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COMPARATIVE RATES OF HEAT RELEASE FROM FIVE DIFFERENT TYPES OF TEST APPARATUSES

by

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Abstract

Previously reported rates of heat release using five different bench-scale test methods are compared with each other and against a limited series of large-scale tests. The materials tested were low-flammability wall lining materials, of a construction similar as might be used for aircraft cabin walls. Based on the peak values at different irradiances, three of the methods gave similar results: the Cone Calorimeter, the FMRC Flammability Apparatus, and the Flame Height Apparatus. The other data, from the OSU calorimeter in the thermopile mode and the OSU calorimeter in the oxygen-consumption mode, gave results typically 1/2 of the first three methods. Simple techniques for predicting full-scale performance from bench-scale data are emerging. The preliminary application of these appears promising.

Keywords: aircraft cabin materials; fire tests; flashover; ignitability; plastic composites; rate of heat release tests.

Background

The rate of combustion energy evolved from a fire is one of the most important, and in many cases the single most important, measure of fire hazard. Over the years, a number of techniques have been developed for measuring this quantity. Due to early measurement techniques being based on sensible heat measurement techniques, this quantity is typically referred to as rate of heat release. Measurement principles and techniques have been reviewed in some detail by Tsuchiya [1] and Janssens and Minne [2]. Here we will simply state that there are five principles in common or recent use:

- Adiabatic box--this method is based on measuring the temperatures and possibly the flow rates, if not constant, of the exiting fire gases. In practice, the box is not made adiabatic, since this would require guard heaters, but is merely covered with thermal insulation. The Ohio State University calorimeter [3] is an example.

- Isothermal box--this method is based on maintaining a constant exiting gas fire temperature. The constant temperature is maintained by means of a substitution burner, and the amount of increase in the burner heat is the negative of the specimen heat release rate. The NBS-II calorimeter [4] is an example.

- Oxygen consumption--this method is based on determining the amount of oxygen removed from the combustion stream, and using a relationship between heat evolved and oxygen consumed. A box is not necessary for use of this principle, and burning can be in the open air. The Cone Calorimeter [5] is an example.

- Evolution of carbon dioxide and carbon monoxide--this is an open test similar to oxygen consumption, except that CO_2 and CO production are monitored, instead of O_2 consumption. The FMRC Flammability Apparatus was originally developed for this mode of operation [6]; the FMRC apparatus currently is usually used in an oxygen consumption mode.

- Heat release estimation on the basis of flame heights of freely-burning fires [7]--this is a new technique which can be especially useful as an additional diagnostic from tests where free-burning fires are observed.

The two available reviews of the state of the art [1,2] discuss some of the strengths and limitations of various measuring approaches. Nonetheless, with the exception of the recent study by Ostman *et al*. [8], there has been little attempt to study the performance of different heat release rate apparatuses for testing a prescribed set of materials at various irradiances.

Such an opportunity recently occurred. The Federal Aviation Administration (FAA) asked the National Bureau of Standards (NBS) and Factory Mutual Research Corporation (FMRC) to join them in a study of aircraft wall paneling materials. Five materials, intended to represent constructions suitable for use as aircraft cabin interior wall panels comprised the test series (Table 1). The laboratories were asked to use the test apparatuses they thought most appropriate, and to conduct tests over a wide enough range of conditions to ensure capturing the essence of specimen performance. The FAA also arranged to conduct full-scale tests of the same materials to assess the actual expected behavior and to produce rankings.

The detailed reports of the full-scale findings [10] and the bench-scale tests [9,11] are now available. In this paper, we will use that data to compare the performance of the various test methods and point out areas of agreement and disagreement.

Test Apparatuses and Procedures

The test apparatuses used were the following:

- OSU/Thermopile--this is the standard configuration of the OSU method, as described in the ASTM Standard E 906 [3]. The FAA initially conducted this test as specified [3], with the exception of using an improved baseline correction routine [9]. Later, the FAA revised both the test procedures and some of the test hardware and reported further tests [10].

- OSU/Oxygen Consumption--this was an adaptation by the FAA [10], consisting of the standard OSU apparatus, but with the addition of an oxygen probe inside the exhaust duct to monitor O_2 levels, and using the established principles [12] for computing heat release from oxygen consumption. The data were published in Ref. [9].

- Cone Calorimeter--these tests were conducted by NBS with the oxygen consumption Cone Calorimeter apparatus [5] and by using the normal test procedures [13].

- Flame Height Apparatus--these tests were conducted by NBS in a flame spread apparatus, and the results evaluated according to the flame height/heat release rate relationship [7].

