of the investigation. Reportedly, this topic was initially given a budget of $1 million but eventually got $2 million (according to a personal communication with Shyam Sunder, 12 July 2005 at the NFPA High Rise Building Safety Advisory Committee meeting at NIST). My early estimate (in late 2001) of what was warranted for the occupant behavior and egress studies alone totaled about $10 million. Given what has been seen in NIST's draft final report (as well as in numerous presentations before that), my early estimate made more sense than NIST's initial estimate.

Remoteness of Exit Stairwells

Generally, I detect two large problems with NIST's treatment of this important topic. First, as it apparently did during the investigation/study, NIST plays down the importance of inadequate exit remoteness as a major factor in the large life loss in the WTC towers. Secondly, I see errors in the analysis done of remoteness requirements and with estimates of actual remoteness in the upper floors, in the vicinity of the impact on WTC1.

Remoteness of Exit Stairwells Requirements in NYC Building Code. In 1968, the location of a floor exit was required to be as remote from the others as practicable. Specifically, according to my records, subchapter 6, Means of Egress, of the 1968 NYC Building Code, Section 27-363, had the following requirements (as subsequently amended).

> **Remote location -** When more than one exit is required from a floor of a building, each exit shall be placed as remote from the others as is

practicable. Door openings to scissor stairs shall be*(6) at least fifteen feet distant from each other. In all other buildings, the minimum distance between such doors shall be the greater of thirty feet or one-third the maximum travel distance of the floor, provided, however, that where such distance will result in travel distances exceeding those authorized in section 27-357 additional vertical exits shall be provided.

The history of this requirement is described on page 46 of NIST NCSTAR 1-7).

2.5.3 New York City Building Code (October 2003)

As it pertains to the narrow scope of this egress analysis, the requirements related to the egress system in 2003 would be identical to the requirements of 1968, with one significant exception: stairwell remoteness. In 1968, the location of a floor exit was required to be as remote from the others as practicable. New York City Local Law (LL) 16 (1984) imposed a remoteness requirement (not retroactive to an exiting building such as WTC 1 or WTC 2) of 9 m (30 ft) or one-third the maximum travel distance of the floor (55 m [180 ft]), whichever is greater, which for WTC 1 and WTC 2 was 55 m (180 ft). Thus, all floors of WTC 1 and WTC 2 had stairwell separations that exceeded the minimum separation distance requirement of New York City LL 16 (1984).

Page 44-45 of NIST NCSTAR 1-7 provides NIST's findings on exit remoteness in both towers in relation to model code requirements. Note that, as I have indicated with bold italicized text for the concluding sentence, it was found that the remoteness in WTC would ***not*** comply with model code requirements. Also, as discussed below, the 70-foot (21 m) remoteness reported by NIST would just barely comply with NYC Building Code requirements as set out above. *However, as discussed below, NIST's estimate of WTC exit remoteness appears to be overstated by about 10 feet (3 m) relative to my estimate made from a very detailed, dimensioned plan of the floors 84 and higher.* (See appended plan.)

Thus, by my analysis, there would have been a lack of compliance with NYC code—including LL 16 (1984), and model code requirements. Quoting from page 44-45 of NIST NCSTAR 1-7:

> In addition to local changes in the size of the core space, the stairwells in the WTC towers changed floor location throughout the building, as well. This meant that the remoteness (or the distance the stairwells are located apart from one another) of stairwells varied, as well. The greatest separation distance between any two of the three stairwells, as measured by a walking path measurement (assuming that the building is fully sprinklered, which WTC 1 and WTC 2 were) determines the stairwell remoteness. At the two extremes of remoteness found in WTC 1 or WTC 2, floors 83 and higher had Stairwell A and Stairwell B located about 70 ft (21 m) apart, while on floors 77 – 82, Stairwell A and Stairwell C were located approximately 175 ft – 200 ft (54 m – 63 m) apart (depending upon the walking path on a particular floor). Coincidentally, WTC 1 was

