NBSIR 82-2597

Heat Release Rate Properties of Wood-Based Materials

July 1983

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

NBSIR 82-2597

HEAT RELEASE RATE PROPERTIES OF WOOD-BASED MATERIALS

David L. Chamberlain, Research Associate
National Forest Products Association

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Washington, DC 20234

July 1983

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

TABLE OF CONTENTS

Page

List of Figures v

List of Tables vii

Abstract 1

1. Introduction 1

2. Objectives 3

3. Historical Review of Heat Release Rate Calorimetry 3

4. Operating Characteristics of Existing Heat Release Rate Calorimeters . 4
   4.1 The Factory Mutual Construction Materials Calorimeter 4
   4.2 The Parker/Long NBS-I Heat Release Rate Calorimeter 5
   4.3 The NBS-I Rebuilt Calorimeter 5
   4.4 The Ohio State-Smith Heat Release Rate Calorimeter. 6
   4.5 The SRI International Heat Release Rate Calorimeter 6
   4.6 The Forest Products Laboratory (FPL) Heat Release Rate Calorimeter. 7
   4.7 Recent Developments 7

5. Materials and Methods. 8
   5.1 Wood-Based Materials. 8
   5.2 Conditioning. 9
   5.3 Calorimeter Operation 9
   5.4 Heat Release Rate Computation 11

6. Results and Discussion 12
   6.1 Characteristic Heat Release Rate Curves 12
   6.2 Heat Release Rates of Lumber and Other Wood Products. 13
      6.2.1 Lumber 13
      6.2.2 Plywood. 14
      6.2.3 Particle Board 14
      6.2.4 Acoustical Tile. 15
      6.2.5 Hardboard. 15
      6.2.6 General Effect of Density. 15
      6.2.7 Effects of Other Physical Properties 17
      6.2.8 Effect of Fire-Retardant Treatment 18
      6.2.9 Effect of Moisture Content 19
      6.2.10 Effect of Imposed Radiant Heat Flux. 21
      6.2.11 Comparison of First 1-Minute and First 5-Minute Heat Release Rates with the Corresponding Maximum Rates. . . 21

7. Comparison of Heat Release Properties Measured by Different NBS Calorimeters. 22
   7.1 Correlation of NBS-I, NBS-I Rebuilt, and NBS-II Calorimeter Values at 60 kW/m^2 Exposure Flux 22
      7.1.1 NBS-I Rebuilt Calorimeter. 23
      7.1.2 NBS-II Calorimeter 23
      7.1.3 Calorimeter Correlations 24
      7.1.4 Conversion Equations 25

Page

7.2 Effect of Density as Measured in the NBS-I Rebuilt and NBS-II Calorimeters 25
7.2.1 NBS-I Rebuilt Calorimeter 26
7.2.2 NBS-II Calorimeter. 27
7.3 Effect of Imposed Radiant Flux as Measured in the NBS-I Rebuilt and NBS-II Calorimeters 27
7.3.1 NBS-I Rebuilt Calorimeter 27
7.3.2 NBS-II Calorimeter. 28

8. Conclusions 28

9. Acknowledgments 30

10. References. 30

LIST OF FIGURES

Page

Figure 1. Diagram of FM Construction Materials Calorimeter 33

Figure 2. Diagram of NBS-I Calorimeter 34

Figure 3. Artist's View of NBS-I Calorimeter 35

Figure 4. Diagram of OSU Calorimeter 36

Figure 5. Drawing of SRI Calorimeter 37

Figure 6. Diagram of FPL Calorimeter 38

Figure 7. Photograph of FPL Calorimeter. 39

Figure 8. Artist's View of NBS-II Calorimeter 40

Figure 9. Diagram of NBS Oxygen Consumption Calorimeter 41

Figure 10. Typical HRR Curves: Douglas Fir. 42

Figure 11. Typical HRR Curves: Southern Pine. 43

Figure 12. Typical HRR Curves: Medium-Density, Paper-Faced Hardboard. . . 44

Figure 13. Typical HRR Curves: Medium-Density Hardboard 45

Figure 14. Typical HRR Curves: High-Density Hardboard 46

Figure 15a-d. Heat Release Rate Data Comparison of Materials Conditioned at 70°F and 50% RH, Exposed at 60 kW/m^2. 47

Figure 16a and 16b. Effect of Density on HRR Properties: NBS-I Calorimeter 51

Figure 17. Effect of Conditioning Room RH on HRR Properties 53

Figure 18. Effect of Radiant Flux on Heat Release Properties. 54

Figure 19a. Comparison of First 1-Minute HRR with Maximum 1-Minute HRR . . 55

Figure 19b. Comparison of First 5-Minute HRR with Maximum 5-Minute HRR . . 56

Figure 20a-i. Heat Release Rate Properties of Wood Products as Measured by Different NBS Calorimeters 57

Figure 21. Correlations Among NBS HRR Calorimeters. 66

Figure 22. Correlations Among NBS HRR Calorimeters (Cont.). 67

Figure 23. Effect of Density on HRR Properties: NBS-I R Calorimeter . . . 68

LIST OF FIGURES (continued)

Page

Figure 24. Effect of Density on HRR Properties: NBS-II Calorimeter. . . . 69

Figure 25. Effect of Radiant Heat Flux on HRR Properties: NBS-I Calorimeter 70

LIST OF TABLES

Page

Table 1. Heat Release Rate Calorimeters 71

Table 2. Physical Properties of Wood Products 72

Table 3. Format for Recording HRR Data. 73

Table 4. Heat Release Properties of Wood-Based Materials. 74

Table 5. Comparison of Heat Release Properties of Fire Retardant Treated Douglas Fir Plywood and Lumber, Untreated Controls, and Untreated Southern Pine Lumber. 75

Table 6. Effect of Conditioning Environment on Heat Release Properties. . 76

Table 7. Effect of Radiant Flux Exposure on Heat Release Properties . . . 77

Table 8. Comparison of First 1-Minute and First 5-Minute HRR with the Corresponding Maximum Rates. 78

Table 9. Comparison of Mean Heat Release Characteristics of Different NBS Calorimeters. 79

Table 10. Relationships Among Heat Release Values Determined by Different NBS Calorimeters. 81

Table 11. Effect of Radiant Flux on Heat Release Properties Measured in NBS-I Rebuilt and NBS-II Calorimeters. 82

Table 12. Summary of Heat Release Rate Data 83

HEAT RELEASE RATE PROPERTIES OF WOOD-BASED MATERIALS

D. L. Chamberlain*

Center for Fire Research
National Bureau of Standards

ABSTRACT

A background to the present heat release rate calorimetry is presented. Heat release rates and cumulative heat release were measured for 16 different lumber and wood products, using three different heat release rate instruments. The effects of moisture content, exposure heat flux, density of product, and fire retardant on rate of heat release were measured. The three small-scale heat release rate calorimeters were compared, and equations relating the data from each were developed.

Key Words: Acoustical tile; Douglas fir; fire retardants; hardboard; heat release rate; heat release rate calorimeters; irradiance; particle board; plywood; redwood; southern pine

1. INTRODUCTION

Few problems have proved as intractable as that of unwanted fire. Fire is a threat that has had society on the defensive since even before man learned how to produce it.

Bihr [1][1] cited early Roman laws that regulated building materials on the basis of their combustibility. As long as materials of construction were limited to wood and stone or brick, the qualitative definitions of combustible and noncombustible were adequate. As synthetic materials (including composite materials such as wood fiber-reinforced mineral board, gypsum board, and glass fiber-reinforced plastics) found useful places among construction materials, the need for quantitative definitions of the terms combustible and noncombustible became, and still is, urgent. In 1965, ASTM E 136-65, Standard Method of Test for Noncombustibility of Elementary Materials, was adopted for the evaluation of materials for their performance in fire, thereby permitting the use of those desirable materials that failed to meet the simple criterion of noncombustibility. This test defined noncombustibility in terms of (a) the temperature rise within a standard sample subjected to a specified heating cycle, (b) the absence of flaming after the first 30 seconds of exposure, and (c) specific weight-loss criteria.

---

*Research Associate, National Forest Products Association, 1973-1982.

[1] Numbers in brackets refer to the literature references listed at the end of this paper.

The meaning of "noncombustible" within the fire community was further broadened in 1973 by the Standard Building Code [2], which defined the terms in two parts: (a) in terms of the ASTM E 136 test and (b) in terms of the thickness of flammable material permitted on the surface of a noncombustible structural base. Thus, while it is probably clear to most individuals, on a qualitative basis, what is meant by the term "combustibility," the difficulties encountered in attempting to develop a precise and quantitative description of the word as it applies to the behavior of solid materials in real fires have not been overcome.

In recent years there has been a growing appreciation that an important criterion by which to evalute the fire behavior of materials is the rate at which heat is released during burning. Three stages occur in the course of total involvement of a solid material in fire: ignition, flamespread, and sustained burning. Ignition requires that the material receive sufficient heat from an outside source to raise the temperature of the material to its decomposition or pyrolysis temperature. Volatile pyrolysis products must diffuse into the surrounding air sufficiently to provide a mixture that lies within the flammability limits of the gaseous fuel. This mixture must then be heated to the temperature where "ignition" (the appearance of flame) occurs. Finally, heat must be supplied at a sufficient rate to maintain the pyrolysis process at a minimum rate in order that burning continues. If heat is supplied in excess of this minimum, additional material will become involved through the process of flamespread. Continued flame spread to total involvement of the sample, and subsequent destruction will continue only if sufficient heat is fed back from the flame or other sources of radiation to maintain the pyrolysis process in the solid phase of the material.

The development of a fire in the flamespread and sustained burning stages is dependent upon <u>rate</u> of heat release and is <u>not</u> inherently related to the <u>total</u> heat that would be released if the specimen burned to completion. An important aspect of the flamespread and sustained burning stages is the production of smoke and toxic gases. These stages, culminating in flashover when the fire is in an enclosure, are dominant as far as life safety is concerned. The important aspect of the third stage is fire endurance, in which efforts to contain the fire and save the structure depend in part upon the rate of combustion or rate of heat release of building contents and materials of construction.

Test methods to evaluate the performance of building materials with respect to flamespread, smoke production, and fire endurance have assumed major importance in efforts to control fires. Such methods have been developed into ASTM, NFPA, and other national standards. Rate of heat release is a relatively new criterion for evaluating fire behavior and is expected to assume similar importance in research, material assessment, and building regulations.

2. OBJECTIVES

The objectives of this research were:

- o to review the development of heat release rate calorimetry;
- o to establish by appropriate calorimetric methods the heat release properties of a broad range of commercially important wood-based construction materials;
- o to determine the effects of external heat flux and moisture content upon heat release rate of these materials; and,
- o to compare heat release rate values measured by different National Bureau of Standards' calorimeters.

A review of the history of heat release rate calorimetry and of the operating features of available heat release rate calorimeters provided a very helpful background for this work.

3. HISTORICAL REVIEW OF HEAT RELEASE RATE CALORIMETRY

Development of any test method may be characterized by three stages: the development of a concept, the development of an instrument to measure a quantity based on the concept, and the application of the measurements to a problem. The concept of rate of heat release has been described by several workers over the past 20 years. Instruments have been developed in five different U. S. laboratories to measure the rate at which heat is released from a burning material specimen. At some of these laboratories, efforts have been made to apply the measurements to the problems of controlling fires in structures and their contents.

The concept of heat release rate calorimetry is simply the measurement of the rate at which a known weight (volume or area) of a carefully prepared specimen releases heat when exposed to a prescribed and controlled heating environment. It is difficult to determine the original published suggestion that the rate of release of heat from a burning material should provide a good measure of burning behavior. In 1943, Steiner [3] described the measurement of "fuel contributed" during the flamespread measurement in his newly developed tunnel test. "Fuel contributed" was obtained by integration under a recorder plot of time versus flue-gas temperature at the end of the tunnel. While Steiner did not describe the plot as one of rate of heat release resulting from flamespread over the surface and subsequent burning of the sample, a "heat contributed value" was calculated from the temperature rise in the gases entering the stack.

In a similar manner, Robertson, Gross, and Loftus [4] in 1956 described a flamespread index in what is now ASTM E 162, Standard Test for Surface Flammability. The index was a combined value of the rate of progress of the flame front together with a factor involving the heat generation by the material under test. Neither the Steiner nor the Robertson/Gross/Loftus test was designed to provide information on rate of heat release.

Thompson and Cousins [5], in 1959, described the FM Construction Materials Calorimeter developed at Factory Mutual Laboratories, apparently the first instrument intentionally designed for determining rate of heat release from burning materials. The importance of heat release rate began to be more widely recognized in subsequent years. British Standard 476: Part 6: 1968 [6] accounted for "the amount and rate of heat evolved by the specimen while it is being subjected to heat in an enclosed space under prescribed conditions." In practice, a performance index was calculated from data obtained from plots of stack-gas temperature versus time. ASTM E 286-65T, Surface Flammability of Building Materials Using an 8-foot Tunnel Furnace [7], also develops a time-temperature curve from which the total heat release is obtained. This same curve can be used to determine rate of heat release, if desired.

The rate of weight loss of a burning material has also been used as a measure of the rate of energy release during burning [8,9,10]. Weight-loss rate is directly related to rate of heat release only in those cases where fuel composition and combustion efficiency remain constant as burning progresses.

Two fresh approaches to the measurement of heat release rates by burning materials were presented simultaneously in 1972 by Parker and Long [11] at the National Bureau of Standards (NBS) and by Smith [12] at Ohio State University (OSU). Subsequently, Martin and coworkers [13] at Stanford Research Institute (now SRI International) scaled up and modified the NBS calorimeter design. In 1973, Brenden [14,15] reported on heat release rate equipment developed at the Forest Products Laboratory (FPL). More recently, a second NBS calorimeter, similar in principle of operation to the Parker/Long instrument, was designed and built by Tordella [16]. Finally, a heat release rate instrument was developed by Sensenig and Parker [17] at NBS, based upon the principle of oxygen consumption during the combustion process [18].

4. OPERATING CHARACTERISTICS OF EXISTING HEAT RELEASE RATE CALORIMETERS

A number of different methods have been developed for measuring heat release rates of materials under conditions that may be expected in actual fires. The size of samples used and operating features of these different methods vary widely. Those measurement methods designed for possible use as standard test methods are described below.

4.1 The Factory Mutual Construction Materials Calorimeter

The Factory Mutual Construction Materials Calorimeter, referred to as the FM calorimeter [5], Figure 1, has been in use for a number of years for evaluating interior finish materials and floor, roof, and wall assemblies. The exposure imposed on the relatively large sample (1220 x 1220 mm) is obtained from a burning heptane-air mixture and corresponds, roughly, to the standard ASTM E 119 time-temperature curve compressed into a much shorter time. Maximum heat flux is about 150 kW/m^2.

Interior finish materials are usually exposed in the instrument for 10 minutes, while construction assemblies are exposed for 30 minutes. The flue gas temperature is recorded throughout the test run. In a subsequent evaluation run, an inert (or reference) sample is substituted for the test sample and given the identical exposure. The flue gas, time-temperature curve is reproduced by burning propane to make up the difference between the test and reference samples. The rate of heat release of the test sample is thus obtained from the rate of consumption of propane during the substitution run. This instrument is described in detail in FM Bulletin 1929-1 [19].

4.2 The Parker/Long NBS-I Heat Release Rate Calorimeter

The Parker/Long calorimeter, referred to as the NBS-I calorimeter [11], Figures 2 and 3, employs gas-fired radiant panels as the exposure source. It has the advantages of small sample size (114 x 152 mm), uniformity of exposure, and wide range of exposure levels (up to 100 kW/m^2). Thus, materials may be evaluated for their response to a wide range of fire conditions. A pilot flame is required for ignition at exposures below about 40 kW/m^2. Above this exposure, ignition of most materials (plastics and cellulosics) occurs in 5 to 60 seconds. The back side of the sample holder is water cooled to remove heat from the back face of the sample. This instrument was designed to burn pyrolysis products completely by means of a propane diffusion flame in the secondary burner. This instrument is not provided with smoke-measurement equipment. During operation, a pre-set stack temperature is maintained through the use of a secondary burner supplied with propane gas that is metered through a control valve. The controller is activated by a bank of four parallel-connected thermocouples that sense small changes in stack temperature. The change in flow through the control valve is proportional to the change in stack temperature, which is, in turn, proportional to the rate of heat release.

The NBS-I calorimeter, as described above, no longer exists. It was modified into the NBS-I Rebuilt Calorimeter as described in the next paragraph.

4.3 The NBS-I Rebuilt Calorimeter

The NBS-I Rebuilt Calorimeter, referred to as the NBS-I R, was a 1978 modification of the original Parker/Long instrument. The major and only significant change was the removal of the baffled/vent stack above the auxiliary burner and the replacement of the four sensing thermocouples with an array of 48. The purpose of the baffle was to accomplish mixing of the exhaust gases so that their temperature gradient was negligible. The electrical equivalent of mixing is supplied in the rebuilt instrument by the grid of 48 thermocouples uniformly spaced across the exit plane of the exposure chamber. These thermocouples are arranged in parallel so that the resultant emf is the average of the emf for each of the 48 couples.

The major effects of the NBS-I modification were to reduce the response time of the instrument and to increase the magnitude of the initial response of the instrument. This last effect probably resulted from removal of the metal baffle which constituted a significant heat sink. The small sample size for both NBS-I calorimeters provides the convenience of economy and ease of operation. However, the HRR results for small samples of materials cannot be reliably extrapolated to much larger samples. Results from small samples of a single material of regular geometry cannot be used to predict the heat release rate of an assembly of materials in other geometries.

4.4 The Ohio State-Smith Heat Release Rate Calorimeter

The Ohio State-Smith Heat Release Rate Calorimeter, referred to as the OSU [12], Figure 4, is unique in that it was designed to permit simultaneous measurement of flame spread rate, heat release rate, smoke release rate, and toxic gas production rate as a sample is exposed to a known heat flux obtained from electric radiant panels. The apparatus was constructed to have a low heat capacity and low heat losses in order that the rate of heat release from a sample could be calculated from the rate of temperature rise in the well-mixed products of combustion. The instrument accepts a 152 x 152 mm sample in the vertical position and a sample of approximately 102 x 152 mm in the horizontal position. A pilot ignition is generally used.

Uses of the OSU instrument to characterize materials and to predict material behavior in certain fire situations have been variously reported [20-24]. The instrument's main disadvantage is that rate of heat release due to flame spreading over the surface cannot be dissociated from inherent rate of heat release, up until the time when the flame spreading process is completed. For charring materials, initial heat release rate characteristics may be completely obliterated. Furthermore, continuous application of a pilot flame at the bottom edge of the sample may influence heat release rates. The instrument has been modified [25] with silicon carbide resistance heaters that permit operation at exposures up to 100 kW/m^2.

4.5 The SRI International Heat Release Rate Calorimeter

The SRI International Heat Release Rate Calorimeter, referred to as the SRI calorimeter [13], Figure 5, is very similar to the NBS-I calorimeter in basic design but is scaled to accept a sample 16 times larger. Thus, the sample size is 610 mm wide x 460 mm high. Both the radiant heating panels and the secondary burner are fired with a premixed natural gas flame. This instrument has the unique features of a wide range of available radiant fluxes and a capacity to accept large size samples, including model wall and other construction assemblies. By installing a smoke meter in the stack and using a bypass around the secondary burner, smoke measurements may be made.

4.6 The Forest Products Laboratory (FPL) Heat Release Rate Calorimeter

The Forest Products Laboratory Heat Release Rate Calorimeter, referred to as the FPL Calorimeter [14,15], Figures 6 and 7, has a water-cooled sample holder which, like the SRI calorimeter, can accept large size (460 x 460 mm) samples, including model construction assemblies. The exposure imposed on the sample is obtained from burning a premixed natural gas-air fuel mixture. The instrument operates on the substitution principle, similar to the FM calorimeter. Its disadvantages are that it requires two runs to evaluate each sample and is limited to heat flux exposures below 40 kW/m^2.

4.7 Recent Developments

Two new instruments recently have been developed at NBS. The first is a redesigned and scaled-up version of the NBS-I calorimeter. This instrument, the NBS-II calorimeter, Figure 8, was designed and built by Tordella [16]. It operates on the same basic principle as the NBS-I model but differs from the original version in (a) use of a water-cooled metal sample holder, (b) use of a larger sample size (300 x 300 mm), (c) provision for exposure of samples in the horizontal position, (d) use of an air lock and mechanized sample injection device that greatly reduces heat losses and baseline disturbances that occur when a sample is introduced in the NBS-I calorimeter, (e) use of a positive, non-extinguishable spark-ignition device to insure that combustible pyrolysis products could never form an explosive mixture in the calorimeter, and (f) use of a load cell to measure rate of weight loss of the sample. This instrument will be described in a forthcoming NBS/CFR report [16].

The second new instrument at NBS is a prototype design for obtaining heat release rates by measurement of the oxygen consumed in the burning of a sample, Figure 9. The instrument, known as the Oxygen-Consumption Calorimeter, was designed and built by Sensenig [17] and was modified by Babrauskas, as shown in the figure. This technique [18] assumes that the quantity of heat released by a burning material is proportional to the amount of oxygen consumed. Rate of heat release is calculated from measurement of the flow of air and products of combustion and of the oxygen concentration in the exhaust stack. Both the NBS-II and the oxygen-consumption instruments will be fully described in forthcoming reports and will not be further described here.

Important operating characteristics of the seven heat release rate calorimeters described in this section are compared in Table 1.

Development of fire test methods appears to have proceeded along two parallel lines: (a) ignition, flamespread, and smoke tests involving relatively low heat fluxes applied to interior finish materials; and, (b) fire endurance tests involving high heat fluxes or temperatures applied to structural materials in wall, roof, and floor assemblies. The research reported herein was concerned with the performance of wood-based construction materials across the full range of conditions obtained in actual fires. Because the design of the NBS-I calorimeter permits study of material behavior under controlled conditions in both phases of the fire problem (initiation and growth at low heat fluxes and fire endurance at higher incident heat fluxes) and because this instrument has been successfully used in earlier research, the NBS-I calorimeter was used in this research to establish benchmark heat release rate data for wood-based materials.

The project was initiated on the original NBS-I calorimeter and most of the heat release rate data developed were obtained on this instrument. Before the project was completed, construction of a new calorimeter (NBS-II) that would accept much larger samples and function more reliably than the NBS-I was initiated at NBS. Measurement of heat release rates of wood-based materials, therefore, was interrupted for a 20-month period during construction of the new calorimeter. When the new instrument was operational, the original calorimeter was restored to operating condition but with several permanent design changes. As previously described, these changes included elimination of the baffled vent stack and addition of a grid of 48 sensing thermocouples.

Heat release rates for a number of wood materials and exposure conditions were repeated on the NBS-I R and the new NBS-II calorimeters to establish the relationship between data obtained from these instruments and the original NBS-I design.

5. MATERIALS AND METHODS

5.1 Wood-Based Materials

The heat release rate properties of lumber (three species), soft plywood, particleboard, hardboard, and acoustical ceiling tile were determined in this investigation. The effect of fire retardant treatment on the heat release responses of lumber and plywood also was evaluated.

The Douglas fir, redwood, and southern pine lumber samples were cut from two or three 3 to 4.3 m (10 to 14 ft) long pieces of each species that had been specially selected by the supplier to minimize variation in natural grade characteristics (knots, pitch pockets, etc.) and radial variation in age that might confound test results. Douglas fir 2 x 6 lumber samples, both treated and untreated, were cut from pieces taken from regular production.

The material used to provide test specimens for the panel products was obtained from regular production except for the 19/32 in treated and untreated Douglas fir plywood. This plywood, consisting of two 1.2 x 2.4 m (4 x 8 ft) panels, was made by the American Plywood Association using specially selected clear veneer. Cross-bands in each half panel were end-matched to those in the other half. Each panel was cut in half after lay-up, and one half was fire-retardant treated.

All fire-retardant material was pressure-treated and dried at treating-company facilities. Physical properties of these lumber and panel products are given in Table 2. Moisture content values are based on sample weight at test conditions and oven-dry weight. Density values are based on volume at test conditions and oven-dry weight.

Sample sizes tested in the NBS-I and NBS-II calorimeters were nominally 114 x 152 mm (4.5 x 6 in) and 305 x 305 mm (12 x 12 in), respectively. All panel test samples and all lumber 114 x 152 mm samples were single pieces. The 305 x 305 mm lumber samples were constructed by edge-gluing three pieces with a resorcinol adhesive.

5.2 Conditioning

The basic conditioning environment used in this work was 21°C (70°F) and 50 percent relative humidity (RH) [26]. These conditions were obtained in a controlled-environment conditioning room and, as shown in Table 2, produced equilibrium moisture contents of from 6 to 10 percent.

To evaluate the effect of moisture content on heat release rate, some materials were conditioned at 100°C (212°F) and 0 percent RH and 21°C (70°F) and 80 percent RH. The 100°C (212°F)/9 percent RH environment was accomplished with an air-circulating oven. The 21°C (70°F)/80 percent RH environment was obtained in a cabinet with air circulating over a large surface of a saturated solution of ammonium sulfate [27]. The vapor pressure of this solution at 20°C (68°F) is such that the RH of air in equilibrium with the solution is 81 percent. Further, the RH is essentially constant with small changes in temperature. The 0 and 80 percent nominal conditions produced average equilibrium moisture contents of less than 1 and 15 percent, respectively.

Samples were conditioned until the weight did not change more than 0.1 percent in a three-day period and were then transported to the calorimeter in sealed plastic bags.

5.3 Calorimeter Operation*

The main heating panels in the calorimeter that provide radiant heat flux to the samples are operated with a natural gas-air mixture. The mixture ratio is regulated by an "atmospheric regulator" that supplies air in a constant ratio to the fuel supply. The fuel supply is adjusted to obtain the desired irradiance to the sample.

The radiant heat flux to the sample is measured by the temperature rise in a copper-slug calorimeter that is mounted in the center of a refractory board of the same dimentions as the sample. Heat-flux measurements are then taken with the copper slug in the sample position.

---

*The procedure described applies, generally, to both the NBS-I and NBS-II calorimeters.

The secondary burner, used to burn combustion products completely and to maintain a constant temperature in the exhaust stack, is supplied with commercial grade propane. The control temperature is set to a value appropriate to the radiant flux in the sample exposure chamber. The control temperature/irradiance relationship is readily determined experimentally by plotting fuel consumption of the secondary burner against control temperature. The control temperature is chosen from the linear portion of such a plot, a separate plot being made for each desired value of radiant exposure.

The calorimeter is calibrated at a particular control temperature/radiant flux value by adding heat at the sample position in the form of a 99+ percent purity methane diffusion flame. The methane is supplied through a suitable meter at a constant rate. A calibration constant for the instrument is developed from a known total volume of gas supplied at a constant rate, for a measured period of time, and from a known net heat of combustion of the calibrating fuel. With this constant, heat release rates are calculated from the strip-chart record of secondary fuel consumption during a heat release rate run.

In practice, the calorimeter is operated at the desired exposure flux with an unreactive blank sample in the sample holder until a steady baseline (constant fuel consumption in the secondary burner) is obtained. The door is opened, the blank is replaced by the sample, and the door is quickly closed.

The NBS-I/NBS-I R calorimeter is equipped with a sample holder having a water-cooled brass backing-plate. The flow of water through this plate may be adjusted to a desired rate, and the temperature of the water leaving the plate may be measured and recorded. This arrangement serves to permit the estimation of heat released from the unexposed face of the sample and to prevent the rise in temperature of this unexposed face, thereby simulating the conditions of a semi-infinite slab. Two operational problems--the build-up of a tar-like deposit on the cooled plate and the need to insert a backing plate behind thin samples--led to a modified operating procedure. The water flow was maintained at a constant rate, but the water temperature was not measured for each sample. Also, for samples less than 38 mm (1.5 in) thick, a backing plate of mineral board (of thickness equal to, or greater than, sample thickness) was placed behind the sample. Thus, the back-face environment for each sample was not constant. For samples greater than 10 to 12 mm and exposure time 10 minutes or more, this condition should be of no consequence. For the thinner materials (two medium-density hardboards of 10.5 and 9.0 mm and oil-tempered hardboard of 6.4 mm thickness) the usable exposures were 5 minutes with few exceptions. Thus, while the true effect upon heat release rate due to the use of a backing plate is not known, it is assumed to be negligible.

Loss of heat through the open door causes the control-burner fuel-rate to increase rapidly. This rate decreases just as rapidly when the door is closed, but the sudden increase in heat release rate results in an over-compensating decrease in fuel to the secondary burner. As a consequence, a "door-opening transient" is recorded. This transient sometimes can be confused with the heat released from the sample at the time of ignition. This point will be discussed later.

The fuel consumption of the secondary burner changes linearly and inversely with the heat released from the sample after ignition occurs. The strip chart record of changes in fuel consumption is also the record of heat release rate. Two other values may be obtained from this record, with variable accuracy: time to ignition (t_{ig}), if that time is not too short, and time-to-peak heat release rate. Usually, the t_{ig} can also be measured visually with a stop watch. Although more accuracy is obtained when higher chart speeds are used, this practice produces much longer chart records. Chart speeds of 2 min/in or 5 min/in were customarily used in the work.

An exposed sample in the calorimeter may be allowed to burn to completion, although it was usually removed after 20 minutes or when its physical integrity was lost, depending upon the radiant heat flux and the material involved. Heat release data are no longer valid after the sample begins to crumble, warp, or burn on the edges and back, because heat release rates are quoted on a unit-area basis and calculated from the initial area of the exposed surface of the specimen.

5.4 Heat Release Rate Computation

Heat release rates and total heat released for a given time period are obtained from the strip chart record of changes in the fuel consumption required to maintain constant temperature in the exhaust gases from the particular instrument. Typical heat release rate traces are shown in Figures 10 to 14. These traces record the decrease in fuel flow that is equivalent to the fuel contribution of the sample. An instantaneous heat release rate, expressed in watts/cm^2 area of sample, is obtained by multiplying the net scale deflection at a given time by the calibration constant.

The total heat release for a particular time interval was derived by graphic integration of the area under the curve between the desired time limits. The convention was established that zero time was the moment the sample "saw" the radiant flux in the exposure chamber (i.e., time was measured from the moment the door was closed).

The average heat release rate for a given time period was obtained by determining the area under the curve (i.e., total heat released) and dividing by the time period of interest. In practice, this averaging was done for each successive 1-minute interval under the curve. Average rates were calculated and recorded for the first 1-minute, first 5-minute, first 10-minute, first 15-minute, and first 20-minute time periods. Time to ignition, time-to-peak (maximum) heat release rate, and the values of total or cumulative heat released for the 5-, 10-, 15-, and 20-minute time periods also were determined.

The format for recording basic heat release rate (HRR) is shown in Table 3.