- FMRC Flammability Apparatus--these tests were conducted by FMRC using their standard procedures, which use oxygen consumption measurement, supplemented with the use of CO_2 and CO generation data [6].

The test specimens were especially procured by the FAA for their test program, and were generally similar, but not actually identical, to production panels in current use. The specimens were all tested in the thickness as manufactured (approximately 7 mm), but were of varying sizes and orientations, as needed for the specific test method. Table 2 summarizes these test conditions. In all cases, piloted ignition was used, but with different designs of pilots being used in the different apparatuses. In the case of the FMRC Flammability Apparatus, the specimens were painted prior to test with a dull black paint of very close to unity emissivity. In all other cases, the surfaces were used as manufactured, being of a white color on the exposed face.

Test Results

The results which were obtained from each of the test apparatuses [9,10,11] are summarized in Figures 1 through 5. Peak values are tabulated, since prior work [16] has shown that they can be useful for the evaluation of hazards on combustible wall linings. The aircraft panels tested were difficult-to-ignite, highly fire-retardant materials; as is typical with such materials, a fair amount of data scatter is noted in the results. With three test apparatuses, the Cone Calorimeter, the FMRC Flammability Apparatus, and the Flame Height apparatus the results were generally close, ranging from about ±5% for the case of the specimens in Figure 5 to about ±25% in the worst case (Figure 1). In general, for these three methods the results can be considered in reasonable agreement, to within the general scatter of the data. (The average coefficient of variation, i.e., the standard deviation expressed as a fraction of the mean, was 8.4% for the Cone Calorimeter; it is estimated that the coefficients of variation for the other apparatuses were also in the range of 5% to 10%.) With the Cone Calorimeter, a slight, but systematic effect can be seen whereby higher heat release rate values hold for the vertical orientation than for the horizontal. Such a relationship is not always obtained; data for red oak, for instance, show the opposite trend [5]. Thus, the aircraft panels' increased heat release rate in the vertical orientation may be due to some specific thermostructural features of the panels, possibly related to the way the outer layers tend to delaminate and curl during the test exposure.

The values from the OSU apparatus, as tested with the original procedure [9], were consistently about half the value of data from the other instruments. The differences between OSU/thermopile and OSU/O_2, however, were not so pronounced, being typically 10 to 20% higher for the O_2 mode. The exact reasons for such a pronounced difference between the OSU and the other instruments are not definitively known. The available investigations [1,14,15] suggest that radiative losses in a thermopile-sensing apparatus can result in significant under-accounting of heat release. The same investigations, however, show that such errors are substantially reduced when the O_2 consumption technique is used. For the present measurements, the 10 to 20% increase of OSU/O_2 rates over the OSU/thermopile rates do not put the OSU/O_2 data into agreement with the remaining techniques. Data at only a single irradiance value (35 kW/m^2) are available for the revised OSU/Thermopile test procedure [10]. These values are higher than ones from the original test procedure, but still lower than the data from the other test apparatuses. More detailed conclusions are not possible since data are not available at other irradiance values.

Comparison with Full-Scale Data

The FAA also conducted full-scale tests, comparing the performance of the five panelling materials in a C-133 aircraft cabin. Since for significant hazard to develop, these tests had to include cabin seats and other combustible, a simple test of the panels alone could not be evolved. Nonetheless, when tested in the end-use configuration, the different panels showed substantially different results [10]. Table 3 shows the flashover times measured.

Until recently, techniques had not been available for accurately predicting the full-scale hazards of wall lining materials based on bench-scale tests. A technique has recently been proposed, however, for which significant success has been obtained for wall lining materials of buildings [16]. It is useful to consider the application of this technique to the present case of aircraft paneling. The technique states [16] that the flashover speed, v_f, is proportional to the peak bench-scale heat release rate, $\dot{q}''$, divided by the time to ignition, t_{ig}.

$$v_f = \frac{\sqrt{A}}{t_f} \propto \frac{\dot{q}''}{t_{ig}}$$

The flashover speed is a quantity which increases with increasing hazard, and was defined as equal to the typical ceiling distance (taken as $\sqrt{A}$, where A = the ceiling area) divided by the time to flashover, t_f. The test irradiance from which the $\dot{q}$ values should be determined should represent the actual fire conditions, but is, in fact, not known prior to testing. Once bench-scale results are obtained for various irradiance values, the proper one to use might be found from performing a correlation between the full-scale and the bench-scale result.

In the case of the aircraft tests, the area of the ceiling was not clearly defined, since the test cabin was partly divided into two sections. The area did not vary from test to test, however, so we will simply set $v_f \propto 1/t_f$. This value is also listed in Table 3. Since the flashover relationships have been developed on the basis of bench-scale values obtained from the Cone Calorimeter, relevant measurements from the Cone Calorimeter on the aircraft panels are listed in Table 3. The usefulness of the other bench-scale test methods in predicting full-scale flashover conditions has not been explored.

