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THE RATIONAL DEVELOPMENT OF BENCH-SCALE FIRE TESTS FOR FULL-SCALE FIRE PREDICTION

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The Rational Development of Bench-Scale Fire Tests for Full-Scale Fire Prediction

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ABSTRACT

National standards for flammability have, in most countries, been established for many years. Thus, they are based on an understanding of fire physics which may be several decades old. In more recent times, however, significant strides have been made in developing test methods which are based on an improved understanding of building fires. The best-possible estimate of the flammability of building products or contents would be, by definition, a full-scale fire experiment. These are recently being standardized, and will serve an important reference function. Because of cost and practical difficulties, however, it is generally desirable to do the majority of product evaluations by bench-scale tests. In this paper the rational bases for achieving validated bench-scale tests for flammability are examined, and a number of recent examples are cited where such a process has been followed. It is also shown that these test results have a correct relationship to the full-scale phenomena.

BACKGROUND

When trying to describe the flammability, or "reaction-to-fire" of combustible products, the most relevant and fundamental understanding must be obtained from full-scale fires, real or experimental. Experimental fires have, of course, been conducted throughout history. It is striking to note, then, that the actual standardization of methods for conducting full-scale room fire tests is so recent a development. The draft method from the International Organization for Standardization (ISO) dates only to 1986 [1], developed on the basis of a proposal from the American Society for Testing and Materials of 1982 [2] and a comparable one from NORDTEST of 1986 [3]. National flammability standards--based on various small-scale testing devices--meanwhile, go back several decades. The existing ones [e. g., 4] have generally been developed on an ad hoc basis, to exclude some specific materials known to be poor performers, and not on a detailed understanding of fire behavior.

More than ten years ago, Prof. Emmons obtained the results of flammability tests on a number of materials, when tested according to various national flammability standards [5]. Not surprisingly, he found that the relationship between the test results according to the different standards was almost completely random. Östman and Nussbaum [6] have very recently returned to re-examine this issue; the situation is seen to be improved only slightly.

Since the best possible estimate of the flammability of products is, by definition, a full-scale experiment, and since standardized procedures for such testing have now become available, it might seem that the problem has been solved. Because of cost and practical difficulties, however, it remains desirable to do the majority of product evaluations by bench-scale tests.

BETTER UNDERSTANDING OF FIRE PHYSICS ALLOWS A NEW GENERATION OF TESTS

In general, it can be seen that standard bench-scale tests can be used to serve at least three different purposes:

1) prediction of expected full-scale behavior
2) quality control assurance in manufacturing
3) guidance in product development.

Objective #2, tests for quality control (QC), traditionally constituted a very large family of tests. Here the requirements are that the test must be highly sensitive to small variations in the specimen's physical or chemical properties, that it be well-repeatable, and that it be simple and inexpensive to conduct. It is especially important to note that stringent rules of validity are not required for tests to meet this objective. A much looser requirement for validity here is merely that most production-line changes, which can possibly occur in manufacturing and which could affect the flammability of the specimen, should be reflected in a statistically significant deviation in the test's results. Tests for objective #3, guidance in product development, can vary greatly and do not, in principle, need to be standardized at all, since they are to be used only internally within an organization.

Tests conforming to objective #1 are the most difficult to develop. The tests of the 1950's or the 1960's were applied to full-scale fires typically not by any quantitative understanding of the full-scale fire, but by merely asserting that a certain test shall be deemed usable in this context. This, we now realize, is not adequate. Better understanding of the physics has now allowed starting development of an entirely new generation of tests. The rational steps required for these can be seen summarized [7,8]:

(i) Identify the governing physical and chemical principles of the phenomenon to be measured.
(ii) Design a candidate bench-scale test using these principles.
(iii) Identify the range, best to worst, of relevant full-scale product behaviors and assemble specimens having those expected traits.
(iv) Assemble a data base by testing this range of specimens at full-scale, and gather data using instruments appropriately designed to measure the governing physical and chemical phenomena.
(v) Conduct bench-scale tests, varying those features of fire behavior which cannot be assigned known constant values.
(vi) Attempt to correlate the bench-scale results against the full-scale data base not only by ranking but also for quantitative values.
(vii) Select those bench-scale test protocol features which lead to the best correlation with the full-scale data.