most heavily damaged on floors in the 90s (where the stairwells were the closest together) and all three stairwells were destroyed, while WTC 2 was attacked in a region where the stairwells were the most remote (floors 78 through 82) and one stairwell remained passable. The angle of the airplane impact, the length-wise orientation of the core, and the presence of elevator machinery near the passable stairwell may also have been contributing factors to the stairwell survivability, however. For context, most current codes require that two exits be located a distance apart no less than one-third of the diagonal distance of the area served (if the floor has full sprinkler protection) or no less than one-half of the diagonal distance of the area served (if the floor is not fully covered by sprinkler protection). One-half of the diagonal distance of the area served was 147 ft (45 m) and one third of the diagonal distance was 98 ft (30 m). ***Thus, in separate areas within the same building, stairwell remoteness distances would have been less than that required for sprinklered buildings, as well as greater than that required for unsprinklered buildings.***

Not understood is why there is a discrepancy between the maximum travel distance of 180 feet (55 m) noted on page 46 of the NIST report and the maximum travel distance stipulated in the NYC code's section 27-360, which references Table 6-1, with a 200-foot maximum (61 m).

As a logical rule on remoteness, tying it to travel distance makes little sense to me, having first investigated the whole issue of remoteness and its regulation (35 years ago while with NRC Canada as a researcher) and dealt with it through a few decades of committee work, especially with the NFPA Means of Egress Committee. Quantitative remoteness criteria are supposed to be large; travel distance is supposed to be small (i.e., limited by a maximum). But, even by the relatively lax, badly drafted rule based on travel distance (of 200 feet), the NYC code would have required at least 67 feet (20 m) between exit entry doors. Using both the floor plan shown in the report NIST NCSTAR 1 (page 9), Figure 1-5, and a much more detailed, dimensioned, core area plan (Drawing A-B-148) I have of similarly configured floors, the impact floors of Tower One provided only about 45 feet (14 m) measured in a straight line, and about 60 feet (18 m) measured along the path of travel in the corridors, between the most distant of the exit entrance doors. A copy of the detailed core-area plan, marked with my distance estimates is appended to these comments.

According to my analysis of WTC plans, the third- and half-diagonal rules in current model building codes in the USA would require the travel distance between exit doors to be a minimum of about 95 feet or 142 feet (29 m or 43 m)—based on a 284-foot (87 m) diagonal dimension, depending on whether the sprinkler-based relaxation of the rule applies. (The minor differences between my analysis and that by NIST does not affect the conclusion that the WTC would not comply with the diagonal-based rules.) Notably, when initially constructed, the WTC towers were not sprinklered and, on 9/11, sprinklers were not operational.

Thus by all measures, there was not reasonable redundancy—provided to exit remoteness—on critical floors of the WTC and many people above impact areas were trapped. However, this reader of the NIST reports—and frequent attendee at NIST staff presentations—gets the impression that NIST is trying to play down this design defect, including by giving mixed messages about compliance with codes.

Below I reproduce, as my Figure 1, a modified version of NIST's Figure 1-5 which is a simplified version of the plans I had available of comparable floors (with one example appended to these comments).

Figure 1. Floor plan of WTC 1, floor 96. with superimposed circles connecting and enclosing the three exit stairwells, designated as A, B and C. (Derived from Figure 1-5 from NIST NCSTAR 1)

