FIRE TESTING AND FIRE REALITY: WHAT DO FIRE TESTS REALLY TELL US ABOUT MATERIALS?

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ABSTRACT

Fire tests are a critical component used in the process of designing a fire safe environment. For example, how do you know the fire protection in a large storage facility for chemical oxidizers is sufficient? How do you test the fire safety of and recommend performance-based criteria for engine compartment and interior materials for the variety of passenger road vehicles? For example, fire modeling predicted that a high density polypropylene product would auto-ignite when exposed to a radiant heat source when, in suitable tests or real fires, the same object melted away from the heat source. Fire tests must be carefully developed and monitored to make sure they correspond to reality. Fire experimentalists are always concerned with real-world fire parameters in the development, execution and application of fire tests and fire test data. Ageing, scaling, calculations, fire modeling and cost all require careful consideration in developing, evaluating and communicating the advantages and limitations of data from laboratory tests with the real world. Where no reliable fire test data exists, evaluation of historical fires and preliminary bench scale test data are often better than no data. But in any case no one should rely unquestioningly on small scale tests. This presentation will examine the challenges of fire testing and related progress in fire safety science.

FIRE TESTS AND MATERIALS

While materials properties and the effects of fire are well understood, the circumstances and environment specifically contributing to ignition scenarios are more complex. Fire tests tell us about the behavior of a material(s) under the very specific conditions of the test(s). The test method and data generated need to be researched and assessed to determine if the specific conditions of the test are applicable to the given fire scenario(s) or the end-use of the test subject. If the test method is applicable to the fire scenario, the test can be used to determine if a material, product or assembly meets expected requirements and/or specifications. If the test method is not applicable to the fire scenario, custom tests may be required.

Test data may be intrinsic or extrinsic. By definition, an intrinsic property is ‘belonging to the essential nature or constitution of a thing’ while extrinsic is ‘originating from or on the outside’.[i] Intrinsic properties are composition-dependent and include heat of combustion and melting temperature. Flash point, flame height, burning time and mass loss are examples of extrinsic properties of materials. The most common data from fire tests are extrinsic and dependent on materials properties including geometry, thickness, surface area, particles size and test parameters such as the size and kind of ignition source and the duration of exposure.

The limitations of standard test method(s) are that the test conditions may not capture known or potentially important fire parameters and may not be sufficiently versatile for different environments and new technologies. Some existing fire tests are severely limited in which case the data is not 'bad' in and of itself, but the application of this severely limited data has no beneficial consequence or, even worse, promotes complacency or increases the hazard. In some cases, a standard test method may be identified as insufficient, limited, or loosely applicable and the preferred evaluation should involve ad hoc or custom tests that require development. At a minimum, the ad hoc or custom fire test must have a scientific basis and provide a description of the need based on specific deficiencies in existing standard test methods. Guidance for the development of scientifically sound fire tests, strategies or hazard analysis are available.[ii,iii]

The greatest challenges posed by fire tests are cost and scale. Large scale fire tests are the most 'real world' but are cost prohibitive. In some cases, historical fires provide information that can be used in fire test development, modeling or code improvements. Modeling large scale fires is more cost effective but lacks the 'reality factor'—a necessary compromise. Most standard fire test methods are small or intermediate scale. Fire experimentalists are aware of the difficulty in extrapolating data from bench scale type tests to large scale events. If the limitations of the bench scale test are known and well-defined, the data from bench scale tests should provide a reasonable prediction about the interaction of known potential ignition sources and fuels and fire spread based on the end use and environment (e.g., geometry, ventilation, fuel load,etc).

FIRE LOSS INVESTIGATIONS

Every structure, transportation, storage and processing-related fire presents an opportunity to evaluate, examine and improve fire test methods, the fire performance of materials and fire mitigation and protection strategies. The result of a thorough fire loss investigation is a determination of the environment and the circumstances of various combinations of ignition sources and fuels that interact or react and result in a fire. Near misses and fire loss investigations are useful when the data is used to: 1) improve the fire performance of materials, 2) evaluate processes and procedures, 3) improve existing test methods, 4) illustrate the limitations or the complete failure of loss protection and prevention strategies, and 5) provide input for regulations to reduce the hazard. Laboratory analysis, calculations, demonstrative testing and modeling are 'tools' used to complement fire loss investigations.

