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Heat Release Rate: The Single Most Important Variable in Fire Hazard*

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ABSTRACT

Heat release rate measurements are sometimes seen by manufacturers and product users as just another piece of data to gather. It is the purpose of this paper to explain why heat release rate is, in fact, the single most important variable in characterizing the 'flammability' of products and their consequent fire hazard. Examples of typical fire histories are given which illustrate that even though fire deaths are primarily caused by toxic gases, the heat release rate is the best predictor of fire hazard. Conversely, the relative toxicity of the combustion gases plays a smaller role. The delays in ignition time, as measured by various Bunsen burner type tests, also have only a minor effect on the development of fire hazard.

INTRODUCTION

The 1988 edition of the compilation of fire tests[1] by the American Society for Testing and Materials (ASTM) alone lists some 77 tests. ASTM is only one of many US and international organizations publishing fire test standards; thus, the actual number of fire tests in use is at least in the hundreds.[2] It is customary to divide the actual fire test standards into two broad categories: (1) reaction-to-fire, or flammability, and (2) fire endurance, or fire resistance.

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Reaction-to-fire is how a material or product responds to heating or to a fire. This includes ignitability, flame spread, heat release, and the production of various—toxic, obscuring, corrosive, etc., products of combustion. Reaction-to-fire largely concerns the emission of undesired things, e.g. how much heat is emitted, how much smoke, or how fast does the first emission start (ignitability). A reaction-to-fire test is typically performed on *combustibles.*

Fire endurance, by contrast, asks the questions: how well does a product prevent the spread of fire beyond the confines of the room? And, how well does it continue to bear load during the fire? Such a test is performed on *barriers to fire* and *load-bearing elements,* such as walls, floors, ceilings, doors, windows and related items.

The scope of the present paper is restricted to reaction-to-fire tests only.

Manufacturers of resins, fire retardants, and plastic products are accustomed to describing reaction-to-fire performance according to two tests: the UL 94 vertical Bunsen burner test[3] and the limiting oxygen index (LOI) test.[4] The LOI test determines under how low an oxygen fraction a test specimen can continue burning in a candle-like configuration. It has never been correlated to any aspect of full-scale fires. The UL 94 test was developed to determine the resistance to ignition of small plastic parts, such as may be found inside electric switches. For this purpose, it is an accurate simulation of a real fire source. A problem arises when UL 94 data are used, as they often are, to imply how large surfaces or objects made of a particular material might perform. For such situations, when the product is larger than the very small objects envisioned by UL 94, we wish to ask what the proper approach is to evaluating the fire performance.

In this paper, we will provide a brief historical overview of bench-scale reaction-to-fire tests and the relation to hazard in fires. We will then turn to the meaning of heat release in a fire. We will show that although bench-scale heat release rate tests were developed quite early, they could not be put to widespread use without the parallel capability for making heat release rate measurements in full-scale room fires, as a basis for validating the bench-scale tests. We will then provide several examples illustrating the development of fire hazard in full-scale room fires and demonstrate that the heat release rate is, in fact, the most essential variable controlling the rate at which untenable conditions occur. Finally, we will illustrate, by example, the process of combining bench-scale testing and computational techniques to predict successfully the full-scale development of fire hazard.

HISTORICAL BACKGROUND

Early reaction to fire tests

Early reaction-to–fire tests were not developed for general fire protection use. Instead, the development of tests was first done for very narrow, specialized product categories. The earliest standard reaction-to-fire test of which we have a record was for the performance of fire-retarded wood. In 1902, the pioneering Columbia University professor Ira H. Woolson started working with the US Navy to develop a standard test for the burning behavior of fire retardant wood.[5] This test (Fig. 1) was called the 'timber test' and was used for a number of years. Later, additional specialized test methods were devised for that purpose[6] in the 1920s.

