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FIRE-RELATED STANDARDS AND TESTING

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INTRODUCTION

The state of the art in the flammability testing has been changing rapidly. In this paper, the progress in developing general test methods for solid materials and products exposed to an external fire will be reviewed, the special requirements pertinent to environments of concern to NASA will be examined, and some indications for possible directions for future test method developments will be given.

FLAMMABILITY ENGINEERING TESTS

Flammability tests developed in the 1950's and the 1960's tended to be of a very ad hoc nature. Typically, some problem materials were identified, and a program was launched to eliminate their use by finding some test, often of a Bunsen burner type, which would fail some of them, while allowing more desirable materials to pass. In those times, this was a reasonable course of action, since the underlying combustion physics and chemistry were largely unknown. Most of the existing tests on the books are still of this philosophy. The latest compilation, for example, by the American Society for Testing and Materials (ASTM) lists 70 distinct flammability test methods, most of them of this ad hoc nature (ref. 13). Recently, however, the philosophy of designing proper tests has changed considerably. It is taken that a useful test is a full-scale fire test, where the test article is subject to a worst-design case scenario. The results can usually be interpreted fairly directly. Standardization of such a test is not necessarily desirable, since, by definition, it must incorporate project-specific features. Nonetheless, ASTM has seen fit to establish both a guide (ref. 14) and a standard (ref. 15) for room fire tests.

In most instances of fire safety engineering, full-scale testing is not appropriate, and suitable bench-scale tests must be sought. It can now be seen that 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

The advances of the last 15 years or so in fire physics and chemistry have enabled a systematic approach to be taken for producing tests suitable to meet objective (1). The steps required are as follows:

(1) Identify the governing physical and chemical principles of the phenomenon to be measured.

(2) Design a candidate bench-scale test using these principles.

(3) Identify the range, best to worst, of relevant full-scale product behaviors and assemble specimens having those expected traits.

(4) 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.

(5) Conduct bench-scale tests, varying empirically those features of fire behavior that cannot be assigned known constant values.

(6) Attempt to correlate the bench-scale results against the full-scale data base.

(7) Select those bench-scale test protocol features that lead to the best correlation with the full-scale data.

Examples illustrating the details of such a procedure have been published for determining the rates of heat release of upholstered furniture (refs. 16 and 17) and both time to flashover (ref. 16) and rate of heat release (ref. 18) for combustible wall lining materials.

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. The stringent rules of validity that are required of a test for objective (1) are not required. A much looser requirement for validity here is merely that most production-line changes, which can possibly occur in manufacturing to affect the flammability of the specimen, should be reflected in a statistically significant deviation in the test's results. The ASTM standards contain a very large number of examples of these types of tests. Because of its application to the aerospace industry (e.g., the European Space Agency adopted it for qualifying Group I materials (ref. 19)), one example, the Limiting Oxygen Index (LOI) Test (ref. 20), is discussed here.

The LOI test involves the candle-like burning of a rod of plastic material. The apparatus is supplied with an adjustable oxygen/nitrogen flow mixture; the test requires that the minimum concentration of oxygen be found for which the specimen will continue burning downward without flame extinction. Since the results are quoted as an oxygen concentration, the results have widely been interpreted to suggest that a material will not burn in a given atmosphere if its LOI is greater than the oxygen concentration in that atmosphere. Such, of course, is not the case at all. A number of theoretical analyses of the method have been made (refs. 21 to 23). These show that the LOI value, far from reflecting a general property of the material, simply determines the oxygen concentration for which laminar, downward, against-the-wind flame spread ceases in the absence of external heating. The test, in fact, has nothing to do with burning rates at all, but is a flame spread test of a very specific geometry, with data unlikely to be applicable to differing geometries. It has become understood within the fire protection engineering community that the test should not be used to predict actual fire hazard conditions, but it may be a satisfactory quality control test, due to its high sensitivity.