NEWER BENCH-SCALE TEST METHODS, BASED ON THE UNDERSTANDING OF FIRE PHYSICS

The understanding of the room fire process has indicated that three major parameters need to be considered, [c.f. 9]:

- ignition
- flame spread
- burning and product generation rates.

Ignition here will be assumed to be from an external source of heat or fire. In some design cases, a unique ignition source will be seen to exist. In many other cases, the substance can be ignited from several different external events. It is important to realize that theories are available to describe ignition only for the case of a uniform heating of a planar face [e. g., 10]. ISO has recently adopted a radiant exposure ignitability test [11]. There is also a new proposed ASTM method, P 190 [12], the "Cone Calorimeter," primarily a heat release rate method, which uses a cone heater similar to the ISO method, producing a highly uniform flux distribution over the specimen surface. Recent work [13] has shown that this method leads to useful, high quality ignition data, although the ultimate goal of complete apparatus-independence of results may never be achieved with a real instrument.

In most fires there is a period where the material gets progressively involved by a gradual spreading of flame. Thus, it is important to be able to characterize this flame spread process. Several standard test methods are available, but the results are given as ratings on arbitrary scales and cannot be analyzed within the current-day fire modeling capabilities. Lacking this, such data cannot be re-interpreted in the context of a new design geometry. Newer tests for flame spread are being developed. An example is the International Maritime Organization (IMO) [14] and also a proposed ISO [15] flame spread test, the behavior of which has been analyzed according to theory [16]. It should be noted, however, that the full incorporation of appropriate flame spread features into room fire models has been the most difficult task, although attempts are being made for walls and for upholstered furniture items. Actual determination of flame spread rates requires an apparatus especially dedicated to this task. In the case of many room fires, however, what is desired is not a detailed measure of the local flame spread rates, but, rather, an overall expression for fire growth which includes the individual flame spread contributions. Such information is, in fact, available as a measurement from the Cone Calorimeter, and is discussed in one of the examples below.

The third combustion behavior which must be considered is the burning rate i.e., the mass loss rate of a specimen when it is fully ignited, after flame spread has already covered its entire face. The units are typically expressed as kg m^{-2} s^{-1}. Product generation rates include a number of related properties which are distinguished by being proportional to the specimen mass loss rate. Heat release rate (kW) can be viewed as the product of the mass loss rate, times the instantaneous effective heat of combustion (kJ/kg), although it is not desirable to measure it in that manner in the laboratory. Sometimes, also, the term burning rate is used to mean heat, instead of mass loss rate. Besides heat, the combustion products generated include various gases of interest for toxicity determinations, and also soot and smoke. For bench-scale testing, the Cone Calorimeter [17], in addition to being a proposed ASTM test method [12], also has been selected by ISO as the apparatus on which they are preparing an ISO rate of heat release standard.

A technique for measuring smoke by the attenuation of a light beam has recently been developed for the Cone Calorimeter [18]. This new technique eliminates the shortcomings of the static box type tests like the NBS Smoke Chamber [19] and the dual chamber according to ISO [20] and allows the preparation of a single test specimen to determine the rate of heat release, ignitability, and smoke obscuration. The smoke measurement technique has also been published as part of the ASTM proposed method [12].

ADVANCES IN FULL-SCALE STUDIES

The new-generation bench-scale tests, such as discussed above, could not be properly validated unless full-scale measurement technology kept apace. Some years earlier, in the late 1970's, the professional consensus was holding that only full-scale fire tests had a real meaningfulness, and that all bench-scale tests lacked plausibility. Thus, room fire experiments were being conducted in the U.S.A. in laboratories such as Underwriters Laboratories and the University of California, Berkeley, with a goal of developing standard full-scale test methods [2]. Similar room fire tests, or so-called Room/Corner Tests, have also been put forth by NORDTEST [3] and by ISO [1]. They all consist of a small room, 2.4 m by 3.6 m, and 2.4 m high with one opening, a doorway. The specimen--which is intended to be a surface lining material--is mounted on the walls and on the ceiling. The ignition source, a gas burner, is placed in a corner and is operated at different output levels according to the three mentioned methods. The fire gases leave the room by the doorway and are collected outside in a hood and a duct system where concentrations and flows of gas species of interest are measured.

