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AN EXAMINATION OF THE CAUSES OF VARIABILITY
IN THE 7.6 M TUNNEL TEST

by

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PREFACE

The causes of variability in results from the 7.6 m tunnel test are discussed by identifying the controlling processes and examining available test data. The tunnel method ranks favourably with other flame spread test methods in terms of the precision with which flame spread classifications are measured. Comparisons of precision of smoke developed estimates, however, indicate the tunnel to be less than satisfactory. Some recommendations for improvements are presented.

OTTAWA
September 1981

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An important consideration in the development of a performance test method, whose suitability, design and operating procedure are established, into a standard test for widespread use, is the precision of the results from it. Precision may be assessed on the basis of the ability to generate results that are both repeatable (within a laboratory) and reproducible (between laboratories). The latter quantities are now well defined (1) and are usually based on an analysis of results of replicate tests on a selection of materials by a number of laboratories. With this approach, the precision of the test method on its own cannot be deduced as the estimate obtained is inextricably linked to the variability of the materials tested.

A requisite for obtaining acceptable precision is careful specification of tolerances on those test variables that significantly influence performance. This requires an appreciation of the controlling mechanisms and how they may be altered by manipulating test variables.

The subject of flammability of building materials, unfortunately, is poorly understood. The term "flammability" itself has not been satisfactorily defined and has been used variously to include the following fire properties of a material: ignitability, and propensities to spread flame, to generate smoke and toxic products and to release heat. In practice, the processes affecting each of these properties are complex interactions of physical, chemical and thermal phenomena which, in turn, are subject to external factors such as geometry of the fuel bed and the characteristics of the surrounding environment. Several tests that purport to measure these properties, were developed for general application rather than to address specific fire scenarios and for many no theories exist to enable prediction of their results. The 7.6 m tunnel test is an example of such a test (2). It is widely used to rank materials on an empirical scale by providing comparative measures of potential for flame spread and smoke generation.

In the present paper, the precision of results from the tunnel test is discussed, given the foregoing handicap, by identifying the controlling processes qualitatively, and examining existing data in that light. Although several revisions have been made in recent years, recommendations for further improvement are offered.

GENERAL CONSIDERATIONS

For a fire to thrive and spread, the heat evolved must exceed the amount lost to the surroundings. This excess heat, when fed back into the fuel bed, serves to thermally decompose the fuel into flammable products. The next stage involves the mixing of gases and vapours with air, usually under natural draft conditions, and is heavily dependent on the physical constraints of the system. The final stage is that of chemical reaction which results in further heat release. Reaction rates increase rapidly as the local mixture temperature is raised.

All the foregoing processes are at work within the tunnel under forced draft conditions. The gas burner provides the initial pyrolysis heat source and ignites whatever flammable vapours are released. Broadly speaking, an increase in propagation rate can be occasioned by an increase in the rate of any of the three principal controlling processes: (i) heat transfer to the unburned fuel, (ii) mixing of pyrolysis products with air and (iii) chemical reaction.

The mechanisms of smoke formation are less tractable, even on a rudimentary basis. It is known that smoke comprises solid and liquid particles dispersed in air and results principally from incomplete combustion. Thus any measures to improve combustion will reduce smoke formation. A drop in gas temperature will enhance coagulation of liquid droplets while an increase in residence time of the gases before measurement will promote settling and result in a lower smoke value being recorded. The effects of visible smoke may also be reduced by dilution.

Table I lists the variables that are likely to affect tunnel performance and thus its precision. The operational variables will influence within laboratory variation, while the design variables can be expected to cause inter-laboratory variation. Some of these parameters have been investigated experimentally and are discussed in the following sections.

SENSITIVITY STUDIES

In 1970, Endicott and Bowhay (3) reported that the flame spread classification (FSC) for Douglas fir plywood and particleboard were significantly affected by specimen moisture content, thickness and preheat time and by tunnel lining temperature at the start of a test, but were relatively insensitive to small variations in draft velocity. In contrast, the smoke developed classifications (SDC) were strongly influenced by draft velocity. Similar conclusions were reached by Underwriters' Laboratories, using a considerably wider range of draft velocity (4).