Tests for objective (3), guidance in product development, do not, in principle, need to be standardized, since they are to be used only internally within an organization. In practice, however, industry tends to use published ASTM and other standard tests. The requirements for a good development test are somewhat different than those for a QC test. A good development test must not show crossovers in ranking of materials or products, when compared to full-scale behavior. Its sensitivity is of less concern, however, since minute performance differences would probably not make it worthwhile to redesign a system.

There have not been any comprehensive studies to determine which existing flammability tests are suitable for QC or product development purposes. This type of guidance is usually developed within a given industry on the basis of experience. It must be emphasized, however, that it is never prudent to use a test method as a bench-scale means of assessing the full-scale hazard solely on the basis of its good history of performance as a QC or development test.

MODERN CONCEPTS OF TEST METHOD DEVELOPMENT

The understanding of fire development in compartments has been advancing substantially in the last decade, to the point now that there are general purpose computer codes for predicting fire development (e.g., refs. 24 and 25). These codes have been based on an elucidation of the physics of the fire process (ref. 26). The process has three major components that need to be evaluated:

(1) Ignition

(2) Flame spread

(3) Burning and product generation rates

Ignition

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 there are theories available that can be used to explain an ignition that comprises a uniform heating of a planar face (e.g., ref. 27). The modeling of ignition from a concentrated, point source is difficult and has not been solved (ref. 28). A Bunsen burner represents a concentrated, nonuniform source; thus data obtained from Bunsen burner tests are not readily usable in modern fire protection engineering designs. As an additional, practical consideration, some materials, which shrink or melt upon heating, can often pass a Bunsen burner test by retreating from the fire, yet they can show serious ignition propensities in actual fire experience.

In addition to the geometric complexity, a specification has to be made whether a primarily radiant or a primarily convective heat source is to be utilized. Hermance (ref. 29) has urged that radiative sources be selected due to the consequent "ability to select the heat flux applied...independently of all other environmental parameters: namely, pressure, initial temperature, and chemical composition of the gas phase." In most cases, also, a well-calibrated radiant source is easier to devise than a convective one, and results are easier to analyze.

For such reasons, the International Organization for Standardization (ISO) adopted a radiant exposure method as its ignitibility test (ref. 30). ASTM lists a number of Bunsen burner type tests, but no uniform-flux ignitibility methods, per se. There is one ASTM method, E906 (ref. 31), which can be used to measure radiant ignitibility; unfortunately the heating fluxes are not well controlled there. There is also a new proposed ASTM method, P-190 (ref. 32), which is primarily a heat release rate method, but which uses a cone heater similar to the ISO method, producing a highly uniform flux distribution over the specimen surface. Recent work (ref. 33) 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 real instruments.

Flame Spread

Solid materials may be ignited at a point, or they may be ignited over a large exposed area; nonetheless, in most fires there is a period where material not yet involved in fire gets progressively involved by flame spread. Thus, it is important to be able to characterize this process. Flame spread has traditionally been measured in the ASTM E84 tunnel (ref. 34). The E84 tunnel is a large-scale instrument; many other ASTM tests and also tests such as the Federal Aviation Administration test FAR 25.853 (ref. 35) are small Bunsen burner tests where the spread of flame is observed. Results from these types of tests are given as ratings on arbitrary scales and cannot be analyzed within the current-day modeling capabilities. Lacking this modeling, such data cannot be reinterpreted in the context of a new design geometry.

Newer tests for flame spread are being developed. An example is the International Maritime Organization (IMO) flame-spread test (fig. 1, ref. 36), the behavior of which has been analyzed according to theory (ref. 37). It should be noted, however, that the full incorporation of appropriate flame-spread features into fire models is difficult, although attempts are being made for walls and for upholstered furniture items (ref. 38).

Burning and Product Generation Rates

The third combustion behavior that must be considered is the burning rate. In older literature this is sometimes confused with what is nowadays described as flame spread rate. Burning rate is the mass loss rate of a specimen when it is fully ignited, with flame spread having covered its entire face. The units are typically expressed as kg/m^2 s. 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. 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.

