# PERFORMANCE CODES FROM FIRE SAFETY RESEARCH

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## 1. INTRODUCTION

For those unfamiliar with fire and those made complacent by the environment they are in, fire can produce a surprising rate of growth that can be deadly. In The Station fire, a nightclub in Rhode Island, occurring on the evening of Feb. 20, 2003, overcrowding and the use of fireworks to initiate a rock concert, caused up to over 100 to perish in the ensuing fire. The fire was initiated on foam polyurethane soundproofing that lined the stage backdrop. Some exits were inaccessible. The irony of the event was that a television crew was filming the crowded nightclub to explore the environment of a crowd egress disaster that had led to the deaths of several in the crush of people herded to an exit from a nightclub in Chicago several months before.

Fig. 1 shows the ignition of the soundproofing in this horrific fire event. The question is who or what is responsible. Currently there are criminal and civil actions going forward in the US of The Station fire. Are the owners responsible, or the fire safety inspectors, or the foam manufacturers, or the band, or the fire regulation themselves? No pre-warning was evident from the circumstances, as rock bands commonly use fireworks, and owners or officials did not perceive a problem. Can we expect lay people to recognize fire hazards, or can we expect regulations to screen all hazards? These questions and the associated fire safety deficiencies motivate many to advocate "performance codes" for fire safety.

Some say that the use of sprinklers would have eliminated the hazard in The Station fire and other similar events. Some authoritative sources even claim that the use of sprinklers in buildings should allow the required fire resistance time to be cut in half. I presume this means that if the sprinkler system fails, the fire will respond by burning in only half the time. Of course, I am being facetious. But such practices exist and are strongly advocated by fire safety regulators. Indeed, many see these "trade-offs" as the essence of performance codes. I am not among them, as the early start of the fire in which sprinkler could control the fire growth has nothing to do with the consequences of a fully developed fire in a structure that will only occur if the sprinkler system is non-existent or fails to operate.

This paper will address the current state of codes and standards, the role of education, the proliferation of flammability tests, and the 9/11 event of the WTC collapse as an example of issues in performance codes.


**Fig. 1: Scene from The Station fire at ignition on the stage**

## 2. CURRENT PRACTICE IN CODES AND STANDARDS

National and international standards bodies have an infrastructure that enables the expression of views and information on current and proposed standards. Many of the rules adopted for fire standards are similar from one agency or body to another; however, some are so disparate to make even the most ignorant wonder. Some nations have national codes that bring the government into the process as an objective partner. Yet special interests abound. It can be said that fire safety regulations are a drag on the economy, so they are generally unwanted by those that are affected. Independent standard groups usually claim, at least in the US, that all interested parties can attend meetings leading to standards. These groups meet periodically and travel requires time and expenses. Hence, only those that are affected and can afford to attend play a role. Of course, some independent parties are dedicated to play a role, but they are not entirely without ulterior motives, as they usually consult or are required to attend by their agency.

The group pictured in Fig. 2 is representative of a typical meeting on standards. But that photograph is only a prop, as it depicts a meeting of fire researchers trying to find a common strategy for getting funding. And the funding issue is at the core of the standards process. In my opinion, funding is required to insure that objective technical information is brought to the meeting process. Researchers play a key role here, and without that input, I worry that a change to performance codes can be worst that the system that currently exists. Indeed, the issue to me is not that prescriptive codes are wrong and performance codes are the new way, but that research must provide the technical basis for the regulations and that documentation must be clear to all. The administration of the regulations might best be served by having prescriptive tenets that are based on the results of performance criteria. The administration should be simple; the development is complex, and needs to be recognized as such.

**Fig. 2: A typical meeting indicative of standard development**

Rules are born from catastrophes. But this process has a short lifetime. It is interesting to note that the World Trade Center (WTC) was built at a time when codes in New York City were relaxing requirements for structural protection in fire. The 1961 code revision changed the 1938 requirement of 4 hours to 3 hours for main structures, and recognized the floor system as a subsidiary system requiring only 2 hours of protection from fire. Following 9/11, a major code body in the US, NFPA, proposed changing the requirement of 3 hours back to 4 for all buildings over 40 stories. Actually, the WTC complex was built under the NYNJ Port Authority that has no obligation to following any code except what they deem fit.