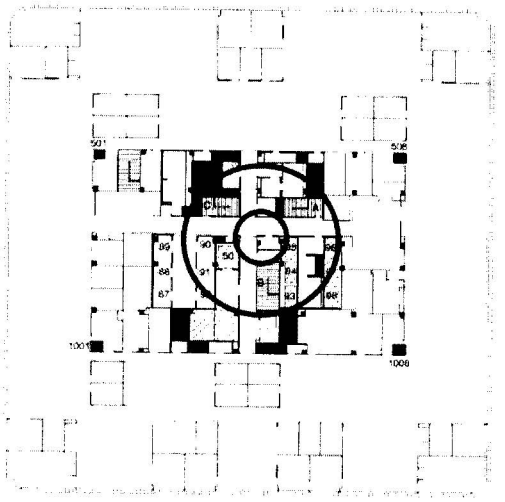


Figure 1 shows the floor plan for WTC1, 96th floor which had a fourth stair (in the upper left corner of the core), a convenience stair between three local floors and not serving as an exit. One of the problems in the World Trade Center towers was the close proximity of all three of the exit stairs on almost all floors and especially on the impact floors for WTC 1, including the 96th floor illustrated in Figure 1. On these floors the direct-line distance separating exit enclosures was, *at best*, only about 21 feet (6 m). Indeed if a triangle were drawn connecting the three exit enclosures, it would have an area of only about 180 sq ft. (17 sq m). This would be relative to an overall (interior) floor plan dimension of about 206 feet (63 m) per side (about 284 feet or 87 m in diagonal dimension) and an area of about 42,000 sq ft (3,940 sq m) according to my estimates.

Superimposed on the plan in Figure 1 are two circles. The smaller circle, touching the closest walls of the three exit stairwells (A, B, and C), has a diameter of about 21 feet (6 m) and an area of 360 sq feet (33 sq m); the larger circle encompasses all three stairwells and has a diameter of about 66 feet (20 m) and an area of about 3,400 sq ft (316 sq m). In other words, an event impacting as little as a 360 sq ft (33 sq m) circular area could damage a portion of the shaft walls of all three exit stairwells while an event destroying

as little as a 3,400 sq ft (316 sq m) circular area could eliminate all three exit stairwells—essentially what happened on 9/11. Relative to the overall floor area, these circular areas are respectively only about 1 percent and 8 percent of the floor area. Note that the core area, within the major interior columns, measured about 86 feet by 137 feet (26 m by 42 m), making an area of about 11,800 sq ft. (1,100 sq m) or about 26 percent of the floor area overall. Thus an event devastating as little as one-third of the core area could (and did) destroy all three exit stairwells.

Surely it cannot be reasonably argued that the exits, especially on upper floors such as floor 96, were as far apart as was practicable nor that reasonable redundancy was provided. Moreover, contributing to my professional opinion that NIST is unreasonably de-emphasizing the role of exit remoteness, is its flawed assessment of the degree with which the WTC towers complied with the NYC building code at the time of its design. Specifically, as discussed above in relation to my Figure 1, the three exits in the impact zone of WTC1 complied with neither the spirit nor the letter of the NYC building code of 1968. Yet NIST NCSTAR 1, on page 58, asserts the following.

> The 1968 NYC Building Code contained a requirement that the stairwells be "as far apart as practicable." Since the stairwells on the impact floors of WTC 1 were substantially closer together than those on the impact floors of WTC 2, it certainly was possible to have designed a greater separation in WTC 1. Local Law 16 (1984) added a quantitative requirement that the separation between exit door openings be at least one-third of the maximum travel distance of the floor. For the WTC towers, this maximum distance was 180 ft, and the smallest separation of stairwell doors was 70 ft. The towers were consistent with this requirement.

Again, my reading of the NYC building code is that the maximum travel distance was 200 feet (61 m), not 180 feet (55 m). Furthermore, my estimate of the *largest* (not the "smallest") travel distance between exit entry doors was only about 60 feet (18 m)—measured per NFPA 101 requirements. Thus, by my assessment, the towers were ***not*** consistent with the NYC requirements in either letter or spirit.

Evidence of Benefit of Increased Remoteness of Exit Stairwells. It is well documented that, due to an unusual, more-remote positioning of exit stairwell A in WTC 2—in the vicinity of its impact zone, several people were able to descend through the impact zone shortly after impact (e.g., see page 156 of NIST NCSTAR 1).

> Eighteen people in or above the impact zone when the plane struck are known to have found the one passable stairway and escaped. It is not known how many others from the impact floors or above found their way to the passable stairway and did not make it out or how many could have been saved had the building not collapsed. A delayed or avoided collapse could have provided the additional time for more people to learn about and use the passable stairway.

There is a possibility that, later, exit stairwell A was once again usable because

evacuees were reported coming down—*below the impact zone of WTC 1*—just prior to collapse.