The time to ignition value is that for spontaneous ignition in those cases where spontaneous ignition occurs. For the NBS-I and the NBS-I R calorimeters, ignitions at incident heat fluxes of less than 35 kW/m^2 were not spontaneous, and a pilot ignition source was required. Where such an ignition pilot was used, three options were available: to place the pilot at a point above the sample so that it would ignite the gases produced by pyrolysis; to place the pilot so that it contacted the sample at the center of the top edge; or, to place the pilot so that it contacted the sample at the center of the bottom edge. All data obtained by the use of a piloted ignition source are identified. Piloted ignition exposure of some materials was made with bottom as well as top pilot flames for the NBS-I and the NBS-I R calorimeters. Top ignition was accomplished by the second option, with the pilot flame in contact with the sample.

All data for the NBS-II calorimeter, except where noted, were obtained with a spark-ignition pilot placed above the sample in the boundary layer of the pyrolysis products.

6. RESULTS AND DISCUSSION

6.1 Characteristic Heat Release Rate Curves

HRR curves for a given material obtained from a particular instrument are quite reproducible in a qualitative sense. In Figures 10 and 11, HRR curves are shown for Douglas fir and southern pine lumber, respectively, as measured on the NBS-I calorimeter. Time is measured from the moment that the specimen becomes exposed, i.e., from the moment of door closing. Time to ignition was measured with a stop watch or was taken from the strip-chart record. It is the time from door closing to the appearance of flames as viewed through the window in the door or it is the time from door closing to the time of heat release as indicated on the strip-chart record. The peak heat release rate for Douglas fir occurs immediately upon ignition, while the peak for southern pine occurs later following a period where the initial rapid rate subsides. This behavior of southern pine may be due to the distillation of terpenes and resins as the bulk of the wood is heated following ignition.

Figure 12 shows the HRR curve for medium density hardboard surfaced with a thin layer of paper (to facilitate painting, etc.). Rapid ignition and burning of the paper results in a high initial HRR that subsides slowly to a minimum, or a plateau, at about 5 minutes. (The rate at this minimum is still relatively high for wood products.) After this time, the rate increases due to disintegration of the sample and the consequent increase in the actual surface of burning. Measurements beyond this point have no numerical meaning because the area of burning surface has increased by some large and unknown factor.

Figure 13 is the HRR curve for medium density hardboard having an embossed surface to represent weathered flat-grain lumber. The HRR after ignition is almost constant for about 5 minutes, at which time the sample fails catastrophically.

Lastly, another typical type of behavior is illustrated in Figure 14. This figure shows the HRR for high density, oil-tempered hardboard. For this material, ignition was delayed for about 30 seconds. Initial HRR was low but increased rapidly as the bulk of the material became heated and the board disintegrated and fell from the sample holder. Factors which contributed to the response of this material are the high density, which extends time to ignition; the low thickness, 5.6 mm (0.22 in), which allows the bulk temperature to rise rapidly; resin binder (about 5 percent), which supplies volatile fuel; and thermal relief (or annealing) of fiber stresses, produced in the manufacture of the board, which precedes the loss of physical integrity.

6.2 Heat Release Rates of Lumber and Other Wood Products

Average heat release properties of wood-based materials, conditioned at 21°C (70°F) and 50 percent RH and exposed at 60 kW/m^2 incident radiant heat flux in the NBS-I calorimeter, are shown in Table 4. Properties tabulated are time to ignition, peak HRR, time to peak HRR, first 1-minute average HRR, first 5-minute average HRR, and cumulative 10-minute total heat release. To facilitate comparison of the responses of different materials, mean values are also expressed in Table 4 as a percentage of corresponding values for southern pine lumber. Mean HRR properties and the range in individual property values, based on three tests for each material, are compared in Figures 15a to 15d.

6.2.1 Lumber

Rate of heat release from a material, once it is burning, is a function of a complex interaction of chemical and physical properties including density, thermal conductivity, heat capacity (or specific heat), the chemical structures responsible for the effective heat of vaporization (the heat required to convert unit mass of solid to volatile fuel), and the effective heat of combustion per unit mass, thickness, and mechanical stability. Since cellulose and lignin constitute the bulk of all woods, it would be expected that heat of vaporization and heat of combustion values would not vary greatly among wood species.

Mean heat release property values for untreated southern pine, Douglas fir, and redwood lumber appear in the following ranges: t_{ig} 11 to 17 seconds; peak HRR, 98 to 134 kW/m^2; first 1-minute HRR, 59 to 96 kW/m^2; first 5-minute HRR, 69 to 109 kW/m^2; and 10-minute total HR, 38080 to 57710 kJ/m^2 (3352 to 5080 Btu/ft^2). Mean time to peak HRR ranged from 20 to 60 seconds.

In all cases, heat release property values for southern pine were higher than those for the other two species. This is attributed to the relatively higher density and high resin and volatile hydrocarbon (terpene) content of the species.

Redwood generally exhibited the lowest HRR values of the three species. Time to ignition, peak HRR, 1-minute HRR, 5-minute HRR, and 10-minute total heat release were 65, 88, 99, 65, and 66 percent, respectively, of corresponding southern pine values. The relatively high (99 percent) ratio of redwood to southern pine first 1-minute average HRR is attributed to the fact that the peak HRR for southern pine was not reached until 60 seconds into the test, while that for redwood was reached in 20 seconds. In addition to its low density, redwood contains relatively high percentages of tannins and tannic acid. These constituents are responsible in part for the resistance of redwood to fungus and insect attack. These tannins also are believed to function as natural fire-retardant agents, produced in-situ, and to account for the resistance of the species to forest fires.

All heat release values for the 2 x 8 Douglas fir sample lie between those of southern pine and redwood. However, the 2 x 6 sample of this species exhibited lower values of peak, 1-minute average HRR, and 5-minute average HRR than redwood. The density of both samples 5f Douglas fir was intermediate to that of the other two species.

6.2.2 Plywood

Heat release values for untreated 15.1 mm (19/32 in) and 19.1 mm (3/4 in) Douglas fir plywood samples were similar to those for Douglas fir lumber. Because the five-ply test panels were made of natural wood veneer, the similarity in response is not unexpected. The density of the plywood, however, was slightly greater than that of the Douglas fir lumber. This is attributed, in part, to the plywood manufacturing process which involves bonding the component veneers with phenolic resin adhesives under elevated temperature and pressure.

6.2.3 Particle Board

In line with its significantly higher density, the 15.9 mm (5/8 in) particle board had a significantly higher time to ignition and 10-minute total heat release than plywood--26 seconds versus 8 to 14 seconds and 58840 kJ/m^2 (5180 Btu/ft^2) versus 38850 to 43400 kJ/m^2 (3420 to 3820 Btu/ft^2), respectively. However, peak and 5-minute HRR values were only slightly higher than those for plywood, and 1-minute HRR values were essentially the same. Time to peak HRR was a long 104 seconds for particle board, compared to 17 to 19 seconds for plywood. Compared to southern pine lumber, t_{ig} for particle board was longer (26 versus 17 seconds), and time to peak heat release rate was significantly longer (104 seconds versus 60 seconds). However, particle board heat release rate properties were very similar to those of southern pine lumber, corresponding values ranging between 99 and 102 percent.

6.2.4 Acoustical Tile

The two acoustical tile materials had the lowest density and exhibited the lowest heat release rate properties of any of the untreated wood products. Time to ignition, peak HRR, 1-minute average HRR, and 5-minute average HRR were 55 to 57 percent, 72 to 75 percent, 71 to 86 percent, and 56 to 60 percent of the corresponding values for southern pine lumber. Times to peak HRR were relatively high, however, being 42 and 62 seconds compared to 60 seconds for southern pine and only 17 to 19 seconds for plywood.

6.2.5 Hardboard

The hardboard products had, as a class, the highest heat release properties and also the highest densities of all the materials assessed in the study. Times to ignition of the medium-density embossed, medium-density paper-faced, and high-density oil-tempered hardboard samples were 124, 147, and 194 percent of the southern pine lumber ignition time.

Peak and first 1-minute average HRR values for these three materials were 118, 265, and 284 percent and 98, 156, and 117 percent, respectively, of corresponding southern pine lumber values. The paper-faced product reached a peak HRR in only 29 seconds, while the embossed and high-density oil-tempered products reached peak HRR in 197 and 153 seconds, respectively.

6.2.6 General Effect of Density

The general correlations of peak, first 1-minute average, first 5-minute average, and first 10-minute average HRR with density are shown in Figures 16a and 16b. The data illustrated in these figures are given in Tables 2 and 4.

It can be seen from Figure 16a that the paper-faced and high-density hardboards exhibited a much higher peak HRR for their densities than the other products. In the case of the paper-faced hardboard, the "flashing" of the paper face was undoubtedly responsible for the high value. In the case of the high-density product, the high rate may be a result of the oil-tempering process used in manufacturing and also the thickness of this material (5.6 mm, 7/32 in). The low thickness caused this material to disintegrate before a 5-minute mean rate could be measured.

The relationship between first 1-minute average HRR and density shown in Figure 16b is distorted by the fact that the peak HRR of five of the 12 products was not reached until 60 or more seconds into the test. In these cases, first 1-minute average HRR values tend to be lower for a particular density than products which had much shorter time to peak HRR. This distortion does not appear to be significant in the

5-minute and 10-minute average HRR versus density relationships, shown in Figure 16b.

Linear regressions were fitted to the HRR-density relationships by least square analysis. Regression constants and coefficients of determination (r^2) are shown below.

HRR	Number of products	Regression Constants: Intercept, kW/m^2	Regression Constants: Slope, $kW \cdot m/g$	r^2, %
Peak	12[a]	-24.2	0.327	50
	10[b]	72.3	0.092	78
1-minute average	12[a]	52.6	0.073	39
	7[c]	7.8	0.176	66
	6[c,d]	49.2	0.077	20
5-minute average	11[a]	29.8	0.109	82
	10[d]	32.3	0.102	80
10-minute average	7[a]	29.6	0.091	80

a/All products for which rates are available
b/Excluding paper-faced and high-density hardboards
c/Excluding products with time to peak HRR of 60 seconds or greater
d/Excluding paper-faced hardboard

It can be seen that when the paper-faced and high-density oil-tempered hardboards are excluded from the analysis, the slopes of the regression equations for density versus the peak, the 5-minute average, and the 10-minute average HRR are approximately the same. In these cases, density accounts for between 75 and 80 percent of the variation in HRR between products. The same regression slope also adequately describes the relationship between 1-minute average HRR and density when those materials exhibiting time to peak HRR of 60 seconds or longer and the paper-faced hardboard are excluded.

In general, these results indicate a reasonably constant effect of density on the HRR properties of untreated non-overlaid wood products greater than 6.4 mm (0.25 in) thick. This relationship applies to any HRR having a time period base which includes the peak rate. At 60 kW/m^2 radiant flux in the NBS-I calorimeter, an increase or decrease in density of 600 kg/m^3 causes an increase or decrease in peak, first 5-minute average, and first 10-minute average HRR of approximately 10 kW/m^2.

The HRR-density regression for the peak rate had a significantly higher intercept than the intercepts for the 5-minute and 10-minute average regressions when the two atypical hardboard products were excluded. This simply indicates that, after adjusting for density differences, heat release rates for untreated, non-overlaid wood products greater than 6.4 mm thick generally are lower after the burning process is well established. Such behavior is considered reasonable as the peak HRR includes the process of ignition and flamespread, as well as sustained burning. The former process is different from that of sustained burning which includes, among other characteristics, the presence of a protective char layer.

6.2.7 Effects of Other Physical Properties

Grain angle, number of growth rings per inch (radially), and percent of summerwood are considered likely to have some influence on the heat release response of lumber. These properties are tabulated in Table 2 for the three species evaluated. The effect of these variables, however, cannot be determined from the available data because any one of the properties cannot be isolated from the others in a series of controlled experiments.

Although the effects of growth rate, grain angle, and percent of summerwood on heat release may, in fact, be small, relative to the variability in test values, it is reasonable to assume these properties affect or relate to both charring and heat release rates. As a wood surface receives heat, a thin layer of char is rapidly formed. The insulative and reradiative effects of intact char layers are well known [28,29]. The cells of the wood shrink as char forms causing stresses to be set up in the char layer. The properties of the char and of the underlying wood determine the time at which these stresses in the char layer are relieved by cracking and spalling, with subsequent reduction in the protective effects of the char layer. The finer and more uniform the texture of the lumber (i.e., slower growth and least pronounced difference in summerwood and springwood), the longer the char layer is expected to remain intact. This was the case for the three species tested in this study. (Redwood was the finest textured of the three lumber species tested and had the most stress-resistant char layer.)

Schaffer [28] showed that charring rates of wood decrease as the density increases. McLean [30] attributed this effect to the variation of thermal diffusivity with density. Thermal diffusivity, a measure of how quickly a material absorbs heat from its surroundings, is defined as the ratio of thermal conductivity to the product of density and specific heat: $\alpha = (k/\rho C)$. A limited number of charring-rate measurements were made on the three lumber species in the course of this study. Observed char rates for samples conditioned at 21°C and 50 percent RH and exposed at 60 kW/m^2 radiant flux were as follows:

Material	Char Rate mm/min	in/min
Southern pine	0.65	0.025
	0.79	0.031
Douglas fir	0.69	0.027
	0.71	0.028
Redwood	0.74	0.029
	0.76	0.030
	0.73	0.031

The general trend shown by these data of increased charring rate with decreased density of the species involved is in agreement with the previously cited literature. However, in view of the positive correlation found in this study between heat release rates and density, it would appear that other factors, in addition to charring rate, contribute to the relative heat release rates of different wood species and wood products.

6.2.8 Effect of Fire-Retardant Treatment

The effect of the pressure-process fire retardant treatment on Douglas fir 2 x 6 lumber (treatment A), 15.1 mm (19/32-in) Douglas fir plywood (treatment B), and 12.7 mm (1/2-in) Douglas fir plywood (treatment B) was evaluated. The 15.1 mm treated plywood was taken from the same panel as the untreated plywood of this thickness. Therefore, a comparison of the heat release properties of these matching materials provides a very sensitive evaluation of the treatment effect. The 12.7 mm treated plywood was provided by a treating company. Because matching untreated plywood was not tested at the same 60 kW/m^2 exposure in the original NBS-I calorimeter, control data are not available for making an optimum assessment of the effect of treatment on this particular plywood sample.

The treated (incised) and untreated 2 x 6 Douglas fir lumber also was supplied by a treating company. It is assumed that the treated and untreated samples were originally obtained from the same inventory lot and, therefore, a comparison of the data for the two samples does provide a reasonably good measure of the treatment effect. The large difference observed in the densities of the treated and untreated lumber (540 versus 450 kg/m^3, Table 2) is attributed to the high loading of dry salt in the former. The fire retardant treatment used with the 15.1 mm and the 12.8 mm plywoods did not cause such an increase in density.

Heat release data for the treated materials, untreated controls, and untreated southern pine lumber are compared in Table 5. It can be seen from this table that the fire-retardant treatment of the 15.1 mm Douglas fir plywood caused a reduction in peak, first 1-minute average, and first 5-minute average HRR values by 30, 71, and 63 percent, respectively. Ten-minute total heat release was reduced 59 percent relative to the matching untreated material. Although no untreated control data are available for the 12.7 mm plywood, it can be seen that the treated plywood of this thickness exhibited heat release rates similar to those of the 15.1 mm treated material. The same commercial fire retardant treatment was used for both materials.

The treated Douglas fir lumber material exhibited even greater reduction in HRR than the treated plywood. Peak, 1-minute average, and 5-minute average rates were reduced to 33, 12, and 17 percent, respectively, of the untreated material. Ten-minute total heat release was reduced to 24 percent.

The use of fire-retardant treatment for wood products, thus, is shown to significantly reduce the rate at which heat is contributed under a moderately severe exposure. The char from treated materials appeared to be more dense, less friable, and in greater yield, compared to untreated wood materials.

6.2.9 Effect of Moisture Content

Wood and other cellulosic materials are hygroscopic. Water occurs in wood as free water, absorbed in the larger voids and capillaries, and as adsorbed or bound water held within the submicroscopic structure of the wood. Adsorbed water is of two types, surface-adsorbed and capillary-condensed. The amount of such water (moisture) in a particular wood product increases or decreases directly with change in relative humidity and inversely with change in temperature.

Absorbed water may be reversibly removed without affecting the physical or chemical properties of wood. Adsorbed water may be reversibly removed, but its removal causes shrinkage and changes in mechanical properties of wood. The last few percent of adsorbed water may be held so firmly that its removal (by heating) causes degradation of the structural components of wood. One process in the thermal degradation of cellulose is the dehydration of hydroxyl groups, resulting in the non-reversible loss of water of constitution.

The effect of three different relative humidity and temperature conditioning environments on the heat release properties of southern pine lumber, redwood lumber, Douglas fir plywood, acoustical tile, and hardboard is shown in Table 6. It can be seen from this table that time to ignition and time to peak HRR generally increased and peak HRR, 1-minute average HRR, 5-minute average HRR, and 10-minute total heat release generally decreased with increase in relative humidity. This behavior is consistent with that expected. The higher the moisture content, the greater the amount of energy required to remove the bound water and the longer the exposure time required before pyrolysis is initiated.

Regression equations for the relationship between heat release response (expressed as a percentage of the response at 50 percent RH) and relative humidity were determined for peak and 5-minute average HRR and 10-minute total heat release of each product. These least square regressions are compared with experimental values in Figure 17. It can be seen that, with the exception of peak HRR for paper-faced hardboard, all products exhibited a consistent trend of decreasing heat release rate with increasing relative humidity between 0 and 80 percent.

The slopes of the regressions illustrated in Figure 17 are tabulated below.

Material	Regression Slope, Heat Release Response (% of 50% RH Value) Against % Relative Humidity		
	Peak HRR	First 5-min. Average HRR	10-min. total heat release
Hardboard, paper-faced	+0.320	-0.2800	--
Hardboard, embossed	-0.999	--	--
Southern pine lumber	-0.353	-0.440	-0.450
Redwood lumber	-0.199	-0.174	-0.174
Douglas fir plywood	-0.448	-0.485	-0.510
Acoustical tile A	-0.120	-0.307	--
Acoustical tile B	-0.667	-0.667	--
Average (excluding paper-faced hardboard)	-0.4644	-0.414	-0.378

It can be seen from Figure 17 that the average regression slope (excluding paper-faced hardboard) provides a reasonable description of the effect of relative humidity on each of the remaining products. Further, relative to the variation between products, the average slopes for the peak HRR, 5-minute average HRR, and 10-minute total heat release appear to be reasonably similar.

In general, a 10 percent increase in relative humidity during the conditioning period causes an approximate 4 percent decrease in the peak HRR, the 5-minute average HRR, and the 10-minute total heat release for untreated, non-overlaid wood products of thickness greater than 6.4 mm (1/4 in) exposed at 60 kW/m^2 in the NBS-I calorimeter.

These results are in general agreement with those obtained by Parker and coworkers [31].

6.2.10 Effect of Imposed Radiant Heat Flux

Heat release properties for wood-based materials exposed at 25, 40, 60, and 80 kW/m^2 in the NBS-I calorimeter are given in Table 7. A pilot ignition source, located either at the top or bottom edge of the test sample, was used at the lowest flux level exposure.

Heat release rates were expected to show a positive correlation with radiant flux exposure because the rate of pyrolysis is a function of temperature. As can be seen from Table 7 and Figure 18, this relationship was generally observed between the 25 and 60 kW/m^2 exposure. However, consistently lower HRR values were observed at 80 kW/m^2 than at 60 kW/m^2.

Mean values of peak HRR, first 5-minute average HRR, and 10-minute total heat release at 25, 40, and 60 kW/m^2 radiant flux were found to be reasonably well described by a line connecting the 40 and 60 kW/m^2 data points (Figure 18). For all test materials combined, average response at 40 kW/m^2 flux expressed as a percent of that at 60 kW/m^2 was 83 percent (7 materials), 67 percent (6 materials), and 79 percent (5 materials) for peak HRR, 5-minute average HRR, and 10-minute total heat release, respectively. Longer times to ignition and to peak HRR account for the 5-minute average and 10-minute total percentage values being lower than the percentage for peak HRR.

As expected, time to ignition for top ignition at 25 kW/m^2 flux was consistently longer than that for bottom ignition at this same flux level. The long times to ignition for the former case and for some samples at the non-piloted 40 kW/m^2 exposure account for the low or zero first-minute average HRR given in Table 7.

No reasonable explanation has been found as to why the 80 kW/m^2 exposure values were consistently lower than those at 60 kW/m^2. On the basis of data obtained from the NBS-I calorimeter, it is assumed that the results at 80 kW/m^2 exposure are low because of some unidentified measurement malfunction of the original calorimeter at this high radiant flux.

6.2.11 Comparison of First 1-Minute and First 5-Minute Heat Release Rates With the Corresponding Maximum Rates

While most materials exhibit the highest HRR in the early period of burning, some materials exhibit the highest HRR later in the period. The tables of HRR data show time-averaged heat release rates calculated from time zero. That is, the first 1-minute average heat release was calculated from the heat release rate curve starting at time zero, the time when the sample first "saw" the radiant heat source. Heat release rates derived in this manner will be affected by the time to ignition (t_{ig}). Thus, a long t_{ig} may have a significant effect upon the first 1-minute and the first 5-minute average heat release rates. Beyond five minutes, t_{ig} would be expected to have insignificant effect.

This section presents a comparison of 1-minute and 5-minute average heat release rates calculated as the first and maximum average rates.

Table 8 summarizes the 1-minute average and 5-minute average heat release rates for ten wood products. These products were conditioned at 21°C (70°F) and 50 percent RH and were exposed in the NBS-I calorimeter. Heat release rates were calculated for the first 1-minute and maximum 1-minute periods and for the corresponding 5-minute periods. The ratio of maximum to first HRR is also shown for each material.

The data in Table 8 are also plotted in Figure 19a for the 1-minute values and in Figure 19b for the 5-minute values. The straight lines represent the linear regression plots of the data. The departure from the dashed line illustrates the differences between these two methods of calculation.

The 1-minute data show that the values for (8), (9) and (10) (two medium-density hard boards and the particle board) are much out of line, with a correlation coefficient of 0.77. When the data for these three materials are deleted, the least squares plot has a correlation coefficient of 0.95. The differences between the first and maximum values for the 5-minute average HRR are much less, with a slope of 1.11 and a correlation coefficient of 0.998 for all samples. The slope and correlation coefficient are 1.07 and 0.999, respectively, when samples 8, 9 and 10 are deleted.

The densities of the two hardboards and the particle board, as shown in Table 2, are substantially higher than for the remaining seven materials. Therefore, one may conclude that the much higher ratio of maximum to the first 1-minute average HRR is due to their longer times to ignition caused by their greater heat capacities.

The above discussion illustrates the importance of choosing a method of data reduction that is appropriate to the intended use of HRR data.

7. COMPARISON OF HEAT RELEASE PROPERTIES MEASURED BY DIFFERENT NBS CALORIMETERS

7.1 Correlation of NBS-I, NBS-I Rebuilt, and NBS-II Calorimeter Values at 60 kW/m^2 Exposure Flux

Mean time to ignition, time to peak HRR, peak HRR, first 1-minute average HRR, first 5-minute average HRR, and 10-minute total heat release values for thirteen materials as obtained in the NBS-I, NBS-I R, and NBS-II calorimeters are shown in Table 9. Mean values and ranges in individual values are compared in Figures 20a to 20i.

7.1.1 NBS-I Rebuilt Calorimeter

Both the NBS-I calorimeter (which is no longer available) and the NBS-I R calorimeter accept 115 x 152 mm (4.5 x 6.0 in) samples. The differences between these two instruments are that the rebuilt instrument does not have a baffle in the stack, which reduces by 30 percent the distance between sample and sensing thermocouples and that the rebuilt instrument has 48 sensing thermocouples instead of four. The effects of these changes should be the reduction of heat storage during periods of very high heat release rate or flame impingement on the baffles and the electrical equivalent of more thorough mixing (temperature uniformity) of the exhaust gases as they pass the temperature sensor.

Times to ignition, from Table 9, for the NBS-I R calorimeter range from 29 to 100 percent of those for the NBS-I calorimeter, with an average of 52 percent for the 13 materials listed.

The NBS-I R calorimeter gave consistently higher heat release values than the original NBS-I calorimeter, for a given material. The values in Table 9 include a tabulation of results for the rebuilt calorimeter as the percent of the corresponding results for the original NBS-I calorimeter.

For untreated wood, these values are 106 to 221 (average 176) percent for peak HRR, 105 to 262 (average 145) percent for the first 1-minute average HRR, 112 to 167 (average 132) percent for the first 5-minute average HRR, and 114 to 154 (average 131) percent for the 10-minute total heat release.

For treated wood, the average values are 239 percent for peak HRR, 192 percent for first 1-minute average HRR, 163 percent for the 5-minute average HRR, and 141 percent for the 10-minute total heat release.

7.1.2 NBS-II Calorimeter

The NBS-II calorimeter differs from the NBS-I calorimeter in these major features: sample size, 305 x 305 mm versus 114 x 152 mm; sample holder, hollow water-cooled metal frame versus solid mineral-board frame; ignition, spark ignition for all exposures versus pilot-flame ignition for exposures below 40 kW/m^2; and sensors, 48 thermocouples (in parallel) versus four thermocouples (in parallel). The NBS-II instrument is also equipped with a load cell for measuring rate of weight loss, concurrently with rate of heat release. Another difference was the use of a mineral-board backing plate in the NBS-I and NBS-I R calorimeters, for samples of 19 mm (0.75 in) or less. It was anticipated that these differences among the instruments would affect heat release values, but the nature and direction of the effects could not be predicted. The effect of a mineral-board backing on the heat release rate of a material should be apparent only on thin samples, or when the combustion zone approaches the back face of thicker samples.

Heat release data for nine materials as measured in the NBS-II calorimeter are compared with corresponding values as measured in the NBS-I calorimeter in Table 9. Times to ignition for eight of the nine materials were greater in the NBS-II instrument than those for the NBS-I. Individual times ranged from 80 to 471 percent and averaged 227 percent of NBS-I calorimeter values. Time to peak HRR from the NBS-II calorimeter ranged from 58 to 432 percent of those from the NBS-I calorimeter, with an average of 184 percent.

Six of nine materials exhibited higher peak heat release rates in the NBS-II than in the NBS-I. Values ranged from 69 to 194 percent (average 135) of those from the latter instrument. First 1-minute average HRR values from the NBS-II calorimeter ranged from 0 to 136 percent (average 72) of values obtained from the NBS-I. Five-minute HRR and 10-minute total heat release values showed smaller differences, ranging from 92 to 148 percent and from 63 to 121 percent, respectively. The average response for each of these two properties was 106 percent and 97 percent. Whereas, HRR values for fire-retardant treated wood products were consistently higher in the NBS-I R calorimeter than in the original NBS-I, these values were consistently lower in the NBS-II.

7.1.3 Calorimeter Correlations

As previously indicated, differences in absolute response values obtained in different calorimeters are not unreasonable. Robertson [32] classifies test methods into two general categories, property tests and system tests.

> A property test would involve determination of one specific physical, chemical, or behavioral characteristic of a material, product, or system. A system test would characterize the overall behavioral reaction of a material, product, or system with the environmental as well as internal variables which influence its performance. When classifying test methods on this basis, it is important to remember that a system test involves interactions between the material, product, or system with its surroundings. Heat release rate test methods are among those classified as system tests.

While individual calorimeters may differ in absolute values of response, it is reasonable to expect that values from two or more different instruments should be correlated, assuming that each apparatus is designed to account for the known and important variables.

Regression analyses were made of the relationship among heat release property values obtained from the three NBS calorimeters. Regression of mean NBS-I heat release values on mean NBS-I R and on mean NBS-II values are shown in Figure 21. It can be seen from this figure that good correlations were found between NBS-I and NBS-I R calorimeters for all four properties analyzed: peak HRR, first 1-minute average HRR, first 5-minute average HRR, and 10-minute total heat release. The coefficients of determination, r^2, for these relationships were 74, 71, 92, and 94 percent, respectively. These high values of r^2 indicate that the response of one calorimeter to a material is generally matched by a parallel response of the other calorimeter to that material.

Five-minute average HRR and 10-minute total heat release values from the NBS-I and NBS-II calorimeters also were highly correlated. The coefficients of determination, r^2, for these two cases were 88 percent and 98 percent, respectively. As shown in Figure 21, the relationship between NBS-I and NBS-II peak HRR values, although significant, was reduced because of the value for paper-faced hardboard. Excluding this datum point from the regression analysis increased the r^2 from 48 percent to 85 percent.

Virtually no correlation was found between NBS-I and NBS-II first 1-minute HRR values (r^2 = 0.3 percent). This reflects the effects of major differences in time to ignition and time to peak HRR between the two calorimeters and the fact that the time to ignition enters into the calculation of the first 1-minute average heat release rate.

As shown in Figure 22, the degree of correlation between NBS-II and NBS-I R heat release values was similar to that found between NBS-I and NBS-II values. Correlations of NBS-II and NBS-I R peak HRR, 1-minute average HRR, 5-minute average HRR, and 10-minute total heat release values, as measured in terms of r^2, were 65, 3, 91, and 96 percent, respectively.

7.1.4 Conversion Equations

To facilitate use of existing and future new information on the heat release properties of construction materials, equations for estimating HRR values related to a particular NBS calorimeter from values experimentally determined on a different NBS calorimeter are desirable. Regression equations and related statistics based on least-squares analysis of the experimental data obtained in this study are presented in Table 10 for this purpose. The equations are applicable to materials conditioned at 21°C and 50 percent RH and exposed at 60 kW/m^2 radiant flux.

7.2 Effect of Density as Measured in the NBS-I Rebuilt and NBS-II Calorimeters

Relationships between heat release rates and density for untreated materials, conditioned at 21°C and 50 percent RH and exposed at 60 kW/m^2 radiant flux in the NBS-I R and NBS-II calorimeters, are shown in Figures 23 and 24. It can be seen from these figures that the same positive high correlation between density and peak, 5-minute average, 10-minute average HRR observed in the NBS-I calorimeter also was observed in the NBS-I R and NBS-II calorimeters. Due to the confounding effect caused by significantly different times to ignition, the 1-minute HRR values for these instruments showed no correlation with density. The same effect was observed in the corresponding NBS-I calorimeter data.

Linear regression data for the HRR-density relationships shown in Figures 23 and 24 are tabulated below.

HRR	Number of Products	Regression Constants Intercept kW/m^2	Slope, kW·m/g	r^2, %
NBS-I R				
Peak	10[a]	+113.6	+0.220	48
	9[b]	+138.0	+0.153	60
1-minute average	10[a]	+101.1	+0.047	19
	9[b]	+106.4	+0.032	19
	7[b,c]	+ 59.9	+0.146	51
5-minute average	10[a]	+ 30.0	+0.161	90
	9[b]	+ 33.0	+0.153	90
10-minute average	9[a]	+ 18.0	+0.160	89
	8[b]	+ 19.7	+0.156	86
NBS-II				
Peak	7[a]	+ 69.7	+0.275	92
	6[b]	+ 81.1	+0.243	92
1-minute average	7[a]	+123.0	-0.104	25
	6[b]	+ 94.7	-0.025	3
	4	+ 81.0	+0.032	89
5-minute average	7[a]	+ 17.7	+0.164	81
	6[b]	+ 14.4	+0.173	78
10-minute average	4[a]	- 11.7	+0.181	88

a/All untreated products for which rates are available.
b/Excluding paper-faced hardboard.
c/Excluding products with time to peak HRR of 57 seconds or greater.