The function $\dot{q}''/t_{ig}$ shows distinctions between the specimens reaching flashover more slowly in full scale (PH/FG, PH/GR) from the faster group (EP/FG, PH/KV); since full-scale data were not reported on the EP/KV specimen, conclusions about its flashover behavior cannot be reached. From the four full-scale data points given in Table 3 it could be concluded that not only $\dot{q}''/t_{ig}$, but also $\dot{q}''$ itself, and also some function such as $\dot{q}''/t_{ig}^2$, which weights the time response more heavily, could distinguish between the better group and the poorer group. It is relevant to observe that companion FAA full-scale tests on panels without seats [10] showed that specimens EP/FG and PH/KV, while sharing an identical time to flashover, did not have similar curves of heat buildup. Specimen PH/KV showed a slower buildup to peak, but a higher peak temperature. Thus, under somewhat different ignition scenarios different results and rankings might be obtained. Four full-scale tests, while informative, do not represent a statistically sufficient number of samples on which to base a general purpose prediction rule. The analysis conducted for the FAA by Parker [17] showed that methods based on rate of heat release alone, when used for predicting compartment flashover due to combustible wall linings, tend to satisfactorily predict that performance only if a narrow range of specimens is considered. When the possibility of a wider range of specimens, with thermal properties dissimilar from each other, has to be allowed for, a function involving both the heat release rate and the ignition time has been shown necessary to avoid erroneous rankings [16]. The function as developed for combustible materials in buildings [16], and as discussed above, may not necessarily be appropriate to aircraft paneling. Thus, it will be desirable to conduct more full-scale (and companion bench-scale) tests to be able to establish with confidence a predictive function suitable for a range of future materials.

Conclusions

Heat release rate data on materials of low flammability tested with five different test methods showed that for three of the test methods--Cone Calorimeter, FMRC Flammability Apparatus, and Flame Height apparatus--the disagreements between the methods were small, generally within the scatter of the data. Three different sensing principles were used in these three methods. For the OSU/Thermopile and OSU/O_2 methods with the original test procedure, however, the values reported were about 1/2 those from the remaining three methods. The agreement between the two different sensing principles in the OSU apparatus (thermopile and O_2 consumption) was much closer (∿20%) than between the methods (Cone Calorimeter and OSU/O_2) which shared the same sensing principle (∿factor of 2). Data from the revised OSU/Thermopile procedure suggest better agreement to the remaining methods, but the number of available data points is small. This suggests that, for data validity purposes, physical features and operation protocols for the test methods may be just as important as the sensing principles, the effects of the latter having been previously demonstrated [14,15].

New techniques are becoming available for predicting the full-scale performance of wall linings based on bench-scale data. The present data give encouragement for such attempts, and it will be interesting to pursue these techniques as larger data sets become available.

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Table 1

Properties of the test specimens [10]

Designation	Description
EP/FG	Epoxy glass facings, face and back 1-ply 7781 fiberglass impregnated with resin, fire retardant, and co-cured 1/8 cell, 1.8 lb, 1/4-inch thick Nomex™ honeycomb. Outer surface covered with 2-mil white Tedlar™ Wt. = 0.36 lbs/sq. ft.
PH/FG	Phenolic glass facings, face and back 1-ply 7781 style woven fiberglass impregnated with a modified phenolic resin, and co-cured to 1/8 cell, 1.8 lb, 1/4-inch thick Nomex™ honeycomb. Outer surface covered with 2-mil white Tedlar™ Wt. = 0.42 lbs/sq. ft.
EP/KE	Epoxy Kevlar tm facings, face and back 1-ply 285 style woven Kevlar impregnated with epoxy resin, fire retardant, and co-cured to 1/8 cell, 1.8 lb, 1/4-inch thick Nomex™ honeycomb. Outer surface covered with 2-mil white Tedlar™ Wt. = 0.38 lbs per sq. ft.
PH/KE	Phenolic Kevlar facings, face and back 1-ply 285 style woven Kevlar impregnated with a modified phenolic resin and co-cured to 1/8 cell, 1.8 lb, 1/4-inch thick Nomex™ honeycomb. Outer surface covered with 2-mil white Tedlar™ Wt. = 0.38 lbs per sq. ft.
PH/GR	Phenolic graphite facings, 1-ply 8 harness satin, 3K fiber T-300 woven graphite impregnated with a modified phenolic resin, and co-cured to 1/8 cell, 1.8 lb, 1/4-inch thick Nomex™ honeycomb. Outer surface covered with 2-mil white Tedlar™ Wt. = 0.36 lbs/sq. ft.