Even though some of the necessary theoretical rudiments for developing room fire models were available *circa* 1975 [21], and some more modern test development had started to take place [22], the stage was not yet set for a rational development of newer methods. Until the late 1970's, full-scale room fire experiments could be conducted in a reasonably routine manner, but it was difficult to obtain the single most essential item of information: the rate of heat release. The early room fire tests were usually instrumented with a plethora of thermocouples, some heat flux gages, and one or two points of gas sampling. None of these instrumental measurements could determine the actual heat being liberated by the items undergoing combustion. Lacking this measurement, the room fire models could not be used for engineering problem solving purposes. A major breakthrough occurred in the late 1970's, when the principle of oxygen consumption [23,24] was developed. This principle allows the rate of heat release to be determined indirectly by monitoring oxygen concentrations and flows, and provided the first practical means of obtaining heat release measurements in a room fire. It is, thus, not surprising that once this principle was available, rapid progress in both full-scale and bench-scale test method development started.

Another development which was almost as necessary as a prerequisite was the availability of good quality computer codes which could be used to compute the physics of the room fire numerically. Such computer models are now readily available [*e.g.*, 25-27]; their availability allows the understanding of the different physical and chemical phenomena to be interpreted as a unified whole. It can never be expected that there would be a physical test to represent every conceivable fire situation. Instead, one can strive to design tests which present simple, mathematically well-described heating conditions to geometrically easy-to-analyze specimens. From such tests, measurements can be obtained which represent the materials' fire properties. When design conditions and geometries change, instead of having to re-test with a different test, it becomes only necessary to re-interpret the existent property data by using a computer fire model.

GENERAL PRINCIPLES FOR THE DESIGN OF A PHYSICS-BASED BENCH-SCALE TEST METHOD

Out of the development of some of the newer, physics-based bench-scale test methods can be distilled some general principles, which will make possible more valid and more widely applicable future methods to be constructed:

- planar, thermally thick specimens;
- the testing of composites as composites, instead of testing individual layers;
- simulated fire exposure to consist of a uniform adjustable radiant flux;
- design of tests to give 1-dimensional heat transfer;
- design of apparatus such that specimens do not melt out of holder or retreat from their ignition source;
- the measurement of heat, species, soot and smoke on a per-gram basis;
- use of oxygen consumption for measuring heat release rates;
- the selection of both irradiance conditions and test times to predict full-scale data;
- the focus on predicting volume-integrated full-scale variables (e.g., heat release rate) instead of point variables (e.g., temperature at a given station).

These principles are all based on the main requirement that the results gathered by the method be suitable for analysis within the context of a numerical fire model. A complete theoretical understand is not, of course, in place yet. But it is expected that as additional, rationally-based bench-scale test methods are developed, considerations such as those given above will serve to unify these trends.

Example 1 --
Prediction of upholstered furniture fires with the Cone Calorimeter

One of the earliest examples of a successful application of these principles has been in the area of upholstered furniture. The initial full-scale data were obtained at NBS in the Furniture Calorimeter [28], which was first designed for the express purpose of utilizing the oxygen consumption principle in obtaining the full-scale burning rates of furniture. The prediction of the burning behavior of upholstered furniture is an extremely complex endeavor. It will eventually be accomplishable from first principles; however, current mathematical modeling efforts in this area illustrate the magnitude of the problem [29]. Lacking this complete mathematical formulation, considerable engineering progress can, nonetheless, be made by identifying the essential physics of the problem and then constructing a data-correlation solution. Full-scale tests on upholstered furniture [28] showed that the important specimen variables were the combustible mass of the specimen, the frame type (wood, thermoplastic, charring plastic, or metal) the geometric style, and the performance of the fabric/padding composite.

The first three variables are all determinable only from examining the full-scale article; the fire behavior of the fabric/padding composite, however, is amenable to bench-scale testing. The most important variable to be determined is the full-scale peak rate of heat release, since that is the quantity which most closely describes the actual fire hazard expected from the item.