> Stairwell A in WTC 2 remained passable for at least some period of time after the aircraft impact because (1) only the end of the left wing, empty of jet fuel, was in line with the stairwell; (2) Stairwell A was behind the structural/architectural core in the area of impact; and (3) the aircraft debris had to travel through the longer dimension of the core and thus was slowed by a greater number of columns, shafts, walls, and mechanical equipment, and (4) Stairwell A was widely separated from Stairwells B and C.
>
> Eighteen people successfully used the debris-cluttered Stairwell A in WTC 2 to leave the building after being on or above the 78th floor when United Airlines Flight 175 hit the building. It is possible that additional occupants from above the impact floors were making their way down the stairwell some minutes before building collapse.

Page 188 refers to situation awareness about Stairwell A.

> Some occupants did not get information that potentially could have saved their lives, such as notification that Stairwell A was passable from above the impact zone.

Even more detail is provided on page xxxiv of NIST NCSTAR 1-7.

> Minutes prior to the collapse of WTC 2, an NYPD Emergency Services Unit (ESU) officer radioed from a floor in the 20s to the outside that he was having trouble ascending the stairwell due to the large number of occupants descending (Interview 24 NYPD [NIST 2004]). As only seven occupants who started evacuating below the impact region were known not to have survived, among several possibilities, a large group of occupants from above the impact floors may have identified the passable stairwell (Stairwell A) and may have been making their way out of the building as it collapsed.

Thus the largest "what if" question about 9/11 (at least for me) is about the possibility of fewer trapped occupants if the exits had been located for greater redundancy—even if still located in the core column area, let alone outside the core area. During NIST's investigation/study, it certainly appeared to me that the remoteness issue was being given short shrift by NIST staff. The draft final reports seem to confirm that impression and worse.

What the NIST Reports Say and Do Not Say Generally about Exit Remoteness. Looking at NIST NCSTAR 1, specifically the PDF file of the report, remoteness of exit stairs is referred to only five times with the term "remote." The first of these occurs on page 168 in a section titled, "7.3 FACTORS THAT CONTRIBUTED TO ENHANCED LIFE SAFETY." It refers to exit stairwell A in WTC 2. All of the other uses of "remote," in relation to location of exit stairwells, occur in the recommendations section,

specifically on pages 212 and 213, for Recommendation 18 with its wordy, but not very helpful or definitive discussion. A second word search of NIST NCSTAR 1 used the term "separation." This search identified 18 occurrences related to exit remoteness, on pages xiv, 57, 58, 151, 173, 194 and 212.

Balancing (partly) the section titled,"7.3 FACTORS THAT CONTRIBUTED TO ENHANCED LIFE SAFETY" (as described above), was section 8.6, on page 194, "FUTURE FACTORS THAT COULD HAVE IMPROVED LIFE SAFETY." However, nowhere is there any mention in this section of improved remoteness of exits even though it refers to "capabilities that could have increased the survival rate of those in the WTC towers, had they been in place on September 11, 2001." In my professional opinion, greater—*more effective*—remoteness of exits, combined with more-robust construction around the exit stairwells, could have made a major difference with life loss in both towers on 9/11.

Page 173 of NIST NCSTAR 1, while addressing the issue of a fourth exit stairwell possibly being required to serve the top-level assembly occupancy, made the following comment that reinforces the potential value of better distribution of the three provided exit stairwells.

> It is conceivable that such a fourth stairwell, depending on its location and the effects of aircraft impact on its functional integrity, could have remained passable, allowing evacuation by an unknown number of additional occupants from above the floors of impact.

Summing Up. Regarding NIST's treatment of exit remoteness, improvements are recommended to more consistently—and forcefully—describe the benefits of more effective exit remoteness than was provided in the WTC towers. Also, NIST staff should check the accuracy of the 180-foot (55 m) travel distance limit they assert—when my information is that it is 200 feet (61 m). NIST staff should also reconsider their contention that the travel distance between the doors of stairwells A and B was 70 feet (21 m) versus the 60 feet (18 m) I found. Finally, I would hope that NIST would reconsider the weight it gives to the remoteness issue and treats it with the same degree of attention given to some of the structural and collapse mechanism issues. The fact that all three closely-spaced exits were destroyed in WTC 1 and mostly destroyed in WTC 2—and thus trapped many people who might, otherwise, been able to escape—should be dealt with much more seriously in NIST's final report issued after public comment.