Fire losses are 'real world' and the 'data' from these events provide a 'check' on the design, interpretation, and application, including limitations, of existing fire test data and methods. Any new information from fire losses and fire statistics should be studied and can be useful in the evaluation of an existing test method or fire test response characteristic and in the development of a new test method or mitigation strategies. Fire loss investigation experience and good laboratory practices are advantageous when evaluating materials, ignition sources and reactions, when interpreting fire test data and in the development of fire test methods.

MATERIALS SCIENCE IN FIRE AND EXPLOSION ROOT CAUSE ANALYSIS

A materials scientist is trained in the engineering properties of materials--plastics, ceramics, metals, natural materials, and composites. Closely related and overlapping disciplines include chemistry, metallurgy and chemical engineering. The chemist is trained in the fundamental properties and thermodynamics of solid, liquid and gaseous chemicals, mixtures and their reactions. Metallurgists focus on the properties of metals, alloys and composites. Chemical engineering involves the large scale processing of chemicals and reactions with specific focus on the influence of composition, phase, temperature and pressure on the kinetics, mass and energy flows.

The diversity of chemicals and materials include not only composition but also various material thermal and mechanical properties, reaction with the environment (e.g., corrosives, temperature, pressure) and the effects of ageing on performance, life-expectancy and potential failure modes. Product designers, manufacturers, fire investigators, fire service personnel, fire protection engineers and regulators rely on the acquired knowledge base of materials science, chemistry, metallurgy and chemical engineering experts and research.

The materials scientist involved in fire loss investigations can apply principles of failure analysis in determining the root cause of fires and explosions. Consider the conveyance of natural gas. Requisite for the safe conveyance of natural gas is the prevention of leaks from pipelines, pipes, tubing, connections, and at appliances. A leak of natural gas, if able to accumulate to concentrations within its flammable range, can result in a devastating fire or explosion if a competent ignition source is available. The different materials used to convey natural gas include ferrous, non-ferrous and plastic materials. Various connections from source to site may be fused, formed, butted and/or threaded. The ferrous, non-ferrous and plastic materials range in materials properties and failure modes. The fire investigator determines the source of the leak and identifies potential ignition sources. A materials engineer may be required to examine the gas main, transmission or distribution pipelines or appliance connectors containing the source of the leak to determine or confirm its root cause. Step-by-step protocols for the forensic examination of ferrous and non-ferrous flexible gas appliance connectors from fire and explosion losses have been published to assist fire investigators.[iv]

The premature failure of older (circa 1960-1980) buried plastic pipe for natural gas from brittle-like cracking was attributed to the assumptions made about plastics response to stress and the test method used to rate its strength.[v] At the time plastic was considered in place of steel to convey natural gas, the plastic industry experts did not have a procedure for rating the strength of plastic for the buried pipe end-use. Instead, they made assumptions about the ductile property of plastic materials to withstand stress and used an existing stress rupture test for determining material strength. The extrapolation of data from the test underrated the strength of the material over time. Field failures showed slit-like cracks where the plastic pipe was subject to stress intensification or stress concentrators. This was in contrast to the assumption that the material would deform and re-distribute localized stress. The test conditions were refined to include prolonged stress rupture tests which produced brittle-like cracks. The catastrophic failure of a gas main or distribution line that results in a fire or explosion is not an acceptable method of monitoring pipeline material integrity however these events and the age, environment and installation provide information on the materials performance over time and their susceptibility to different potential failure modes.