A predictive procedure has been evolved, which entails determining the frame type and the geometry from the full-scale article, and also determining its combustible mass by weighing. The heat release rate behavior of the crucial fabric/padding composite is then to be determined by bench-scale testing with the Cone Calorimeter. The proper irradiance to be used in the bench-scale test should correspond to an average which is seen by the full-scale specimen during the fire, and which is attributable to adjoining surface elements burning. Experimentally, this would be difficult to determine and has not been attempted. Instead, an empirical approach was taken, whereby bench-scale test series were conducted at different levels of irradiance, and the actual test irradiance to be used was selected on the basis of best fit to full-scale data [30].

For upholstered furniture, the desired full-scale variable to be predicted is the peak rate of heat release. In developing a bench-scale data correlation, however, it must be emphasized that the proper bench-scale quantity is not necessarily the peak value, but may be a time-average. The actual best-fit average was, in fact, for a 180 s bench-scale rate of heat release average [30]. The way to understand this is that, during the peak burning in full scale, not all portions of the specimen's surface are undergoing their peak burning. Some portions are not yet ignited, some are mid-way through burning, while others may be already burned out. Figure 1 shows the over-all success of this study. Even though flame spread plays an important role in this problem, it should be noted that it was not expressly modeled. Good results were, nonetheless, achieved since there is a high degree of intrinsic correlation between flame spread and rate of heat release behavior. An explicit inclusion of flame spread might improve the correlation even more; such work is still continuing.

Example 2 --
Prediction of Room/Corner fires with the Cone Calorimeter

Another area where a completed example is available is the flammability of room wall and ceiling linings. The comparative studies, showing lack of agreement among various test methods intended for the same purpose [5,6], which were cited at the start of this paper, were, in fact, concerned with such linings. Thus, it is encouraging to note that useful methods, based on improved understanding of fire physics are also becoming available in this area. Wickström and Göransson [31] have suggested a method for predicting the heat release rate of Room/Corner Tests, based on data from the Cone Calorimeter. A similar method developed for the same purpose has also been outlined by Magnusson and Sundström [32]. Their method aims to become more general and requires, therefore, more input data. The Wickström-Göransson method is designed to predict the full-scale heat release rate. It is based on the assumption that the actual flame spread rate depends on the ignition time obtained in the bench-scale test only. Further, the heat release rate per unit area in the full scale is assumed to vary with time in the same manner as in the bench scale. Thus, a convenient superposition technique is derived which considers the entire heat release process. Both the ignition time and the heat release rate are measured in bench scale by the Cone Calorimeter. The method has been applied to nine products tested in the Cone Calorimeter [33] and compared against full-scale data from the NORDTEST Room/Corner Test [3,34].

The theory assumes that the heat release rate in the test room, $\dot{Q}$, is obtained by summing the contributions from each part of the burning area. In incremental form, $\dot{Q}$ at the N^{th} time increment is obtained as

$$\dot{Q}^N = \sum_{i=1}^{N} \Delta A^i \ \dot{q}''^{N-i}_{bs}$$

where ΔA^i is the incremental burning area growth at the time increment i, and $\dot{q}''^{N-i}_{bs}$ is the heat release rate per unit after (N-i) time increments, as measured in the Cone Calorimeter. Experimental data suggest that the burning area in full scale can be expressed as a function of $\xi = (t/t_{ig}^{0.6})$, where t is the time, and t_{ig} is the time to ignition in the Cone Calorimeter. A best-fit expression is obtained as

$$A\ (\xi) = \exp\ (\xi/3) - 2$$

From this expression the increments ΔA^i can easily be calculated. Figure 2 shows that the success of this method in predicting full-scale heat release rate histories.

DESPITE LIMITATIONS OF BENCH-SCALE TESTS, THERE IS MUCH TO BE GAINED

The new-generation of bench-scale flammability tests, designed on the basis of knowledge of the physics of room fires, have been demonstrated to be capable of satisfactory predictions of some very complicated real-life fire phenomena. Such predictions have not been successfully made by existing, older national tests, While such applications have not yet been made in very many areas, it is encouraging that in each case where such attempts were made, success has been achieved.