Many regulations take on a special mystique. Mythology surrounds their origin, and when one asks about a certain criterion, the answer is usually couched in folklore from a faraway meeting for which the records have been lost. Researchers seeking to rationalize the criterion usually go to bizarre extremes to fathom a meaning. I remember when the issue of fire spread in building corridors was an issue in the development of a new standard, and the flow velocity of 100 ft/min of air in a candidate test method was explored by seeking to measure corridor velocities in random buildings. Needlessly, the connection could not be made. A clear tracking to a scientific analysis is sorely needed.

## 3. EDUCATION IN FIRE ENGINEERING

Today we are endowed with a growing list of educational programs on the undergraduate and graduate level that recognizes fire engineering safety as a special discipline. In my view, this is happening particularly among the developing countries. The established countries already have their safety standard infrastructures, and these established practices do not come in for questioning. But the developing countries are asking how to protect their industry and people, and regulations are not automatically adopted. This is a good situation. It is promoting the technology of fire safety by requiring informed input.

About 20 years ago a notion emerged in Australia in a study by the Warren Center at the University of Sidney on the merits of performance codes for fire safety. That had its significant advocates – architects who wanted flexibility in design, the steel industry that wanted market parity with concrete construction, and scientists who saw the opportunities of predictive methods. Japan, in my opinion, had already an emerging standards process of analysis in fire safety design. Of course, the US codes are predicated on the option that alternatives to the regulation, *if equivalent*, could be acceptable. But equivalency is a slippery concept if the intent of the regulation is not analytically clear.

The Australian exercise in performance codes was adopted by its government, and that attracted attention and examples for others to follow. New Zealand followed suit, and Denmark also. University programs developed in those countries to provide the needed technical input and engineering expertise. For example, the University of Canterbury in New Zealand provides graduate training in fire protection, and the Technical University of Denmark (DTU) launched a distance-learning program for the Master's degree in 1999. Currently, I estimate that there are about 20 programs at the university level that have degrees directed at fire protection engineering. But this probably only translates into about 200 students, at most, being graduated each year. Although this may seem to be a small number, if they are educated in fundamentals and stay in the field, they could have a significant impact on the fire standards of the future.

On the other hand, if one considers the need for fire safety engineers, a rule of thumb might be 1 per million of population in a developed or developing country. This was not arrived at scientifically by data, but empirically from a knowledgeable US source. Alternatively it could be suggested that every industrial operation of 1000 employees should have at least one fire safety specialist, and every fire fighting operation of 500 personnel should have an engineer trained in fire science. These are my senses, and if they were followed, the need for fire safety engineers to be graduated each year in the world should be in the thousands. In the US, the demand is higher than the production rate, and many that have the need do not realize that fire protection engineering even exists. A technologically advanced fire service should demand more engineers.

All indications are that the education of fire engineers and the need is growing. These factors should bear on the advancement and quality of performance codes.

## 4. FLAMMABILITY TESTS

An indicator of the ignorance and activity in fire safety is an appreciation of the quantity of test methods that exist for the measurement of material flammability. Every country has a different national test, and in the US where national tests are not recognized, several primary tests exist. In addition, the product classification, e.g. plastic appliances, automobile passenger compartment materials, pallets, building construction lining materials, etc., all have different tests. Tables 1 and 2 show the diversity of the standards for material flammability by standard test, and by agency. It makes a layperson wonder why there is a need for so many different tests. Hopefully, the practice of performance codes will take us in a new direction. But as this is being written, someone is thinking about a new test. What makes this happen: ego, ignorance, an attempt to simulate reality, or marketing?

Many of these tests are justified by their smallness, e.g. incidental pre-mixed or laminar diffusion flames acting as igniters of small samples; or their intermediateness, e.g. radiant panels encouraging samples of representative use-size to burn; or their largeness, e.g., simulation of nearly the entire product as a representation of reality. Such testing approaches discourage any need for prediction methods and the understanding of the processes. Indeed, they stand in the way of engineering performance analyses, as they produce nothing from which to extrapolate to other scenarios.