7.2.1 NBS-I Rebuilt Calorimeter

It can be seen from the regression data for the NBS-I R calorimeter that when paper-faced hardboard is excluded from the peak HRR data set, the slope of the HRR-density relationship for peak, 5-minute average, and 10-minute average HRR is essentially the same, with values ranging between 0.15 and 0.16 kW·m/kg. When the paper-faced hardboard and those materials exhibiting time to peak HRR of about a minute or more are excluded, the results are very similar to those obtained in the NBS-I calorimeter.

In general, these data indicate that at 60 kW/m^2 radiant flux in the NBS-I R calorimeter an increase or decrease in density of 100 kg/m^3 causes an increase or decrease in peak, 5-minute average, and 10-minute average HRR of approximately 15 kW/m^2. The corresponding density effect in the NBS-I calorimeter was 10 kW/m^2. In view of the greater sensitivity of the rebuilt instrument, this difference appears reasonable.

7.2.2 NBS-II Calorimeter

The NBS-II HRR values do not show the close correlation with density that is found with the other two calorimeters. When paper-faced hardboard is excluded, the peak, 5-minute average, and 10-minute average HRR versus density regression curves had slopes of 0.24, 0.16, and 0.18 kW•m/kg, respectively. The high coefficients of determination for these relationships (92, 81, and 88 percent, respectively) suggest that the differences among the peak, 5-minute, and 10-minute regression values may be due not only to the small number of samples but to other factors as well.

Thus, in general, the effect of density on the heat release rate of wood-based materials exposed at 60 kW/m^2 flux in the NBS-II calorimeter is approximately a change of 25 kW/m^2 in peak HRR and 17.5 kW/m^2 in both the 5-minute and 10-minute average HRR for each 100 kg/m^3 change in density.

7.3 Effect of Imposed Radiant Flux as Measured in the NBS-I Rebuilt and NBS-II Calorimeters

7.3.1 NBS-I Rebuilt Calorimeter

Heat release values for nine wood-based materials exposed at 40, 60, and 80 kW/m^2 in the NBS-I R calorimeter are given in Table 11 and illustrated in Figure 25. It can be seen that heat release rates increased with an increase in imposed flux, as expected, with most materials exhibiting a greater incremental increase from 60 to 80 kW/m^2 than from 40 to 60 kW/m^2. The fact that the 80 kW/m^2 exposure values were higher in all cases than those at 60 kW/m^2 suggests that the reverse trend observed in the NBS-I calorimeter data was the result of some malfunction at the high radiant flux exposure.

For the combined data for eight materials, the average ratio of heat release property at 40 kW/m^2 to that at 60 kW/m^2 was 74, 79, and 81 percent for peak HRR, first 5-minute average HRR, and 10-minute total heat release, respectively. A comparison of average ratios of 40 kW/m^2 to 60 kW/m^2 values from the NBS-I R and NBS-I calorimeters, for the same test materials, shows reasonable agreement between the two data sets. Average peak HRR, 5-minute average HRR, and 10-minute total heat release for four products tested in both the NBS-I R and NBS-I calorimeters were 73, 68, and 74 percent (rebuilt) and 84, 64, and 78 percent (original), respectively. These differences between matching property values are considered within experimental error. (See correlation equations, Table 10.)

The average ratio of heat release at 80 kW/m^2 to that at 60 kW/m^2 for six materials tested at the higher flux in the NBS-I R calorimeter was 148, 169, and 180 percent for peak HRR, first 5-minute average HRR, and 10-minute total heat release, respectively. These ratios are 1.85, 2.65, and 4.21 times larger than those obtained by simple linear extrapolation of the 40 to 60 kW/m^2 exposure values. However, there is no justification for expecting simple linear relationships among these variables.

As expected, time to ignition and time to peak HRR generally decreased as imposed radiant flux increased. Only in two instances, 3/4-in plywood and 5/8-in particle board, was this behavior reversed. The reversal in these instances is attributed to experimental error.

7.3.2 NBS-II Calorimeter

Heat release properties for one material, acoustical tile B, were determined at 80 kW/m^2 in the NBS-II calorimeter in order to compare the response of this instrument and that of the NBS-I R at this radiant flux level. Results of these tests and matching tests at 60 kW/m^2 are given at the bottom of Table 11. It can be seen that the ratios of heat release at 80 kW/m^2 to those at 60 kW/m^2 from the NBS-II calorimeter were lower than those from the NBS-I R but still above 100 percent. Ratios for peak HRR and first 5-minute average HRR were 128 and 115 percent for the NBS-II calorimeter, as compared to 150 and 136 percent for the NBS-I R. These differences between calorimeter responses are considered to be relatively small and within the standard deviation of the relationship between the two calorimeters. For example, estimated NBS-II calorimeter peak and 5-minute average HRR at 80 kW/m^2 based on NBS-I R calorimeter values and the correlation equations in Table 10 are 256 ± 49 and 104 ± 15 kW/m^2, respectively, compared to NBS-II calorimeter observed values of 217 and 85 kW/m^2.

Ratios of time to ignition and time to peak HRR at 80 kW/m^2 to those at 60 kW/m^2 from the NBS-II calorimeter also follow reasonably well those from the NBS-I R (64 versus 67 percent and 81 versus 58 percent).

These limited data indicate that the effect of imposed radiant flux measured in the NBS-II calorimeter is similar to that measured in the NBS-I R.

8. CONCLUSIONS

(1) There is a general high level of correlation between heat release rate properties of wood-based products measured in the NBS-I, NBS-I R, and NBS-II calorimeters.

Equations relating peak heat release rate (HRR), first 1-minute average HRR, first 5-minute average HRR, and 10-minute total heat release mean values for a range of wood materials measured at 60 kW/m^2

radiant flux in the NBS-I calorimeter and similar values measured in the NBS-I R calorimeter have coefficients of determination (r^2) of 74, 71, 92, and 94 percent, respectively. Equations relating these mean property values measured at 60 kW/m^2 in the NBS-II calorimeter and similar values measured in the NBS-I R calorimeter have r^2 values of 65, 3, 91, and 96 percent, respectively. The low correlation existing between the NBS-II and NBS-I R 1-minute average HRR values is attributed to differences in the construction and operation of the two calorimeters. These differences significantly affect time to ignition and time to peak HRR of certain materials. The time to ignition, in turn, is a determining factor in the first 1-minute average heat release rate. This is demonstrated by the high ratio of maximum 1-minute HRR to the first 1-minute HRR.

(2) Density accounts for a significant percentage of the difference in peak HRR, first 5-minute average HRR, and first 10-minute average HRR of untreated lumber and other wood-based materials. The effect of density is approximately constant for the peak, the 5-minute and 10-minute average HRR, and for the 10-minute total heat release.

At 60 kW/m^2 radiant flux, an increase or decrease in density of untreated wood-based products of 100 kg/m^3 is associated with an average increase or decrease in peak, 5-minute average, and 10-minute average HRR of approximately 15 kW/m^2 when measured in the NBS-1 R calorimeter and of approximately 10 kW/m^2 when measured in the NBS-I calorimeter. At the same radiant flux, a 100 kg/m^3 change in density of untreated wood materials exposed in the NBS-II calorimeter is associated with a change of 25 kW/m^2 in peak HRR and 175 kW/m^2 in 5-minute and 10-minute average HRR.

(3) Fire-retardant treatment causes a significant reduction in the rate at which heat is released from wood products. Based on NBS-I and NBS-I R calorimeter measurements on treated lumber, on plywood, and on matching controls, fire-retardant treatment caused a 30 percent reduction in peak HRR values and about 60 percent reduction in the values for first 1-minute average HRR, first 5-minute average HRR, and the 10-minute total heat release.

(4) Heat release rate values of wood-based materials decrease with increase in moisture content. Based on NBS-I calorimeter measurements at 60 kW/m^2, a 10 percent increase in relative humidity during conditioning causes a decrease of approximately 4 percent in the peak HRR, in the first 5-minute average HRR, and in the 10-minute total heat release of untreated, non-overlaid wood products of thickness greater than 1/4 inch.

(5) Heat release rates increase non-linearly with an increase in imposed heat flux. Based on NBS-I R calorimeter data, peak HRR, first 5-minute average HRR, and 10-minute total heat release values decrease by an average of 26, 21, and 19 percent, respectively, when the imposed

flux is reduced from 60 to 40 kW/m^2. The values also increase an average of 48, 69, and 80 percent, respectively, when the imposed flux is increased from 60 to 80 kW/m^2.

(6) Basic heat release properties for wood-based materials, conditioned at 70°F and 50 percent relative humidity and exposed at 60 kW/m^2 in the NBS-I R calorimeter, are summarized in Table 12.

9. ACKNOWLEDGMENTS

Mr. William J. Parker and Mr. Daniel Gross provided consultation and many helpful discussions throughout the course of this work. Dr. John Tordella, NBS Research Associate from E. I. duPont de Nemours and Company during 1977 and 1978 was very helpful with instrumental trouble-shooting. Special thanks are due to Mr. Charles Veirtz and Mr. William Twilley for help with sample preparation and operation and maintenance of the heat release rate calorimeters. Special credit is due Dr. Edward King, National Forest Products Association, for the detailed statistical correlations among the various sets of data.

10. REFERENCES

[1] Bihr, J. E., Ignition, Heat Release, and Noncombustibility of Building Materials, ASTM STP 502, p. 310, American Society for Testing and Materials, Philadelphia, PA, (1972)

[2] Standard Building Code, pp.2-6, Southern Building Code Congress International, Inc., Birmingham, AL (1973)

[3] Steiner, A. J., Method of Fire Hazard Classification of Building Materials, ASTM Bulletin No. 121, pp.19-21, American Society for Testing and Materials, Philadelphia, PA (1943)

[4] Robertson, A. F., D. Gross, and J. Loftus, A Method for Measuring Surface Flammability of Materials Using a Radiant Energy Source, Proc. Am. Soc. Testing and Materials, 56, pp.1437-1453 (1956)

[5] Thompson, Norman J., and E. W. Cousins, The FM Construction Materials Calorimeter, NFPA Quarterly, 52, No. 3, pp.186-196 (Jan. 1959)

[6] British Standard 476: Fire Tests on Building Materials and Structures; Part 6. Fire propagation tests for materials (1968)

[7] Bruce, H. D., and V. P. Miniutti, Small Tunnel-Furnace Test for Measuring Surface Flammability, Report No. 2097, Forest Products Laboratory, U. S. Department of Agriculture, Madison, WI (1957)

[8] Blackshear, P. L., Jr., B. D. Wood, N. J. Alvares, J. W. Matthews, and N. J. Barsic, Combustion Laboratory Technical Report No. 7, Final Report OCD Contract No. N0022869C1172, University of Minnesota, pp.68-93 (Nov. 1969)

[9] George, Charles W., and Aylmer D. Blakely, Energy Release Rates in Fire Retardant Evaluation, Fire Technology, 6, No. 3, 203-210 (Aug. 1970)

[10] Fransden, William H., and Richard C. Rothermel, Measuring the Energy-Release Rate of a Spreading Fire, Combustion and Flame, 19, pp.17-24 (1972)

[11] Parker, W. J., and M. E. Long, Development of a Heat Release Rate Calorimeter at NBS. Ignition, Heat Release, and Noncombustibility of Materials, ASTM STP 502, pp.135-151, American Society for Testing and Materials, Philadelphia, PA (1972)

[12] Smith, E. E., Heat Release Rate of Building Materials, ibid, pp.119-134

[13] Amaro, A. J., A. M. Kanury, A. E. Lipska, and S. B. Martin, Thermal Indices From Heat Release Rate Calorimetry, Paper No. 37, Presented at the Western States Section of the Combustion Institute Fall Meeting, California State University at Northridge, CA (1974)

[14] Brenden, John J., An Apparatus Developed to Measure Rate of Heat Release from Building Materials, FPL Research Paper No. 217, USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin (1973)

[15] Brenden, John J., Rate of Heat Release from Wood-Based Building Materials Exposed to Fire, FPL Research Paper No. 230, USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin (1974)

[16] Tordella, John, and William H. Twilley, Development of a Calorimeter for Simultaneously Measuring Heat and Mass Loss Rate, Nat. Bur. Stand. (U.S.), NBSIR 83-2708

[17] Sensenig, D. L., An Oxygen Consumption Technique for Determining the Contribution of Interior Wall Finishes to Room Fires, Nat. Bur. Stand. (U.S.), NBS Technical Note 1128 (July 1980)

[18] Huggett, Clayton, Estimation of Rate of Heat Release by Means of Oxygen Consumption Measurements, Fire and Materials, 4, pp.61-65 (1980)

[19] Anon., Fire Hazard Test Procedures, Class I Building Materials, Bulletin No. 1929-I, Factory Mutual Research Corporation, Norwood, Massachusetts

[20] Smith, E. E., An Experimental Determination of Combustibility, Fire Technology, 7, No. 2, pp.109-119 (May 1971)

[21] Smith, E. E., An Experimental Method for Evaluating Fire Hazard, Proc. 4th Int. Fire Protection Seminar, II, Zurich, pp.133-146 (1973)

[22] Smith, E. E., Evaluation of the Fire Hazard of Duct Materials, Fire Technology, 9, No. 3, pp.157-170 (1973)

[23] Smith, E. E., Model for Evaluating Fire Hazard, J. Fire and Flammability, 5, pp.1979-1989 (July 1974)

[24] Smith, E. E., Application of Release Rate Data to Hazard Load Calculations, Fire Technology, 10, No. 3, pp.181-186 (1974)

[25] Smith, E. E., private communication

[26] ANSI/ASTM E-171-63, Standard specification for Standard Atmospheres for Conditioning and Testing Materials, Annual Book of ASTM Standards, Part 41, American Society for Testing and Materials, Philadelphia, PA

[27] Perry, J. H., (ed.), Chemical Engineers' Handbook, Third Edition, McGraw-Hill, New York, p.797 (1950)

[28] Schaffer, E. L., Charring Rate of Selected Woods--Transverse to Grain, FPL Research Paper No. 69, pp.14-15, U. S. Forest Service, Madison, WI (April 1967)

[29] Schaffer, E. L., Review of Information Related to the Charring Rate of Wood, U. S. Forest Service Research Note, FPL 0145, U. S. Forest Service, Madison, WI (Nov. 1966)

[30] McLean, J. D., Rate of Temperature Change in Laminated Timbers Heated in Air Under Controlled Relative Humidity Conditions, Mimeograph No. R1434, Forest Products Laboratory, Madison, WI (1943)

[31] Parker, W. J., D. C. Brackett, R. E. Willard, and R. H. Zile, A Preliminary Investigation of the Effect of Humidity on the Ignition, Heat Release and Smoke Density Tests for Typical Room Finishing Materials, NBSIR 73-139, Tables V-IX (March 1973)

[32] Robertson, A. F., Test Method Categorization, ASTM Standardization News, 3, No. 11 (Nov. 1975)

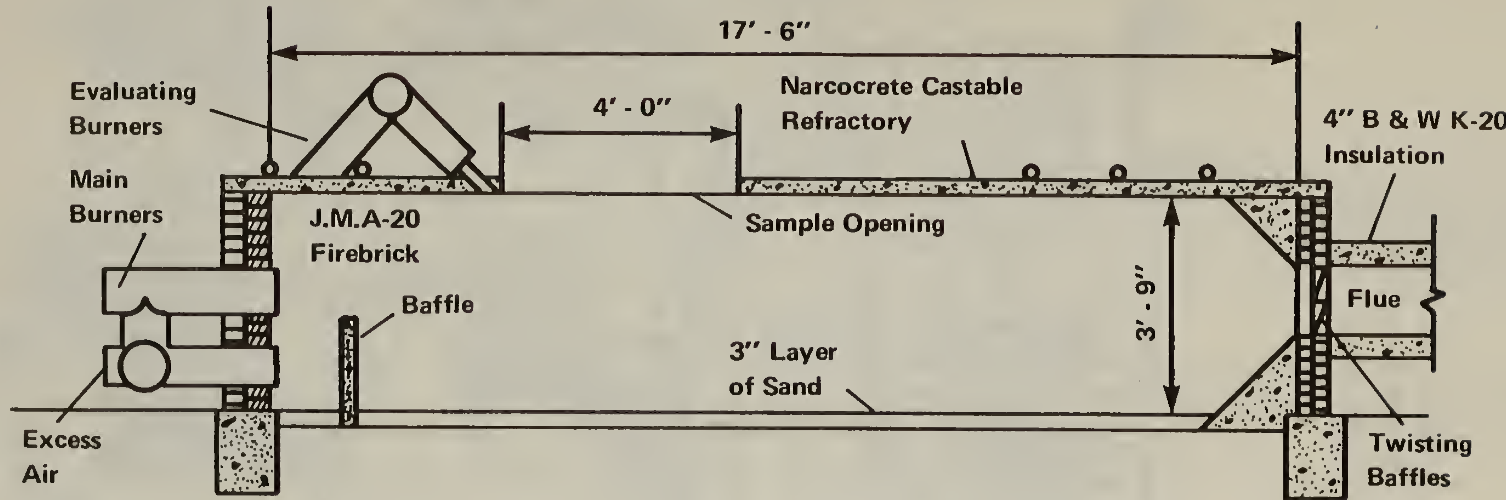


Figure 1. Diagram of FM Construction Materials Calorimeter

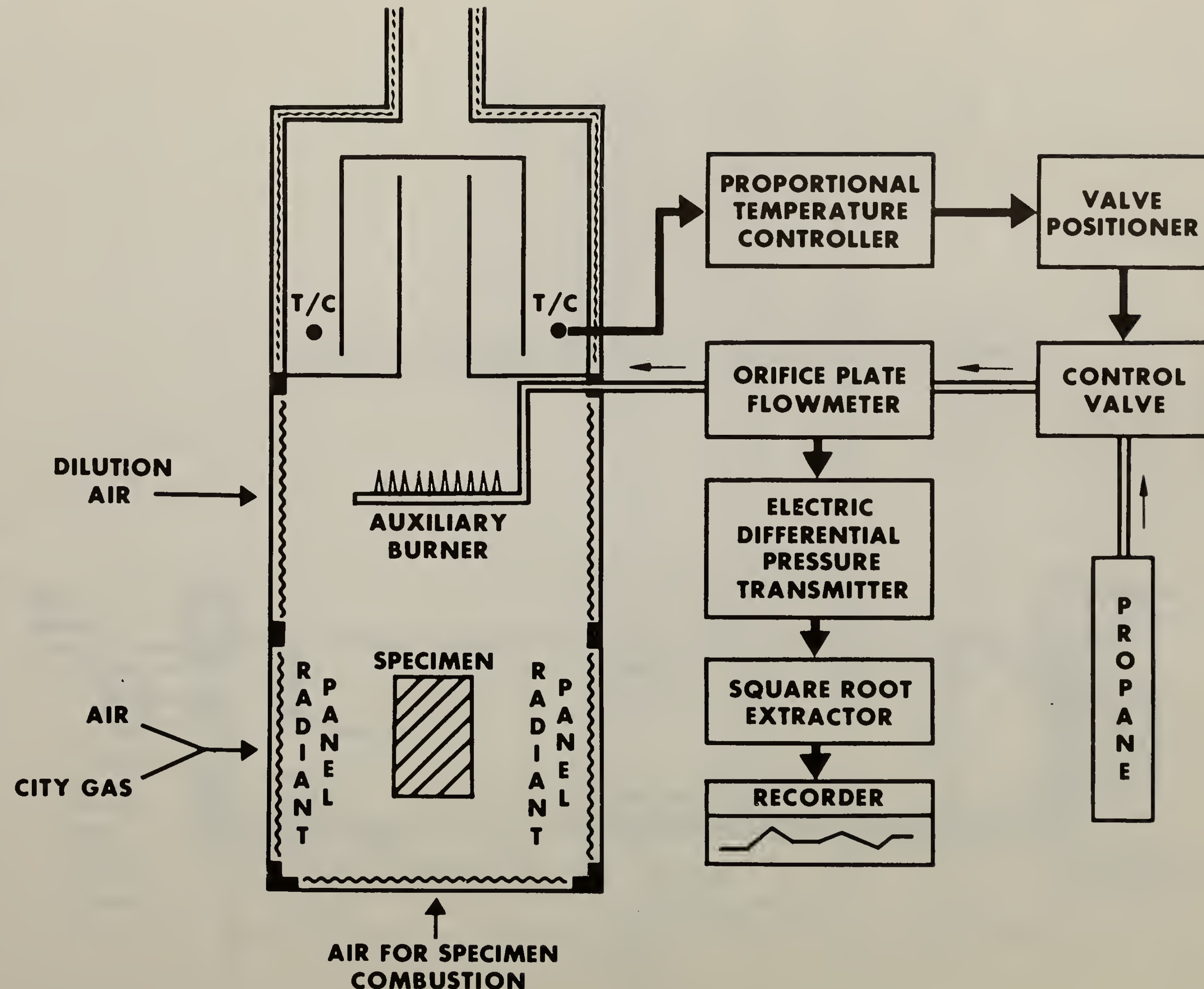


Figure 2. Diagram of NBS-I Calorimeter

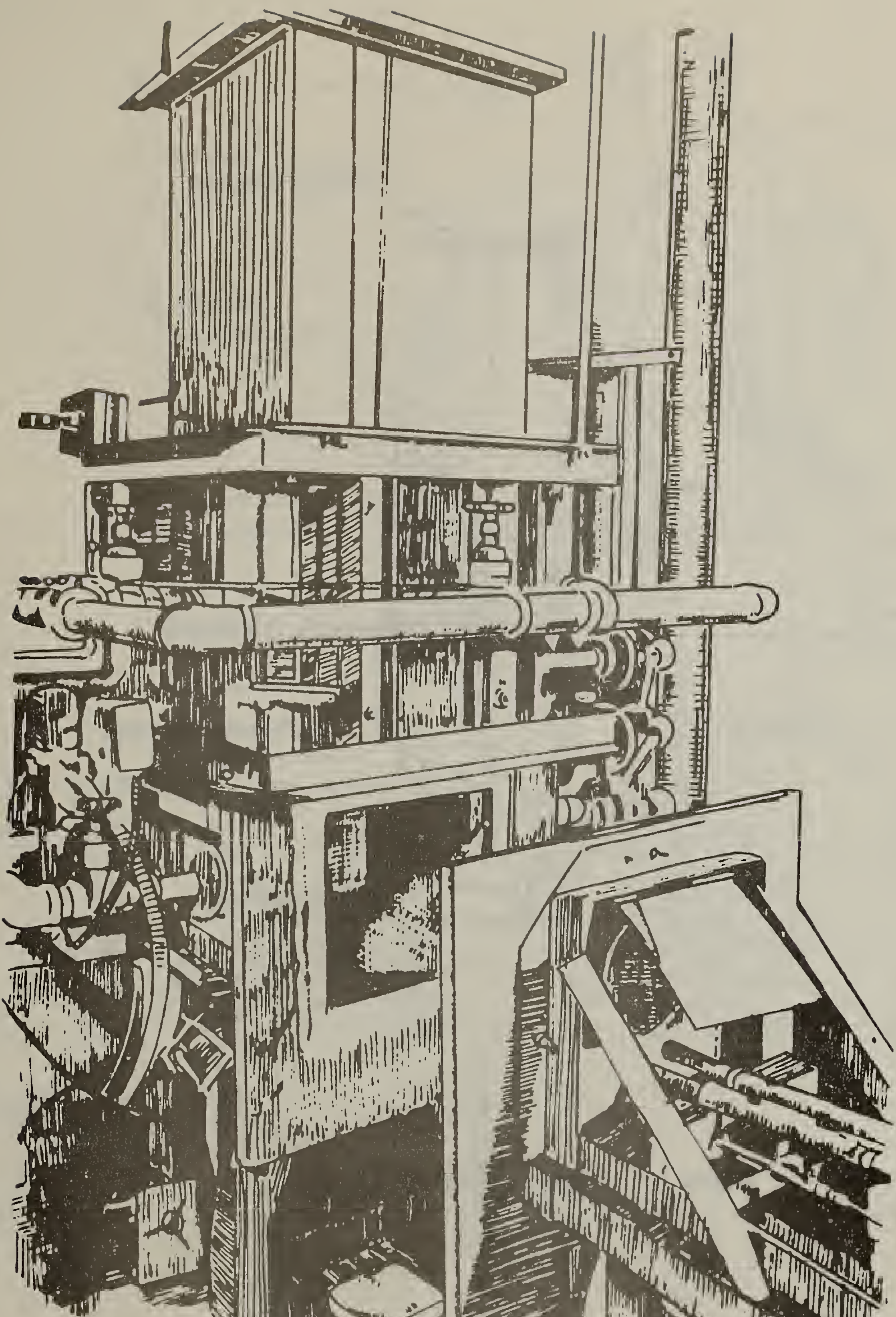


Figure 3. Artist's View of NBS-I Calorimeter

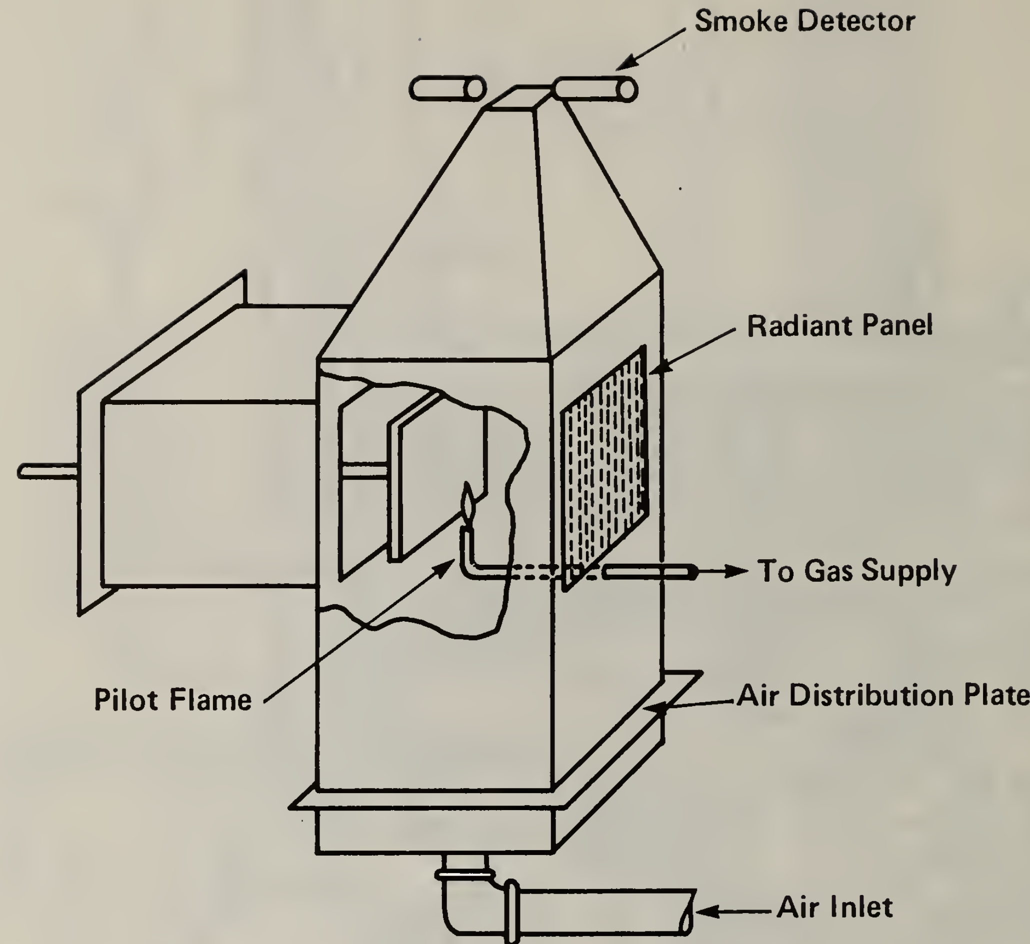


Figure 4. Diagram of OSU Calorimeter

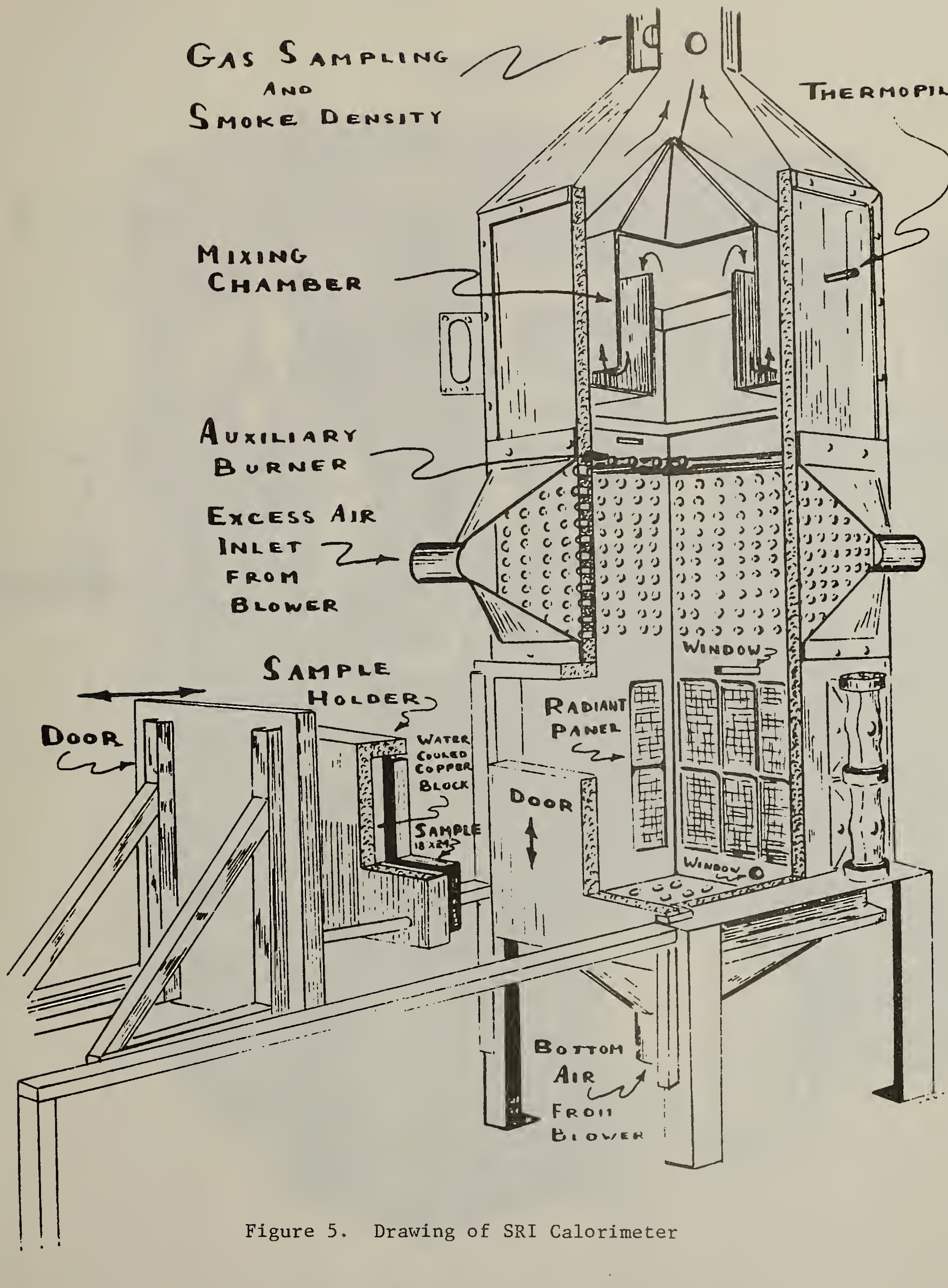
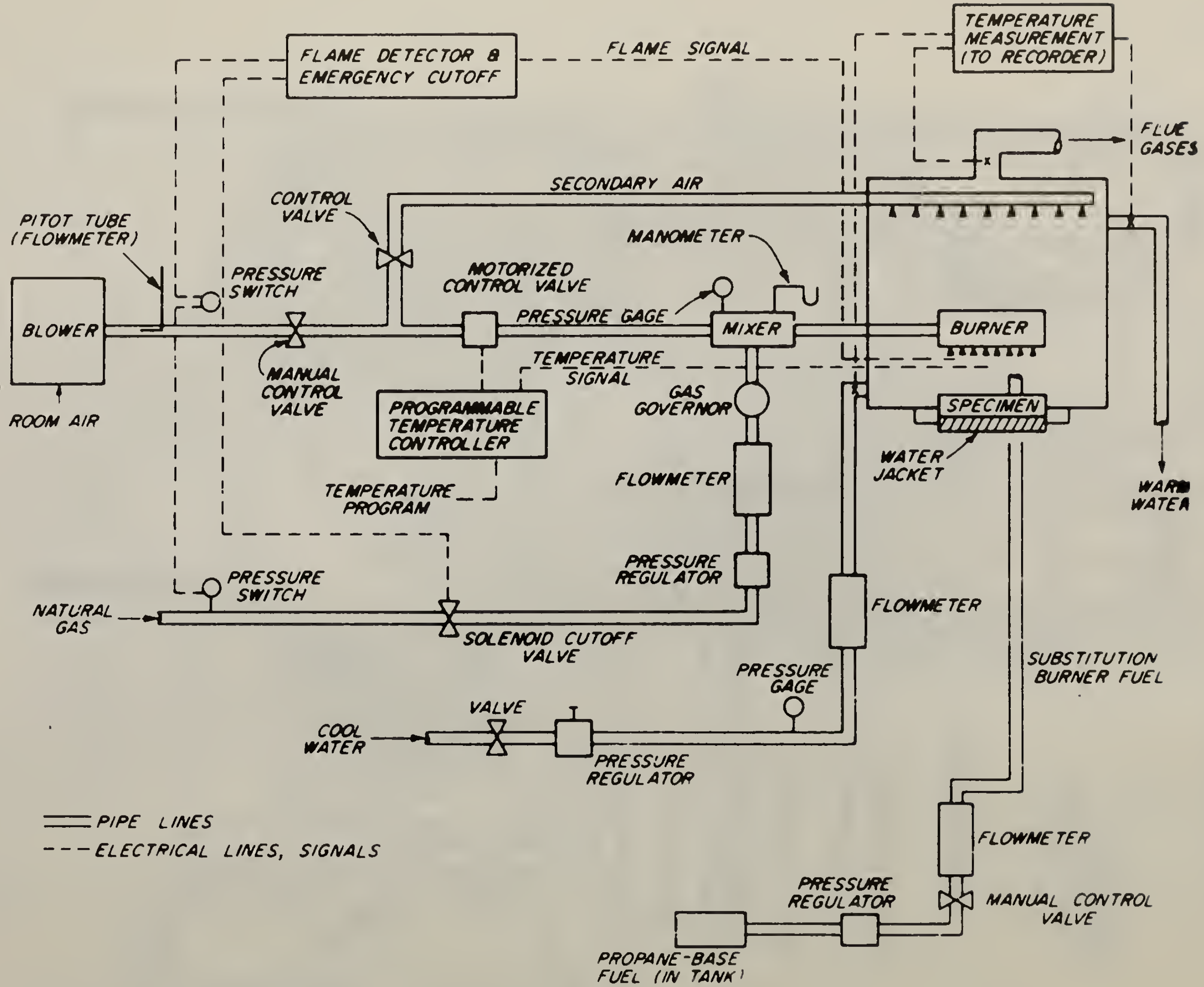