The next reaction-to-fire test of which we have a record was from 1905. After a series of disastrous theater fires, the famed American engineer John R. Freeman developed a 'stovepipe' test for flammable fabrics.[7] In this test, strips of test cloth were hung inside a 2-ft-high chimney, and lighted by excelsior kindling at the bottom. Since this was not a readily portable test, he also commissioned the development of an

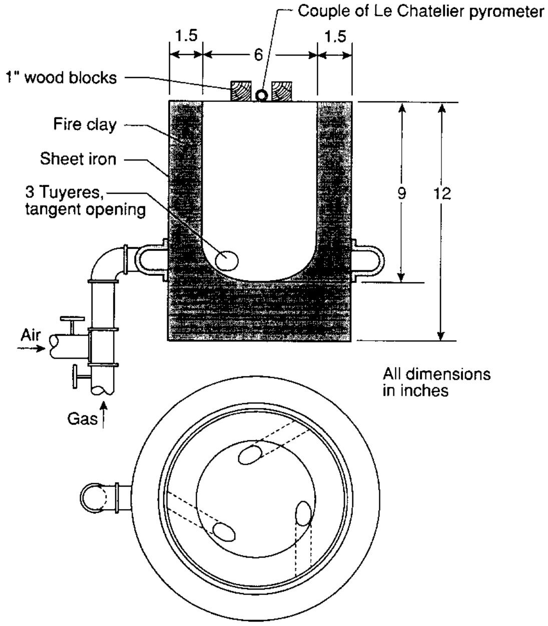

Fig. 1. The first-ever standard reaction-to-fire test method, the 'timber test'.

alcohol-lamp field test. This was known as the Whipple–Fay test, after the names of the two persons hired by Freeman to develop the test. Neither of these became a standard test. The first standard tests for the flammability of textiles arose in England with the alcohol-cup test of the British Standards Institution in 1936,[8] and in the USA with the first version of the current NFPA 701 Bunsen-burner test, proposed by the National Fire Protection Association in 1938.[9]

Flammable fabrics, however, pose a very specialized fire hazard. These can cause injury if they are garments which are ignited on the wearer. In addition, in public spaces, curtains and decorative fabrics can spread fire at a very high speed. Such fires, however, typically burn only a very short time and are not likely to be directly hazardous to those not intimately involved with them. The more serious danger comes from the fact that other combustible materials can be ignited by such textiles. Thus, for materials such as textiles, which are thin and have little combustible mass, the main fire hazard that must be recognized and measured is rapid flame spread. For most other combustibles, the situation, as we shall see, is different.

The need to measure the flammability of additional categories of combustibles was seen during the late 1930s. This resulted in the first Bunsen burner tests for plastics being developed in 1940.[10] In the same period, A. J. Steiner, of Underwriters Laboratories, also developed the Steiner Tunnel Test.[11] This was intended primarily for testing flame spread along cellulosic products, and has since become the main reaction-to-fire test used in US building codes. The method also incorporated a smoke measurement and a 'fuel contributed' measurement, which can be taken to be a crude form of heat release rate. In recent years, this 'fuel contributed' measurement has been deemphasized, and the current ASTM procedure no longer requires that a specific classification be derived from it.[12]

Quantifying hazard in fire

During the 1970s it came to be felt that knowledge about the toxicity of materials was the 'missing link' in understanding fire hazard. Thus, a number of tests were developed and proposed in this area, although none have yet been accepted by US or UK standards organizations or by ISO. Nonetheless, methods for measuring the toxic potency of materials (e.g. the NBS Cup Furnace Method[13]) started being widely used in the 1980s. Yet, the data from them could not be treated in a useful engineering way, since a suitably comprehensive analysis methodology was lacking.

One of the earliest milestones in the search for methods to quantitatively evaluate the fire hazard in buildings was a 2-day workshop on 'Practical Approaches for Smoke Toxicity Hazard Assessment',[14] sponsored by the National Fire Protection Association in February 1984. This workshop convened groups of leading toxicologists, fire protection engineers, fire scientists, fire modelers, and code and fire service representatives to study the problem. Later in 1984, the Toxicity Advisory Committee of NFPA proposed a simple four-step procedure[15] derived from the workshop's efforts. As the project progressed, papers were published which discussed the evolving philosophy and structure of the hazard assessment methodology.[16,17] These papers, and the growing questions regarding combustion product toxicity, stimulated some early hazard analyses using both hand-calculated estimates and some of the available fire models.