Studies have shown that rankings in the order of flammability among these tests for the same array of materials will not give the same rankings among the materials. This means the tests are measuring different attributes of flammability. The meaning of “flammability” needs definition. Recently, in our work, we have focused on the measurement of the primary flammability processes as a function of applied radiant heat flux. The processes are listed below, and their associated properties are displayed.

**Table 1: Some flammability test standards**

| | | | |
|---|---|---|---|
| ASTM C 1166 | ASTM E 1590 | CFR 163 | NFPA 702 |
| ASTM D 568 | ASTM F 501 | CPAI 75 | NFPA 1971 |
| ASTM D 635 | ASTM F 814 | CPAI 84 | NFPA 1975 |
| ASTM D 1230 | ASTM F 1506 | CS 191-53 | SBCC 9-88 |
| ASTM D 1692 | BFD IX-1 | CS 192-53 | FTM 5903 |
| ASTM D 1929 | BFD IX-10 | FAR Part 25 | FTM 5906 |
| ASTM D 2863 | BFD IX-11 | FF 1&2 | UBC 31-1 |
| ASTM D 3675 | CA TB 106 | FF 3&5 | UBC 42-1 |
| ASTM D 4108 | CA TB 116 | FF 4 | UBC 42-2 |
| ASTM D 4151 | CA TB 117 | FMVSS 302 | UBC 8-2 |
| ASTM D 4372 | CA TB 121 | MSHA 7.27 | UBC 55-1 |
| ASTM D 5238 | CA TB 129 | NFPA 102 | UFAC |
| ASTM E 84 | CA TB 133 | NFPA 253 | UL 94 |
| ASTM E 136 | CA Title 19 | NFPA 255 | UL 214 |
| ASTM E 162 | CFR 1500.44 | NFPA 258 | |
| <u>In addition:</u> | British Stds | Canadian Stds | IMO & ISO |

**Table 2: Agencies producing specialized flammability test methods**

| |
|---|
| Airbus Industries |
| (ANSI) American National Standards Institute |
| (ASTM) American Society for Testing and Materials |
| (BIFMA) Business & Institutional Furniture Manufacturers Assoc. |
| Boeing Company |
| (BFD) Boston Fire Department |
| (BS) British Standards Institute |
| California Fire Marshal |
| Calif. Bureau of Home Furnishings & Thermal Insulation |
| (CG) Coast Guard |
| (CPSC) Consumer Product Safety Commission |
| (DOD) Department of Defense |
| (FAA) Federal Aviation Administration |
| (IFAI) Industrial Fabrics Association Int'l |
| (IMO) International Maritime Organization |
| (ISO) International Standards Organization |
| (NFPA) National Fire Protection Association |
| Port Authority of New York and New Jersey |
| (UFAC) Upholstered Furniture Action Council |
| (UMTA) Urban Mass Transportation Administration |
| (MSHA) Mine Safety Health |

Processes:

1 Ignition
2 Burning rate per unit area
3 Energy release rate (firepower)
4 Flame spread

Properties:

1 Heat of combustion, $\Delta h_c$
2 Heat of gasification, $L$ *(heat needed per mass loss)*
3 Thermal inertia, $k\rho c$
4 Ignition (pilot) temperature, $T_{ig}$

The flammability processes can be modeled in terms of the following equations.

1. The time to ignition can be expressed in terms of the ignition temperature and thermal properties:

$$t_{ig} = \begin{cases} \dfrac{\rho c \delta (T_{ig} - T_\infty)}{\dot{q}_e''}, \text{ Thin} \\ \text{or} \\ \dfrac{\pi}{4} k\rho c \left( \dfrac{T_{ig} - T_\infty}{\dot{q}_e''} \right)^2, \text{ Thick.} \end{cases} \quad (1)$$

{$((\pi/4)k\rho c)^{1/2}$ $(T_{ig} - T_\infty)$ is defined as the Thermal Response Parameter, TRP, by Tewarson.}

2. The critical heat flux for ignition can be related to the ignition temperature, (and the ignition temperature, piloted, is in principle the flashpoint corresponding to the lower flammable limit of the fuel. So this is a fuel property.

