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Development of a Radiant Panel Test for Flooring Materials

L. G. Hartzell, Research Associate
Armstrong Cork Co.
Lancaster, Pa.

Fire Programs
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National Bureau of Standards
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Final Report

U. S. DEPARTMENT OF COMMERCE
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L. G. Hartzell

ABSTRACT

This paper summarizes the work of a year long program to continue the development of a radiant panel type test for flooring materials, the original concept of which was developed at the Armstrong Cork Company's Research and Development Center in Lancaster, Pennsylvania. This program at the National Bureau of Standards had as its goal, the further development of the test for possible adoption as a standard ASTM test method.

The program work was divided into five phases. During the first phase, an attempt was made to duplicate the performance of the original apparatus in a similar one at the National Bureau of Standards Laboratory. The proof of this duplication was shown in replicate testing using a wide range of flooring on both apparati.

In the second phase of the program, a new set of test conditions were found in an attempt to eliminate some of the more serious equipment and procedural problems of the test. These new conditions provided the test with the ability to rate flooring materials according to their ability to resist the surface flame spread.

Under the third and fourth phases of the program, the effects of changes in some test parameters were investigated and other test characteristics were measured. Phase V, the data analysis and report, concluded the program.

Key words: Carpet; fire test; flammability; flooring; heat flux; ignition; radiant panel.

1. INTRODUCTION

During this century, the importance of public safety has been recognized and with it have come tests designed to determine performance characteristics of various materials. The measurement of the effects of fire on a material, and, more particularly, the material's surface flammability represents a need that touches upon a critical aspect of life safety.

During the past 25 years, much effort has been given to develop test methods for flammability. The driving force behind this development is usually need. In the past, experts have felt that the surface flammability of walls and ceilings has played a key part in propagation of fire within a structure. However, the experts also have held that flooring has not been considered a major hazard. Mr. J. A. Wilson, of the Factory Mutual Engineering Division, in answering a letter of comment to his paper on surface flammability methods [1][1], stated that the lack of a test procedure for evaluation of floor coverings was primarily the result of a relative lack of need for such data. Furthermore, Mr. Wilson went on to state that, "Within the Factory Mutual experience, which covers many years, there has been no fire where the combustibility of the floor coverings was a significant factor."

The above referenced symposium was published in 1961. Undoubtedly, at that time there were reasons not to consider floor coverings as a major hazard, given all other combustibles usually located above the floor covering. However, recently floor coverings and more particularly carpeting has found its way into places where it had not usually been placed, such as hospitals, nursing homes, and hotel corridors and lobbies. Furthermore, reports of recent fire tragedies have proven that the flooring can be a major contributor through spread of flames, and smoke and heat evolution. When under the influence of a high thermal load, flooring can act as a means of transferring fire and its products from its point of origin to areas that would otherwise be inaccessible to the fire.

Logically, then, as Mr. Wilson has said, since the need for evaluation has arisen, test procedures have been suggested. Unfortunately, due to pressures of economics and time, standards makers have in the past found it easier to specify flooring to be tested under the existing surface flammability tests for wall or ceiling material. The problem with this approach is that until very recently there was not one accepted test method which employed a sample mounted horizontally and face up. In the two most commonly used surface flammability tests, the Steiner Tunnel (ASTM E-84) and the radiant panel (ASTM E-162), the sample is mounted either horizontally upside down or upside down at a 30° angle to the vertical, respectively. Obviously this sample mounting procedure serves to create testing problems for flooring. In addition, these tests do

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[1] Figures in brackets indicate the literature references at the end of this paper.

not simulate any real life situation for floors and thus should not be expected to properly examine differences in types of flooring (resilient flooring, shag carpet, plush carpet, etc.) and the differences in their reaction to fire. With the acceptance of the methenamine tablet test, DOC-FF-1-70, there is now a test with proper sample mounting. However, the tablet test is only an ignition standard and is still inadequate to determine relative surface flammability for flooring materials under severe fire loading conditions.