In May of 1984, the Toxicity Advisory Committee of the National Fire Protection Association published a procedure for providing 'order of magnitude estimates' of the toxic hazards of smoke for specified situations.[18] In this report, Bukowski based the estimating procedure on a series of algebraic equations, which could be solved on a hand calculator. Individual equations were provided to estimate steady-state values for such parameters as upper layer temperature, smoke density, and toxicity; and graphical solutions were provided for room filling time. This work was followed by the more extensive compilation of such equations for use by the US Navy in assessing fire hazards on ships.[19] Subsequently, the Toxicity Advisory Committee was asked by the National Electrical Code Committee for assistance in addressing a toxicity hazard question regarding polytetrafluoroethylene (PTFE) plenum cables. In providing that help, a hand-calculated analysis was performed.[20] This paper concluded for a single, specified scenario, that the size of room fire needed to cause the decomposition of the cable insulation would itself cause a toxicity hazard in an adjacent space before the cable would become involved.

Several systematized procedures for evaluating the fire hazard in buildings by means of 'hand-crank' computations have been put forth.[21,22] Such computations are simple to perform and can be suitable for estimating. However, the algebraic equations used are limited to steady-state analyses, and cannot deal consistently with the transient aspects of fire behavior. A more complete answer requires a computer to solve the differential equations which describe these transient phenomena. This is the role of computer fire models.

The computer models currently available vary considerably in scope, complexity, and purpose. Simple 'room filling' models such as the

Available Safe Egress Time (ASET) model[23] run quickly on almost any computer, and provide good estimates of a limited number of parameters of interest for a fire in a single compartment. A special purpose model can provide a single function, e.g. COMPF2[24] calculates post-flashover room temperatures. And, very detailed models like the HARVARD V code[25] predict the burning behavior of multiple items in a room, along with the time-dependent conditions therein. In addition to the single-room models mentioned above, there are a smaller number of multi-room models which have been developed. These include the BRI (or Tanaka) transport model[26] which served as a basis for the FAST model included as part of HAZARD I, and the HARVARD VI code[27] a multi-room version of HARVARD V. All of these models are of the zone (or control volume) type. They assume that the buoyancy of the hot gases causes them to stratify into two layers; a hot, smokey upper layer and a cooler lower layer. Experiments have shown this to be a relatively good approximation. While none of these models were written specifically for the purpose of hazard analysis, any of them could be used within the hazard framework to provide required predictions. Their applicability depends upon the problem and the degree of detail needed in the result.

Over the past few years, models began to be used within a hazard analysis framework to address questions of interest. In 1984, Nelson published a 'hazard analysis' of a US Park Service facility which used a combination of models (including ASET) and hand calculations.[28] The calculations were used to determine the impact of various proposed fire protection additions (smoke detectors sprinklers, lighting, and smoke removal) on the number of occupants who could safely exit the building during a specified fire incident.

In 1985, Bukowski conducted a parametric study of the hazard of upholstered furniture using the FAST model.[29] Here, the model was used to explore the impact of changes in the burning properties of furniture items (burning rate, smoke production, heat of combustion, and toxicity) on occupant hazard relative to the random variations of the different houses in which the item might be placed. These latter variables were room dimensions, wall materials, and the effect of closed doors. The conclusion was that reducing the burning rate by a factor of two produced a significantly greater increase in time to hazard than any other variable examined. So much so that the benefit would be seen regardless of any other parameter variation. Results such as this can show a manufacturer where the greatest safety benefit can be achieved for a given investment in redesign of his product.

A more recent example of a hazard analysis application is the elegant work of Emmons on the MGM Grand Hotel fire of 1980. This work, conducted during the litigation of this fire was only recently published.[30] Using the HARVARD V model, Professor Emmons analyzed the relative contributions of the booth seating, ceiling tiles and decorative beams, and the HVAC system, all in the room of origin, on the outcome of the fire. A report issued by the National Academy of Sciences[31] provides two hazard analysis case studies—one making use of the HARVARD V model and the other using experimental data. The cases deal with upholstered furniture and a combustible pipe within a wall, respectively.