Table 2

Specimen testing conditions

Test method	Orientation	Specimen size (mm)	Test heat fluxes (kW/m^2)	Surface condition
OSU/Thermopile[a]	V	150 x 150	25, 50, 75	as received
OSU/Thermopile[b]	V	150 x 150	35	as received
OSU/O$_2$	V	150 x 150	25, 50, 75	as received
Cone Calorimeter	H	100 x 100	25, 50, 75	as received
" "	V	100 x 100	25, 50, 75	as received
Flame Height	V	284 x 284	20, 25, 30, 37	as received
FMRC	H	100 x 100	26, 39, 61	blackened

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[a]--using initial testing procedure [9]
[b]--using revised testing procedure [10]

Table 3

Comparison to full-scale results

	Full-scale		Bench-scale[a]			
Specimen Code	Time to flashover (s)	$1/t_f$	$\dot{q}''$ (kW/m^2)	t_{ig} (s)	$\dot{q}''/t_{ig}$	$\dot{q}''/t_{ig}^2$
EP/FG	73	0.0137	271	7.9	34	4.3
PH/FG	239	0.0042	140	8.0	18	2.2
EP/KV	--[b]	--[b]	188	6.5	29	4.5
PH/KV	73	0.0137	219	8.5	26	3.0
PH/GR	200	0.0050	178	9.5	19	2.0

a -- Data obtained in the Cone Calorimeter, vertical orientation, 50 kW/m^2 irradiance. The coefficient of variation for $\dot{q}''$ is 8.4%, while for t_{ig} it is 5.5%.

b -- Data not available.

Figure 1. Rate of heat release for specimen EP/FG

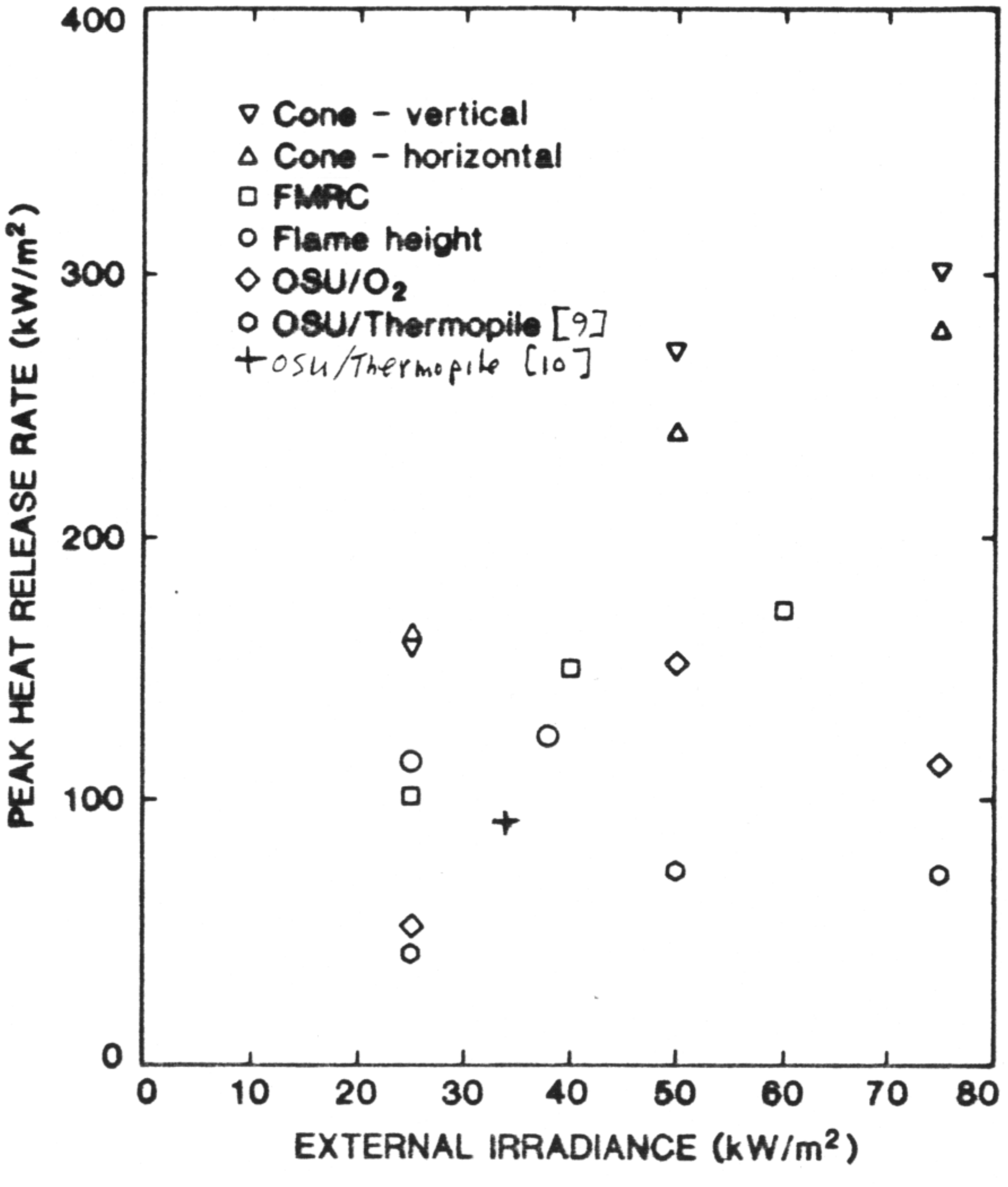
Figure 2. Rate of heat release for specimen PH/FG