Figure 5. Drawing of SRI Calorimeter



M 141 469

Figure 6. Diagram of FPL Calorimeter

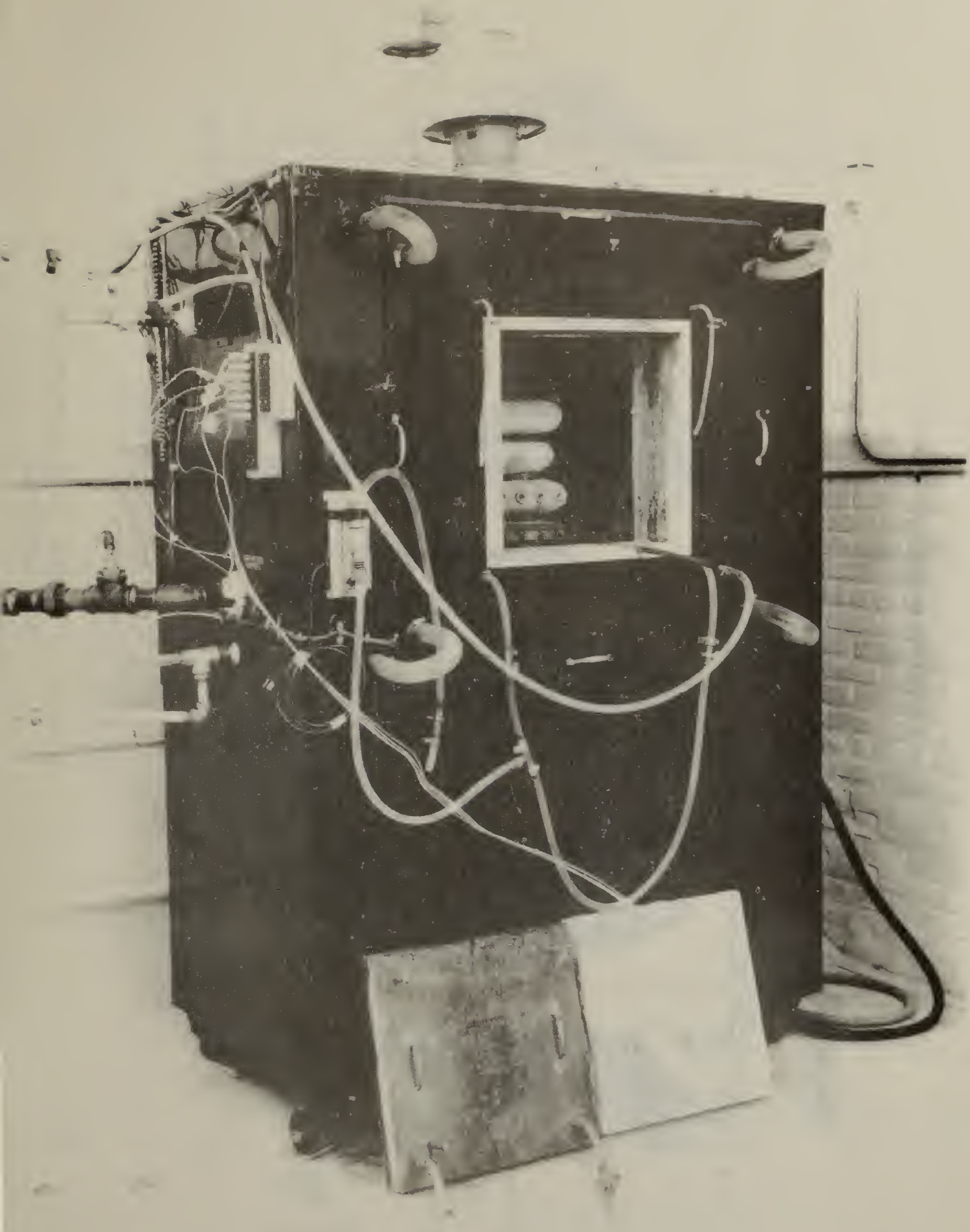


Figure 7. Photograph of FPL Calorimeter

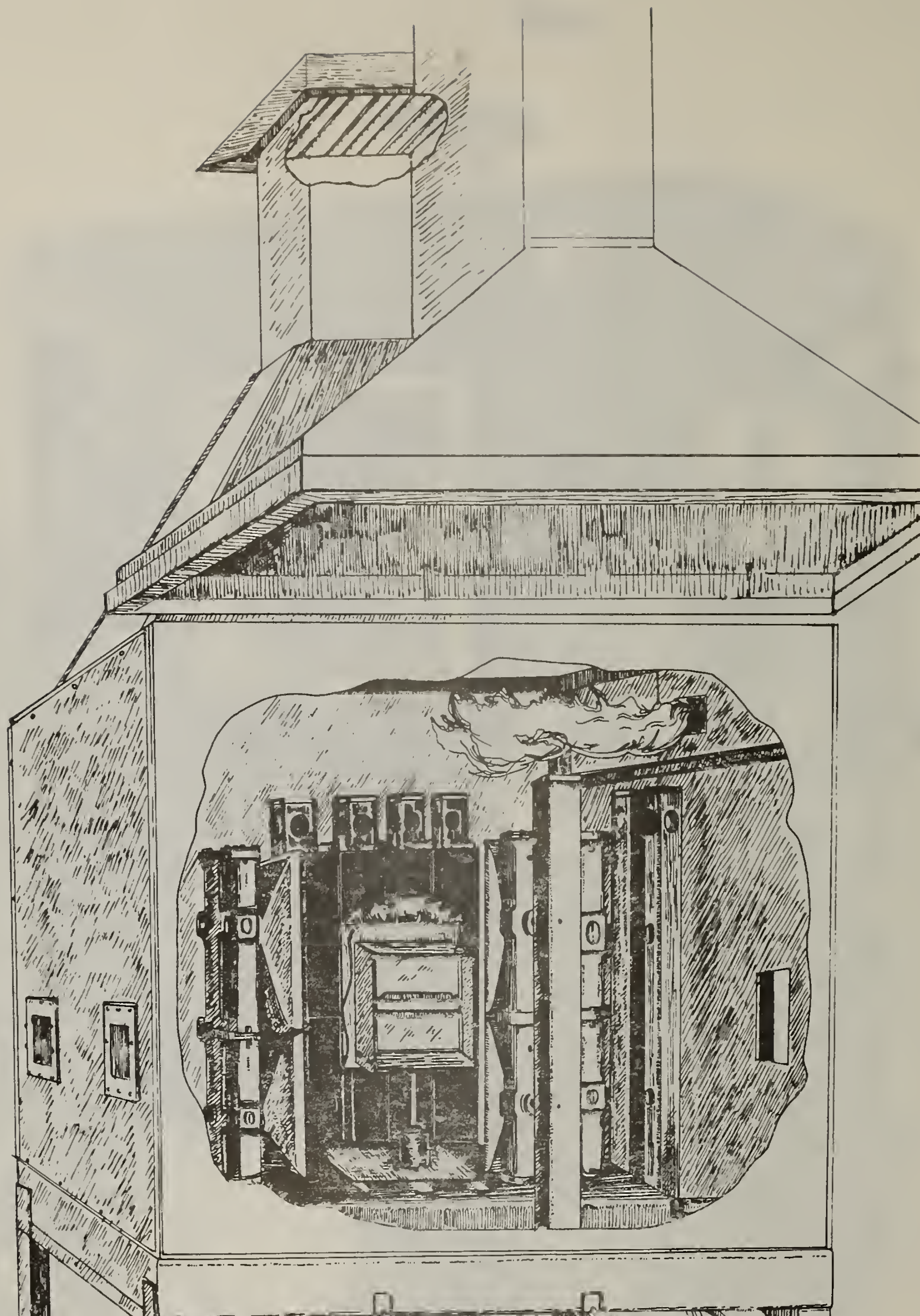


Figure 8. Artist's View of NBS-II Calorimeter

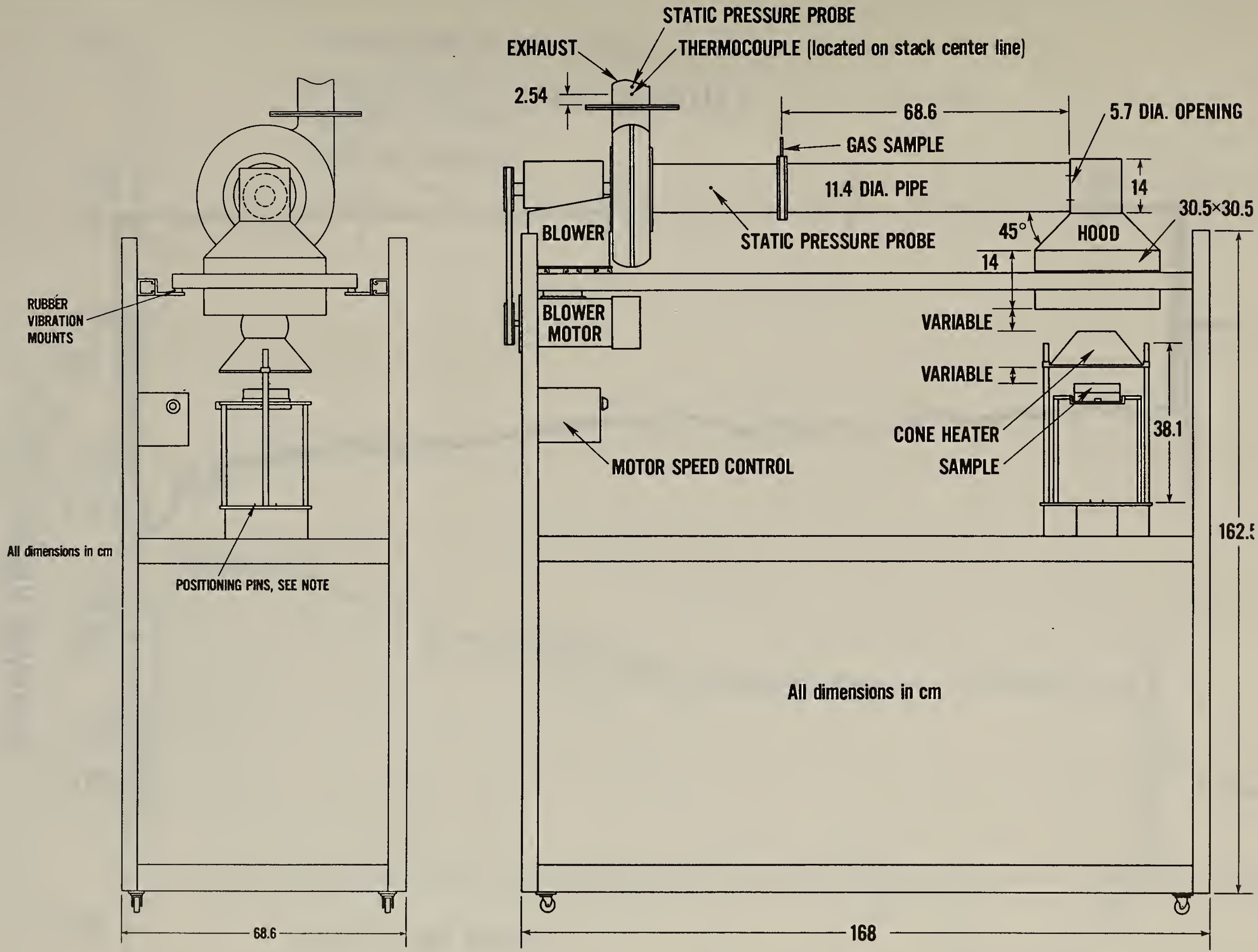


Figure 9. Diagram of NBS Oxygen Consumption Calorimeter

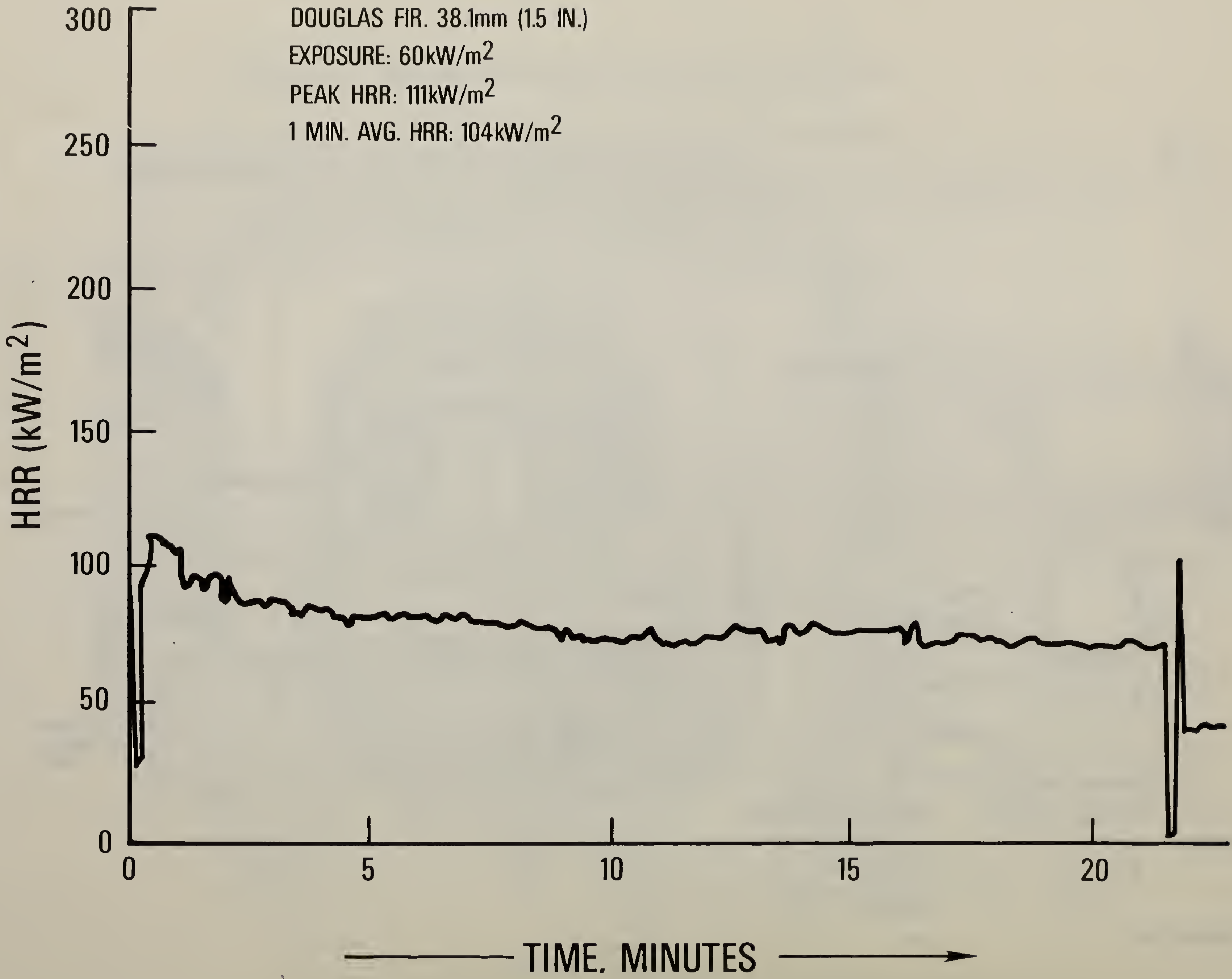


Figure 10. Typical HRR Curves: Douglas Fir

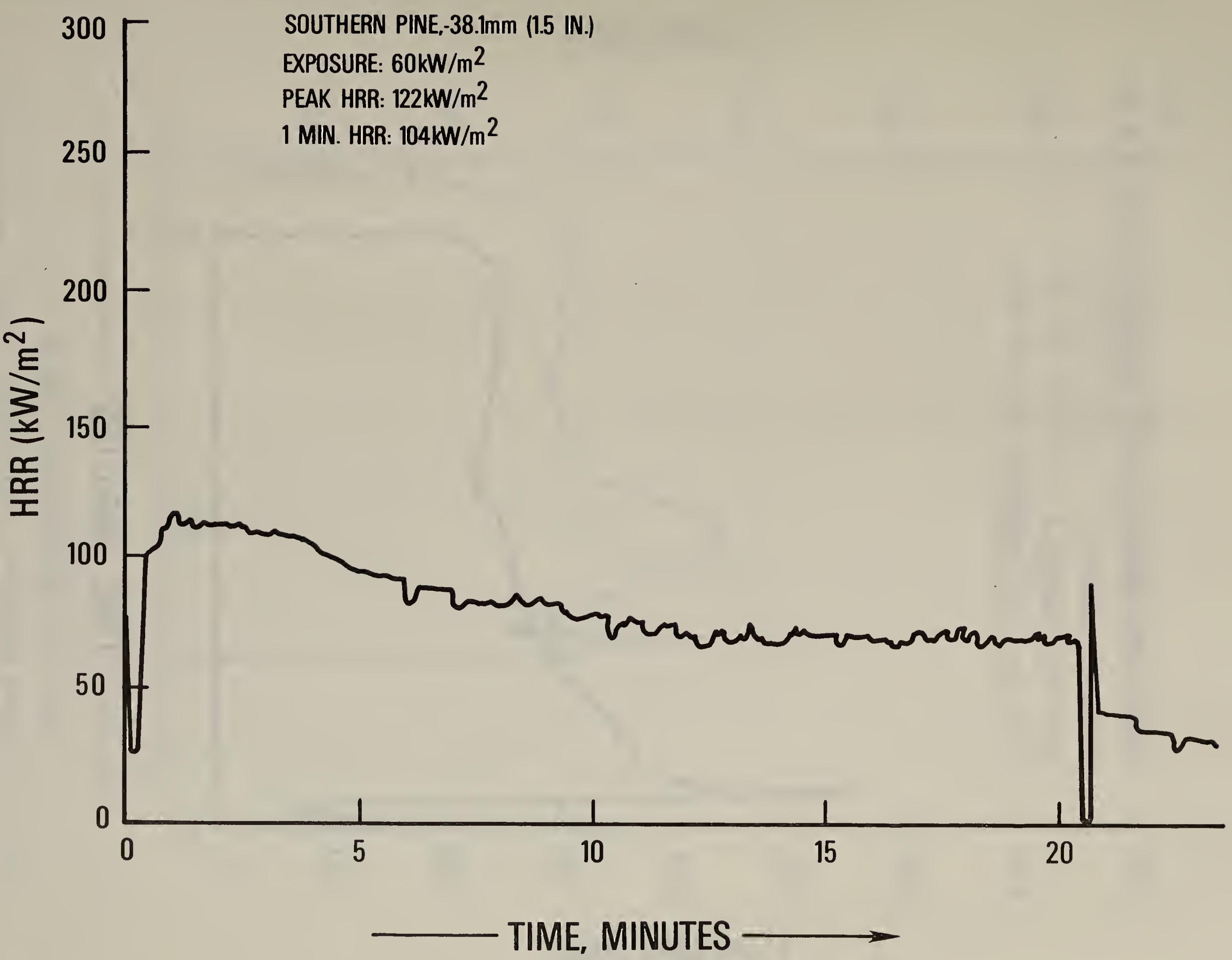


Figure 11. Typical HRR Curves: Southern Pine

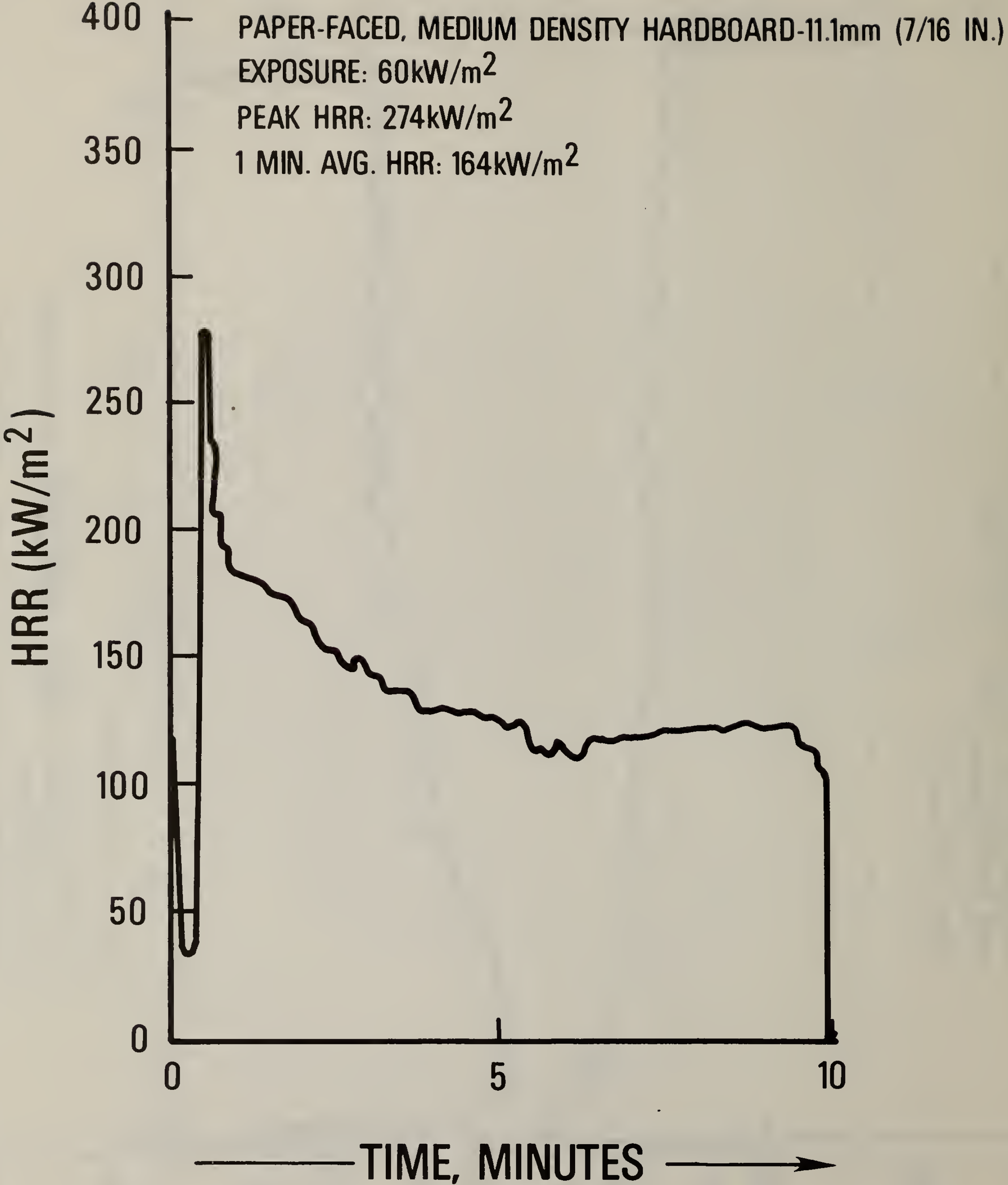


Figure 12. Typical HRR Curves: Medium-Density, Paper-Faced Hardboard

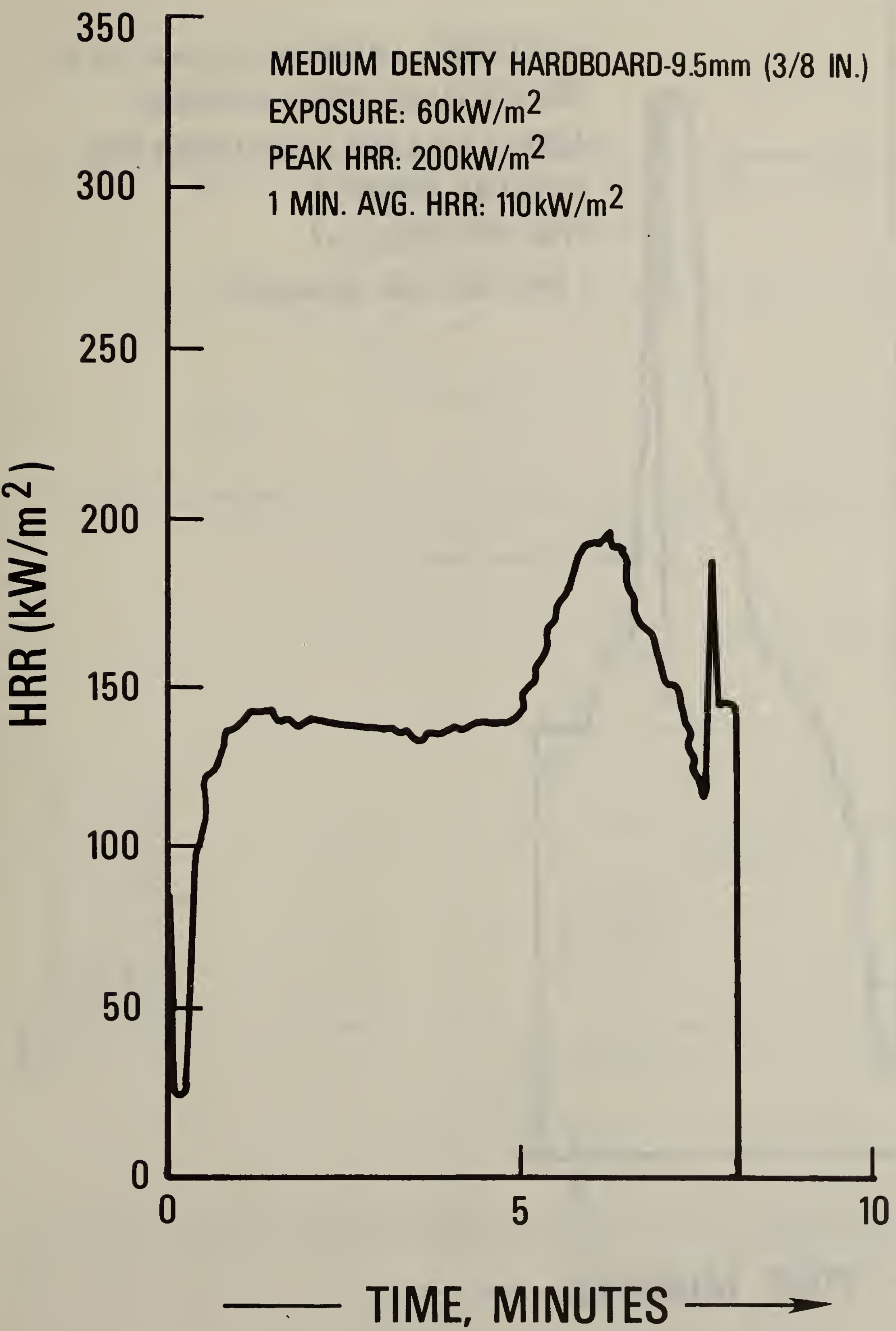


Figure 13. Typical HRR Curves: Medium-Density Hardboard