It is fairly obvious that one of the first questions a person might wish to ask about the hazard of a building fire is 'How big is the fire?' Thus, it is exceedingly curious, in hindsight, that until fairly recently there was no quantitative way of asking or answering this question. Nowadays, we know that, in quantitative terms, this means, 'Tell me the heat release rate of the fire.' We also know that the heat release rate is measured in kilowatts (kW), or some multiple, e.g. megawatts. We further realize that this is not the same thing as asking what is the flame spread rate of the fire. Thus, neither the E 84 flame spread test nor the Bunsen burner ignitability tests will help us answer this question. It is clear that knowledge of underlying variables related to burning rate is the key to understanding and quantifying the hazard in unwanted fires. Measurement of the heat release rate provides this understanding.

MEASUREMENT OF HEAT RELEASE

Small-scale tests

The fuel-contributed measurement done in E 84 does not qualify as a *measurement* of heat release rate since it is not in the physically correct units of kW. The first apparatus in which heat release rate was measured quantitatively, in correct (albeit, British) units was the FM Construction Materials Calorimeter. It was developed by Thompson and Cousins at the Factory Mutual Research Laboratories in 1959.[32] This was a medium-scale test, with a specimen size of 1·22 by 1·22 m. The method was cumbersome to run and has only been used by the FM system. It is still in use at FM today as part of an approval standard for steel deck roofs.[33]

Progress in heat release rate was still not being made, once the FM test was available, for two reasons: (1) the method was only intended for testing roof decks; and (2) it was a medium-scale test, and there was no room-scale test yet available. If we assume the purpose of a bench-scale test is to reproduce room-scale fire behavior, it becomes clear that little progress in developing bench-scale test methods could be made until heat release rate could be satisfactorily measured in room fires. During the 1970s the small-scale HRR test which came into the widest use was the Ohio State University apparatus (ASTM E 906).[34] This was accompanied by a room fire model[35] which used the bench-scale HRR data to predict large-scale product performance. The OSU HRR apparatus was appealing for its simplicity even though substantial systematic errors accompanied the measurement; thus, it became rather well-known and used in the era prior to when the profession shifted over to using oxygen consumption based methods. The OSU room fire model, however, was based on physics approximations which were not well accepted and, thus, did not play a significant role in hazard quantification.

During the 1970s Parker[36] and Sensenig[37] pioneered the use of oxygen consumption calorimetry as a way of making HRR measurements substantially freer of systematic error. The technique for doing it has been described by Parker[38] and forms the basis for all subsequent HRR measuring apparatuses, both bench-scale and room-scale. As an example, the FMRC Flammability Apparatus[39] was developed using the oxygen consumption technique, but it did not become a standardized HRR test. In fact, during the late 1970s and early 1980s interest in bench-scale HRR testing remained rather small. We now realize that the proper fire hazard assessment role for a bench-scale test is to predict the full-scale fire behavior.[40] However, correlations establishing the successful prediction of the full-scale fire behavior could not be established until adequate capability was available to measure the heat release rate in the full scale.

Having established some of the major historical milestones in this area, we shall examine the current situation in a later section.

Room-scale tests

The first attempt to develop some technique for measuring rate of heat release in full scale was in 1978, by Warren Fitzgerald, at Monsanto Chemical.[41] The Monsanto Calorimeter involved measurements of temperatures at numerous thermocouple locations, from which a heat release rate was computed. This method, because of its uncertain computational premises and its limited measurement capacity, did not obtain acceptance.

The first room-scale test for heat release rate to win widespread acceptance was the 1982 draft ASTM room fire test.[42] This method forms the basis of all current-day room fire tests, which are only different in minor details from the 1982 draft method. Peacock & Babrauskas have reviewed the history of room fire tests in greater detail;[49] again, we will return to the current situation later in this paper.