Figure 3. Rate of heat release for specimen EP/KV

Figure 4. Rate of heat release for specimen PH/KV

Figure 5. Rate of heat release for specimen PH/GR

Fig 1



▽ Cone - vertical
△ Cone - horizontal
□ FMRC
○ Flame height
◇ OSU/O₂
○ OSU/Thermopile [9]
+ OSU/Thermopile [10]
PEAK HEAT RELEASE RATE (kW/m²)
400
300
200
100
0
0
10
20
30
40
50
60
70
80
EXTERNAL IRRADIANCE (kW/m²)

fig 2

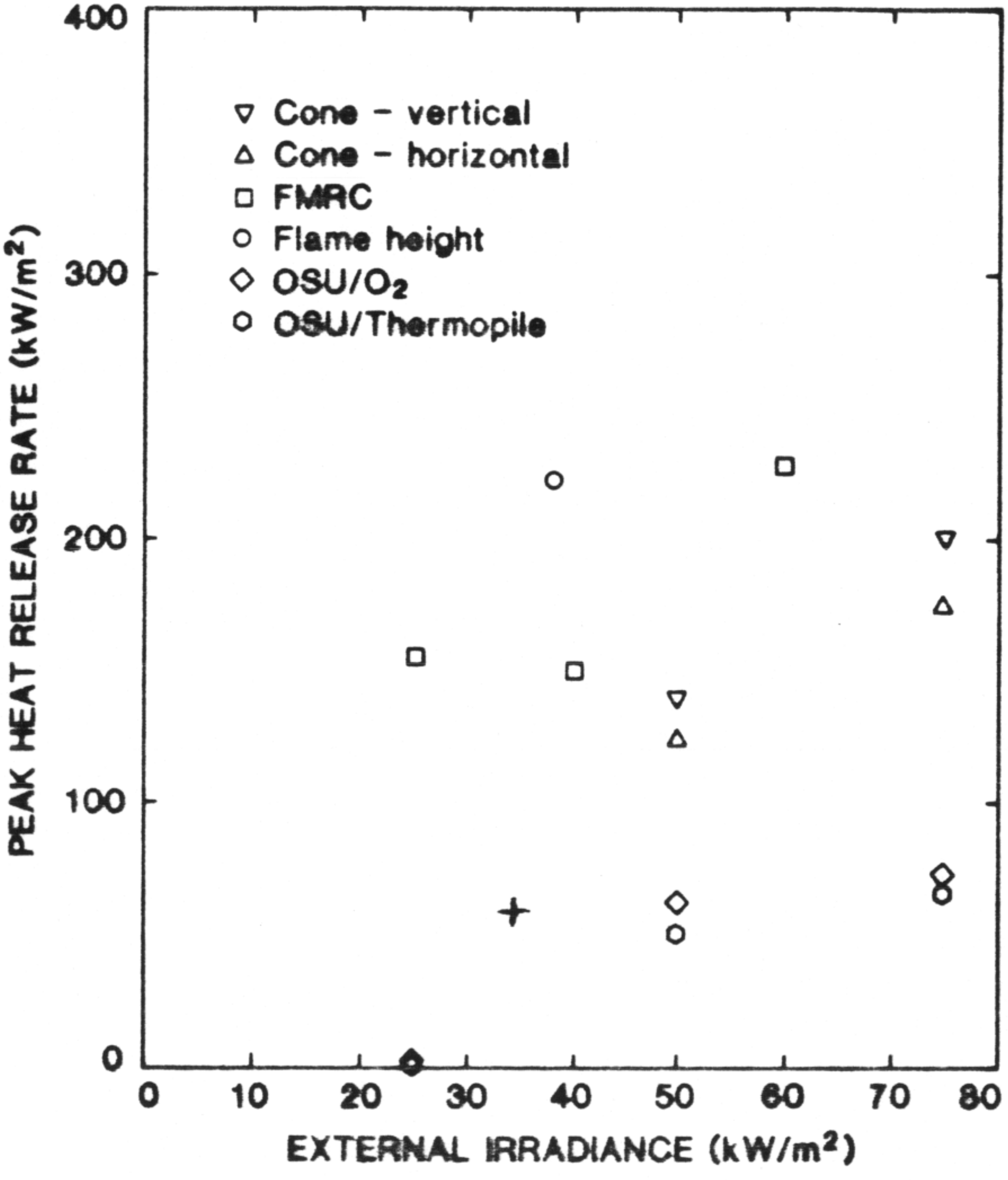
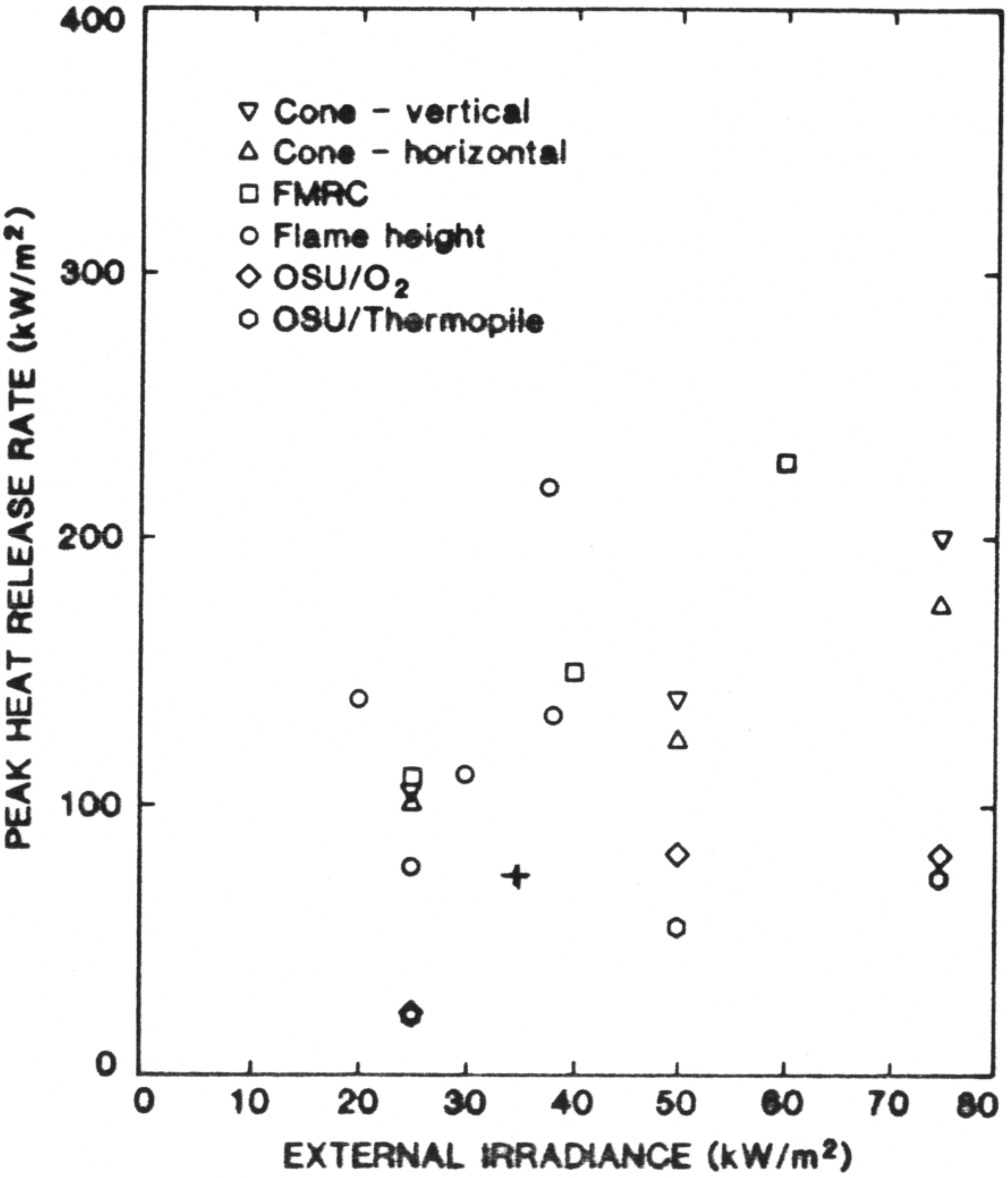