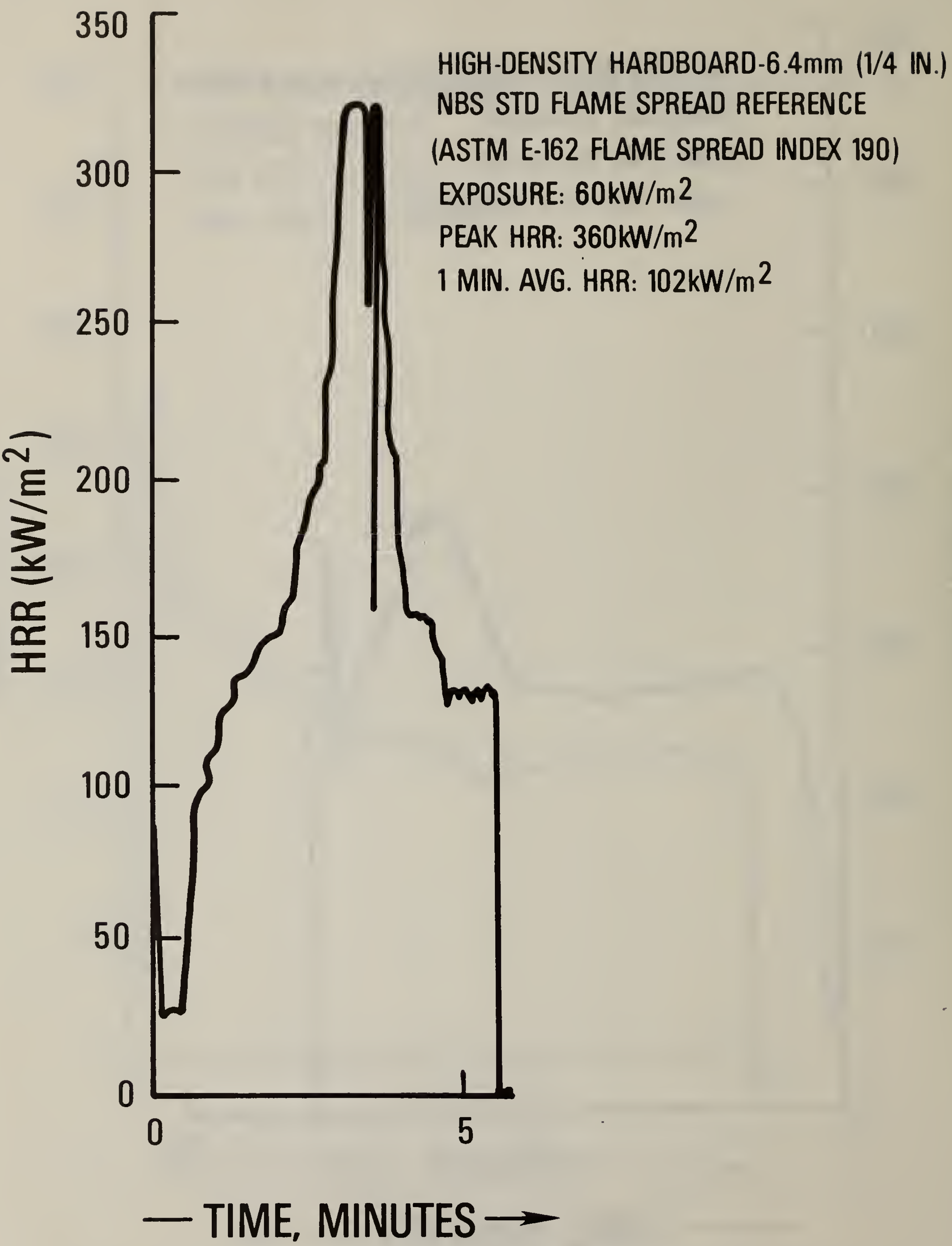


Figure 14. Typical HRR Curves: High-Density Hardboard

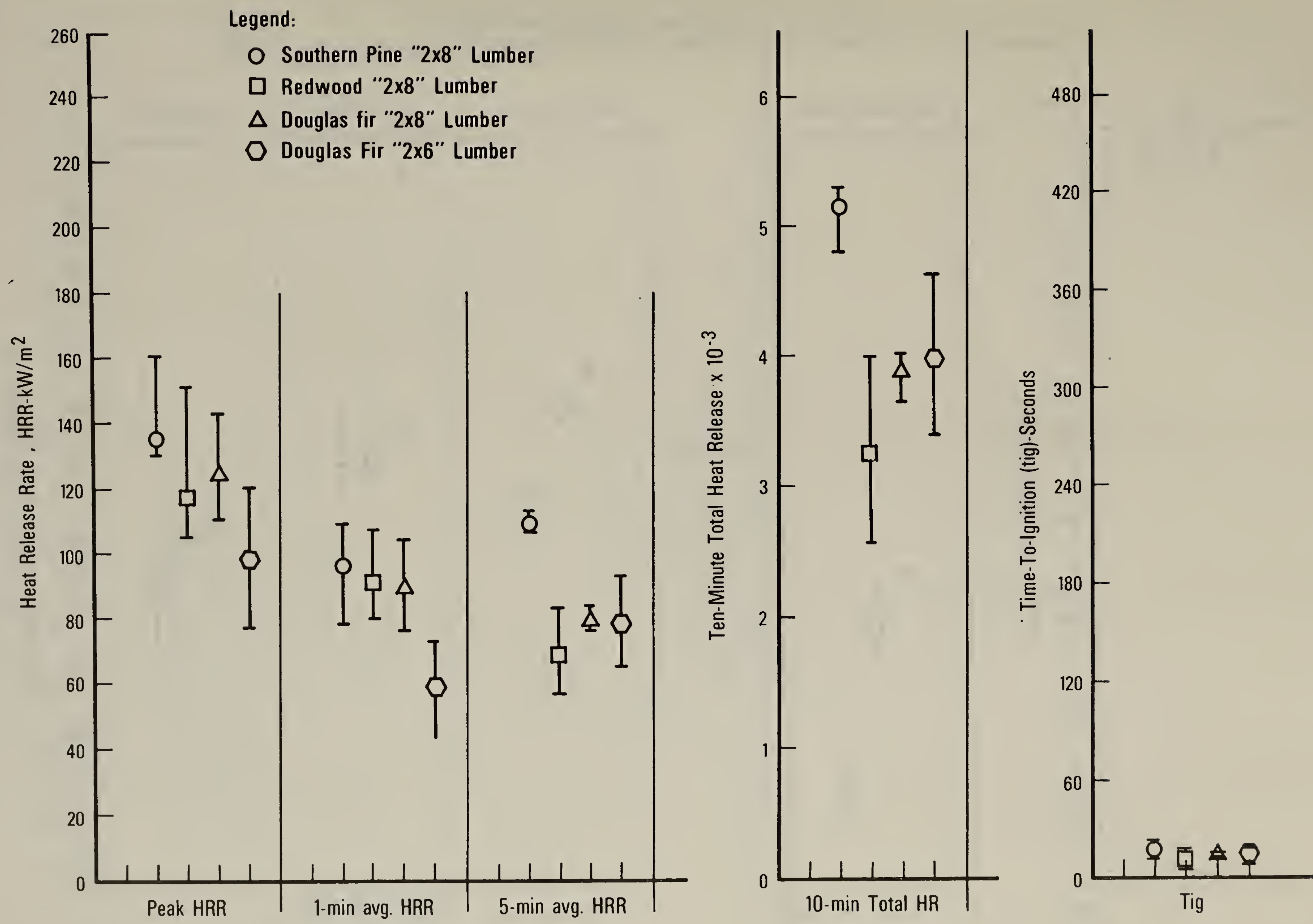


Figure 15a. Heat Release Rate Data Comparison of Materials Conditioned at 70°F and 50% RH, Exposed at 60 kW/m^2

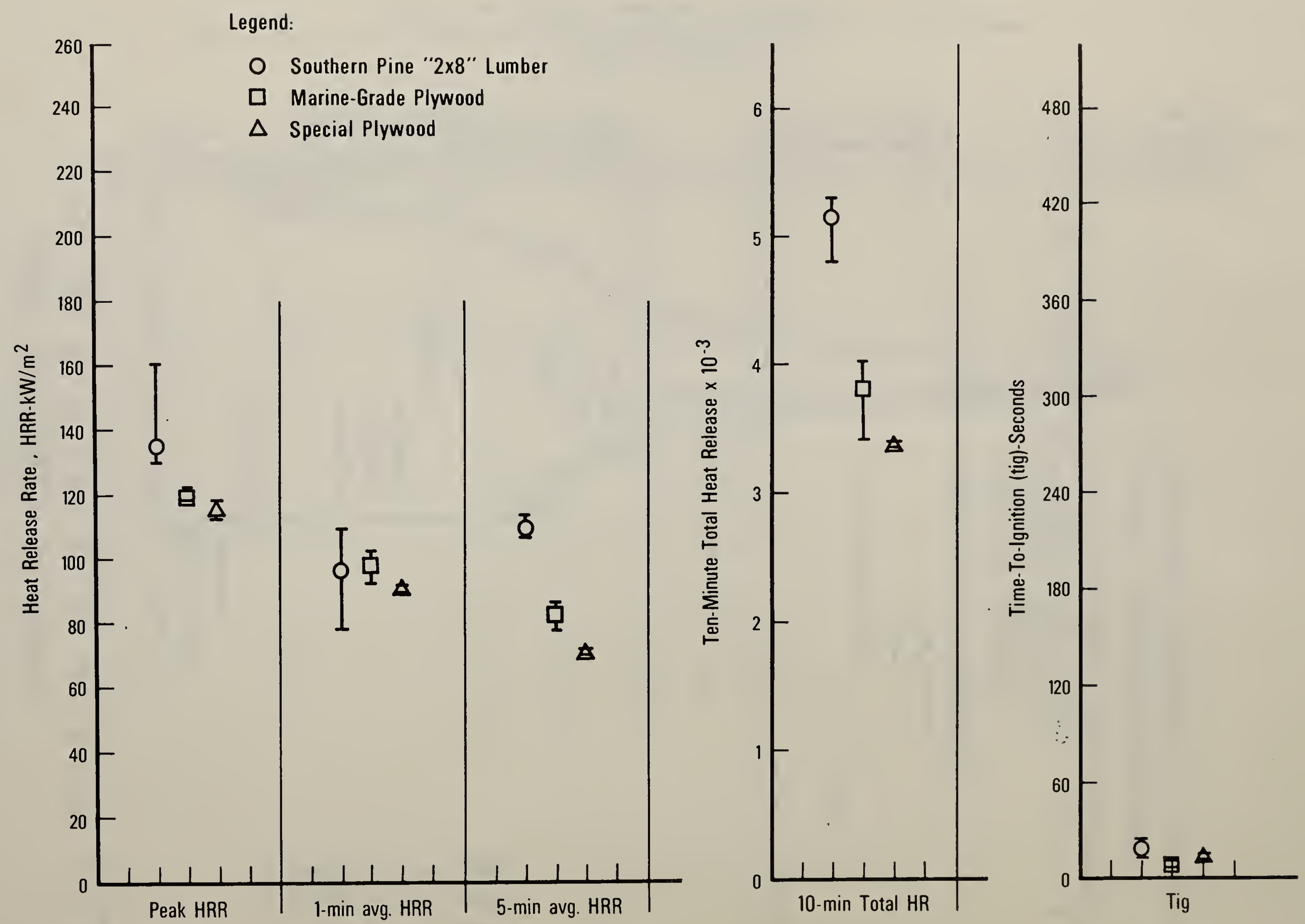


Figure 15b. Heat Release Rate Data Comparison of Materials Conditioned at 70°F and 50% RH, Exposed at 60 kW/m^2

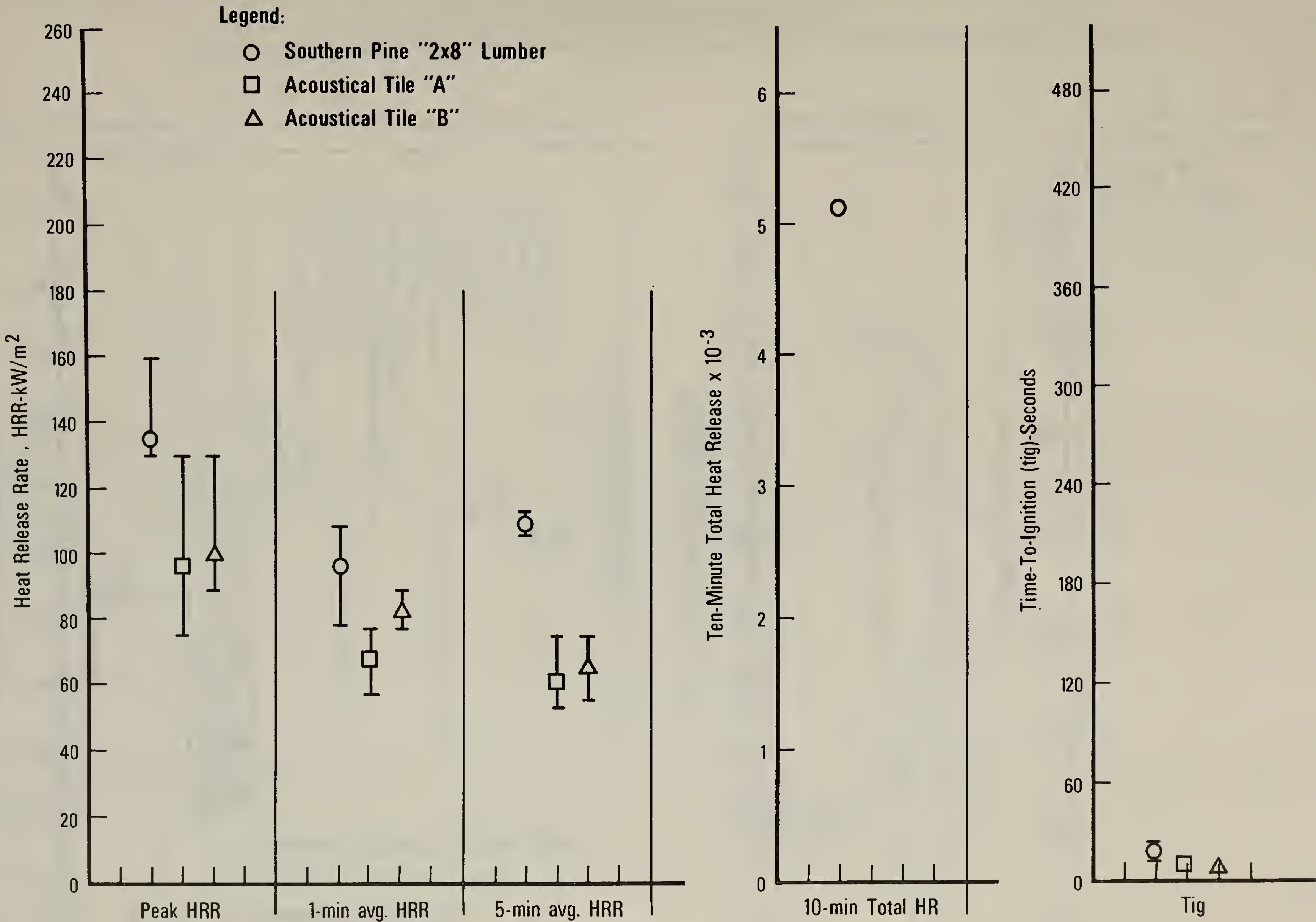


Figure 15c. Heat Release Rate Data Comparison of Materials Conditioned at 70°F and 50% RH, Exposed at 60 kW/m^2

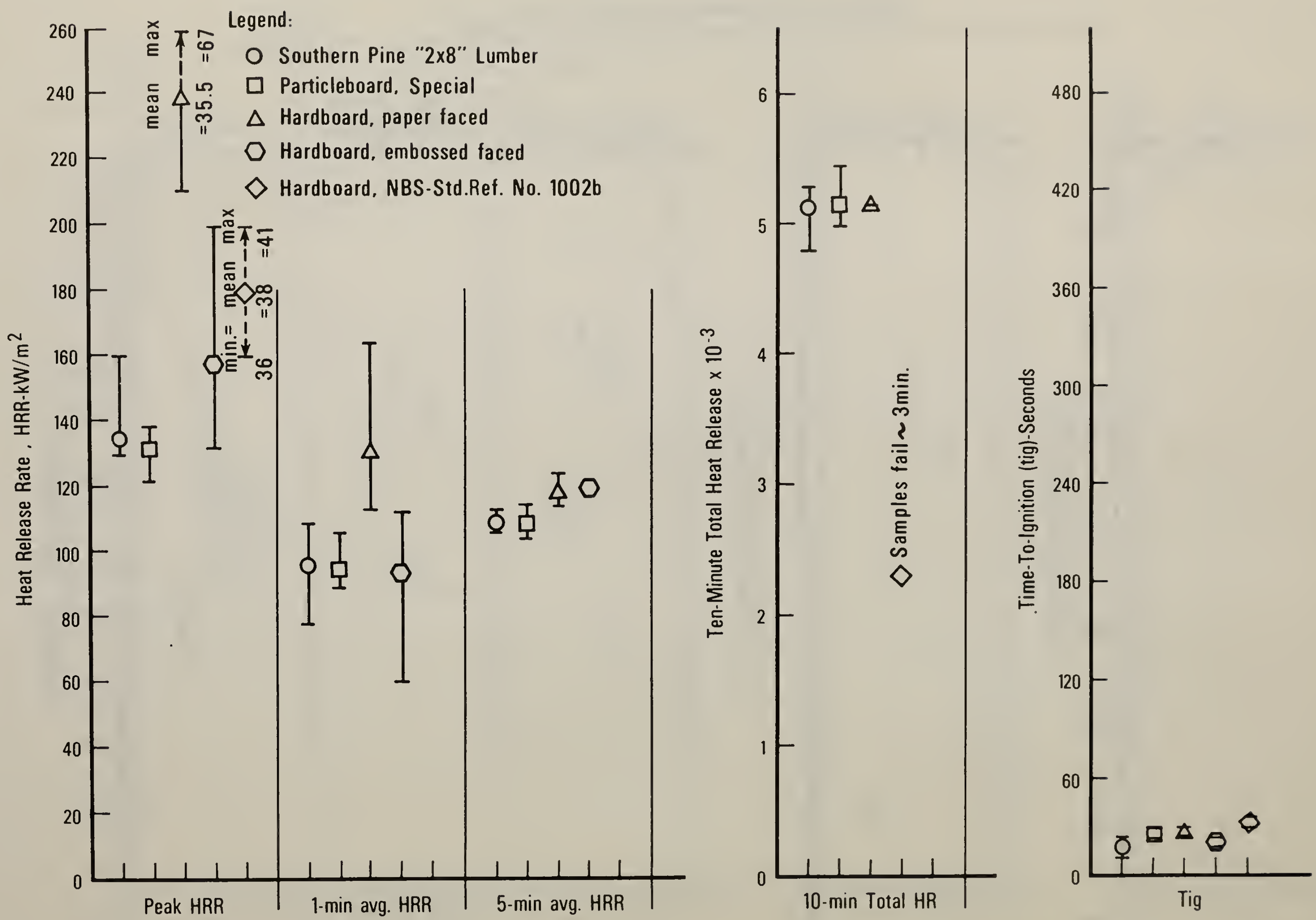


Figure 15d. Heat Release Rate Data Comparison of Materials Conditioned at 70°F and 50% RH, Exposed at 60 kW/m^2