3. The energy release rate per unit area can be shown to be related to the fuel's heat of combustion and heat of gasification as:

$$\dot{Q}'' \sim \text{HRP, where HRP} = \frac{\Delta h_c}{L} \quad (2)$$

4. Flame spread can be related to the ignition time and the flame heat flux. For wind-aided or upward flame spread, the distance heated ($z_{p,o}$) by the flame depends on the flame length and consequently, the energy release rate. Hence, for upward spread, speed depends on variables as:

$$v \sim \frac{\left(\dot{Q}''\right)^n Z_{p,o}^n}{t_{ig}} \sim \frac{\left(\dfrac{\Delta h_c}{L}\right)^n \left(z_{p,o}\right)^n}{(TRP)^2} \quad (3)$$

The dependence on the flame heated length effect may explain some the anomalies of small flame ignition tests.

The theoretical equations listed here are generally accepted and serve to correlate much material data in fire research. Researchers can argue about their completeness or accuracy, but the overall principles are sound. Hence, they serve to justify the limited set of property data that are needed to characterize material flammability. The number of these properties is far fewer than the number of flammability test methods. Hence, we have a disparity and are being very inefficient in our testing. Lessons from research are needed to break the traditional hold of the multitude of flammability tests. There is a challenge here.

## 5. COLLAPSE OF THE WTC TOWERS – A CASE STUDY

We all know what caused the events at the World Trade Center in New York City on September 11, 2001. The significant issue for fire safety is "what caused the towers to fall". Now there is an on-going investigation by the National Institute of Technology (NIST) at more than a cost of $16 million to determine the answer to this question and more. That investigation should issue a report of its findings early in 2005. They have made much information available at http://wtc.nist.gov/. If we are to fully reveal the lessons learned for fire safety from such an event, we need to have a rapid, objective, and capable investigative team. NIST now has that authority from the federal government, but it took 9/11 to establish it. Moreover, it took one year after the event to initiate. A discussion of some history will present issues important to this event, and its significance in the realm of performance-based codes.

When 9/11 occurred two federal agencies had the authority to investigate: (1) the National Transportation Safety Board (NTSB) for airline crashes, and (2) the Bureau of Alcohol, Tobacco and Firearms (ATF) for interstate arson. Both were excluded as the Federal Bureau of Investigations (FBI) had the authority for terrorism. So no federal team controlled the site with the purpose of establishing the role of the aircrafts, fire, and structure. The American Society of Civil Engineers (ASCE) stepped forward with a voluntary team, but was excluded from the site for weeks. Later the Federal Emergency Management Agency (FEMA) commissioned the ASCE to conduct a "building performance study". This led to an informative report in early 2002, but not clear conclusions or analyses. Amidst the clamor calling for an investigation, and the halting (to no avail) the removal and selling of the structural steel, was the Skyscraper Safety Campaign (SSC), http://skyscrapersafety.org. This was a group of two women that lost family in the collapse of the WTC, who wanted answers. Their vocal and persistent action among the 9/11 families produced the Congressional funding for NIST. While some few pieces of steel were left for NIST, it is a loss to say that nearly all of the steel (which was embossed with numbers signifying its location in the buildings) was sold. Metallurgical analyses of its thermal changes could have revealed valuable temperature information concerning the significance of the fire's heating.

Currently NIST has offered the theory that the towers fell due to damage of the core by the aircraft impacts and subsequent heating by the fire. Alternatively, without this core damage, the towers could have been vulnerable to fire due to insufficient insulation on 'bar-joist" floor truss assembly. This latter theory is not accepted by NIST. Nevertheless, let us examine it to assess a performance-based process. Of course, a performance-based process was not used in selecting the insulation and rating requirement for the floor assemblies in the WTC, but it is useful to examine what we know about that design process.