▽ Cone - vertical
△ Cone - horizontal
□ FMRC
○ Flame height
◇ OSU/O_2
⬡ OSU/Thermopile
PEAK HEAT RELEASE RATE (kW/m²)
400
300
200
100
0
EXTERNAL IRRADIANCE (kW/m²)
0
10
20
30
40
50
60
70
80

Fig 3



▽ Cone - vertical
△ Cone - horizontal
□ FMRC
○ Flame height
◇ OSU/O_2
○ OSU/Thermopile
PEAK HEAT RELEASE RATE (kW/m²)
0
100
200
300
400
0
10
20
30
40
50
60
70
80
EXTERNAL IRRADIANCE (kW/m²)

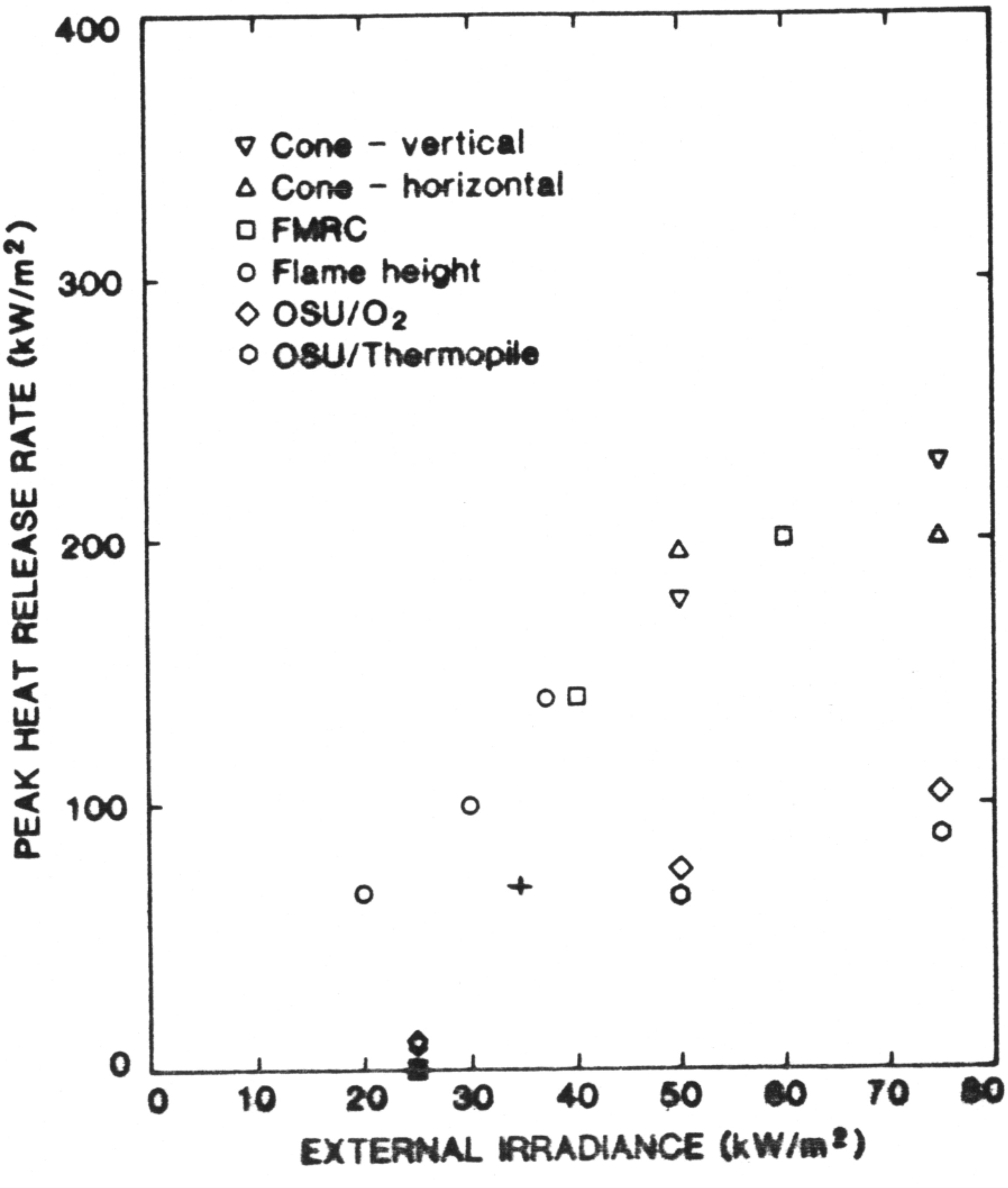