This, then, was the background for the flooring radiant panel originally developed by the Armstrong Cork Company [2] which satisfies the need for a test of floor covering materials and not only simulates realistic mounting conditions for flooring but also the energy inputs expected in a real fire situation. The original researchers of the project put fire situations into two classes, the room class and the corridor class. In the room class, the situation is that of an average size office space about 10 ft x 20 ft x 10 ft high with a high heat load in furniture, papers, periodicals and carpeting. This class assumes relatively quiescent ambient conditions. In the corridor class, there is variable draft available, but little in the way of combustibles is present outside of the corridor lining materials.

The room class was chosen since its condition could be easily simulated by a radiant panel apparatus. In addition, this choice eliminated the need for a complicated study of draft air conditions. In the early stages of a room fire following ignition, typically one object of relatively high heat load such as a stuffed chair or sofa is burning. This provides to the flooring an ignition source and a radiant input which is at its maximum near the ingition source, (See figure 1). The original radiant panel apparatus was designed to simulate this situation. Materials were assigned a flame spread index based on flame spread distance or on time to spread the full length using red oak = 100 as a comparison standard similar to the procedure in ASTM E-84. A description in Appendix A is given from early correspondence of Z. Zabawsky, the Project Director, to Subcommittee IV of ASTM Committee E-5, which details the early thinking that went into the design of the original apparatus to simulate this condition. The Appendix also shows the design and procedure that resulted (refer to figures 2 and 3 for sketches).

Although the original design of the apparatus was the result of considerations of a room fire situation, nevertheless in the present work, which is directed to the corridor situation, the test was still considered valid since it serves to measure a basic property of flooring regardless of its end use.

2. A REVIEW OF PREVIOUS EXPERIMENTAL RESULTS ON THE TEST METHOD

During the past two years, extensive testing was done by Zabawsky on a wide range of flooring materials over a wide range of substrates. Feedback from the results led Mr. Zabawsky to a number of apparatus and procedure changes. For example, the horizontal sample level inlet ports along the sides and ends of the sample were opened. This provided sufficient combustion air and eliminated strong drafts across the sample. Also, the specimen rating length was increased from 24 to 32 inches and with it also the red oak rating time. These improvements made the test easier to perform and more repeatable.

In all, 271 tests were conducted by Zabawsky covering five different resilient floorings, red oak, hardboard, and various carpets using seven different types of fibers. The carpet was tested over three different pads (underlayment cushion) and four different substrates including 1/4 inch asbestos cement board, 1/2 inch phywood, 5/32 inch pressed hardboard, and 2 inch concrete. Of these tests, 197 were run in replicate, achieving a 3.5% coefficient of variation level[1]. Carpets tested over asbestos-cement board and concrete generally achieved lower flame spread indices than when tested over the hardboard or plywood, presumably due to the relative heat sink and thermal insulating values.

3. STRATEGY FOR TEST DEVELOPMENT PROGRAM AT NBS

The first task of the program at its new location was the formulation of project goals. Toward this end, a three part attack was formulated to study performance, relevance, and feasibility.

Under performance, the goal is to achieve a high degree of reproducibility. That is, not only must there be good agreement in the results of duplicate samples tested on the same apparatus, but the agreement must cover duplicate samples tested in two different apparatus. In the present study it was decided that a deviation of less than 10% from the mean for 95% of the population of results for a given specimen would indicate satisfactory reproducibility.

The accuracy and precision of a test notwithstanding, the test is meaningless if nothing is gained by the knowledge of its results. This comes under the term relevance. Ideally, small scale tests correlate with the full scale situation.

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[1] The percent coefficient of variation is the standard deviation divided by the mean of a group of data expressed as a percent.

Feasibility is an important consideration in a test method. Is the test economically suited to widespread use? Is the apparatus small enough to be located in a typical laboratory? Does the test take hours of preparation and testing for one single result, or does the test consume an unreasonable amount of material? These are questions to be answered in the consideration of feasibility. In the study of flooring flammability, a full scale corridor would probably rate high in the areas of performance and relevance. However, in answering the questions above, one finds the corridor unfeasible as a laboratory size test.