In the 1960's when the WTC was being built, NYC was changing its building code from 1938. The criterion for primary structural members was changed from 4 hours to 3 hours, and floor assemblies from 3 to 2 hours for fire duration. The New York New Jersey Port Authority (NYNJPA), under which the WTC was being built, decided to adopt this new NYC proposed code change. However, no fire endurance test was actually performed on the WTC towers' floor assembly. The saga of the insulation requirement for both towers is a sequence of decisions and records that have not been fully explained. If this process is typical of tall buildings, fire safety is being remiss. Table 3 portrays this evolution of the insulation thickness for the North and South towers. It is dramatic that the South tower was hit where the insulation was 0.5 to 0.75 inches (12 to 18 mm), and the North was hit having an upgrade to 1.5 inches (37 mm), but as much as 2.5 to 4 inches (62 to 100 mm) could have been applied according to NYNJPA audit. The latter gives an incredibly large radius to a 1-inch (25 mm) diameter steel web element of the floor assembly. The rationale for the specified thicknesses appears to have been referral to UL listings of similar floor assemblies. However, the original ½ inch thickness appears to have been based on an inappropriate I-beam floor system. Testimony or records documenting these decisions is lacking. The upgrade to 1.5 inches was based on a reassessment of the thickness in 1995. The higher thickness level applied is credible to some extent as contractors would tend to err on the side of adding more, but nearly 2 to 3 times more on a cylindrical element is difficult to comprehend.

Hopefully, the NIST final report will have better explanations of this design process.

NIST conducted standard furnace tests of the full-scale short span of the floor assembly at 35 feet, and also a scaled version (made shorter in height) at 17 feet. The results of those tests and their rating according to current practice and the ASTM E 119 version of 1961, are given in Table 4, taken from NIST.

The NIST furnace test results reveal several issues. (1) The tests conducted at ¾-inch insulation should yield the same steel temperature rise for the standard time-temperature furnace-heating curve. The three tests conducted give variations in the time to achieve the average temperature of 1100 $^{o}$F (593$^{o}$C) of 66, 76 and 86 minutes. Since this temperature criterion is commonly used to establish the rating, its variation is alarming. The ½-inch test gave 66 minutes. The actual rating formula, which is not so straight-forward to describe, gave variations as well with differences between the early 1961 version and the 2000 version of ASTM E 119. Only the unrestrained 35 foot span test achieved the required rating of 2 hours for E 119-00. (2) Single truss web elements representative of the WTC assembly were tested in a furnace at a constant gas temperature of 800$^{o}$C and are shown in Fig. 3. These were done by this author in cooperation with the Isolatek International, the supplier of the original WTC insulation. The single element results are compared to the NIST assembly tests, and the WTC actual failure times, also in Fig. 3, for a range of probable insulation thicknesses. One single element was tested in the same small furnace at the temperature conditions of ASTM E 119, and it shows a shorter time to reach 593ºC than its counterpart tested in the constant 800ºC furnace. However, this is in contrast to the opposite trend of the NIST/UL data for the full truss assemblies. This could be due to the placement of the thermocouples to develop the average temperature in the UL tests. These inconsistencies in temperature need to be reconciled. (3) The actual failure time for WTC 2 (South tower) corresponds to times to achieve 593$^{o}$C for the single element results over the range of likely insulation thicknesses applied. For the North tower, an applied specified thickness of 37 mm would correspond to the actual failure time as well, but higher thicknesses would give much longer times, especially if 62 mm were actually applied over the specified amount of 38 mm. It is remarkable that a constant fire temperature of 800ºC, indicative of typical fully developed compartment fires, results in single web element "critical" steel temperatures at times similar to catastrophic failure of the WTC-towers. (4) It is noteworthy, that a NIST computation of a loaded truss at temperatures of 593 $^{o}$C would lead to severe deformation and failure of the end connections. Yet the NIST analyses attribute the air-crash induced loss of insulation from the core columns as the primary cause of the WTC failures.

Such analyses for the fire heating of structural members are needed for performance-based criterion. Would such analyses have revealed a weakness in the prescribed design insulation thickness in this case, and would such a result have been accepted as a code compliant alternative?

The uncertainties in the establishment of an insulation requirement for the critical lightweight floor assemblies of the WTC should be reason to pause on the practices of fire safety in high-rise buildings. We can follow the rules, such as ASTM E-119, but the standard test seems to have unexplained variations in the careful NIST tests for the WTC truss assemblies. We can use engineering analysis of heat transfer and structural evaluation that may highlight critical issues, but we also need to have certainty of the actions during construction, e.g., on the insulations thicknesses applied. The WTC collapse should be reviewed in more detail to learn lessons from its cause. Getting the mechanism of the cause right is very important for fire safety.