The other major topic dealt with in my comments—the criticism of NIST's relative lack of attention to what was happening in those portions of the exit stairwells that were usable—likely cannot be fixed in the final report. An opportunity to deal with an important aspect of tall building evacuation was missed, apparently because the investigation/study team was more intellectually excited about pre-evacuation behavior. The only fix for this, that I can see, is to make survey data available to other researchers who can still glean, from the survey records, a clearer picture of what happened in the exit stairwells and why it differed so substantially from prevailing expectations about evacuation speed and flow for example. In my opinion NIST has a major problem here,

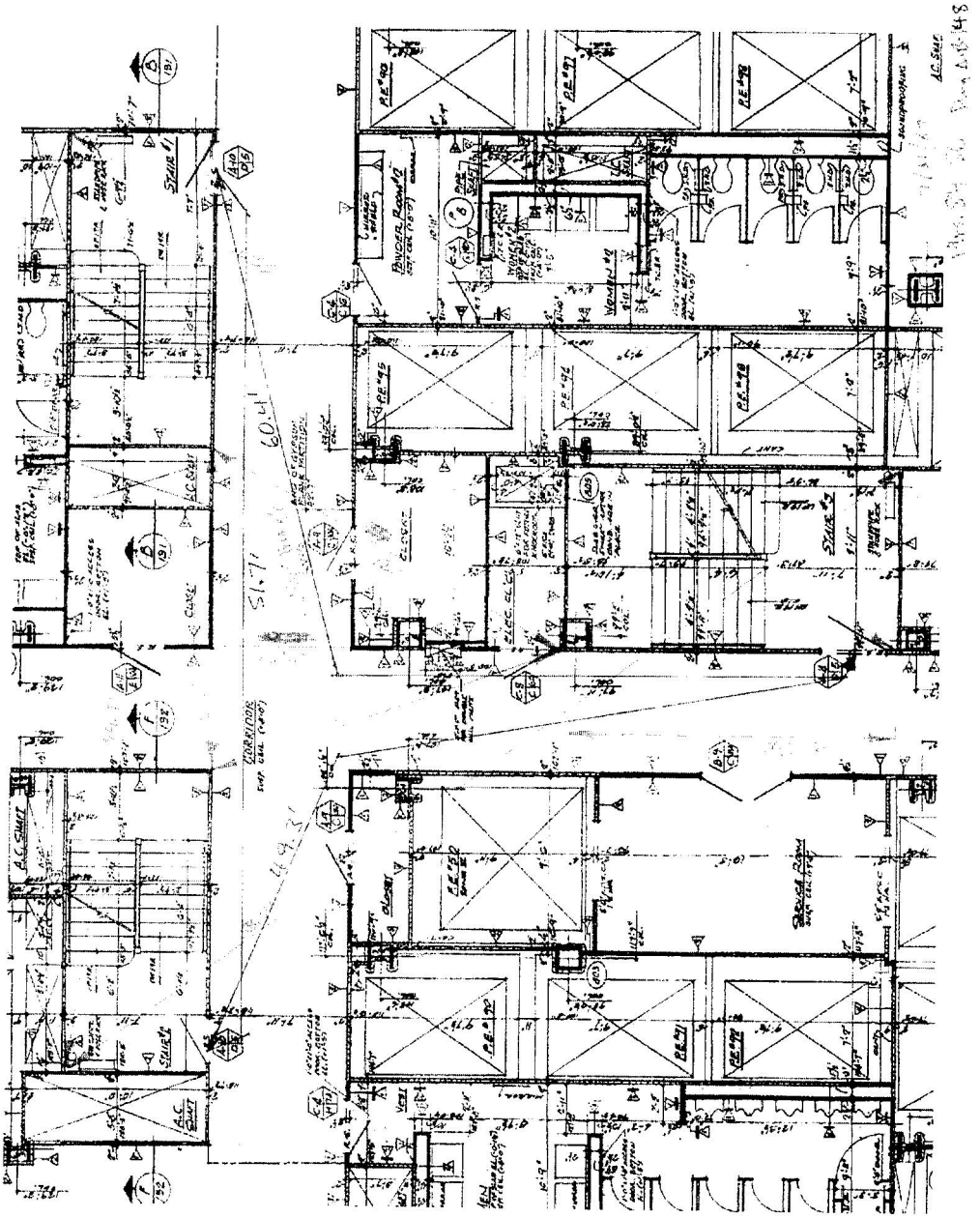
particularly with two predictions that have gotten much media attention. Flawed assumptions about egress performance in the exit stairwells directly affect the prediction that a total evacuation with a full occupancy would have entailed a time of 4 hours. Related to this is the estimate of how many people would have died (the 14,000-fatality figure)—especially due to inadequate exit capacity—had the population been higher. These are based on a highly questionable analysis—based on skimpy data—of what happened in the exit stairwells on 9/11.