The earliest bench-scale instrument for rate of heat release measurement was the ASTM E906, developed in the late 1960's. This instrument is based on a direct measurement of sensible enthalpy and is subject to substantial errors, since adiabatic conditions are not maintained. It also lacks means of measuring the specimen mass. A major breakthrough occurred in the 1970's, when the principle of oxygen consumption (ref. 39) was developed. This principle allows rate of heat release to be determined indirectly by monitoring oxygen concentrations and flows and has provided a much more reliable technique for use in both full-scale and bench-scale fire testing. For bench-scale testing, this principle has been incorporated into the Cone Calorimeter (ref. 40). The Cone Calorimeter (fig. 2), in addition to being a proposed ASTM test method (ref. 32), also has been selected as the apparatus for a proposed ISO rate of heat release standard.

Over the last two decades, smoke has been most commonly measured by using the NBS Smoke Chamber method (ref. 41). This has been considered to be the best standard on the books, but its limitations--limited flux range, no horizontal orientation, no mass monitoring during the test, and the inability to properly test heavier samples--have shown a need for a newer technique. Such a technique has been developed, in the form of a smoke extinction beam for the Cone Calorimeter (fig. 3, ref. 40). This new technique eliminates these Smoke Chamber shortcomings. The fraction of specimen mass converted to soot mass is a quantity that is related, but not redundant, to the smoke extinction measurement. Thus, for research purposes, the Cone Calorimeter is also equipped with a gravimetric soot measuring system.

Progress is being made at a rapid pace in characterizing the fire toxicity of materials by the use of an appropriately specified set of gas measurements (ref. 42). For obtaining the relevant combustion gas data, the efforts at NBS are focused on using the Cone Calorimeter. This technique is still under development, however, so recommended procedures are not yet finalized.

THE EFFECTS OF VARIABLES OF SPECIAL INTEREST TO NASA

Oxygen Concentration

Ignition of solids from radiant heating may be understood most readily as occurring at a time when there is a critical rate of pyrolysis products leaving the surface (ref. 43). This rate is typically seen to be about 1 to 4×10^{-3} kg/m^2-s in ignitions under normal oxygen conditions and is presumed to correspond to the lower flammable limit being attained for the mixture above the surface of the material. It is reasonable to suppose that varying oxygen concentrations would change the minimum pyrolysate generation condition by reflecting the new fuel vapor concentration required at the new oxygen value.

Experimental work in this area has been largely confined to studies of solid rocket propellants. A theory by McAlevy et al. (ref. 44) suggests that the ignition time t_{ign} should depend on the oxygen mass fraction m_{ox} to the minus two-thirds power; however his experimental results show that the dependence is of the order of the minus 1.2 to 1.5 power of the oxygen mass fraction.

Kumar and Hermance (ref. 45) also conducted a theoretical study of propellant ignition. Evaluated for various material properties, their results typically show that ignition time depends on oxygen mass fraction to the minus 1 to 2 power for mass fractions greater than 0.20. For lower oxygen mass fractions, ignition time is independent of oxygen mass fraction.

The solid propellant studies, however, characterized heterogeneous systems, where an oxidizer is already mixed in with the fuel. For accidental fires, the condensed phase will most likely be pure fuel, with no oxidizer admixture. A theoretical analysis of this case by Kashiwagi (ref. 46) showed that for oxygen mass fractions below 0.20, there is a substantial variation of ignition times, but that the actual relationship is strongly dependent on the exact ignition criterion chosen. For higher oxygen mass fractions, however, ignition time was seen to be only very slightly dependent on oxygen fraction, dropping about 10 percent as the mass fraction goes from 0.23 to 1.00.