Debris and artifacts collected during on-scene investigation procedures are often subject to chemical analyses and laboratory examination. In litigation-related fire loss investigations, a reasonable degree of ‘scientific and engineering certainty’ is required. Chemical analyses performed according to standard test methods only provide additional information in the engineering analysis of fire causation. Examples of basic laboratory analyses include the identification of unsaturated oils that may self-heat or the presence of residual volatile compounds that may be indicative of an accelerant. However, the positive identification of unsaturation in an oil residue or the presence of volatile compounds in a fire debris sample is not conclusive that the fire occurred from the reaction or involvement of these materials. Similarly and especially when the fire damage is extensive or the sample is significantly altered during fire suppression, the absence of unsaturation or volatile compounds is not conclusive that they didn't somehow contribute to the fire's cause. Background information including pre-fire activities, the fire timeline, systematic elimination of other potential ignition sources, the environment of the sample collected, sampling techniques and preservation, and the collection and analysis of controls are necessary for reliable analysis and interpretation of the analytical data. It is recommended that the analyst work closely with the fire investigator such that the results of chemical analysis correspond with other information from the fire scene.

Evidence from fire losses are also subject to laboratory analysis and damage evaluation. Examples include the analysis and identification of a plastic to determine its composition, the analysis and identification of fire retardants, and characterizing localized melting damage resulting from eutectic mixtures or electrical activity. Elemental analysis and phase diagrams are used to identify melting as a result of eutectic mixtures. The appearance of electrical activity can be found on numerous power cords and wiring at residential fire losses. Evidence of arcing is associated with definite, localized melting of the conductor. Currently, there are <u>no</u> scientific methods for determining whether arc damage occurred before or during a fire. However, it is not difficult to characterize high temperature localized melting of copper using a stereomicroscope and after cleaning loose debris and/or scale from the conductors. This information is used in conjunction with examination of circuit protection devices during arc mapping--a tool used in engineering analyses of fires to identify, isolate or eliminate potential ignition sources in a fire's area of origin provided the fire scene is not sufficiently disturbed and the electrical wiring can be traced and documented from the distribution panel to the receptacle or appliance.[vi]

Fire calculations are another useful tool to support fire causation engineering analyses but they should not be used in place of a thorough investigation. For example, a fire originated inside a cabin in the woods. The area of origin contained a wood burning stove. Assorted tools were found in the debris adjacent to the stove and hearth. Witness interviews revealed that the tools were contained inside a black polypropylene toolbox. The fire investigator concluded the most likely cause of the fire was the ignition of the plastic toolbox by radiant heat from the wood burning stove. The stove consisted of a black painted steel enclosure with 1 inch thick firebrick lining the cavity. Calculations and demonstrative testing were done to determine if the toolbox at 6 inches from the stove could be ignited by thermal radiation. The results of calculations showed that temperature of the stove could reach the auto-ignition temperature of polypropylene[vii] supporting the fire investigator's hypothesis. The heat flux calculation did not account for the firebrick insulation between the fire and stove wall and the geometry of the burning wood above an ash box inside the stove. Demonstrative testing using an exemplar stove and toolbox were done. With the firebrick in place, the temperature at the toolbox 6 inches from the stove did not exceed 100 degrees C. When the firebrick lining inside the stove was removed simulating a worse-case scenario, the temperatures predicted by the calculations were reached on the outside of the stove but the plastic melted away from the stove and did not ignite. The results of the demonstrative testing were in conflict with the fire investigators hypothesis and the fire calculations. Fire statistics and product recalls should also be used with caution when applied to fire loss origin and cause investigations.

FULL SCALE RECONSTRUCTION AND DEMONSTRATIVE FIRE TESTING

When feasible, full scale fire testing of products or assemblies is highly recommended. The results of full scale fire tests can validate the behavior of materials subject to bench scale tests and can be used to clarify limitations of the bench scale test methodology. Similarly, full scale reconstruction can be useful in applying or comparing fire mitigation strategies to foreseeable conditions and environments that promote ignition. The data collected from full scale fire tests range from visual burning behavior to heat release rates and combustion gas analysis. The visual burning behavior is particularly meaningful when interpreting the heat release rate profiles. Well documented full-scale testing is typically easier for non-scientists to understand.

Plastic enclosures for electronic devices and appliances are rated based on the materials response to a flaming ignition source (50 W, 10 s) using the UL 94 test method.[viii] The standard states the tests ‘serve as a preliminary indication of (material) acceptability with respect to flammability’ and ‘are not intended to provide correlation with performance under actual service conditions’. HB materials are characteristically easy to ignite and spread flame while V-rated materials exhibit ignition resistance to small ignition sources.