EXAMPLES OF THE IMPORTANCE OF HEAT RELEASE RATE

To determine what is most important to consider in building fires, we first restrict ourselves to 'typical' building fires. This means we exclude as special those fires which are associated with gas or dust explosions, or where the victims are injured by direct burns from flammable clothing or faulty appliances. Instead, we consider the typical fire where occupant death or injury occurs from an ignition source not in immediate contact with this person, the fire spreads, grows, and then does or does not result in death or injury. Such fires can be broken down into their constituent phenomena:[40,44]

ignition;
flame spread;
heat release rate and, closely related, the mass loss rate;
release rates for smoke, toxic gases, and corrosive products.

The real-scale fire hazard can be assessed by tracking incapacitation or mortality of building occupants during the course of the fire. Increased hazard is identified with earlier incapacitation/mortality or with greater total numbers of victims. We now wish to determine which of the above fire phenomena, and, specifically, which variables, are most strongly associated with increased fire hazard. To examine the relative importance of these phenomena, we will consider two examples.

Example I—A single upholstered chair burning in a room

The first example will be a simple case where we consider variations on a scenario of a single upholstered chair burning in a room with a single doorway opening. The procedures detailed for HAZARD I by Bukowski *et al.*[45] and Peacock & Bukowski[46] were used to calculate the hazard for the scenarios. Fire performance data for the burning chair in the base case were taken directly from the fire properties data base included with HAZARD I. To assess the relative importance of several factors, the following variations were studied:

- base case, single burning chair in room;
- double heat release rate of chair;
- double toxicity of materials;
- halve ignition delay of burning chair from 70 to 35 s.

The general development of these fires is shown in Fig. 2, where the predicted temperatures and CO_2 levels in the upper layer of the room are given. Although other gas species could be chosen as indicators of toxicity, the CO_2 concentration is representative of the type (and shape) of curves for other gases. As expected, changing the heat release rate has a much greater effect than the change in ignition time. (Although we note that improved ignition performance can also, in some cases, *prevent* a fire from occurring. The analysis of product performance which includes both fires that occur and fires that are prevented falls into the category of risk analysis, and is outside the scope of the present paper.) The relative effect of changes in the toxicity can be seen in Table 1, as calculated from the simulations illustrated in Fig. 2.

Comparing the results for the four scenarios, it is apparent from the predicted time to death that changing the heat release rate has by far the greatest effect on the tenability of the space, reducing the time to death from greater than 600 s (the total simulation time) to about the same time as the time to incapacitation for all other scenarios.

In this simple example we have treated the burning product as if its characteristics were completely uncorrelated, that is, that we could, for example, change the ignition delay time without altering at all the heat release rate characteristics. In practice, there is very likely to be some

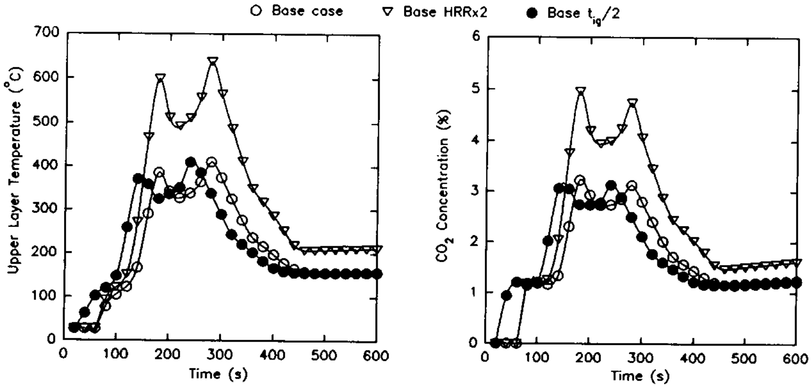

Fig. 2. Results of simulations with HAZARD I: Example I.

TABLE 1
Results for Example 1.

Scenario	*Time to incapacitation (s)*	*Time to death (s)*
Base case	180	>600
Double heat release rate	160	180
Double material toxicity	180	>600
Halve ignition delay	140	>600

degree of correlation amongst various of the reaction-to-fire properties of a product. Thus, it is also of interest, next, to look at the behavior of some actual tested products.