A longer preheat time is effective in reducing the time to reach pyrolysis temperature and thus increases FSC. The importance of this factor is recognized in the current standard but inadequately handled. The size and nature of test specimens are such that installation times are not uniform, especially for non self supported specimens. The specified preheat time, therefore, should include specimen installation. In the case of lining temperature, attention is focussed on surface temperature rather than temperature gradient. The latter quantity is dependent on the method used for cooling between tests. A rapid cooldown will result in a high, positive temperature gradient while slower cooling will produce a negative gradient.

The FSC draft velocity relationship is controlled apparently by two compensating factors: the local availability of oxygen and the average gas temperature. An increase in draft velocity increases turbulence and therefore improves mixing of gases. However, any increase in reaction rate caused by an improvement in the local supply of oxygen is offset by a reduction in reaction rate brought about by a lowering of the average gas temperature. In a recent study, Priest and White (5) noted that a larger tunnel cross-sectional area, within the limits specified in the present standard, resulted in a sharp decrease in FSC. In this instance, gas temperatures were reduced by the higher bulk flow, but operation at the specified velocity did not alter the mixing pattern sufficiently to affect local oxygen supply.

At the time of the Endicott and Bowhay study (3), the tunnel draft was regulated by maintaining a constant pressure drop across the entire test section. Quintiere and Raines (6) showed that this mode of operation resulted in a substantial drop in inlet air flow rate over the course of a test, caused simply by gas expansion (Figure 1). A recent revision to the standard provides for nominally constant mass flow by regulating the inlet shutter pressure drop only.

The SDC is strongly influenced by the diluting effect of increased inlet air flow. This was evident in the various studies.

The major work of Groah (7) concluded that variations in burner fuel input warranted attention. Quintiere and Raines (6) found that, during a run with a specimen of asbestos cement board, 40 per cent of the energy input by the burner was lost to the bounding surfaces of the tunnel before the 4.6 m plane, while at the exit plane the gases contained only 48 per cent of original heat input. In tests on carpets they noted that a net energy production rate between these two planes was not evident until well after the flame spread process was complete (Figure 2). Tests at the National Research Council of Canada have shown that during the flame spread period of fibreboard specimens, the burner accounted for approximately 83 per cent of the total heat released in the tunnel (Figure 3).

Since the burner can be the major source of heat for promoting pyrolysis during the early stages of the test, it is imperative that its characteristics be well defined both in terms of energy release and flame shape. Priest and White (5) concluded that the burner output should be controlled within about 1 per cent of the calibrated value for acceptable accuracy. The calibrated value of energy input, however, is that required to propagate flame over the surface of a red oak specimen in 330 s. Thus ducts with a larger than average cross-sectional area will require a higher burner fuel flow to complement the higher air flow. The present author found that the fuel-to-air ratio required to achieve calibration as specified, remains substantially constant. Without accompanying changes in fuel-air mixing patterns in the short, initial section of the test duct, however, the igniting flame can be lengthened considerably.

Specimen thickness and method of attachment are variables that cannot be standardized conveniently. It is therefore customary to include these two items in a test report.

Priest and White (5) found that the surface emissivity of the furnace lining was not a significant factor. The standard requires that all lining surfaces be maintained in good physical condition, but the influence of lining condition on performance has not been studied.

INTERLABORATORY STUDIES

Four formal interlaboratory studies of the tunnel test have been conducted to date. The three works that have been published, however, concentrated on performance related to specific products.

The problem of poor reproducibility of results was evident in the early 1960's when several organizations acquired the facility for testing purposes. At the time, Yuill (8) ascribed poor correlation between four installations testing acoustical materials to improper construction of the tunnels.

The work of Lee and Huggett (9), primarily on the floor coverings, was the first attempt to quantify tunnel precision. In a survey of the physical attributes of eleven tunnels, it was noted that most did not comply with the ASTM E-84-70 standard. It was also found that the standard was not sufficiently specific in several key areas likely to cause variability. Based on evaluations of nine materials the between-laboratory coefficient of variation ranged from 7 to 43 per cent for FSC and from 35 to 85 per cent for SDC.

The reproducibility of the FSC values was regarded as adequate for carpet assessment. At the time of that study, however, the derived FSC was dependent on the flame spread end point only, i.e., the distance travelled by the flame in 10 minutes if not to the end of the furnace or the time for full travel, if achieved. The measured quantities were arbitrarily related to red oak performance which, as stated earlier, had to undergo flame-over in 330 s under the prescribed exposure conditions. In 1976, the calculation procedure was revised to reflect the history of the flame front in reaching the end point. Presently, the area beneath the distance-time plot is compared to that of red oak for classification so that, in principle, any vagaries in construction or operation are compensated for. Unfortunately, no comprehensive, published data are available to evaluate the effect of this change on precision.