Moreover, the six-week public comment period has not permitted thoroughly and critically going through even the small number of reports bearing on human behavior and egress. Had this been possible, I am sure that there would have been many more comments. Among such comments would be a plea to clean up the terminology used to describe people with disabilities. Thankfully, I recognize that a colleague, Edwina Juillet, has communicated with leaders of the NIST WTC study to suggest better, more-standard terminology to replace "mobility challenged" for example. For persons not having permanent physical disabilities, could I suggest (in addition to what Edwina Juillet recommends) that NIST use more-specific terminology such as, perhaps, "fatigue-reduced" egress speed and flow. This could be used with terminology such as "congestion-reduced" egress speed and flow.

Fortunately, my review activity of at least NIST NCSTAR 1 will continue in a number of ways. First, as a member of NFPA's High Rise Building Safety Committee and as a member of several NFPA technical committees and technical correlating committees, much effort will be given to NIST's reports and, especially, the 30 recommendations. Second, as a member of the Professional Advisory Panel of the Skyscraper Safety Campaign, NIST's work will be closely and critically monitored. Third, over coming months, in giving several presentations in the US and Europe based partly on what NIST has learned and how it has treated the findings, there will be significant references to the reports. (Relative to this activity, I hope that NIST permits my presentation at its conference in September.) Fourth, as part of the public discourse in the trade press as well as mass media, I will continue to be open to extensive contact with journalists. Relative to this, as the second appendix to these comments, I am attaching my early reaction to some of the recommendations made by NIST; these were provided to *Engineering News Record* some weeks ago.

Finally, as one involved as a long-time researcher and consultant in the field of human factors in building safety, I was hoping that the WTC study by NIST would help build a set of capabilities, tools and procedures that could be employed—in a future disaster or other emergency event—much more expeditiously than occurred with the WTC disaster. With the limited staff, time and financial resources apparently available at NIST, this appears to have not happened. For one thing, something needs to be done to reduce—if not eliminate—the delay due to IRB approval of surveys of people directly impacted by an emergency. This will be further taken up with the NCSTAC, I hope.

APPENDIX 1. PLAN OF WTC FLOORS 84-86 (DESIGN DWG. A-B-148) SHOWING REMOTENESS ANALYSIS BY JAKE PAULS



APPENDIX 2. COMMENTS SUBMITTED BY J. PAULS TO *ENGINEERING NEWS RECORD* ON NIST WTC REPORT RECOMMENDATIONS

Rec. 4. NIST is correct in noting that time needed for total evacuation should be taken into account when determining appropriate construction of tall buildings. See also Recommendation 17.