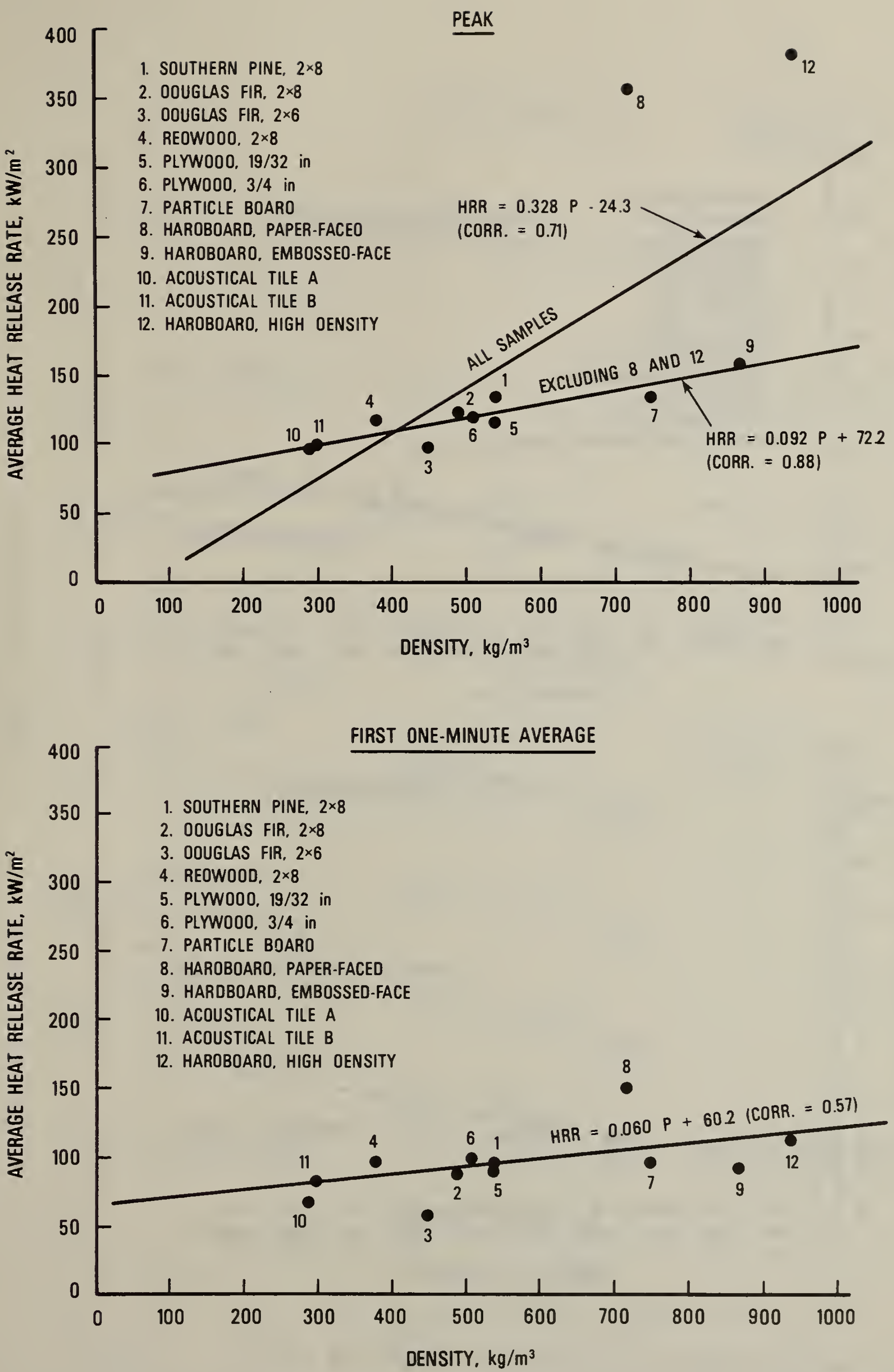


Figure 16a. Effect of Density on HRR Properties: NBS-I Calorimeter

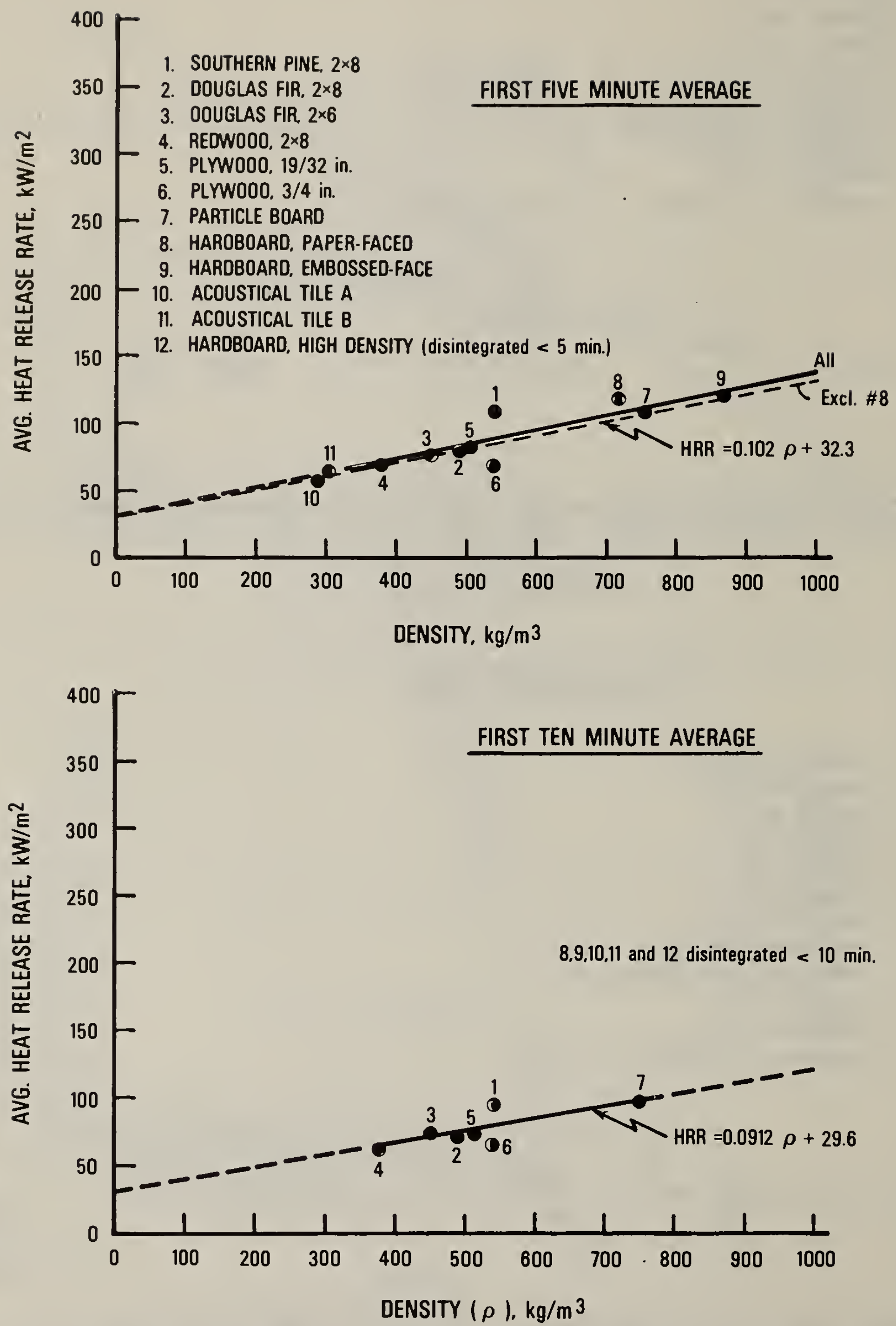


Figure 16b. Effect of Density on HRR Properties: NBS-I Calorimeter

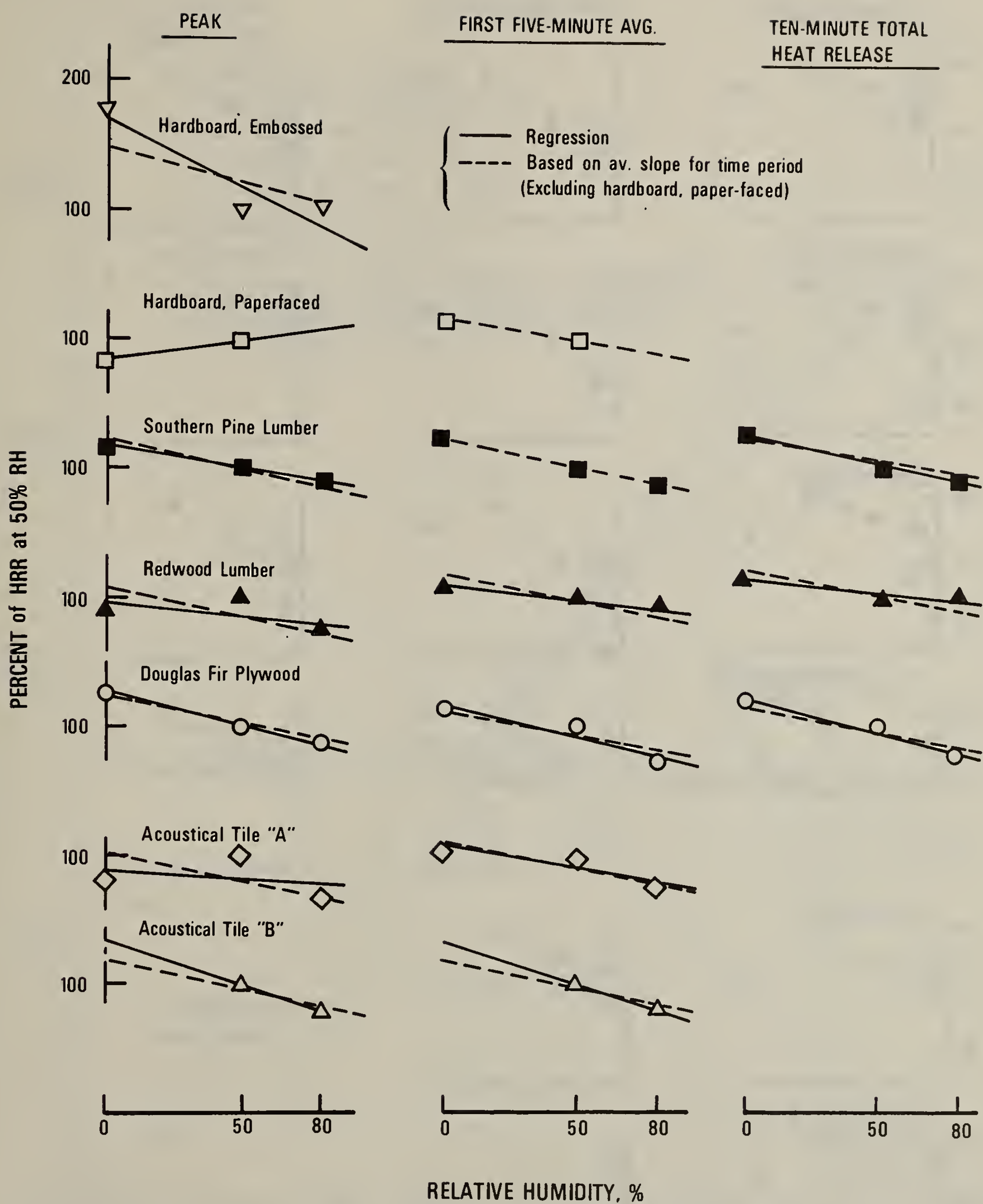


Figure 17. Effect of Conditioning Room RH on HRR Properties

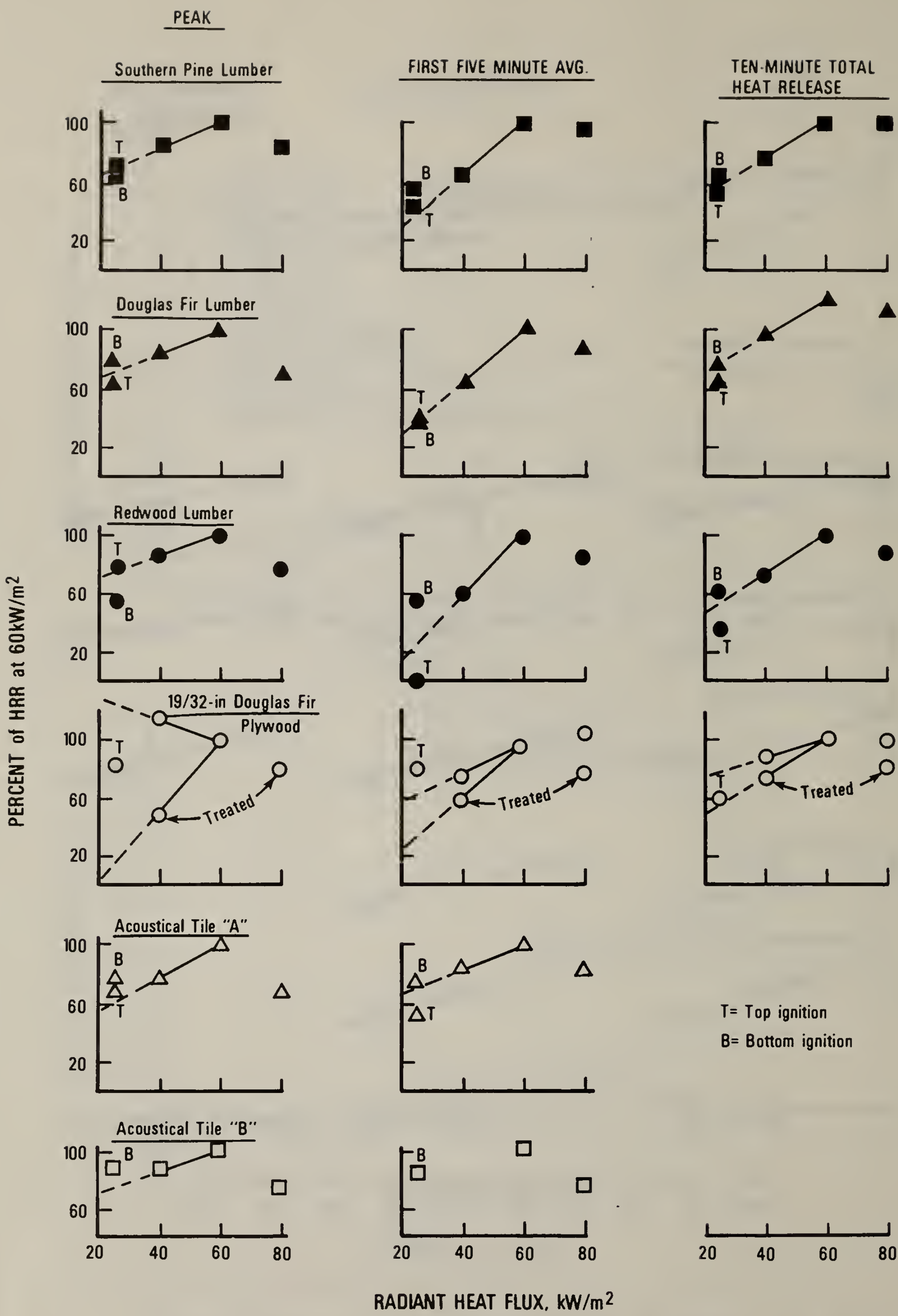


Figure 18. Effect of Radiant Flux on Heat Release Properties

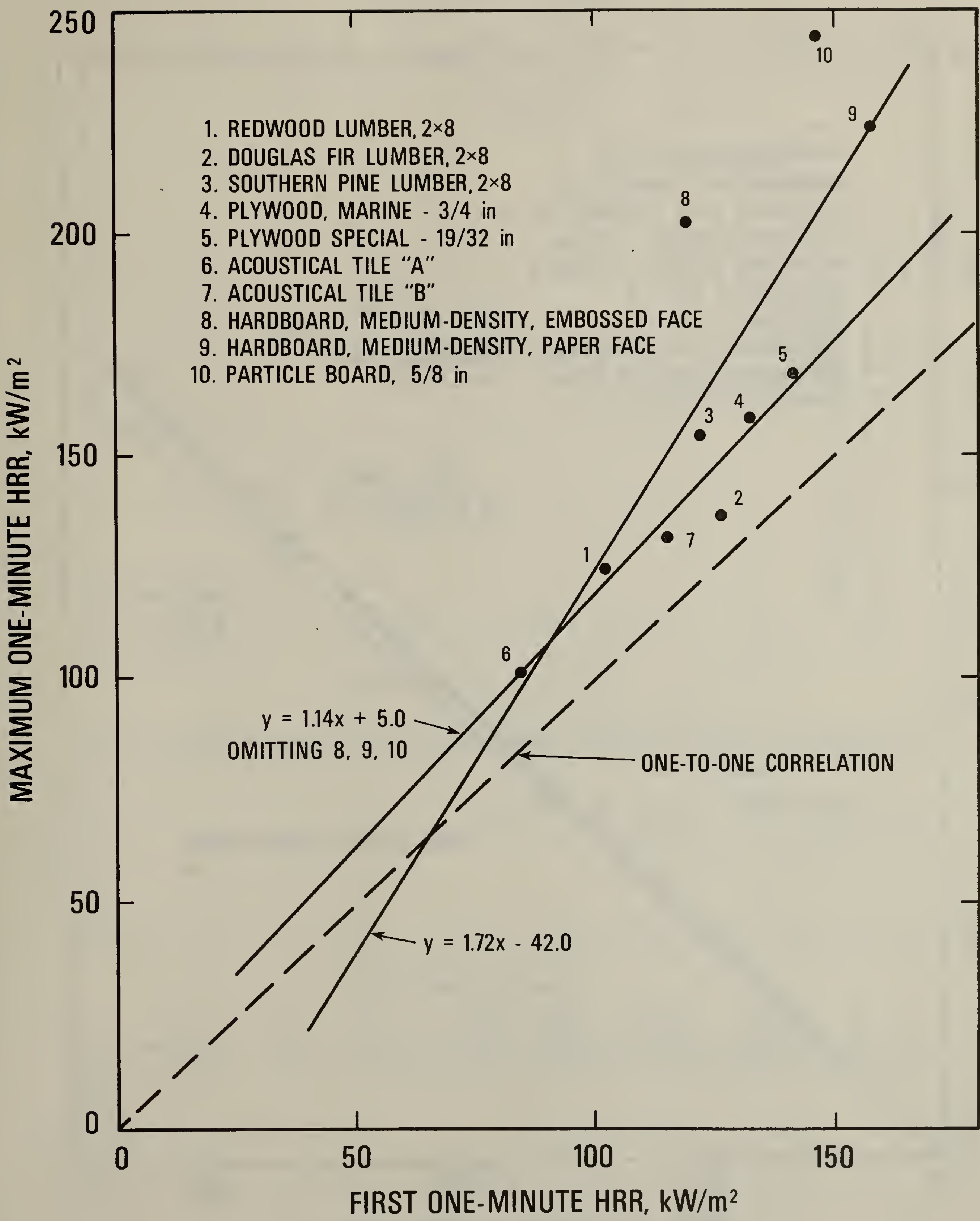


Figure 19a. Comparison of First 1-Minute HRR with Maximum 1-Minute HRR

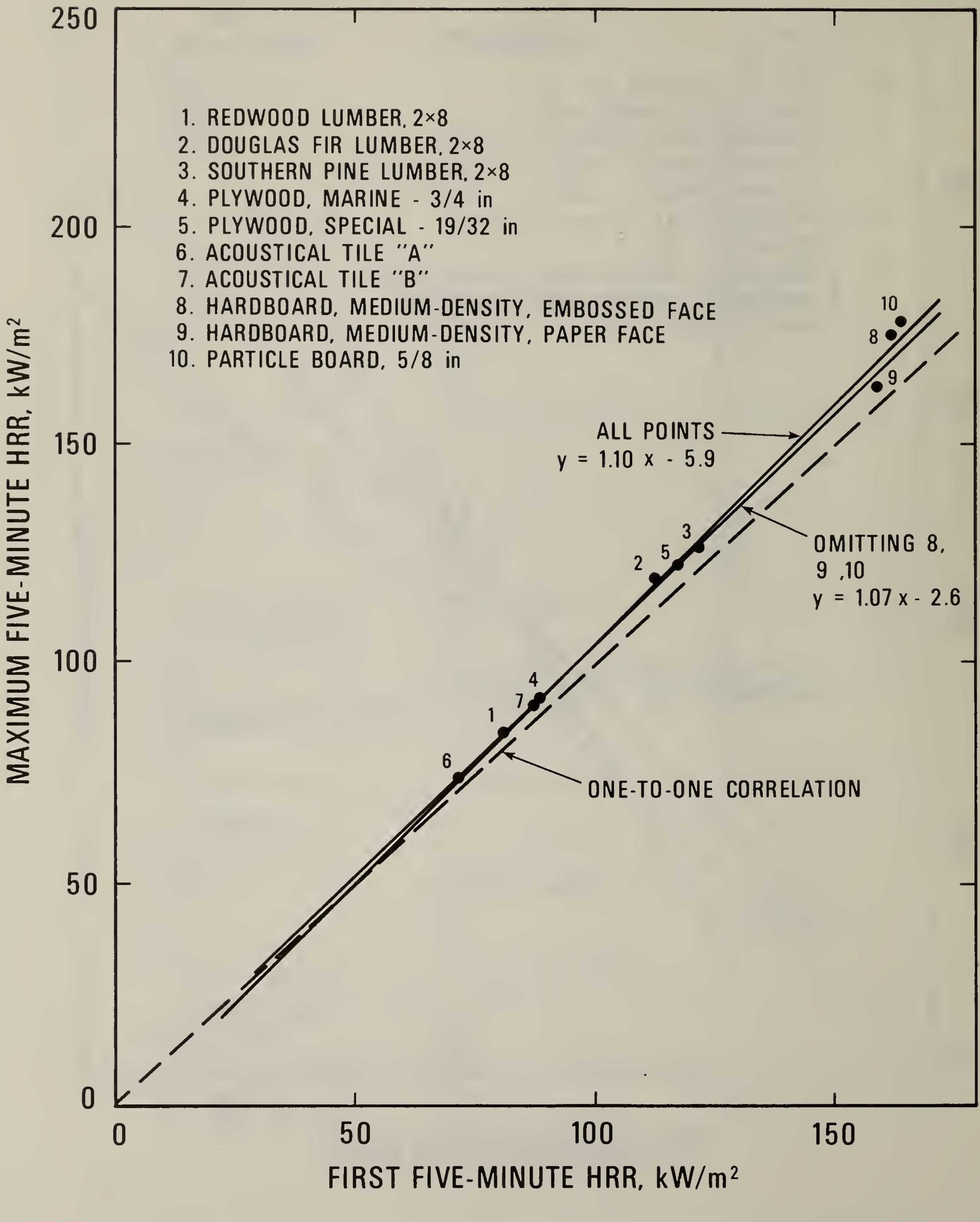


Figure 19b. Comparison of First 5-Minute HRR with Maximum 5-Minute HRR

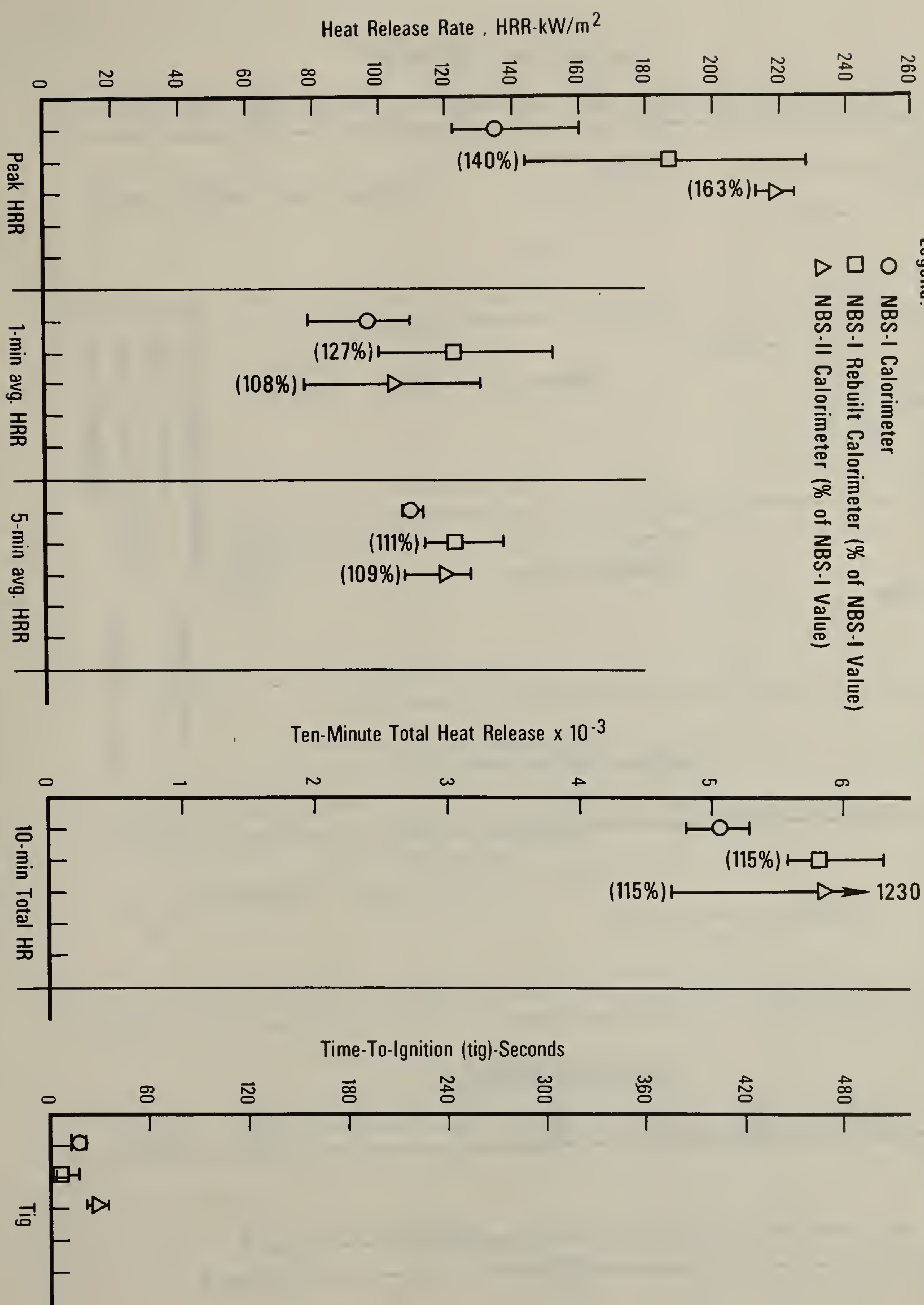


Figure 20a. Heat Release Rate Properties of Wood Products as Measured by Different NBS Calorimeters

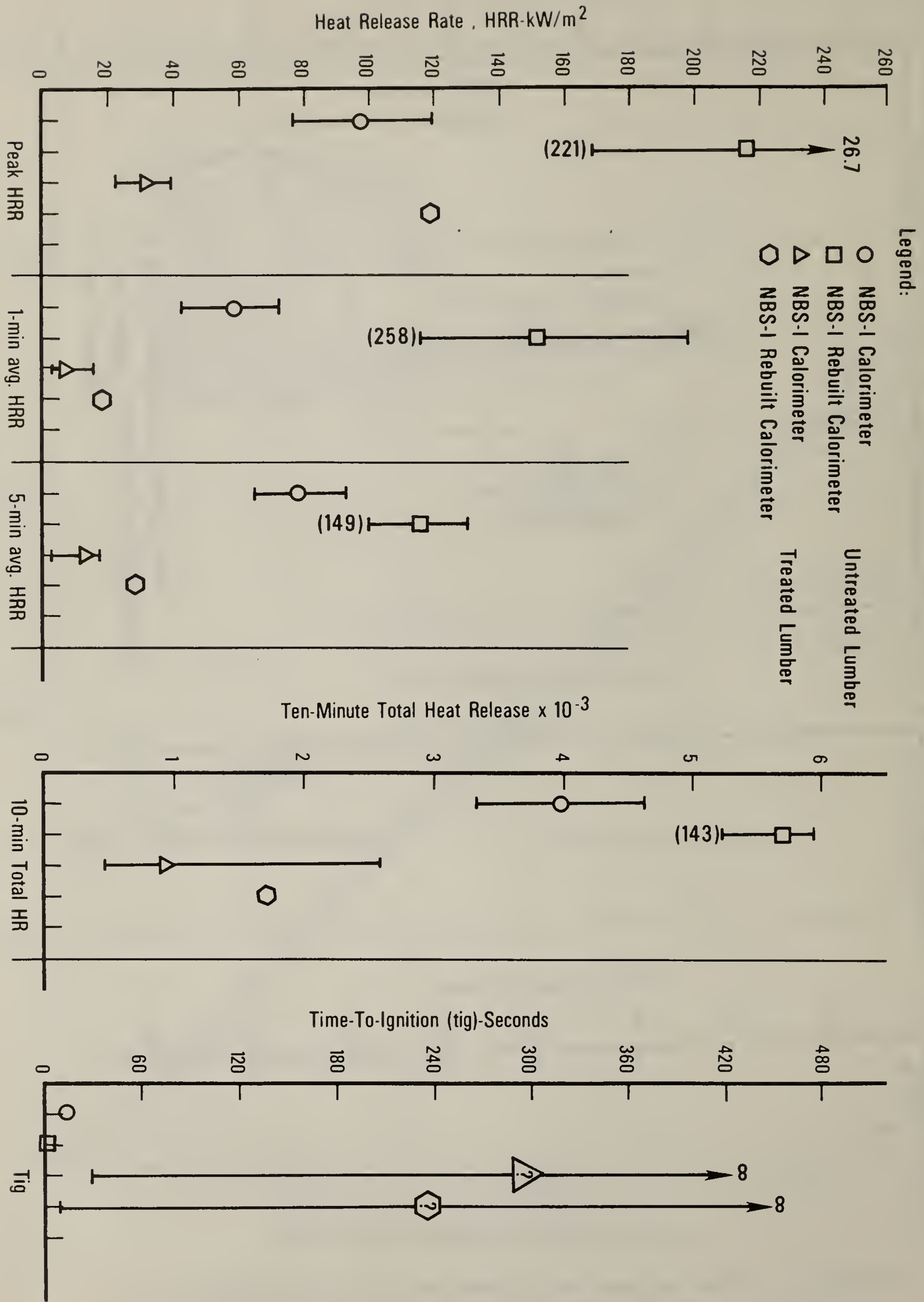


Figure 20b. Heat Release Rate Properties of Wood Products as Measured by Different NBS Calorimeters

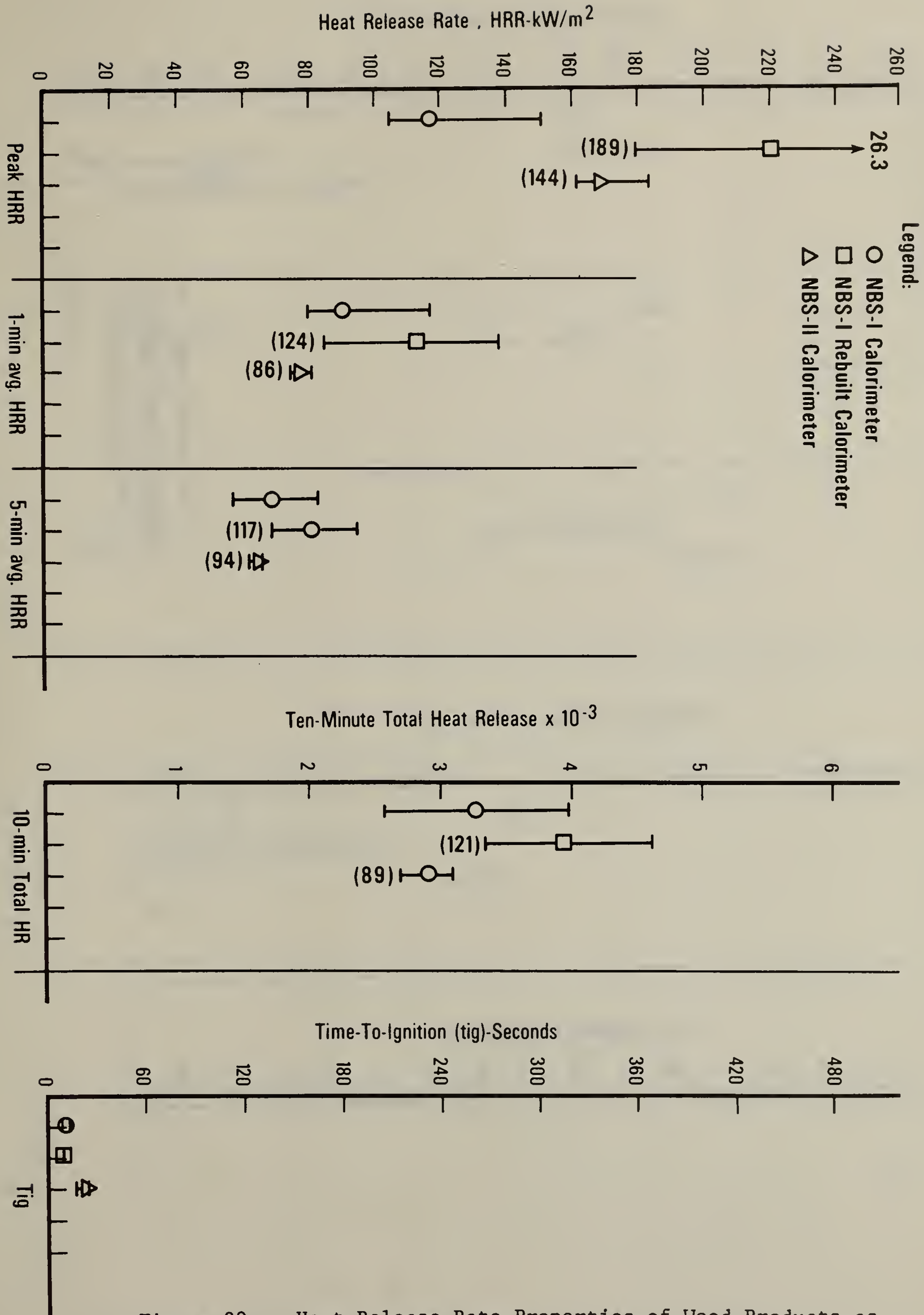


Figure 20c. Heat Release Rate Properties of Wood Products as Measured by Different NBS Calorimeters

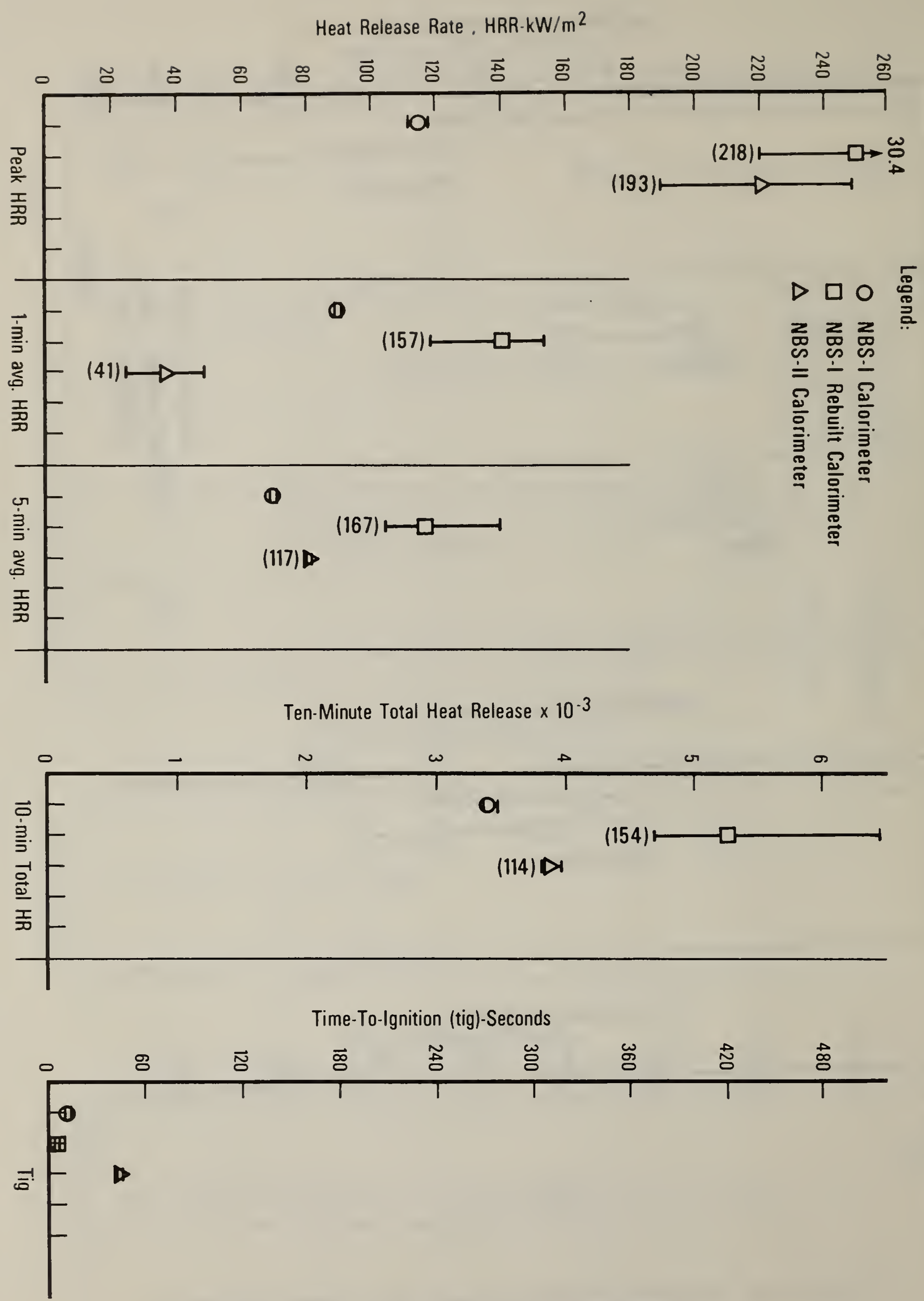


Figure 20d. Heat Release Rate Properties of Wood Products as Measured by Different NBS Calorimeters

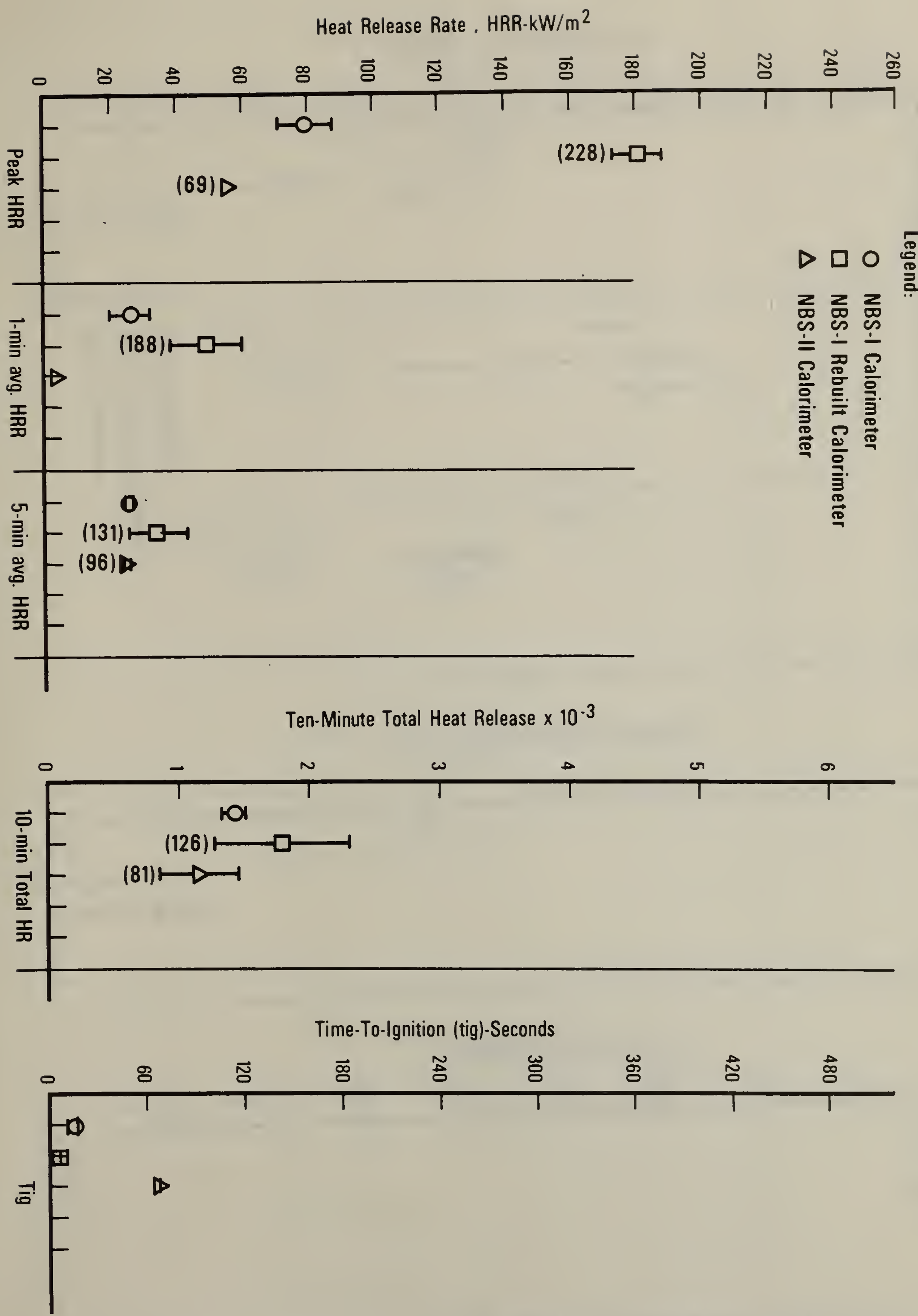


Figure 20e. Heat Release Rate Properties of Wood Products as Measured by Different NBS Calorimeters