The SDC is similarly based on a comparison of the area beneath an obscuration-time plot for the test specimen, to that of the red oak reference. In this case, however, the reproducibility of results was less than satisfactory and was attributed to improper specification of the smoke photometer in the standard. Other explanations are offered later.

Lee and Huggett (9) regarded the specification in the 1970 standard of the draft control pressure tap location as inadequate. McGuire (10) deduced that when the tap was situated at the hot end of the tunnel, failure to install it on the tunnel centre line could result in major differences in inlet flow rate from installation-to-installation and from material-to-material, as the recorded pressure drop (used for controlling draft), was dependent additionally, on tap height and gas density. Given the strong influence of inlet air flow on smoke dilution and the Quintiere and Raines finding (6) that air flow controlled by over-all pressure drop varied during a test, it is more likely that improper air flow control rather than poor specification of the photometer was the major cause of the poor reproducibility of smoke data. The recent change to constant mass flow operation should eliminate this source of error.

The heat transfer characteristics of the exhaust duct, between the tunnel exit and the photometer are another cause for concern. The obscuration due to wood smoke consisting mainly of condensed liquids, is temperature dependent, whereas that of smoke from synthetic polymers, containing mostly carbon particulates, is time dependent because of coagulation (9). Since the reference material used to normalize the smoke data is a wood, differences in results due to dissimilar ducts could be relatively small for other wood products but larger for synthetic materials.

Turbulence in the exhaust duct is also of importance. Gas concentration profiles in the duct at the location of the photometer indicate appreciable stratification, which can be reduced or eliminated by introduction of a mixing baffle a short distance from the tunnel exit (Figure 4). The data of Table II indicate that marked improvements in smoke data repeatability can be achieved by properly mixing the exhaust gas, although it appears that the use of a baffle is not without side effects. It is possible that bends and elbows in the exhaust duct will encourage settling of particles rather than promote homogeneity.

A direct result of the Lee and Huggett study (9) was the introduction of several revisions to subsequent standards to provide for constant mass flow operation, greater attention to detail in tunnel geometry, lining materials, turbulence and photometer design. Unfortunately, these modifications were issued piecemeal so that when a round robin, sponsored by the ASTM tunnel operators' group, was run in 1976 the results were inconclusive as several laboratories had not implemented the prescribed changes.

The most recent interlaboratory study was conducted by Lawson (11) who assessed the method, as mandated by the Consumer Product Safety Commission (CPSC) for use with loose-fill cellulose insulation. Using data from six facilities on eight carefully prepared materials, Lawson found the coefficients of variation ranged from 11 to 23 per cent within a laboratory and from 31 to 41 per cent between laboratories. Smoke was not evaluated. Compared with the results of the Lee and Huggett study (9), it appears that little progress has been made. It should be emphasized, however, that the material tested is known to be highly variable. Although care was exercised in its preparation and installation, the influence of material heterogeneity on performance cannot be discounted. For this reason, Lawson discarded data from tests on two of the eight materials selected.

Certain aspects of the CPSC study warrant further comment. A fine metal mesh used to support the specimen does not permit exposure of the sample in a manner comparable to that for other self-supporting materials. Further, the use of a factor based on similarly screened red oak flooring tests to correct for this disparity is technically unjustifiable.

COMPARISON WITH OTHER TEST METHODS

It is customary in performance test evaluation to compare results from various tests that claim to measure the same characteristic on a given material. Table III provides a comparison of data taken from the literature (12-15) on generically similar materials. Since the mechanisms controlling flame spread are often unknown, the results should not be interpreted too literally.

Because the definition of precision is such as to be synonymous with low variability, the precision of the tunnel FSC appears to rank favourably relative to the other methods. Corresponding smoke data are poor, particularly in regard to correlation between laboratories.

CONCLUSIONS

Available data indicate that although the precision of FSC measurements in the tunnel test is of the same order as other contemporary methods, there is still room for improvement.