**Table 3: WTC truss insulation saga**

| | |
|---|---|
| 1966 | Specified thickness was 0.5 in., but as applied was 0.6 +/- 0.3 inches. Likely based on least cost, and UL 86-3 with a rating of 3 hours. |
| 1995 | Upgraded truss insulation was 1.5 inches (based on UL G805), but was later measured in application as 1.7 +/- 0.4 inches based on photographic analysis. |
| 2001 | A model code recommended 2 inches for 2 hours in an assessment of a similar truss. |
| 2001 | PA Consultant report recommended in that the upgraded insulation could be dropped to 0.5 inches based on an ambient value of the conductivity used in a calculation, but settled on a recommendation of 1.3 inches. |
| 2003 | PA audit documents indicate fire floors of WTC 1 had 2.5 +/0.6 inches, with thickness as high as 4 inches. |

**Table 4: UL results of ASTM E 119 for WTC truss spans taken from NIST**

| Test configuration | Time to reach average steel temperature 1100 ºF (593 ºC)<br><br>minutes | E 119-61 rating<br><br>hr | E 119-00 restrained rating<br><br>hr | E 119-00 unrestrained rating<br><br>hr |
|---|---|---|---|---|
| 35 ft. restrained, ¾ in. insulation | 66 | 1.5 | 1.5 | 1 |
| 35 ft. unrestrained, ¾ in. insulation | 76 | 2 | -- | 2 |
| 17 ft. restrained, ¾ in. insulation | 86 | 2 | 2 | 1 |
| 17 ft. restrained, $^1/_2$ in. insulation | 66 | 0.75 | 0.75 | 0.75 |

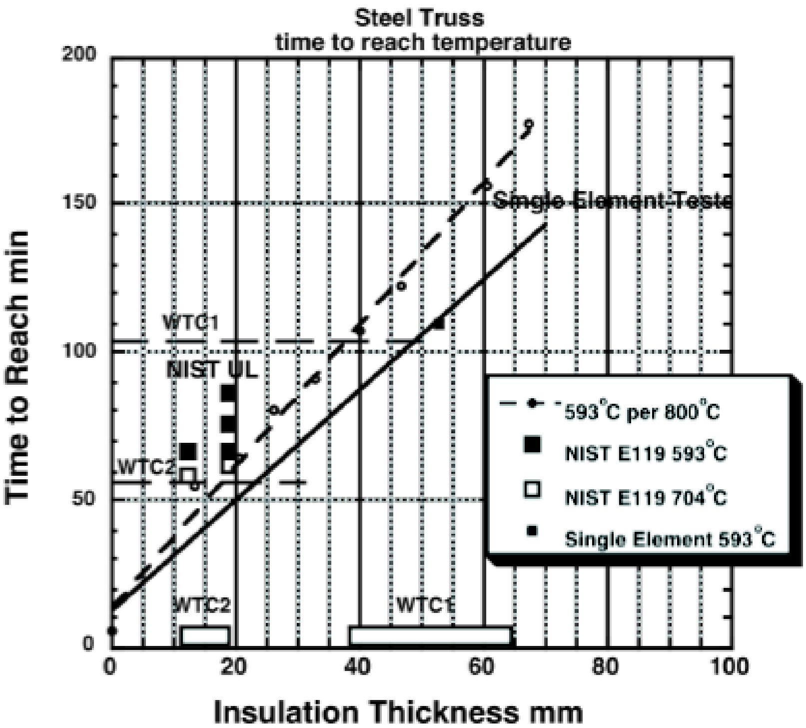


**Fig. 3: Steel heating times for the WTC truss**

## 6. CONCLUDING REMARKS

The adoption of performance codes with sound engineering analysis can produce significant improvement in fire safety. But this has to be managed with care (1) to insure proper methods are used, and (2) to translate the results into practice with clarity. The translation need not, and perhaps should not, be the free-hand use of models. A specified endpoint based on a clearly defined methodology is much more valuable.

The use of flammability tests has been a quick way to measure a material's performance in fire. But the variety and number of different tests are an indication of our ignorance. We have learned a lot about fire growth, and that knowledge suggests that a limited numbers of measurable flammability parameters can and should be rendered.

The collapse of the WTC towers should yield significant, and hopefully, clear lessons for fire safety. The NIST investigation will have a significant impact here. Hopefully, issues of uncertainty about the cause of the collapse of the Towers will be put to rest.