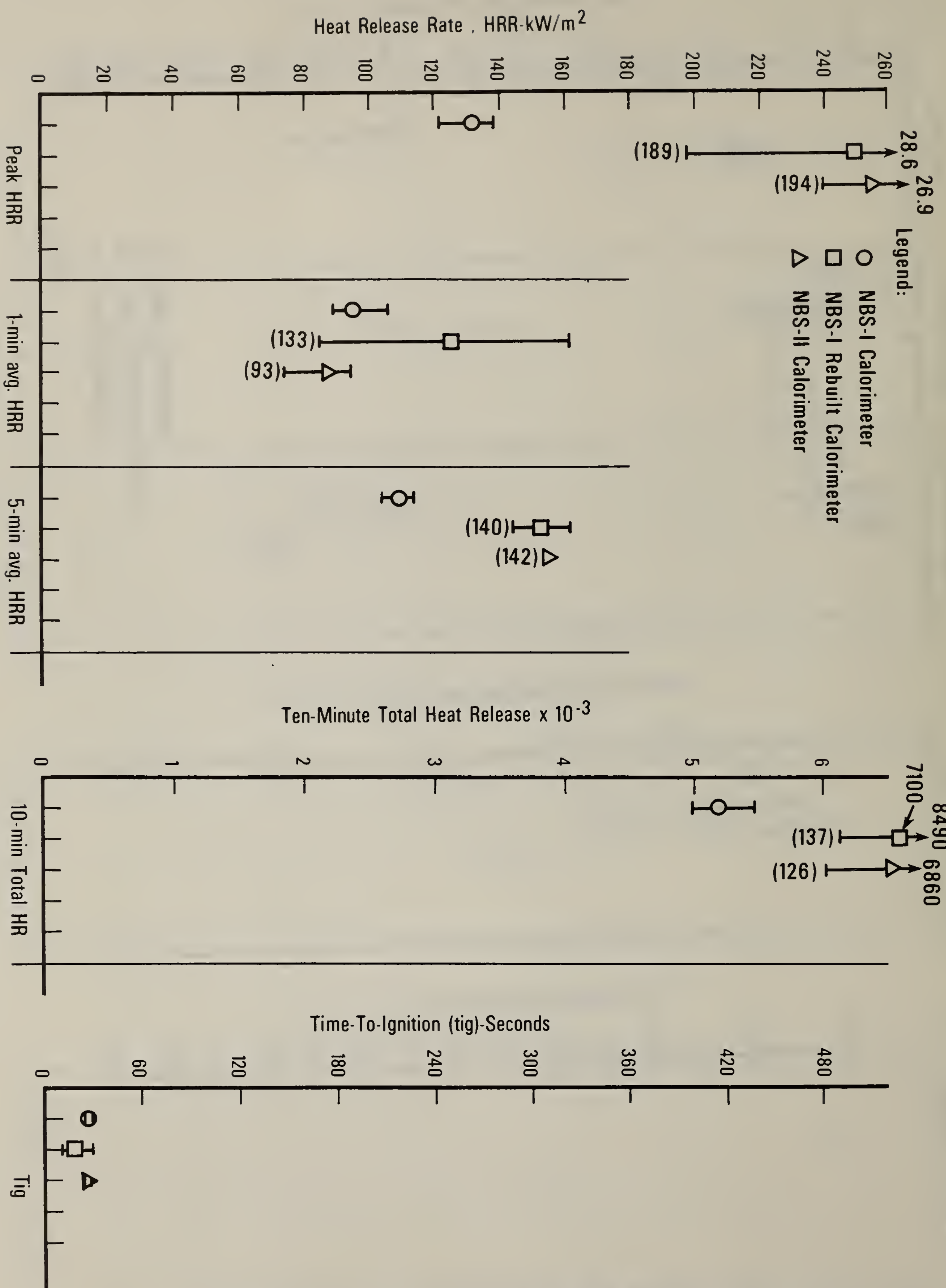


Figure 20f. Heat Release Rate Properties of Wood Products as Measured by Different NBS Calorimeters

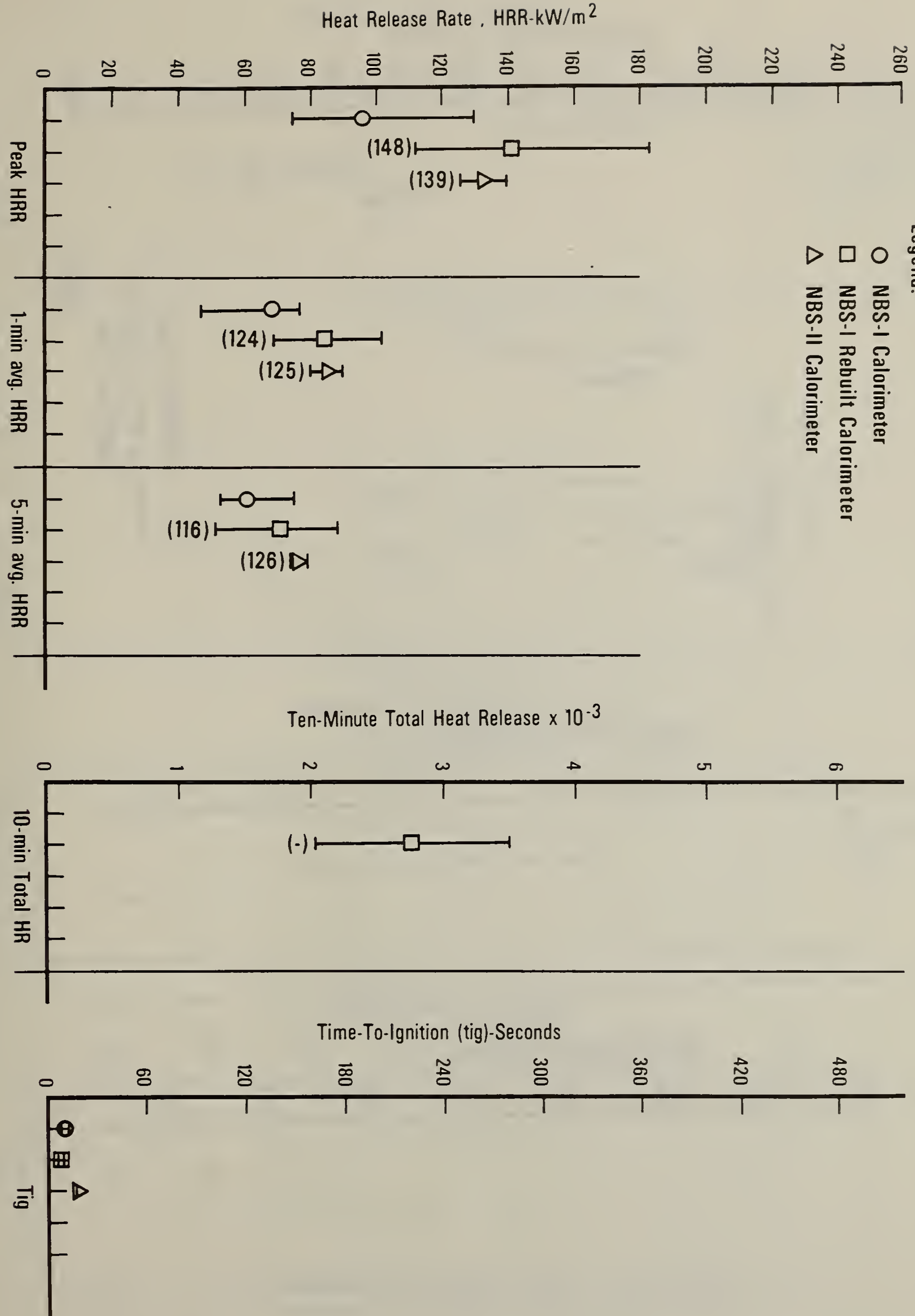


Figure 20g. Heat Release Rate Properties of Wood Products as Measured by Different NBS Calorimeters

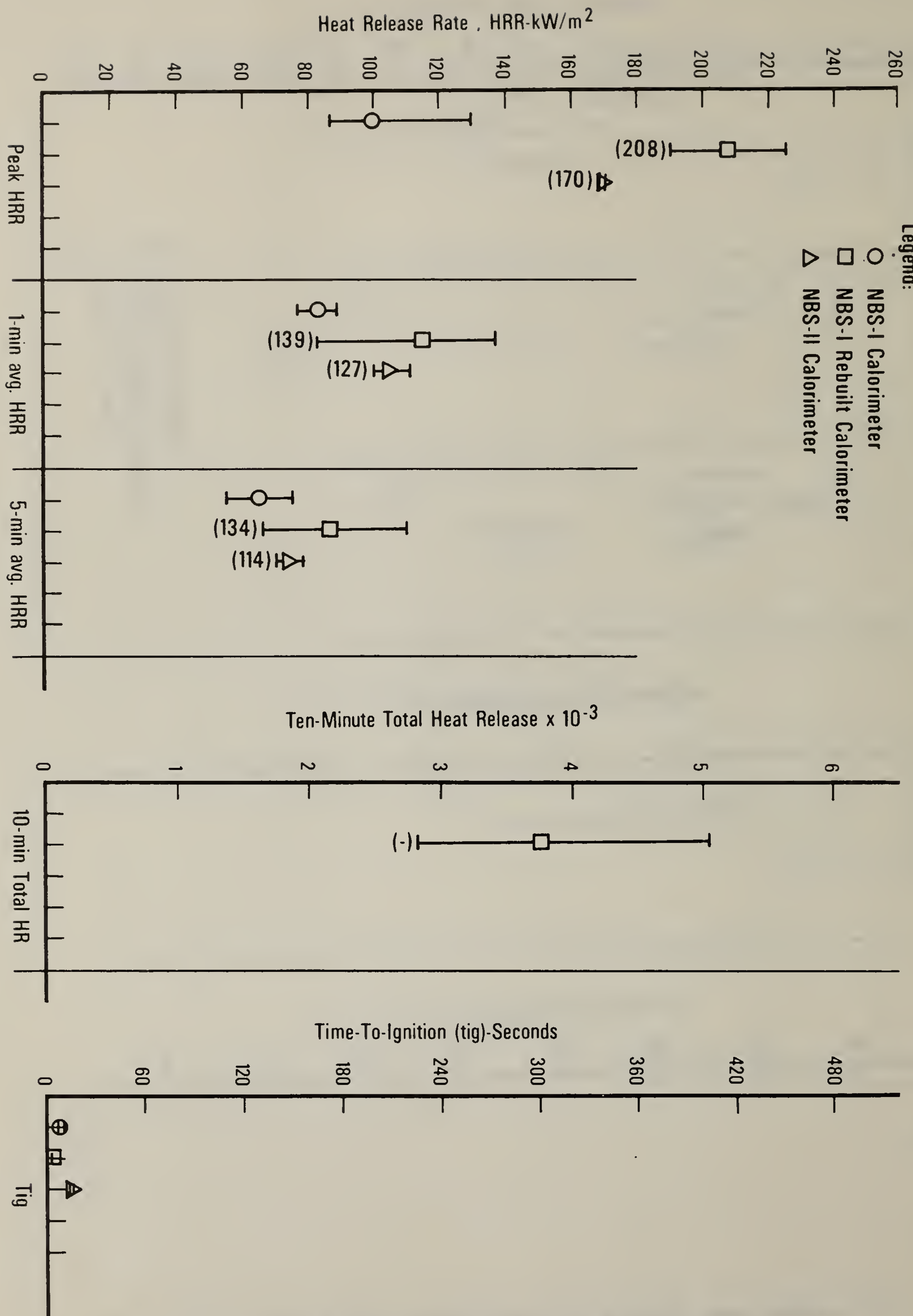


Figure 20h. Heat Release Rate Properties of Wood Products as Measured by Different NBS Calorimeters

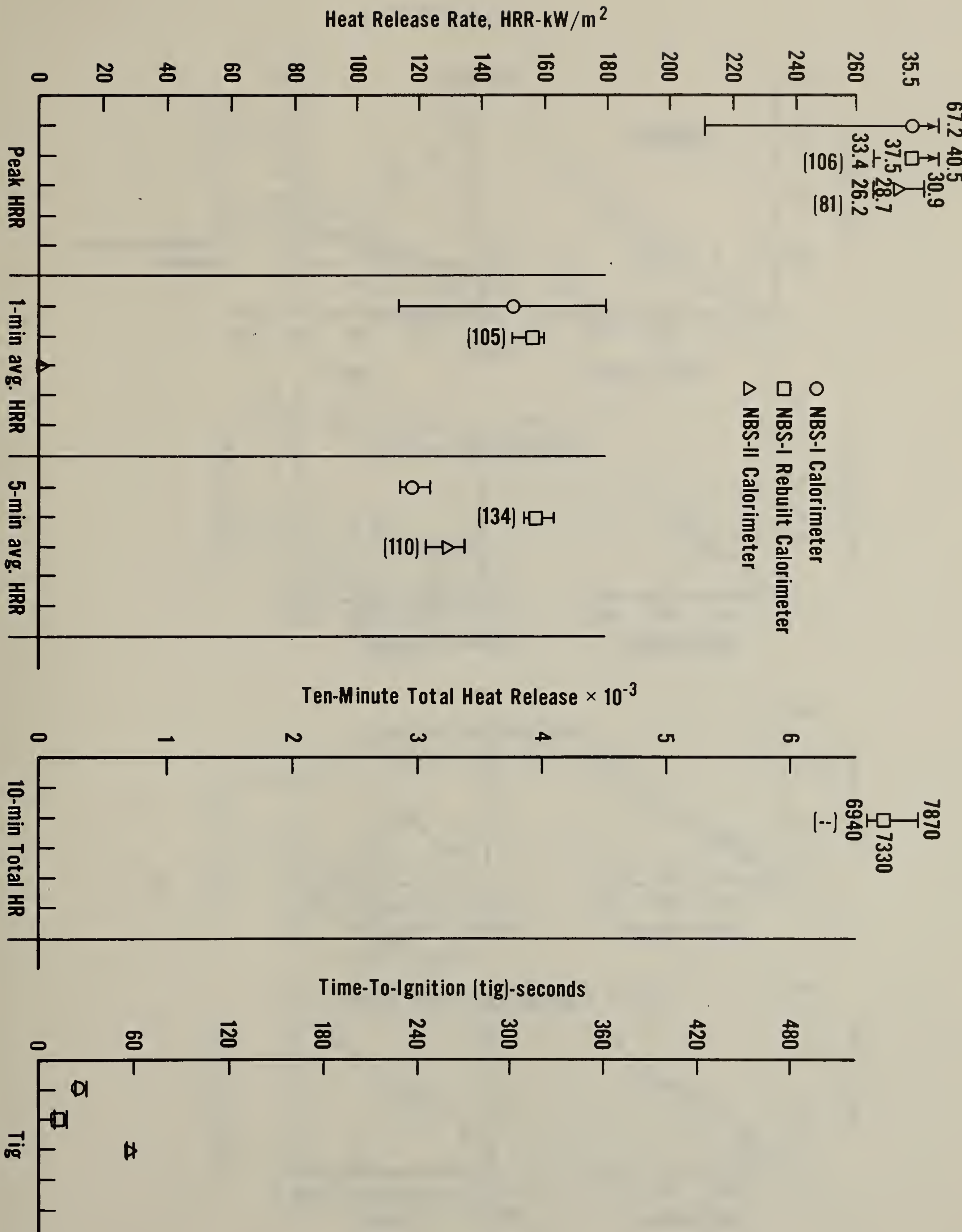


Figure 20i. Heat Release Rate Properties of Wood Products as Measured by Different NBS Calorimeters

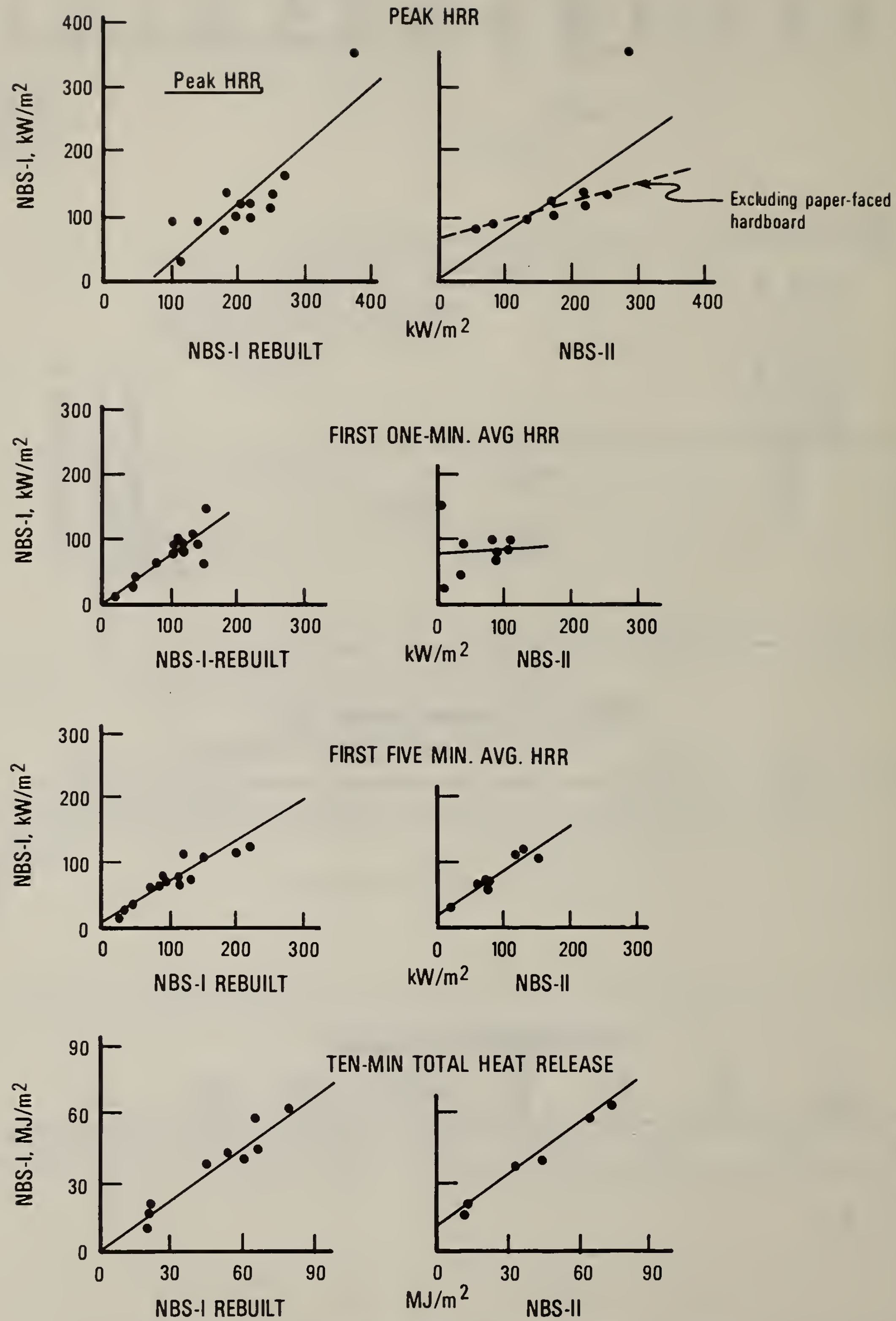


Figure 21. Correlations Among NBS HRR Calorimeters

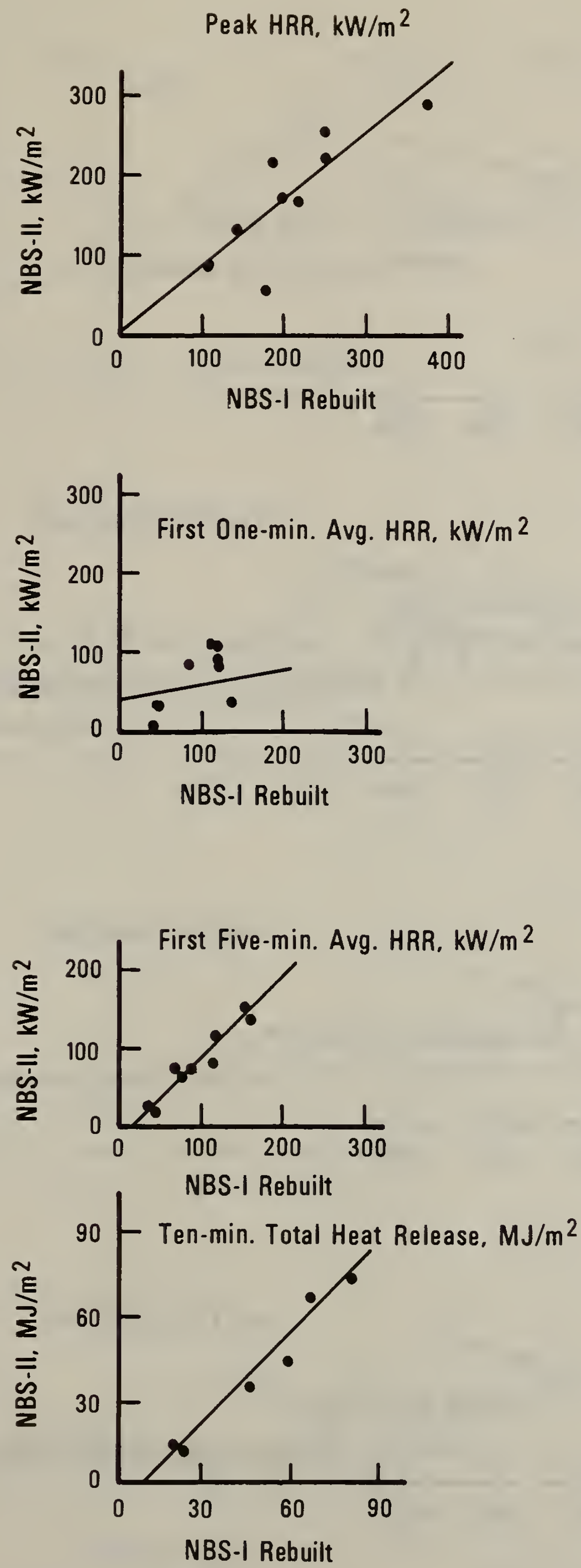


Figure 22. Correlations Among NBS HRR Calorimeters (Cont.)

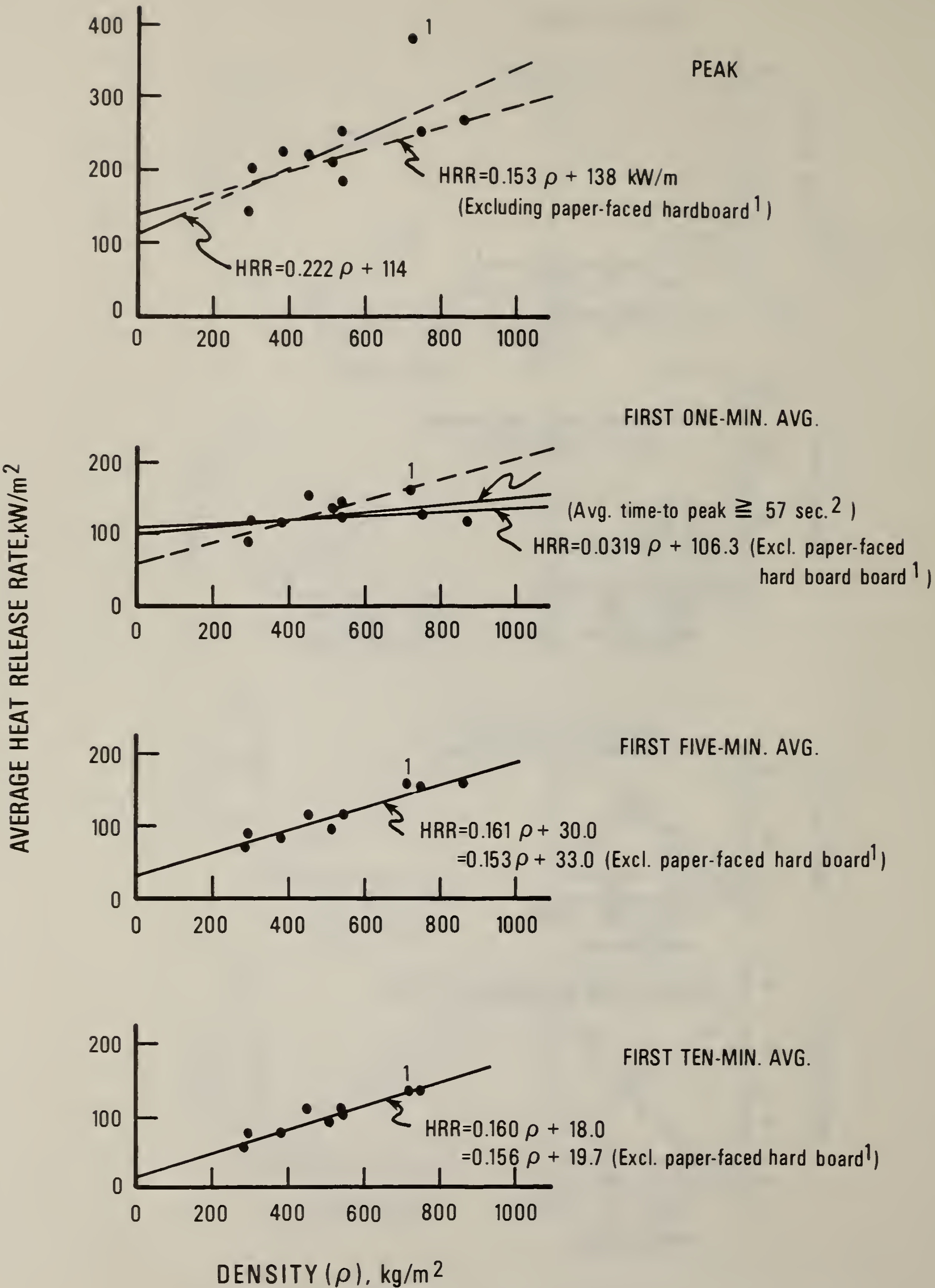


Figure 23. Effect of Density on HRR Properties: NBS-I R Calorimeter

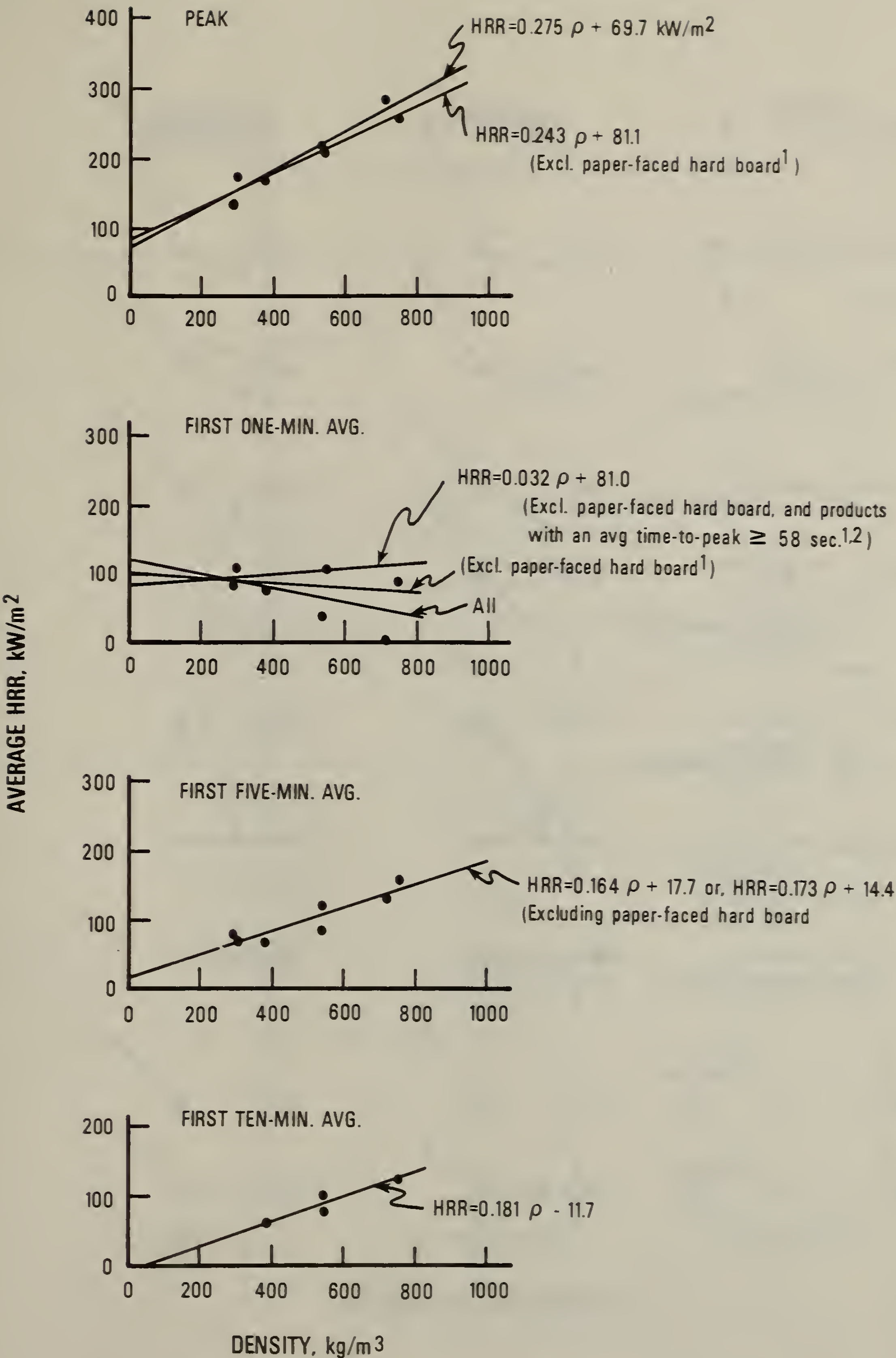


Figure 24. Effect of Density on HRR Properties: NBS-II Calorimeter

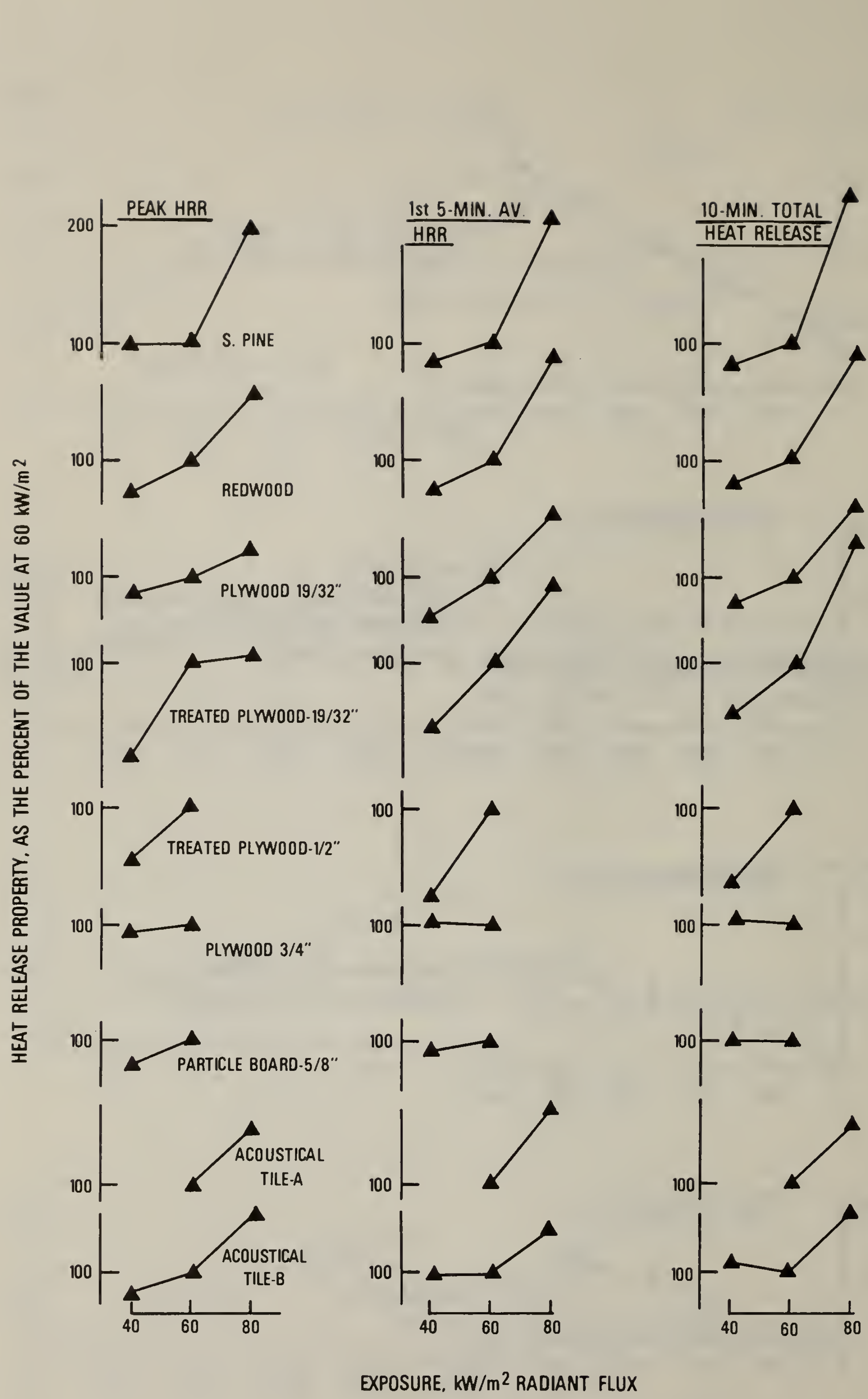


Figure 25. Effect of Radiant Heat Flux on HRR Properties: NBS-I Calorimeter

Table 1. Heat Release Rate Calorimeters

Location	Sample Size mm (in)	Type	Exposure Source (cm)	Exposure Intensity (kW/m^2)
FM	1219 x 1219 (48 x 48)	Substitution, equiv. gas flow	Hot combustion gases	t/T curve, 0-120
NBS	114 x 152 (4.5 x 6.0)	Direct, equiv. gas flow	Gas-fired radiant panel	15-80
OSU	152 x 152 (6 x 6)	Direct, temperature rise	Electric radiant panel	Up to 35
SRI	457 x 610 (18 x 24)	Direct, equiv. gas flow	Gas-fired radiant panel	Up to 80
FPL	457 x 457 (18 x 18)	Substitution, equiv. gas flow	Gas-fired panel	Up to 40
NBS-II	305 x 305 (12 x 12)	Direct, equiv. gas flow	Gas-fired radiant panel	Up to 80
Oxygen Consumption	102 x 102 (4 x 4)	Change in oxygen consumed during combustion	Electrically heated radiant panel	Up to 100