Inlet air velocity does not exert a noticeable influence on the FSC because of the opposing effects of oxygen supply rate and gas bulk temperature reduction accompanying an increase in air flow. Heat transfer to the specimen for pyrolysis is seen as the principal propagation control mechanism. Turbulence is important as a means of convective energy transfer. Tests have shown that, with some materials at least, the heat release by the specimen during the flame spread period is low and that a major portion of the released energy is dissipated within the tunnel. Although there is an effort to control heat losses to the tunnel lining through specification of its thermal properties, more attention should be devoted to controlling burner characteristics as the burner is initially the main source of energy for pyrolysis. The number and axial locations of the observation windows should also be provided in the standard.

The problems associated with smoke measurement are less easily identified. Accurate description of the photometer alone is insufficient to reduce metering uncertainties as variation in inlet air flow is reckoned to be a prime cause of error. Operation with the draft control pressure tap located to give constant mass flow will eliminate this aspect of the problem. Furthermore, the section of the exhaust duct upstream of the photometer needs better description in terms of its geometry and heat loss performance.

The concept of a SDC based on obscuration measurements normalized to those of red oak is questionable. Direct obscuration of a light beam by smoke does not offer a linear measure of smoke concentration as the latter quantity is dependent on the negative logarithm of transmission. Corrections for changes in volumetric flow rate past the photometer, due to gas expansion, should also be included in optical density measurements. Finally, the smoke formation and destruction mechanisms for the reference material cannot be considered representative (as assumed by the standard) of the vast range of building materials encountered in practice.

There is an acute need for comprehensive, reliable interlaboratory test data to establish the precision of the test method following implementation of prescribed changes. In particular, the area based method of FSC calculation needs proper appraisal.

REFERENCES

1. Mandel, J. Repeatability and reproducibility. Materials Research and Standards, Vol. 11, p. 8, 1971.
2. Standard test method for surface burning characteristics of building materials. ASTM E84-79a, American Society for Testing and Materials, Philadelphia, 1979.
3. Endicott, L.E. and Bowhay, R.B. A statistical evaluation of the fire hazard classification furnace (ASTM E84-68). Materials Research and Standards, Vol. 10, p. 19, 1970.
4. Castino, G.T., Beyreis, J.R. and Metes, W.S. Flammability studies of cellular plastics and other building materials used for interior finishes. Subject 723, Underwriters' Laboratories Inc., Northbrook, Illinois, 1975.
5. Priest, D.N. and White, J.A. A statistical evaluation of both the ASTM E84-78, 25 ft tunnel and the proposed ASTM tunnel floor test method. Weyerhaeuser Company, Private communication, 1979.
6. Quintiere, J.G. and Raines, J.W. Thermal and flow characteristics of the ASTM E84 tunnel test method. NBS Internal Report Number 75-705, 1975.
7. Groah, W.J. A study of certain operating and material variables of the 25 ft tunnel flamespread test. Forest Products Journal, Vol. 23, p. 39, 1973.
8. Yuill, C.H. Flame spread tests in a large tunnel furnace. Symposium on Fire Test Methods, ASTM Special Technical Publication No. 344, 1962.
9. Lee, T.G. and Huggett, C. Interlaboratory evaluation of ASTM E84-70 tunnel test applied to floor coverings. Journal of Testing and Evaluation, JTEVA, Vol. 3, p. 3, 1975.
10. McGuire, J.H., Private communication with Tunnel operators' group, 1976.
11. Lawson, J.R. An interlaboratory evaluation of the ASTM E84-77a tunnel test modified by the Consumer Product Safety Commission for cellulosic loose fill insulation. NBS Internal Report Number 79-1922, 1979.
12. Benjamin, I.A. and Adams, C.H. Proposed criteria for use of the critical radiant flux test method. NBS Internal Report Number 75-950, 1975.

13. Lee, T.G. Reproducibility of the radiant panel test method (ASTM E162-67) using polyurethane foam, neoprene and hardboard specimens. NBS Internal Report Number 77-1222, 1977.
14. Lawson, J.R. Interlaboratory evaluation of the attic floor radiant panel test and smouldering combustion test for cellulose thermal insulation. NBS Internal Report Number 79-1588, 1979.
15. Lee, T.G. Interlaboratory evaluation of smoke density chamber. NBS Report Number 10328, 1970.