Flame spread over solid combustibles can take place in several different domains of behavior, the details of which will not be reviewed here. The effects of oxygen concentration, however, have been of concern for quite some time. In an early review (ref. 47), Magee and McAlevy found that for several geometrical and flow arrangements, the flame spread velocity V was related to the oxygen mole fraction Y_{ox} in a power law relationship, with V of the order of Y_{ox} squared. In a more recent examination of this dependency, Fernandez-Pello and Hirano (ref. 48) found that it holds only for large Y_{ox} values. For lower oxygen concentrations, the dependence of the flame spread rate on oxygen mass fraction becomes progressively greater, approaching an infinite-slope asymptote at the Y_{ox} value at which extinction occurs. In an experimental study of flame spread over paper specimens, Frey and T'ien (ref. 49) found a dependency, in their case, to the first power of Y_{ox} at high Y_{ox} values, and a similarly increasing power-law dependency at low oxygen values. Altenkirch has suggested (ref. 50) that oxygen fraction is among the variables which may be successfully correlated by the use of the Damkohler number.

The effects of oxygen level on the mass loss rate m" have been studied in detail by Tewarson (refs. 51 and 52) and Santo (ref. 53). For some materials, they found a direct, linear relationship between Y_{ox} and the burning rate. This relationship remains linear down to the lowest Y_{ox} value at which combustion is sustained, but the relationship has an offset, that is,

$$\dot{m}'' \approx aY_{ox} - b$$

For other materials, including ones showing charring, however, this linear relationship leveled off at higher Y_{ox} values.

Total Pressure

Similarly as for oxygen effects, the total pressure is expected to affect the ignitibility of a material indirectly by its effect on the lower flammable limit. For many materials, over a fairly wide range of pressures, the lower flammable limit is not significantly affected by total pressure (ref. 54). The early propellant studies of McAlevy et al. (ref. 44) showed a theoretical dependence of ignition time to total pressure P_{tot} to the minus 1.44 power, while corresponding experimental measurements gave a dependence to the minus 1.77 power.

Very similar results are also reported by Kumar and Hermance (ref. 45). The work of Beyer and Fishman (ref. 55) suggests that the pressure dependence becomes small at low heat fluxes (such as might be expected from an accidental fire), provided the value of P_{tot} is not also low.

In a more comprehensive study, Shannon (ref. 56) obtained detailed ignition time plots for a number of propellants, covering a wide range of pressures and heat fluxes. The effects of pressure were not well represented as a power law. Instead, for P_{tot} greater than about 200 kPa (2 atm), there was negligible effect on t_{ign}. For P_{tot} less than 2 atm, however, the negative exponent was increasingly greater for lower values of P_{tot}. The experiments of Kashiwagi et al. on both pure fuels and on propellants (ref. 57) indicate a behavior at very large values of P_{tot} (>20 atm) where, instead of becoming independent of P_{tot}, the ignition times vary inversely according to total pressure. Ohlemiller and Summerfield (ref. 58), in a similar study, also show a continued dependence of t_{ign} on P_{tot}, even at high P_{tot} values.

The work of both Kashiwagi (ref. 57) and Ohlemiller (ref. 58) suggests that a combined correlation of the effects of oxygen fraction and the total pressure should not be sought in the use of O_2 partial pressure as a correlating variable, unless only the regime of large m_{ox} and P_{tot} values is considered and only approximate results are sought.

Magee and McAlevy (ref. 47) found that for thick fuels the flame spread velocity was proportional to slightly higher than the 1/2 power of the total pressure. For thin fuels, however, the pressure effect was very tiny, being about to the 0.1 power. Frey and T'ien, again, studied the variables over a wider range (ref. 49) and found a 0.1 power dependence only for thin fuels at high (in comparison to the limiting pressure at extinction) pressures and spreading vertically down. For horizontal spread the exponent was higher, but was not unique, there being a strong coupling between oxygen fraction and total pressure effects. In both cases, similarly as for the oxygen fraction effect, the dependence on the total pressure became much greater as the pressure was lowered towards the extinction value. Fernandez-Pello and Hirano (ref. 48) found that over a limited range extinction could be represented by a constant value of $P_{tot} \times Y_{ox}$, that is, a constant partial pressure of oxygen. Outside of this limited range, however, such a simplification did not hold.