For fire protection as a whole, bench-scale tests will rarely constitute a complete and total replacement for full-scale testing. Because a bench-scale test treats a specimen which is very small compared to the actual construction, it may not represent all the full-scale phenomena which may be occurring during a fire. By itself, this is not a serious limitation, since full-scale testing also does not take into account what might happen under every conceivable full-scale fire scenario! What should be considered is if there are areas which are both crucial to the fire safety evaluation, and which also are ones which cannot be properly studied in bench scale. Such examples so far have been noted primarily in the area of thermostructural failures of non-structural members. For instance, the fire behavior of foam plastic ceiling materials depends crucially on whether the material stays and burns in place, or whether it falls off and burns on the floor [35]. For any practical method of predicting a product's full-scale performance, there may also be additional limitations on the bench-scale technique developed, and, if so, these will need to be clearly stated as part of the method. Despite such occasional limitations, bench-scale fire testing today is, finally, being re-established on a rational basis. Finally, when physics has replaced many of the arbitrary choices in developing the test method, improved ease of international standardization, and the consequent economies to be gained, can be looked forward to.

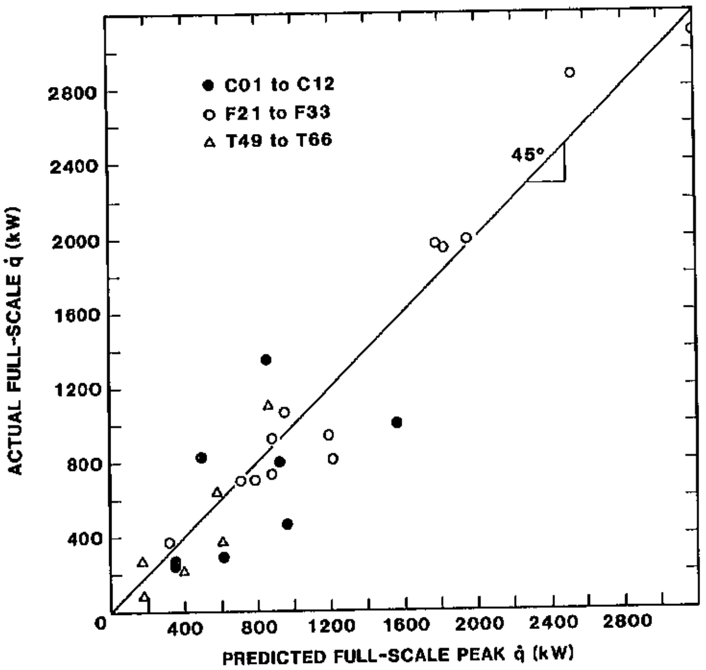

Figure 1. A comparison between the prediction of peak full-scale rate of heat release for upholstered chairs (based on bench-scale Cone Calorimeter measurements) and actual measured peak full-scale values.

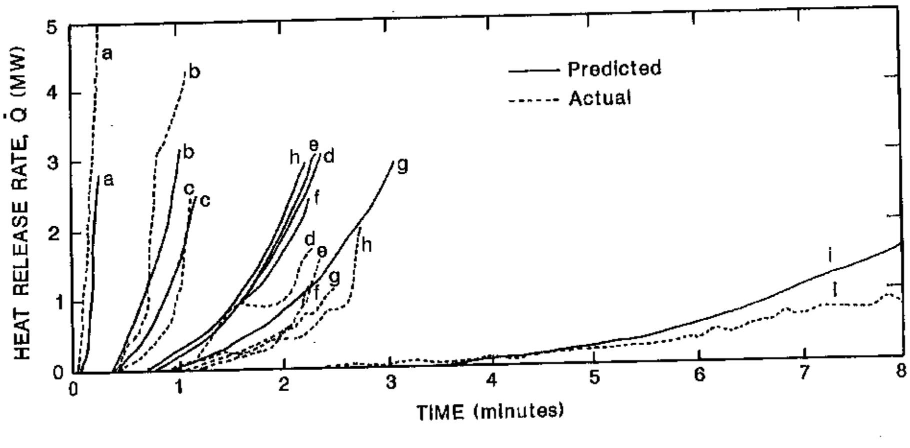

Figure 2. A comparison between predicted heat release rate histories for surface lining materials in Corner Test (based on bench-scale Cone Calorimeter measurements) and actual measured heat release rate histories. The products are a) rigid polyurethane foam, b) textile wall covering on mineral wool, c) insulating fibreboard, d) expanded polystyrene, e) medium-density fibreboard, f) wood panel [spruce], g) paper wall covering on particle board, h) particle board, i) melamine-faced particle board.

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