TABLE I

VARIABLES THAT INFLUENCE TUNNEL PERFORMANCE

Variable		Influences
Apparatus variables		
Inlet and burner design		Mixing and heat release at leading edge
Thermal properties of lining		Heat loss to surroundings
Window design-number and location		Heat loss to surroundings
Turbulence bricks		Mixing
Duct cross-sectional area		Mixing and heat transfer-bulk fluid flow
Specimen locating ledge design		Heat transfer at crucial location
Exhaust duct design		Smoke measurements
Specimen variables		
Thickness		Heat transfer-substrate important if thin
Moisture content		Heat required for moisture desorption
Method of retention		Heat transfer to specimen
Operational variables		
Inlet Air	- velocity	Mixing, heat transfer
	- bulk flow	Mixing, heat transfer, oxygen, smoke
	- temperature	Heat transfer, chemical reaction
	- moisture content	Bulk temperature, chemical reaction
Fuel	- bulk flow	Heat release at inlet
	- heating value	Heat release at inlet
	- temperature and pressure	Minimal, on heat release
Other	- specimen preheat	Heat required for pyrolysis
	- lining temperature	Heat loss to surrounding
	- visual flame spread measurement	-

TABLE II

EFFECT OF MIXING BAFFLE ON SMOKE DATA

Material	No. of Tests	FSC Avge	FSC CV%	SDC Avge	SDC CV%
No mixing baffle					
Particleboard	3	136	5.4	144	31.0
Hardboard	3	129	8.9	166	31.5
Fibreboard	2	267	9.3	118	37.1
Baffle at 0 deg to duct centreline					
Particleboard	3	152	5.7	178	12.3
Hardboard	2	136	2.1	359	1.8
Fibreboard	3	236	13.0	92	8.9
Baffle at 30 deg to duct centreline					
Particleboard	3	152	2.1	153	8.0
Hardboard	3	135	11.1	414	28.8
Fibreboard	3	282	2.1	86	12.0

CV% = (Standard deviation/Average) x 100.0

TABLE III

COMPARISON OF PRECISION ESTIMATES FOR FIRE TEST METHODS

			Max CV %		
ASTM Method	Material	Property	In-Lab	Bet-Lab	Ref
E84-70	Carpet	Flame spread	27	29	9
E648-78	Carpet	Flame spread	19	21	12
E84-70	Luan plywood	Flame spread	23	43	9
E84-77A	Loose fill insul'n	Flame spread	23	37	11
E84-77a	Screened red oak	Flame spread	5	10	11
E162-67	Hardboard	Flame spread	44	45	13
E648-78	Loose fill insul'n	Flame spread	15	28	14
E84-70	Divers	Smoke	35	85	9
E662-(70)	Divers	Smoke-nonflaming	29	27	15
		-flaming	23	34	15

CV % = Coefficient of Variation.

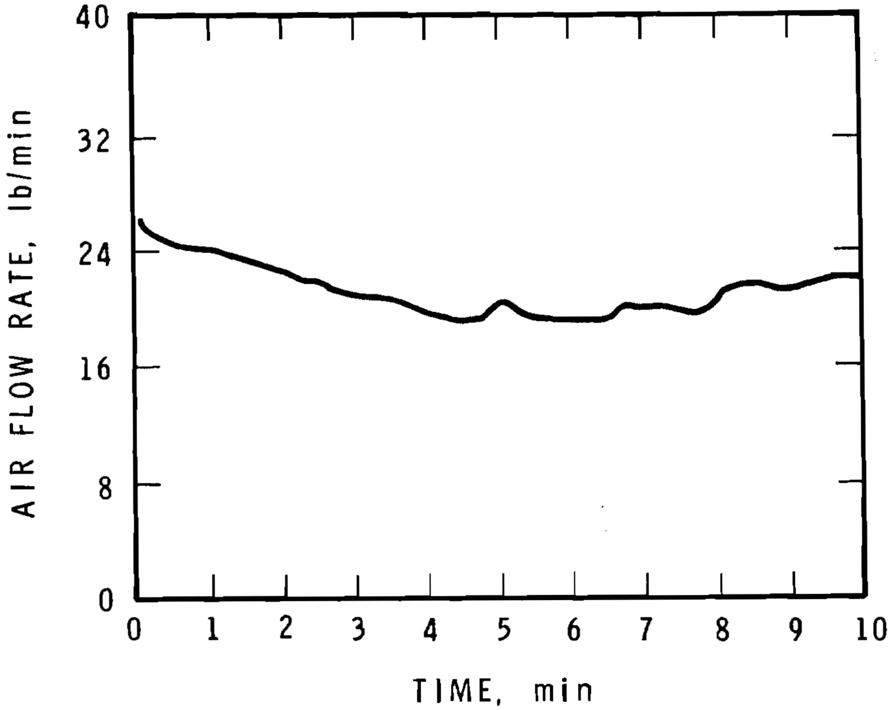

FIGURE 1

AIR MASS FLOW RATE FOR NYLON CARPET (1 lb/min - 0.00756 kg/s) (J.G. QUINTIERE AND J.W. RAINES [6])