In 2003 and 2004, NIST performed and compared the UL 94 vertical burn, glow wire ignitability resistance and standard and modified cone calorimetry test data of 18 plastics typically used for electronic appliance housings.[ix] The test materials included both fire retarded and non fire retarded resins and two thicknesses (1.6 and 3.2 mm). A strong correlation between the UL 94 test results and the cone calorimetry test data for the same materials was not apparent. The differences were attributed to the test methodologies, sample orientation and dripping behavior of the different plastics. Next, component scale, free burn testing was done using computer monitors, formed from five of the 18 resins. The monitors were exposed to a needle flame (38 W), fire exposure from a keyboard (20+/-3 kW) and a radiant panel (21 kW/m^2).[x] A stated goal of the project was to study the relationship between and accuracy of bench scale testing in predicting full scale end-product performance. The tests showed that the HB devices ignited readily and spread flame in comparison to the V-rated appliance enclosures which resisted sustained ignition when the source was removed. The HB and V-rated monitors all ignited and propagated fire when exposed to a larger ignition source or radiant heat. The full-scale fire test results by NIST were consistent with the published results of full-scale fire tests with HB and V-0 rated televisions.[xi] NIST concluded that ‘full scale tests remain the only certain way to obtain a definitive measure of fire hazard’.

The elevation of ignition sources where flammable and combustible liquids are stored is recognized as a mitigation strategy to reduce the occurrence of ignition in the event of a release. There have been numerous residential fires involving the ignition of gasoline vapors by the pilot flame of floor mounted gas fired water heaters. Because of its vapor density, gasoline vapor concentrations are highest near the floor and the vapors spread from the source to distant locations. The likelihood of flammable vapor ignition is significantly reduced when the burner or pilot flame of gas utilizing appliances is located at or elevated 18 inches. Full scale testing reconstructing various floor plans and room configurations from fire losses have demonstrated the effectiveness of ignition source elevation in reducing the occurrence of ignition[xii]. The concentration of gasoline vapors in air at 18 inches is not likely to be in the flammable range. The test results (e.g., ignition, no ignition) were consistent with combustible gas analyzer data at different heights from the floor. Similarly, the use of a flame arrestor and gas shut off devices on newer water heaters have been 'tested' under the same conditions and found to also reduce the occurrence of ignition.

ENTRENCHED AND LACKING FIRE TESTS

In some cases, there are entrenched fire tests that do not provide any valuable data or information on the fire performance of materials. In other cases, there are established fire codes that lack performance-based tests and criteria that are integral in the fire protection strategies. An example of the former includes the US Motor Vehicle Fire Safety Standard 302 that was initially used to determine the ignition propensity of vehicle interior materials by smoldering cigarettes. The existing test involves the application of a flame to one end of a material in a horizontal orientation. A minimum 102 millimeter per minute rate of flame spread from the ignition source is the criterion of fire performance. The test does not account for flaming drips. Nearly all materials meet the test criteria and therefore 'pass'. Statistics from 2004-2006 show however that vehicle fires are initiated by heat from powered equipment (21 percent), radiated or conducted heat from operating equipment (16 percent), electrical arcing (16 percent) and spark, ember or flame from operating equipment (9 percent).[xiii] Heat from engine backfire and heat from cigarettes, cigars, matches and torches result in 10 percent of the fires. There are no regulatory fire tests to evaluate the ignition propensity, heat release rate or fire propagation of materials used in a vehicle's engine compartment even though 34 percent of fatal highway vehicle fires originate in the engine area of the vehicle. The insulation around electrical wiring (28 percent) and flammable liquids (21 percent) in the engine compartment are reported as the items first ignited. Gasoline was the leading type of material first ignited in highway vehicle fires in general (23 percent) as well as fatal highway vehicle fires (52 percent).

Because of the vehicle fire problem, an NFPA committee has developed a guide with relevant test methods and evaluation tools to address the fire hazard to occupants of passenger road vehicles.[xiv] The guide provides a performance-based flow diagram approach with the goal of reducing the likelihood of a fire's initiation, spread and contribution to reduce the tenability conditions in the passenger compartment. The guide contains tables of fire test data of typical interior materials, the results of full scale vehicle fire tests, ignition scenarios and mitigation strategies.