Rec. 15. Black boxes have been a standard feature of passenger aircraft for a long time and have been extremely valuable when a mishap occurs to determine exactly what happened. Very large buildings expose many times more people to potential danger yet few have the means to record, reliably, for subsequent analysis, what happened in an emergency. In making Recommendation 15, I would have been more specific than NIST was; I recommend that all exit stairs be equipped with video cameras capturing egress movement and ingress (by emergency responders for example) on the discharge flight of the stairs. Real-time data are needed on exactly how many people evacuate via each stair, what counterflow they encounter and how this occurs over an accurately recorded time scale. As well as being valuable for real-time situation awareness of emergency responders and building management, the video information should be preserved, by means of the building's black box, for post-incident analysis.

Rec. 17. Two very important recommendations are made here. First, even very tall buildings should be designed to facilitate total evacuation, even if such evacuations will take a substantial time that has to be reconciled with hazards occupants will face. As a last resort, total evacuation cannot be ignored. It happens more often than many in the building industry want to admit and, for any one building, there is a high probability of a total evacuation occurring at least once in a tall building's life. Recall that the World Trade Center had at least three in its relatively short life.

Second, my 38 years of research and other work on evacuation of large buildings, especially by stairs, has underlined serious errors in the technology assumed for building regulation and the resulting design and construction of large buildings. After being critical of NIST and NBS (the old organization name) for some three decades, it is heartening to see that NIST finally recognizes the need for exit stair design to be based on what actually happens in 44-inch wide stairs traditionally assumed to facilitate two-abreast crowd flow but actually too narrow, by 12 inches or more, to facilitate such flow. Emergency responder counterflow, especially with firefighters laden with bulky clothing and other gear, also requires that stairs be much wider. Here it might be appropriate to ask the few organizations in the building industry (e.g. BOMA and GSA) who oppose making exit stairs of tall buildings, even relatively heavily populated tall buildings, wider by 12 inches (as being done in NFPA 101 and NFPA 5000 currently), are they planning to participate in the international conference in Vienna this September, on Pedestrian and Evacuation Dynamics, where a scientific paper on the topic of appropriate minimum stair width is being presented? (The conference is PED2005, www.ped2005.com.)

Rec. 18. I believe that the remoteness of the three exit stairs in the WTC towers did not meet the letter or the spirit of the 1968 NYC building code. Generally, remoteness of the

WTC exits could have been a factor in the large life loss, especially in the south tower where one stair was available for a time after impact and could have been available longer—permitting more people above the impact area to evacuate. In this regard, I believe NIST is incorrect in asserting that nothing in the design would have changed the outcome. Perhaps related to NIST not sufficiently recognizing the importance of exit remoteness in its draft final report is its failure to even address the topic until I kept pointing out its relevance during the study period. As one of the earliest topics I addressed in my research on large building safety during the late 1960s and early 1970s, exit remoteness and appropriate travel distance should be more scientifically addressed instead of utilizing the relatively crude criteria currently in the codes and standards.

Rec. 20. Within the recommendations chapter, NIST does not adequately address the current significant progress being made in relation to standards and codes addressing elevator use for both fire services and occupant evacuation. In all of my 38 years in the building use and safety field, the change in thinking observed in the last year and a half on use of elevators is a true paradigm shift. A smaller development is occurring with certain evacuation devices, specifically "stair descent devices"—not "stairwell navigation devices" as confusingly described by NIST—which are being addressed with substantial guidance information in the editions of NFPA 101 and NFPA 5000 being approved this summer.

Generally, underlying many of the recommendations is an implicit set of assumptions about risk and risk acceptance plus management. Risks of dying due to a fire in a single-family home cannot be used as a basis for assessing the acceptable risk of dying in a tall building. The research literature on risk has dealt with the influence of the degree of control an individual perceives relative to a risk. Thus safety in tall buildings is more like safety of commercial air travel than it is, for example, like safety of private automobile use or home safety. The risks for tall buildings have to be very low—and they are not as low as some reports like to make out. Consider, for example, the six deaths in the Cook County Administration building in Chicago in 2003. There is an inadequate appreciation of how public perception, and acceptance, of tall building safety risk changed over recent years. One indication of these changes is the extra attention -- going well beyond minimum code requirements—in some iconic tall buildings recently, including the replacement Building 7 at Ground Zero. Getting tenants into such buildings is another, albeit mixed indicator. This topic cries out for longitudinal research.