Example II—Multiply furnished rooms

In the previous example, only the burning in a room of a single item is considered. For a more realistic, albeit more complex example, we can turn to the study done by NIST for the Fire Retardant Chemicals Association (FRCA).[47] In the FRCA study, five different categories of products were assembled and tested in full-scale room fires. In one series, all five products were fire retardant, whereas in the other series the same base polymers were used, but without fire retardant agents. The products included upholstered chairs, business machine housings, television housings, electric cable, and electronic circuit board laminates. These products were studied thoroughly in full-scale fires, in bench-scale tests, and by computer modeling. For present purposes, however, we wish to concentrate on one aspect, the identification of the most important physical variable in these tests which is a predictor of the fire hazard.

To do this, we can consider the results in Table 2.

In this test series, the two most important measures of fire hazard were the time to reach untenable conditions (reflecting hazard to nearby occupants), and the total toxicity, expressed as CO-equivalent kilograms (reflecting hazard to far-removed occupants). The differences between the performance of the FR and non-FR product series were striking. (Within each series, the different tests conducted indicate replicates or slight scenario variations.) One might conjecture that the fire hazard performance could be predicted by the yields of CO observed for these two series. Clearly, Table 2 shows that such is not the case. Other variables, such as toxic potencies (LC_{50} values), derived

TABLE 2
Results for Example 2.

Products	*Test no.*	*Fire hazard condition*		*Predictive variable*	
		Total toxicity, expressed as (CO-equiv. kg)	*Time to reach untenable conditions in burn room (s)*	*CO yield (kg/kg)*	*Peak heat release rate (kW)*
non-FR	N1	21	110	0·22	1 590
non-FR	NX0	17	112	0·18	1 540
non-FR	NX1	16	116	0·14	1 790
FR	F1	2·6	∞	0·22	220
FR	FX0	5·5	1 939	0·23	370
FR	FX1	6·1	2 288	0·23	350
FR	FX1a	5·6	1 140	0·23	450

from the individual products tested, although more difficult to evaluate, show the same non-prediction. Likewise, time-to-ignition data for the five products in the two series show ignition time differences ranging from negligible to about two-fold. Thus, ignition behavior is also clearly unable to predict the much superior fire hazard performance exhibited by the FR products. By contrast, the peak heat release rates, shown in the last column, delineate quite clearly the difference between the two series.

The two examples presented above are only several possible illustrations of an infinite number of possible scenarios; a few may exhibit different trends. Nonetheless, these above results are consistent with numerous other studies, such as Ref. 29, and with the detailed understanding of the physics of room fires.[48]

PREDICTION OF REAL-SCALE FIRE HAZARD FROM BENCH-SCALE TESTS

Basically, the same variables—ignition, flame spread, heat release rate, and release rates for other products of combustion—can be measured in real-scale fires and in bench-scale fire tests. The ability to measure these quantities in bench-scale tests has improved enormously since the first efforts of 1959. It has become accepted practice that *all* heat release rate testing—in bench scale, in room scale, and in intermediate scale

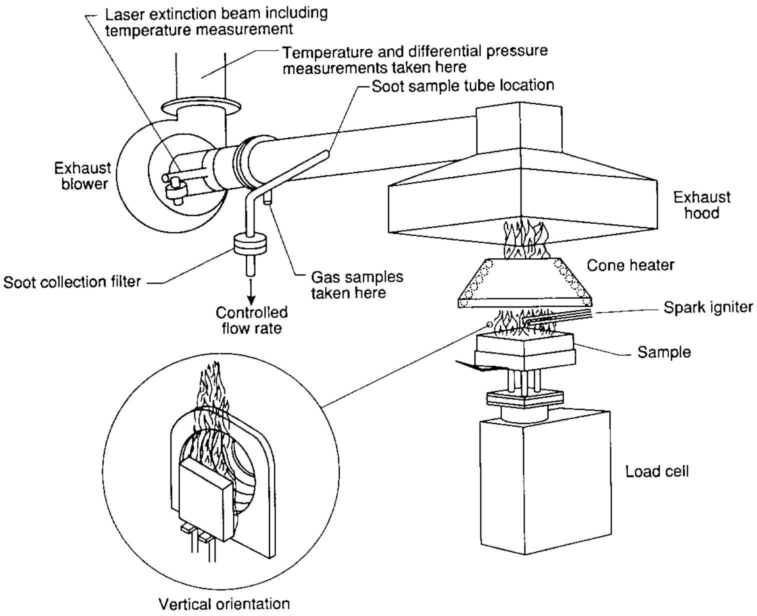

Fig. 3. A schematic view of the cone calorimeter.