It has been argued that vehicle scale fire tests are the best method to evaluate materials with improved fire performance. Manufacturers perform vehicle scale collision tests to study and improve the crashworthiness of vehicles; however, the same test vehicle is not operating, the battery is removed, and the fuel system is not charged with gasoline therefore eliminating the simultaneous investigation of vehicle fires or testing the influence of materials with improved fire performance to resist ignition and spread fire. At the present time, batteries used in hybrid electric vehicles are subject to multiple physical, electrical and thermal abuse type tests but at the cell or module scale and not at the pack or full scale[xv].

An example of entrenched fire protection strategies that lack test methodology and data includes the US Code for the Storage of Solid and Liquid Oxidizers.[xvi] The quantity of stored material and fire protection measures are based on the Class of oxidizer. The Class of oxidizer is based on the oxidizers ability to increase the burning rate of nearby combustible materials. The fire protection strategies are specific while the definition of each Class is subjective. Since 1973, the Code does not contain guidance or a test to determine an oxidizer's Class.

DECONSTRUCTING FIRE TESTS

The following factors are important in the evaluation and application of fire tests and fire test data and in the development of fire tests.

Cost
Bench scale tests are usually less cost prohibitive than intermediate and full scale tests. The ability to perform multiple bench scale tests however, does add up in cost. However, bench scale test data should be assessed by intermediate and full scale testing, existing full scale data and/or historical fires.

Scale
The size or scale of a fire test is notably crucial. In some cases, 'full scale' does not necessarily mean 'large' but may simply involve testing a product or assembly in the environment of its end-use. If there are no existing data or historical fires, a bench scale test is potentially severely limited in applicability. In some cases where there are potential hazardous conditions, bench scale screening type tests are done for safety reasons.

Multiple Hazard Properties
Hazardous chemicals can exhibit a range of physical and health hazards. Available information should be compiled and evaluated when developing test methods or assessing the applicability of the test data for hazardous materials. For example, the degree of enhanced burning rate of typical combustible materials by oxidizers is important in assessing the necessary fire protection where these materials are stored. However, chemical oxidizers, under certain circumstances, may undergo exothermic thermal decomposition, exhibit reactivity and produce toxic decomposition and/or combustion products.

LIMITATIONS OF STANDARD FIRE TEST METHODS

Fire experimentalists are aware of the limitations of standard test methods and ad hoc tests and must communicate these to the user of the data and the limitations or deficiencies should be as specific as possible. The ASTM attributes the test and material variables as the primary sources of variability[xvii]. Variability is the compilation of test limitations which includes the misinterpretation, misuse or misapplication of the method or use of the data generated. In fire tests, variability and limitations include but are not limited to the material's composition, geometry and arrangement of test sample, the ignition source and/or fire exposure (i.e., initiating source, heat flux, duration of exposure), the applicability of pass/fail or performance criteria, the applicability of individual portions of the test methods to the intended scenario given the products end-use.

A single test cannot capture all properties of all materials. Existing test methods should be reviewed and compared provided the properties and geometry of the test subject and the environment of its end-use or application. One test method may be sufficient but test data from multiple tests provide more information. Test data from multiple tests should be assessed individually and in combination. Additional data may include video-recordings, timelines and post-test analyses that further characterize a materials response and fire behavior. If existing multiple tests are not sufficient to capture the fire test response characteristic in question, a test should be designed based on this review further with a basis for an ad hoc or custom test.

CONCLUSIONS

Fire testing materials, products and assemblies are beneficial when the fire scenario is well-defined and when the limitations of the test method are communicated. Experience and/or knowledge in or of fire loss investigations, fire reconstruction, and fire test research and development is advantageous. This is especially the case when performing hazard analyses and applying fire test data to real-world fire scenarios. Recommending a standard test method or developing a custom fire test requires an overall and careful analysis that indicates that an apparent fire scenario is represented, a fire test response characteristic is a useful predictor of fire behavior and an improvement in the fire property or mitigation strategy assessed will result in an actual improvement in fire safety.

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