The next step was the decision of how best to attack the above goals. After consideration of each goal, it was decided to use this program to study test performance. The reasoning behind this decision had to do with past and future studies. To begin with, in a study of relevance, there needs to be sufficient full scale data available for correlation purposes. At the time this program was being planned, that data was not available. However, since it was expected that the data would be available in the future, preparation for attacking this goal could best be served by testing a wide range of flooring, including many materials that would eventually undergo large scale testing. Therefore, at least this much of the relevance goal would be included in the program.

The feasibility goal had essentially been achieved. A cost study done by one of the original developers showed that the complete cost of construction of the Flooring Radiant Panel was around $3,000 in 1970.[3] This is a relatively inexpensive flammability test. In addition, the test takes a 5 in x 25 in sample which is inexpensive to provide, and the average test schedule would easily permit one operator to conduct six to ten tests per day. Finally, the apparatus itself is about 5 ft long by 2 ft wide by 7 ft high. Add an equal amount of space for instrumentation and one can see that the entire setup is small enough for most any laboratory. Furthermore, no unusual services are needed, only a supply of gas fuel, and air, an exhaust hood of at least 600 CFM capacity, and normal electrical service. The conclusion, then, was that the Flooring Radiant Panel Test is a feasible test within the context stipulated.

This left the study of test performance yet to be done. Toward this end, a one year program of five phases was developed. The phases were as follows:

Phase I	Installation of and familiarization with equipment and comparison with previous results from the original apparatus.

Phase II	Determination of optimum test conditions and procedure.
Phase III	Study of effects of sample and test condition parameter changes.
Phase IV	Special studies of test characteristics for research and large scale correlation purposes.
Phase V	Data analysis and report.

Included as part of Phase II was testing of a wide range of floor covering materials as mentioned above for the purpose of future correlation with larger scale work. This range of samples included seventeen carpets, a rubberized hair jute pad backing, six resilient floor coverings, and red oak. The carpet samples were obtained from Man Made Fibers Producers Association (MMFPA) and were part of a series supplied by them to NBS for use in flooring flammability studies. Samples tested in this series were also tested in standard surface flammability tests such as the Steiner tunnel (ASTM E-84) and the radiant panel (ASTM E-162) as well as in experimental facilities such as the NBS corridor, UL-992 chamber and the Man Made Fibers Producers Association Model Corridor [4]. In addition, a selection of this series has already undergone testing in an earlier version of the Armstrong Flooring Radiant Panel. The resilient flooring was supplied by the Armstrong Cork Company for similar purposes. A complete description of all samples is given in table 1.

4. TEST EQUIPMENT

The program was started in May 1972 with the installation at NBS of the second Flooring Radiant Panel in existence. (For the purposes of brevity, the first panel made, which is now in operation at the Armstrong Cork Company's Research and Development Center in Lancaster, will be referred to here as AFRP-1 while the second which is in operation at NBS in Gaithersburg, Maryland will be called AFRP-2.) Some design changes were made in AFRP-2 for development purposes before construction. These include a sample size increase from 5 by 32 inches to 20 x 100 cm (about 8 in x 39 in) in order to negate end and edge effects; chamber length increase from 45 in to 54 in; and the addition of a chimney 10 inches high and 4 in x 14 1/2 in (internal size) over the exhaust port. A picture of the apparatus in its present state is shown in figure 4. The front of the chamber has been removed to expose the inner workings.

For Phases I and II, the instrumentation was modest (figure 5). An instrument board was set up to control and monitor the radiant panel inputs. Air supply rate was measured by a rotameter on the instrument board. From the rotameter the line goes through a gate valve and into the premix venturi. A gas line goes through a shut-off valve, into a safety valve, through a needle valve and into the venturi. The gas-air mixture from the venturi flows directly to the radiant panel. On a separate board are two rotameters for the pilot burner supply lines. A dual pen recorder monitors a thermocouple located in the exhaust end of the chamber (4 inches from the chamber ceiling and 10 inches from the cold wall) on the one channel and the voltage signal output of the smokemeter on the other. A separate recorder reads the output from the pyrometer focused on a 10 inch diameter circle in the center of the radiant panel. When radiant flux measurements were to be taken, a separate duel pen recorder, along with a copper disk calorimeter was employed.