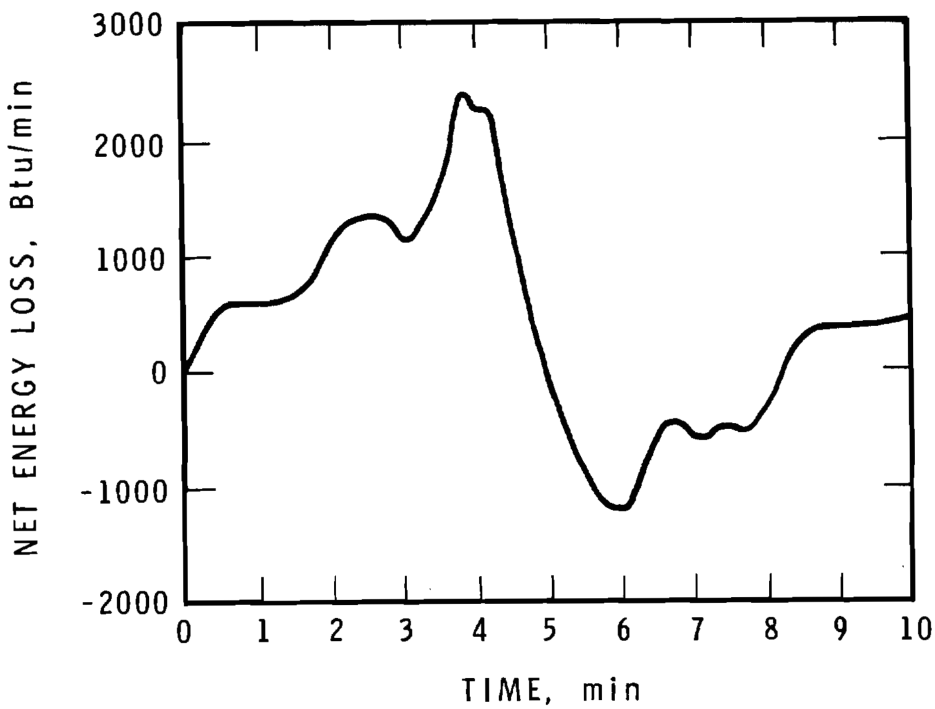

FIGURE 2

NET ENERGY LOSS BETWEEN 15 AND 24 FOOT PLANES FOR NYLON CARPET (1 Btu/min - 17.6 W) (J.G. QUINTIERE AND J.W. RAINES [6])