Test instruments for measuring burning rates have not typically been built to allow pressure to be varied. A pressure modeling program conducted at Factory Mutual Research a few years ago (ref. 59) produced results showing that over a certain range of test variables, a dependence of the mass loss rate was according to the two-thirds power of total pressure. This has not been applied in practical materials testing.

Gravity

Limited experiments have suggested that the ignitibility of a material is not significantly affected by a lowered gravity or by microgravity conditions (ref. 60). This is in agreement with the findings of Strehlow and Reuss (ref. 61), who concluded that gravity had but a minor effect on the lower limit of flammability.

Experiments by Kimzey (ref. 60), Schreihans (ref. 62), and Altenkirch (refs. 50 and 63) suggest that as far as flame spread is concerned, for gravitational values much greater than that on earth, there is negligible effect of gravity. For gravity levels equal to earth's gravity, there is some disagreement whether the dependence is significant or not (ref. 63). At microgravity levels, however, it is evident that flame spread rates may be reduced by an order of magnitude or more (ref. 60).

Some very early experiments (ref. 64) indicated that, once ignited, a material is likely to burn even through periods of weightlessness. Hall's study suggested that burning was in some sense accelerated during weightlessness (ref. 64). In general, extensive studies have not been made of the effects of gravity on burning rates. For small items, where convective effects dominate, it would be expected that the burning rate would follow Spalding's B-number theory (ref. 65). This theory, for example, predicts that the burning rate of a small sphere will be proportional to the 1/4 power of g. The burning of larger items tends to be dominated by radiative transfer. Here the effects of gravity are much smaller and indirect. The only gravity effect will be if the sootiness of the flames or the shapes of the radiating bodies are affected; this, of course, is possible.

PRESENT PROCEDURES USED FOR TESTING SPACECRAFT COMPONENTS

At NASA, the flammability of spacecraft materials is assessed primarily using the methods of NHB 8060.1B (ref. 4). This Handbook provides several methods, both full-scale and bench-scale, for the flammability testing of solid materials. The full-scale procedures include a sectional mockup (Test 10) and a full cabin mockup (Test 11). Both tests are ignited using an electrically triggered solid ignitor. Bench-scale procedures include an upward propagation test (Test 1), a less severe downward propagation test (Test 2), a supplementary test for flash and fire point (Test 3), and special tests for electrical wire insulation (Test 4) and potting compounds (Test 5). Test 1 uses specimens 6.3 cm wide by 30 cm long and ignited at the bottom by either a solid ignitor (for oxygen-enriched atmospheres) or a Bunsen burner. A specimen is acceptable if it meets maximum burn time and burn length criteria. Specimens which fail these criteria may be qualified under Test 2, which relocates the ignitor to the top of the specimen and does not provide specific cutoff criteria. In all these Handbook tests, the test is to be conducted at the atmosphere which constitutes the worst-case condition.

The European Space Agency (ESA) initially adopted a set of bench-scale test procedures (ref. 19) that are somewhat different from those of NASA. The ESA basic test was the Limiting Oxygen Index test. While this is different from the upward burning Test 1 of NHB 8060.1B, the ESA method proceeded in an analogous fashion by describing a downward propagation test for materials that do not pass the basic test, and by supplementing with a special wire insulation test. Currently, however, ESA is using the NASA procedures for actual testing of materials (ref. 66).

POSSIBLE FUTURE DIRECTIONS

It is likely that the intensive development of new test methods and fire design procedures going on in the area of fire protection for buildings will have some impact on the state of the art of fire-safe design in the aerospace environment. Such applications will not be a direct use of design procedures developed for buildings, since these take into account neither the special environments of concern in space missions nor the required criteria. The principles themselves, however, may well be introduced into newer generations of spacecraft standards. This can be expected because the new generation of tests coming into use in the building industry are not conceived of as dedicated "widget testers" but, rather, are intended to focus on the fundamental properties of materials as they relate to flammability. The most essential of these principles for bench-scale testing include the requirements for

(1) Planar, thermally thick specimens

(2) The testing of composites as composites, instead of testing individual layers