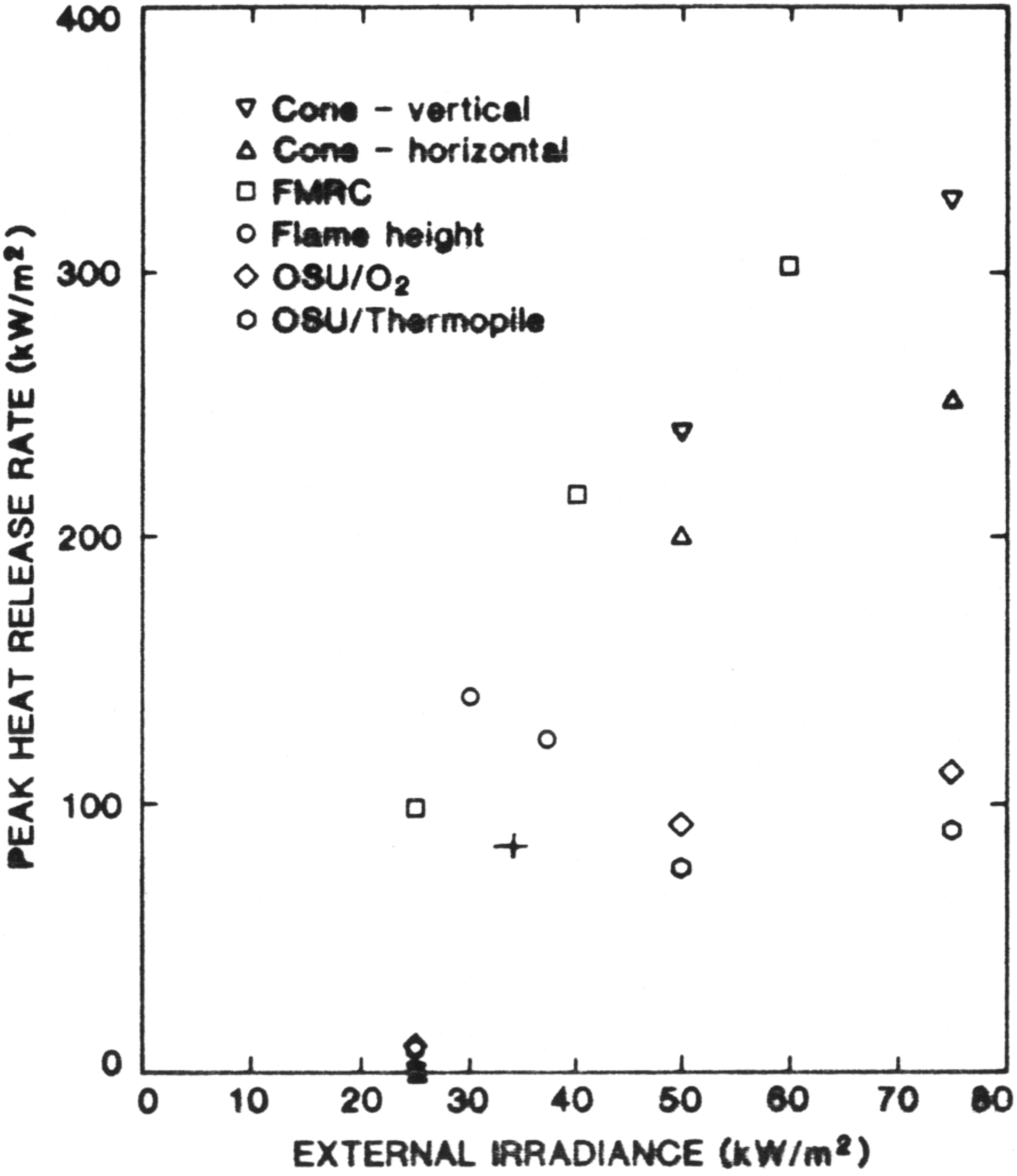

400
300
200
100
0
PEAK HEAT RELEASE RATE (kW/m²)
▽ Cone - vertical
△ Cone - horizontal
□ FMRC
○ Flame height
◇ OSU/O₂
○ OSU/Thermopile
0
10
20
30
40
50
60
70
80
EXTERNAL IRRADIANCE (kW/m²)

Fig 4



▽ Cone - vertical
△ Cone - horizontal
□ FMRC
○ Flame height
◇ OSU/O_2
○ OSU/Thermopile
PEAK HEAT RELEASE RATE (kW/m^2)
400
300
200
100
0
0
10
20
30
40
50
60
70
80
EXTERNAL IRRADIANCE (kW/m^2)