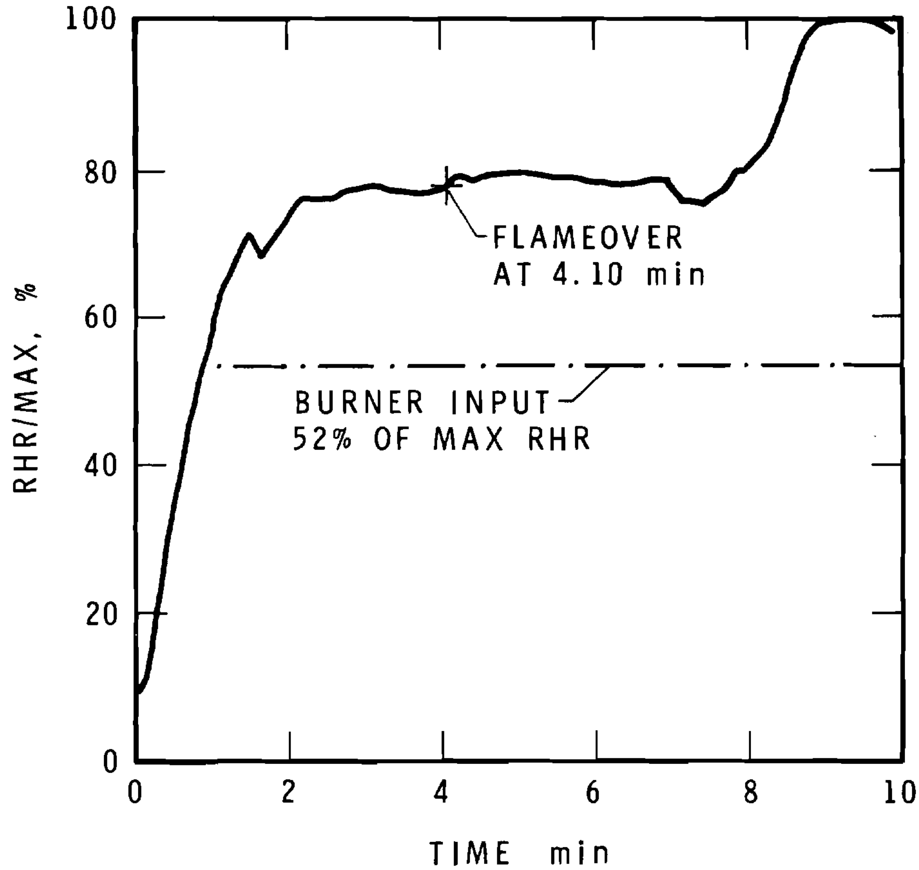

FIGURE 3

TOTAL RATE OF HEAT RELEASE AS PERCENTAGE OF MAXIMUM VALUE FOR 12.7 mm FIBREBOARD

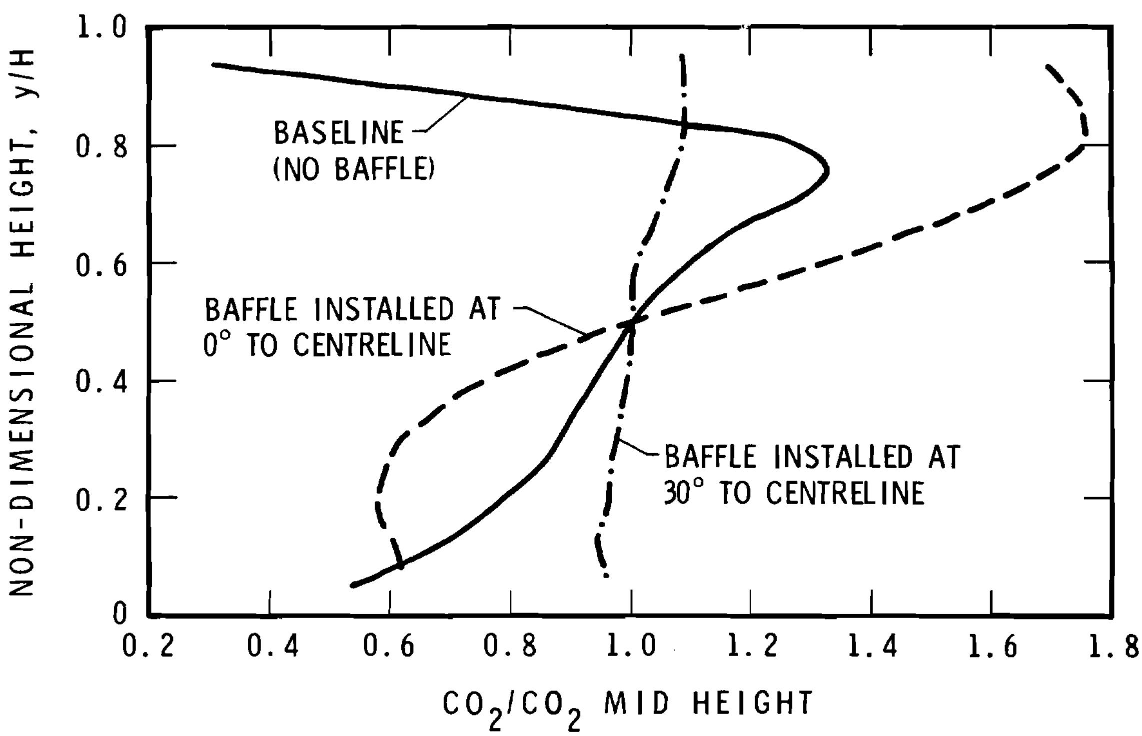

FIGURE 4

VERTICAL PROFILES OF CO_2 AT PHOTOMETER LOCATION DURING BLANK RUN SHOWING EFFECT OF MIXING BAFFLE IN EXHAUST DUCT