(3) Simulated fire exposure to consist of a uniform, adjustable radiant flux

(4) Design of tests to give one-dimensional heat transfer

(5) Design of apparatus such that specimens do not melt out of holder or retreat from their ignition sources

(6) The measurement of heat, species, soot and smoke on a per-gram basis

(7) Use of oxygen consumption for measuring heat release rates

(8) The selection of both irradiance conditions and test times to predict full-scale data

(9) 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)

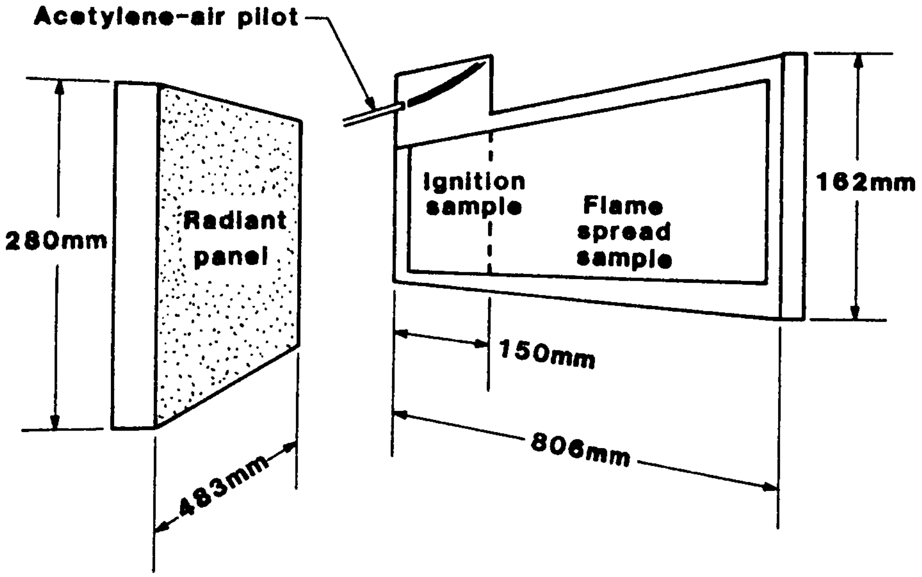

Figure 1. - International Maritime Organization flame spread apparatus.