(furniture calorimeters)—is done in apparatuses which are based on the oxygen consumption technique. The most widely accepted are the ones standardized by the International Organization for Standardization (ISO). ISO has adopted the Cone Calorimeter as its bench-scale method (ISO DIS 5660) for measuring HRR.[49] The same method has also been issued by ASTM as E 1354.[50] The Cone Calorimeter (Fig. 3) has been designed to measure simultaneously, not just the heat release rate, but also ignitability, smoke production, and the production of a number of toxic gas species.[51] For room-scale testing, the ISO room corner test (ISO DIS 9705) is used.[52] For testing products at an intermediate scale, open-air hood systems, again using the oxygen consumption technique, are employed. ISO has not yet worked on standardizing such 'furniture calorimeter,' but the standard most commonly specified is the one published by NORDTEST.[53] The above, then, comprise the modern toolkit for measuring HRR; while scale and appearance is different they are unified by using a common measurement technique for making the fundamental HRR measurement.

Even though the very same phenomena are measured in real-scale fires and in bench-scale tests, it does not mean that there is necessarily a simple, direct relationship between the two. In very simple cases, this can be true. For instance, if small-flame ignition is to be assessed, a bench-scale small-flame ignition test represents identically the situation occurring in the real-scale fire.

As we have seen, however, ignition variations compose but a small component of expected fire hazard. Our primary focus, instead, must be in predicting the real-scale heat release rate. Since peak hazard is associated with peak heat release rate, it is then the peak value that we wish to predict. The first successful example of such prediction has been for upholstered furniture. In an extensive NIST study on fires with residential upholstered furniture, it was found that the peak real-scale heat release rate can, indeed, be predicted from bench-scale Cone Calorimeter measurements.[59] However the relationship is not

peak real-scale HRR versus peak bench-scale HRR

but, rather,

peak real-scale HRR versus 180 s average bench-scale HRR.

An average, rather than the peak HRR is needed from the bench scale due to the physics of burning: at the time the peak HRR is being registered in the room fire, not every portion of the burning item is undergoing its peak burning—some portions are already decaying, while others are barely getting involved. Statistical considerations then lead to 180 s as a useful length of the averaging period.[54]

Another example where a more complicated relationship has to be sought is for combustible wall linings. Wickström & Göransson[55] found that, for predicting room fires caused by combustible wall linings, the heat release rate in the real-scale fires was predicted not by bench-scale heat release rate measurements alone, but by a combination of heat release rate and ignition measurements, as determined in the Cone Calorimeter. The ignition time, here, is not used to describe the ignition event. Instead, it is known that radiant ignition and flame spread are both governed by the same material properties (thermal inertia and ignition temperature) of the specimen. Thus, in the Wickström/Göransson method, use of the ignition time data allows the entire prediction to be made from the use of Cone Calorimeter data, without needing to introduce a second test for obtaining flame spread parameters. More complex models are also available[56,57] which do require input from additional tests.

SUMMARY

Reaction-to-fire tests have been in use since the early 1900s. Those most commonly used for plastics—UL 94 and the LOI test—do not predict the development of hazard in room fires. Fire deaths are most commonly the result of toxic products of combustion. The actual hazard produced depends on many factors, including the rapidity of ignition and the toxic potency of the gases. Nonetheless, it is illustrated that the *most significant predictor of fire hazard is the heat release rate.* Our ability to predict this most important aspect of fires is relatively very recent, since the first standard method for quantitatively measuring heat release rate in room fires was not available until 1982. During the 1980s, bench-scale techniques for making measurements which can predict the real-scale heat release rate were defined and put into place. Thus, all the needed tools are now at hand to enable the correct, quantitative computation of room fire hazard, based on correctly designed bench-scale tests.

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