Table 2. Physical Properties of Wood Products (Conditioned at 70°F and 50% RH)

Material	Thickness mm (in)	Moisture Content[a], %	Density[b] kg/m^3	Rings per in	Grain Angle degrees	Percent Summerwood
Southern pine lumber, 2 x 8	37.9 (1.49)	10.4	540	7-9	0-35	38-52
Douglas fir lumber, 2 x 8	38.2 (1.50)	6.6	490	6-15	35-80	25-44
Douglas fir lumber, 2 x 6						
Untreated	38.3 (1.51)	7.3	450	18-27	68-80	19-39
Treated	38.9 (1.53)	9.9	540	9-18	43-68	29-44
Redwood lumber, 2 x 8	37.5 (1.48)	8.4	380	32-87	60-80	25-30
Douglas fir plywood, 19/32"						
Untreated	15.1 (0.60)	7.1	540			
Treated	15.7 (0.62)	9.0	540			
Douglas fir plywood, 1/2"						
Untreated	12.8 (0.50)	9.2	510			
Treated	12.5 (0.49)	9.7	560			
Douglas fir plywood, 3/4" marine grade	18.8 (0.74)	8.1	510			
Particleboard, 5/8"	15.7 (0.63)	7.4	750			
Acoustical tile A, 1/2"	12.9 (0.51)	7.5	290			
Acoustical tile B, 1/2"	13.5 (0.53)	7.7	300			
Hardboard 7/16" m.d.,[c] paperfaced	10.5 (0.41)	6.3	720			
Hardboard 3/8" m.d., embossed	9.0 (0.35)	6.0	870			
Hardboard 5/32" h.d.,[c] oil tempered	5.6 (0.22)	6.2	940			

[a]Based on oven-dry weight.

[b]Based on oven-dry weight and volume at moisture control indicated.

[c]m.d. and h.d. = medium and high density

Table 3. Format for Recording HRR Data

Time Period	Scale Deflection	HRR $\frac{W}{cm^2}$	HRR $\frac{Btu}{ft^2/sec}$	Total HR $\frac{Btu}{ft^2}$
Peak				
Average				
1-min				
3-min				
5-min				
10-min				
15-min				
20-min				

(Sample Form)

Table 4. Heat Release Properties of Wood-Based Materials
Samples Conditioned at 70°F and 50% RH and Exposed at 60 kW/m^2 radiant flux in NBS-I Calorimeter

Material	No. of Tests	Time to Ignition		Time to Peak HRR		Mean HRR						10-min. Total Heat Release	
						Peak		First 1-min. Avg.		First 5-min. Avg.			
		Sec.	% of SP*	Sec.	% of SP	kW/m^2	% of SP	kW/m^2	% of SP	kW/m^2	% of SP	Btu/ft^2 (MJ/m^2)	% of SP
Southern pine, 2x8 lbr.	5	17	100	60	100	134	100	96	100	109	100	5080 (57.69)	100
Douglas fir, 2x8 lbr.	3	14	79	40	67	124	93	89	93	79	72	3860 (43.83)	76
Douglas fir, 2x6 lbr.	4	15	88	28	47	98	73	59	61	78	72	3990 (45.31)	79
Redwood, 2x8 lbr.	9	11	65	20	33	118	88	95	99	71	65	3352 (38.07)	66
Douglas fir, 19/32" ply.	2	12	71	17	28	115	86	90	94	70	64	3420 (38.84)	67
Douglas fir, 3/4" ply.	3	8	47	19	32	119	89	98	102	82	75	3820 (43.38)	75
Particleboard, 5/8"	3	26	153	104	173	132	99	95	99	109	100	5180 (58.82)	102
Acoustical tile - A	5	10	59	62	103	96	72	68	71	61	56	--	--
Acoustical tile - B	5	9	53	41	68	100	75	83	86	65	60	--	--
Hardboard, 7/16" m.d., paper-faced	4	25	147	29	48	355	265	150	156	118	108	--	--
Hardboard, 3/8" m.d., embossed	3	21	124	197	328	158	118	94	98	120	110	--	--
Hardboard, 5/32" h.d.	3	33	194	153	255	380	284	112	117	--	--	--	--

*SP = Southern pine

Table 5. Comparison of Heat Release Properties of Fire-Retardant Treated Douglas Fir Plywood and Lumber, Untreated Controls, and Untreated Southern Pine Lumber (Conditioned at 70°F and 50% RH and Exposed at 60 kW/m^2 Radiant Flux in NBS-I Calorimeter)

Material	No. of Tests	Time to Ignition Sec	Time to Peak HRR Sec	Mean HRR kW/m^2 Peak	First 1-min Average	First 5-min Average	10-min Total Heat Release Btu/ft^2 (MJ/m^2)
Southern pine lumber, 2 x 8	5	17	60	134	96	109	5080 (57.69)
Douglas fir lumber, 2 x 6							
Untreated	4	15	28	98	59	78	3990 (45.31)
(% of Southern pine)		(88)	(47)	(73)	(61)	(72)	(79)
Treated - A	4	>30	585	32	7	13	940 (10.67)
(% of untreated)		(>200)	(2089)	(33)	(12)	(17)	(24)
(% of Southern pine)		(>176)	(975)	(24)	(7)	(12)	(19)
Douglas fir plywood, 19/32"							
Untreated	2	13	17	115	90	70	3420 (38.84)
(% of Southern pine)		(76)	(28)	(86)	(94)	(64)	(67)
Treated - B	2	14	19	80	26	26	1410 (16.01)
(% of untreated)		(108)	(112)	(70)	(29)	(37)	(41)
(% of Southern pine)		(82)	(32)	(60)	(27)	(24)	(28)
Douglas fir plywood, 1/2"							
Treated - B	3	15	21	91	39	31	1720 (19.53)
(% of Southern pine)		(88)	(35)	(68)	(41)	(28)	(34)

Table 6. Effect of Conditioning Environment on Heat Release Properties
(Exposed at 60 kW/m^2 Radiant Flux in NBS-I Calorimeter)

Material	Conditioning Environment		No. of Tests	Moisture Content	Time to Ignition		Time to Peak HRR		Mean HRR Peak		Mean HRR First 1-min Avg.		Mean HRR First 5-min Avg.		10-min. Total Heat Release	
	Temp. °C	RH %		%	Sec	% of 21/50 Cond.[a]	Sec	% of 21/50 Cond.	kW/m^2	% of 21/50 Cond.	kW/m^2	% of 21/50 Cond.	kW/m^2	% of 21/50 Cond.	Btu/ft^2 (MJ/m^2)	% of 21/50 Cond.
Southern pine lbr., 2 x 8	21	50	5	10	17	100	60	100	134	100	96	100	109	100	5076 (57.64)	100
	100	0	3	0	11	65	92	153	160	119	100	104	134	123	6500 (73.81)	128
	21	80	3	15	23	135	107	178	122	91	53	55	96	88	4720 (53.60)	93
Redwood lumber, 2 x 8	21	50	9	8	11	100	20	100	118	100	95	100	71	100	3350 (38.04)	100
	100	0	3	0	5	45	17	85	110	93	84	88	77	108	3820 (43.38)	114
	21	80	3	12	12	109	30	150	87	74	65	68	67	94	3400 (38.61)	101
Douglas fir ply., 3/4"	21	50	3	8	8	100	19	100	119	100	98	100	82	100	3820 (43.38)	100
	100	0	2	0	8	100	25	132	151	127	81	83	92	112	4560 (51.78)	119
	21	80	3	--	19	238	30	158	110	92	58	59	58	71	2940 (33.39)	77
Acoustical tile - A	21	50	5	8	10	100	62	100	96	100	68	100	61	100		
	100	0	2	0	12	120	48	77	79	82	52	76	62	102		
	21	80	3	--	18	180	88	142	65	68	33	49	46	75		
Acoustical tile - B	21	50	5	8	9	100	41	100	100	100	83	100	65	100		
	21	80	3	--	14	156	49	120	80	80	46	55	52	80		
Hardboard, paper-faced	21	50	4	6	25	100	29	100	355	100	150	100	118	100		
	100	0	3	0	10	40	40	138	298	84	110	73	134	114		
Hardboard, embossed	21	50	3	6	21	100	>197	100	158	100	94	100				
	100	0	2	0	<8	<38	180	<91	280	177	89	95				
	21	80	3	--	20	95	220	<112	161	102	65	69				

[a]21/50 refers to conditioning room environment of 21°C and 50 percent RH.

Table 7. Effect of Radiant Flux Exposure on Heat Release Properties
(Conditioned at 70°F and 50% RH and Tested in NBS-I Calorimeter)

Material	Exposure Flux[a] kW/m²	No. of Tests	Time to Ignition		Time to Peak HRR		Mean HRR						10-min Total Heat Release	
							Peak		First 1-min Avg.		First 5-min Avg.			
			Sec	% of 60 kW/m²	Sec	% of 60 kW/m²	kW/m²	% of 60 kW/m²	kW/m²	% of 60 kW/m²	kW/m²	% of 60 kW/m²	Btu/ft² (MJ/m²)	% of 60 kW/m²
Southern pine lbr., 2 x 8	60	5	17	100	60	100	134	100	96	100	109	100	5080 (57.69)	100
	25 T	1	130	765	180	300	94	70	0	0	47	43	2580 (29.30)	51
	25 B	1	42	247	115	192	88	66	1	1	62	57	3300 (37.47)	65
	40	3	83	488	115	192	111	83	0	0	70	64	3840 (43.61)	76
	80	3	6	35	70	117	122	91	78	81	102	94	5080 (57.69)	100
Douglas fir lumber, 2 x 8	60	3	14	100	40	100	124	100	89	100	79	100	3860 (43.83)	100
	25 T	2	98	700	108	270	78	63	0	0	31	39	1735 (19.70)	45
	25 B	1	26	186	70	175	97	78	42	47	30	38	2180 (24.76)	56
	40	3	65	464	70	175	104	84	0	0	50	63	2980 (33.84)	77
	80	3	5	36	28	70	87	70	57	64	69	87	3540 (40.20)	92
Redwood lumber, 2 x 8	60	9	11	100	20	100	110	100	95	100	71	100	3352 (38.07)	100
	25 T	1	270	2454	335	1675	86	78	0	0	0	0	1170 (13.29)	35
	25 B	1	24	218	66	330	59	54	24	25	38	54	2040 (23.17)	61
	40	3	53	482	68	340	94	85	11	12	42	59	2400 (27.25)	72
	80	3	5	45	20	100	84	76	60	63	59	83	2900 (32.93)	87
Douglas fir 19/32" ply.	60	2	12	100	17	100	115	100	90	100	70	100	3420 (38.84)	100
	25 T	1	140	1167	180	1059	94	82	0	0	55	79	2100 (23.85)	61
	40	2	63	525	75	441	132	115	0	0	53	76	3000 (34.07)	88
	80	2	6	50	22	129	91	79	60	67	59	84	3030 (34.41)	89
Douglas fir 19/32" ply., treated	60	2	14	100	19	100	80	100	26	100	26	100	1410 (16.01)	100
	40	3	0	--	10	53	39	49	6	23	15	58	1050 (11.92)	74
	80	2	6	43	35	184	36	45	21	81	20	77	1140 (12.95)	81
Acoustical tile - A	60	5	10	100	62	100	96	100	68	100	61	100	--	--
	26 T	3	83	830	130	210	64	67	0	0	31	51	--	--
	26 B	2	22	220	43	69	74	77	26	38	45	74	--	--
	40	3	38	380	58	94	74	77	29	43	51	84	--	--
	80	3	6	60	54	87	64	67	42	62	50	82	--	--
Acoustical tile - B	60	5	9	100	41	100	100	100	83	100	65	100	--	--
	26 B	1	15	167	36	88	88	88	32	39	47	72	--	--
	40	2	30	333	60	146	87	87	35	42	--	--	--	--
	80	2	4	44	38	93	74	74	50	60	48	74	--	--

[a]T = pilot ignition flame at top of sample
B = pilot ignition flame at bottom of sample

Table 8. Comparison of First 1-Minute and First 5-Minute HRR with the Corresponding Maximum Rates

No.	Material (Conditioned at 70°F/50% RH, and Exposed at 60 kW/m^2 in NBS-I Rebuilt Calorimeter)	Mean One-minute HRR kW/m^2			Mean Five-minute HRR kW/m^2		
		First	Max.	Max./First	First	Max.	Max./First
1	Redwood lumber, 2 x 8	102	124	1.22	81.0	84.3	1.04
2	Douglas fir lumber, 2 x 8	126	136	1.08	112	119	1.06
3	Southern pine lumber, 2 x 8	122	154	1.26	121	126	1.04
4	Plywood, Marine, 3/4 in	132	158	1.20	88.0	92.0	1.05
5	Plywood, Special, 5/8 in	141	168	1.19	117	122	1.04
6	Acoustical Tile "A"	84.3	101	1.20	71.3	73.3	1.03
7	Acoustical Tile "B"	115	131	1.14	86.7	89.7	1.03
8	Hardboard, med. density, embossed face	119	222	1.87	161	175	1.09
9	Hardboard, med. density, paper face	157	223	1.42	158	163	1.03
10	Particle board, 5/8 in	146	243	1.66	163	178	1.09
	Slope	1.72			1.11		
	Intercept	-48.0			-5.88		
	Corr. Coefficient	0.77			0.9976		
		y = 1.72 x -48.0			y = 1.11 x -5.9		
1-7	Omitting samples 8,9,&10 that are pressed to higher than normal densities.						
	Slope	1.14			1.07		
	Intercept	5.0			-2.63		
	Corr. Coefficient	0.95			0.9991		
		y = 1.14 x +5.0			y = 1.07 x -2.63		

Table 9. Comparison of Mean Heat Release Characteristics of Different NBS Calorimeters (Conditioned at 70°F and 50% RH and Tested at 60 kW/m^2 Radiant Flux)

Material	NBS Calorimeter	No. of Tests	Time to Ignition		Time to Peak HRR		Mean HRR						10-min. Total Heat Release	
							Peak		First 1-min. Avg.		First 5-min. Avg.			
			Sec.	% of I[a]	Sec.	% of I	kW/m^2	% of I	kW/m^2	% of I	kW/m^2	% of I	Btu/ft^2 (MJ/m^2)	% of I
Southern pine lbr., 2 x 8	I	5	17	100	60	100	134	100	96	100	109	100	5080 (57.69)	100
	I-R	4	6	35	36	60	187	140	122	127	122	112	5815 (66.04)	114
	II	3	27	159	44	73	218	163	104	108	119	109	5840 (66.32)	115
Redwood lumber, 2 x 8	I	9	11	100	20	100	118	100	95	100	71	100	3350 (38.04)	100
	I-R	7	6	55	15	75	221	187	113	119	81	114	3950 (44.86)	118
	II	3	22	200	31	155	169	143	78	82	65	92	2950 (33.50)	88
Douglas fir lbr., 2 x 6	I	4	14	100	28	100	98	100	58	100	78	100	3990 (45.31)	100
	I-R	4	4	29	12	43	217	221	152	262	116	149	5710 (64.84)	143
Douglas fir lbr., 2 x 6 treated - A	I	4	30	100	585	100	32	100	7	100	13	100	940 (10.67)	100
	I-R	3	12	40	528	90	119	372	18	257	28	215	1710 (19.42)	182
Douglas fir 19/32" ply.	I	2	12	100	17	100	115	100	90	100	70	100	3420 (38.84)	100
	I-R	3	6	50	27	159	251	218	141	157	117	167	5280 (59.96)	154
	II	2	44	366	58	341	222	193	37	41	82	117	3900 (44.29)	114
Douglas fir 19/32" ply., treated - B	I	2	14	100	19	100	80	100	26	100	26	100	1410 (16.01)	100
	I-R	2	6	43	21	111	182	228	49	188	34	131	1780 (20.21)	126
	II	2	66	471	82	432	55	69	3	12	24	92	1140 (12.95)	81
Douglas fir 1/2" ply., treated - B	I	3	15	100	21	100	91	100	39	100	31	100	1720 (19.53)	100
	I-R	3	8	53	27	129	107	118	51	131	44	142	1980 (22.48)	115
	II	1	12	80	24	114	85	93	31	79	20	65	1080 (12.26)	63
Douglas fir 3/4" ply.	I	3	8	100	19	100	119	100	98	100	82	100	3820 (43.38)	100
	I-R	3	8	100	44	232	211	177	133	136	94	115	4870 (55.30)	127

[a]Refers to NBS-I Calorimeter

Table 9 (Cont.)

Material	NBS Calo-rimeter	No. of Tests	Time to Ignition		Time to Peak HRR		Mean HRR						10-min Total Heat Release	
							Peak		First 1-min Avg.		First 5-min Avg.			
			Sec	% of I	Sec	% of I	kW/m^2	% of I	kW/m^2	% of I	kW/m^2	% of I	Btu/ft^2 (MJ/m^2)	% of I
Particle-board, 5/8"	I	3	26	100	104	100	132	100	81	100	105	100	5400 (61.32)	100
	I-R	3	18	69	57	55	250	189	126	156	153	146	7100 (80.63)	131
	II	3	28	108	66	63	256	194	88	109	155	148	6550 (74.38)	121
Acoustical tile A	I	5	10	100	62	100	96	100	68	100	61	100	--	--
	I-R	3	8	80	21	34	142	148	84	124	71	116	2760 (31.34)	--
	II	2	17	170	36	58	133	139	85	125	76	125	--	--
Acoustical tile B	I	5	9	100	41	100	100	100	83	100	65	100	--	--
	I-R	3	3	33	24	59	201	201	115	139	87	134	3760 (42.70)	--
	II	3	24	267	39	95	170	170	105	127	74	114	--	--
Hardboard, paper-faced	I	4	25	100	29	100	355	100	150	100	118	100	--	--
	I-R	3	12	48	30	103	375	106	157	105	158	134	7330 (83.24)	--
	II	3	57	228	78	269	287	81	0	0	130	110	--	--
Hardboard, embossed	I	3	21	100	197	100	158	100	94	100	121	100	--	--
	I-R	3	9	43	276	140	269	170	119	127	161	133	--	--

Table 10. Relationships Among Heat Release Values Determined by Different NBS Calorimeters (Coordinated at 21°C and 50% RH and Exposed at 60 kW/m^2 Radiant Flux)

Calorimeter[a] From	To	Property	Units	Equation	Standard Deviation from Regression	r^2 %
I	I-R	Peak	kW/m^2	I-R = + 109.9 + 0.801 (I)	3.7	74
		1-minute average	kW/m^2	I-R = + 31.9 + 0.980 (I)	2.4	71
		5-minute average	kW/m^2	I-R = + 5.63 + 1.256 (I)	1.3	92
		10-minute total	MJ/m^2	I-R = + 3.13 + 1.23 (I)	529.0	94
I-R	I	Peak	kW/m^2	I = - 69.4 + 0.926 (I-R)	4.0	74
		1-minute average	kW/m^2	I = - 1.0 + 0.724 (I-R)	2.1	71
		5-minute average	kW/m^2	I = + 1.7 + 0.733 (I-R)	1.0	92
		10-minute total	MJ/m^2	I = - 0.14 + 0.766 (I-R)	418.0	94
I	II	Peak	kW/m^2	II = + 91.5 + 0.632 (I)	6.0	48
		Peak (excluding paper-faced hardbd.	kW/m^2	II = - 191.2 + 3.277 (I)	2.9	85
		1-minute average	kW/m^2	II = + 53.6 + 0.067 (I)	4.4	0.3
		5-minute average	kW/m^2	II = - 13.9 + 1.327 (I)	1.7	88
		10-minute total	MJ/m^2	II = - 12.8 + 1.384 (I)	379.0	98
II	I	Peak	kW/m^2	I = + 1.7 + 0.756 (II)	6.5	48
		Peak (excluding paper-faced hardbd.	kW/m^2	I = + 65.9 + 0.259 (II)	0.8	85
		1-minute average	kW/m^2	I = + 78.0 + 0.049 (II)	3.8	0.3
		5-minute average	kW/m^2	I = + 17.7 + 0.677 (II)	1.2	88
		10-minute total	MJ/m^2	I = + 9.9 + 0.707 (II)	271.0	98
I-R	II	Peak	kW/m^2	II = + 5.5 + 0.807 (I-R)	4.9	65
		1-minute average	kW/m^2	II = + 38.1 + 0.196 (I-R)	4.4	3
		5-minute average	kW/m^2	II = - 11.7 + 0.981 (I-R)	1.5	91
		10-minute total	MJ/m^2	II = - 11.0 + 1.056 (I-R)	516.0	96
II	I-R	Peak	kW/m^2	I-R = + 70.7 + 0.802 (II)	4.9	65
		1-minute average	kW/m^2	I-R = + 97.0 + 0.160 (II)	4.0	3
		5-minute average	kW/m^2	I-R = + 19.5 + 0.928 (II)	1.5	91
		10-minute total	MJ/m^2	I-R = + 12.1 + 0.910 (II)	479.0	96

[a] I = NBS-I, I-R = NBS-I Rebuilt, II = NBS-II

Table 11. Effect of Radiant Flux on Heat Release Properties Measured in NBS-I Rebuilt and NBS-II Calorimeters
(Samples Conditioned at 70°F and 50% RH)

Calorimeter	Material	Exposure flux kW/m²	No. of Tests	Time to Ignition Sec	Time to Ignition % of 60 kW/m²	Time to Peak HRR Sec	Time to Peak HRR % of 60 kW/m²	Mean HRR Peak kW/m²	Mean HRR Peak % of 60 kW/m²	Mean HRR First 1-min Avg. kW/m²	Mean HRR First 1-min Avg. % of 60 kW/m²	Mean HRR First 5-min Avg. kW/m²	Mean HRR First 5-min Avg. % of 60 kW/m²	10-min Total Heat Release Btu/ft² (MJ/m²)	10-min Total Heat Release % of 60 kW/m²
NBS-I Rebuilt	Southern pine lbr., 2 x 8	40	3	11	183	39	108	187	100	89	73	104	85	4910 (55.76)	84
		60	4	6	100	36	100	187	100	122	100	122	100	5815 (66.04)	100
		80	3	2	33	25	69	371	198	286	234	250	205	13000 (147.60)	224
	Redwood lumber, 2 x 8	40	3	12	200	23	153	162	73	70	62	61	75	3160 (35.88)	80
		60	7	6	100	15	100	221	100	113	100	81	100	3950 (44.86)	100
		80	3	2	33	9	60	348	157	198	175	153	189	7550 (85.74)	191
	Douglas fir 19/32" ply.	40	3	12	200	34	126	216	86	85	60	78	67	3960 (44.97)	75
		60	3	6	100	27	100	251	100	141	100	117	100	5280 (59.96)	100
		80	3	2	33	9	33	308	123	230	163	178	152	8380 (95.16)	159
	Douglas fir 19/32" ply., treated - B	40	3	none	--	10	48	39	21	6	12	15	44	1050 (11.92)	59
		60	2	6	100	21	100	182	100	49	100	34	100	1780 (20.21)	100
		80	3	2	33	47	223	196	108	87	178	57	168	3670 (41.68)	206
	Douglas fir 1/2" ply., treated - B	40	2	11	138	288	1067	59	55	4	8	11	25	740 (8.40)	37
		60	3	8	100	27	100	107	100	51	100	44	100	1980 (22.48)	100
	Douglas fir 3/4" ply.	40	2	8	100	31	70	200	95	114	86	96	102	5060 (57.46)	104
		60	3	8	100	44	100	211	100	133	100	94	100	4870 (55.30)	100
	Particle-board, 5/8"	40	1	15	83	70	123	203	81	96	76	141	92	7180 (81.54)	101
		60	3	18	100	57	100	250	100	126	100	153	100	7100 (80.63)	100
	Acoustical tile - A	60	2	8	100	21	100	142	100	84	100	71	100	2760 (31.34)	100
		80	3	7	88	21	100	212	149	154	183	117	165	4220 (47.92)	153
	Acoustical tile - B	40	3	9	300	16	67	172	83	113	98	85	98	4030 (45.76)	107
		60	3	3	100	24	100	208	100	115	100	87	100	3760 (42.70)	100
		80	3	2	67	14	58	311	150	216	188	118	136	5630 (63.93)	150
NBS-II	Acoustical tile - B	60	3	14	100	37	100	170	100	105	100	74	100	--	--
		80	3	9	64	30	81	217	128	141	135	85	115	--	--

Table 12. Summary of Heat Release Rate Data

Material	Density kg/m^3	Mean Time to Peak HRR, Sec	HRR, kW/m^2 Peak Mean	Peak C[a]	First 1-min Average Mean	First 1-min Average C[a]	First 5-min Average Mean	First 5-min Average C[a]	10-min Total Heat Btu/ft^2 (MJ/m^2) Mean	C[a]
Lumber										
Southern pine 2 x 8	540	36	187	20	122	19	122	9	5815 (66.04)	6
Douglas fir 2 x 8	490	--	209[b]	20[c]	119[b]	20[c]	105[b]	12[c]	5022[b] (57.03)	11[c]
Douglas fir 2 x 6	450	12	217	19	152	23	116	11	5710 (64.84)	10
Redwood 2 x 8	380	15	221	12	113	17	81	12	3950 (44.86)	11
Plywood Douglas fir										
19/32"	540	27	251	18	141	9	117	17	5280 (59.96)	19
	510	44	211	26	133	23	94	7	4870 (55.30)	7
Treated										
Douglas fir lumber 2 x 6	540	528	119	14	18	20	28	20	1710 (19.42)	35
Douglas fir plywd 12.7mm(1/2in)	560	27	107	14	51	32	44	13	1980 (22.48)	6
Doug. fir plywd 15.1mm(19/32in)	540	21	182	6	49	32	34	36	1780 (20.21)	41
Particleboard 5/8"	750	57	250	18	126	31	153	14	7100 (80.63)	17
Acoustical tile A 12.7mm(1/2in)	290	21	142	26	84	20	71	26	2760 (31.34)	38
Acoustical tile B 12.7mm(1/2in)	300	24	201	8	115	25	87	26	3760 (42.70)	31
Hdbd paper-faced 11.1mm(7/16in)	720	30	375	10	157	4	158	3	7330 (83.24)	7
Hardbd, embossed 9.5mm(3.8in)	870	276	269	16	119	37	161	17	--	--

[a]Coefficient of variation, percent

[b]Estimated from NBS-I calorimeter values and NBS-I R versus NBS-I regression in Table 9

[c]Standard deviation from regression as percent of estimate mean

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR 82-2597	2. Performing Organ. Report No.	3. Publication Date July 1983

4. TITLE AND SUBTITLE

Heat Release Rate Properties of Wood-Based Materials

5. AUTHOR(S)

D. L. Chamberlain

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

National Forest Products Association
1619 Massachusetts Avenue, NW
Washington, D. C. 20036

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

A background to the present heat release rate calorimetry is presented. Heat release rates and cumulative heat release were measured for 16 different lumber and wood products, using three different heat release rate instruments. The effects of moisture content, exposure heat flux, density of product, and fire retardant on rate of heat release were measured. The three small-scale heat release rate calorimeters were compared, and equations relating the data from each were developed.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Acoustical tile; Douglas fir; fire retardants; hardboard; heat release rate; heat release rate calorimeters; irradiance; particle board; plywood; redwood; southern pine

13. AVAILABILITY

[XX] Unlimited
☐ For Official Distribution. Do Not Release to NTIS
☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.
[XX] Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

90

15. Price

$11.50