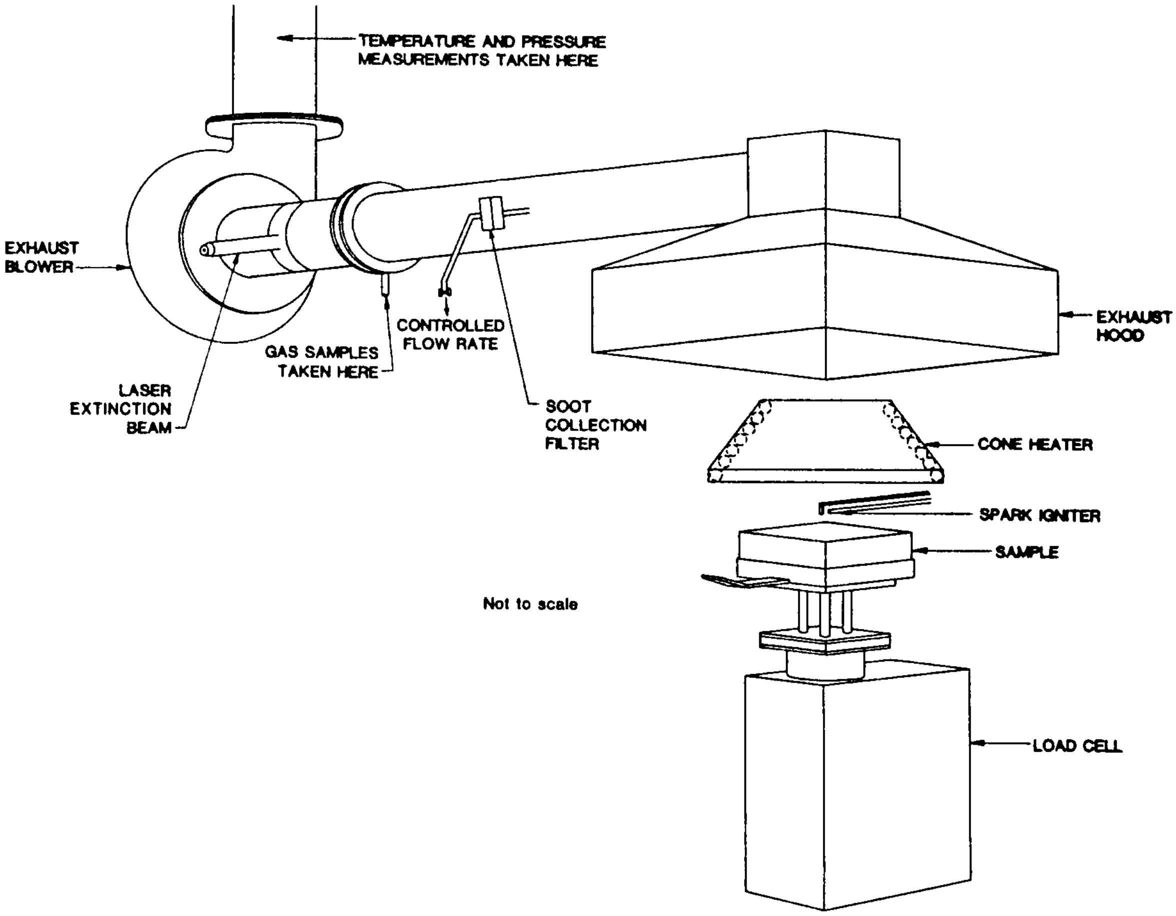

Figure 2. - Cone Calorimeter.

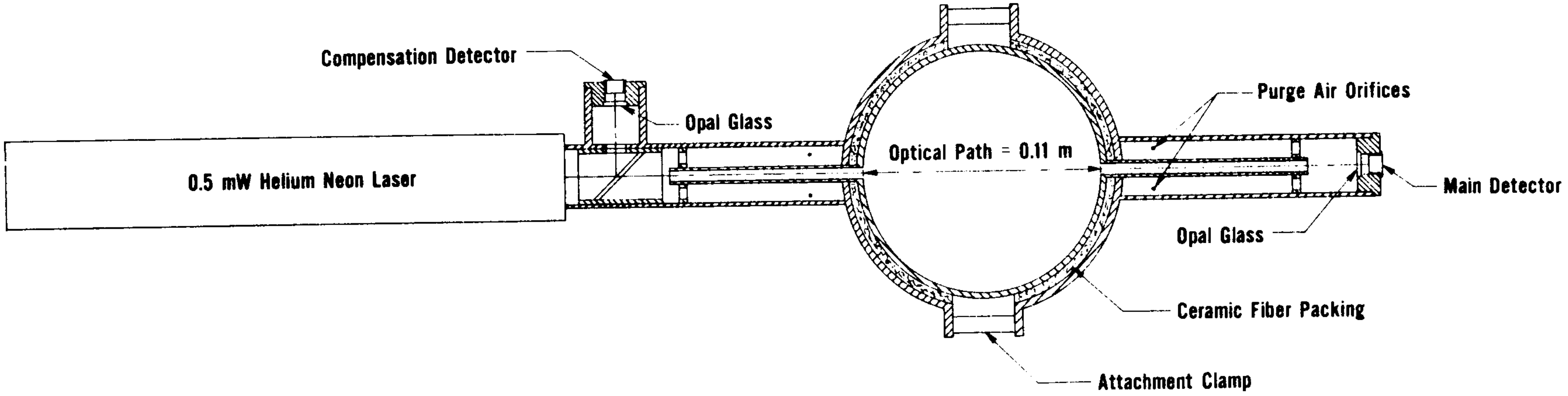

Figure 3. - Smoke extinction beam for the Cone Calorimeter.