5. NBS TEST PROGRAM

5.1. Phase I - Comparison With Previous Test Ratings

After a few preliminary tests run for the benefit of the operator, Phase I was begun. The purpose of this phase was to duplicate the condition of AFRP-1 in the AFRP-2 apparatus. The chamber was blocked off at the 45 inch mark and all other parameters were set according to the previously listed procedure.

First, open chamber incident heat flux measurements were taken at various places along the sample surface using the copper disk calorimeter. A dummy cement-asbestos board specimen with calorimeter locating holes provided at appropriate intervals along the specimen center line was used to simulate the sample surface. Point flux measurements were made by first mounting the calorimeter at the desired location on the dummy specimen in the specimen holder with the assembly outside the chamber. The dummy specimen with calorimeter in place was then moved into the chamber, the calorimeter output read within ten seconds and the dummy specimen with calorimeter immediately removed. Succeeding points on the flux profile curve were determined in the same way. The results are shown in figure 6 along with results obtained earlier on AFRP-1. The comparison was suprising since agreement to this degree was not expected.

Satisfied that a reasonable duplication of AFRP-1 had been achieved, actual testing was begun. A total of 28 different constructions were tested including 12 carpets, with and without underlayment, four resilient floor coverings, and two samples of red oak. All samples, except for one red oak, were backed by 3/8 inch asbestos board and 3/16 inch asbestos cement board. The AFRP-1 procedure was followed as nearly as possible, with the addition of flame front location versus time and smoke determination.

Table 2 shows the results of this testing, and for comparison purposes the AFRP-1 results are also listed. It should be remembered that all flame spread ratings are based on the performance of red oak according to the schedule described previously. The flame spread index shown for AFRP-1 was calculated based on red oak burning 32 inches in 27 minutes, while for AFRP-2, the red oak burned 40 inches in 21.76 minutes. Red oak has an arbitrarily assigned flame spread value of 100. Even though there are many differences, nevertheless, the flame spread ratings show a good correlation. The data can be divided into two categories, those with a rating over 100 and those at 100 or below. For most cases the over 100 category is rated on time and the 100 and under is rated on distance. It would not be proper to compare the ratings based on time alone since the samples are of different length and very few samples burn at a steady rate over their entire length. On the other hand, it has been seen that the input radiant flux to the samples is the same at equal distances from the hot end of the sample. Thus, comparison of the below 100 ratings should be meaningful.

In order to make this comparison, the AFRP-1 ratings were converted to actual distances burned in centimeters regardless of time. The easiest comparison to be made would be to see if the results of AFRP-1 and AFRP-2 are linearly related. A least squares regression analysis of the data indicates the best estimated straight line for the data points shown in figure 7[1]. The correlation coefficient of $r = 0.94$ indicates a high degree of correlation.

The data agreement indicated here is good considering some of the differences in test conditions. An attempt was made to duplicate AFRP-1 in the construction of AFRP-2 for this comparison. However, there were nevertheless some differences. For example, the exhaust port of AFRP-2 measured 4 in x 12 in (48 in^2) due to the installation of smoke measuring equipment, whereas the AFRP-1 chamber makes use of a 7 in radius semicircular hole (77 in^2). Also, the hood above AFRP-1 was apparently considerably stronger than that used with AFRP-2.

These differences did affect the test as is shown by an analysis of an individual test. Figure 8 shows the results for an acrylic carpet tested in both apparatus. Both flame spread and chamber temperature rise are shown. Notice that two phenomena are immediately evident. First, flame front propagation was faster in AFRP-2. Second, the chamber temperature was considerably higher. These two phenomena were evident in all comparison tests in Phase I, including red oak, and they probably stem from the same cause - difference in air flow through the two chambers.

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[1] See Appendix II - statistical analysis.

Although air flow measurements were not taken during this Phase, from the physical conditions of the two apparatus, it is evident that AFRP-1 should allow a larger throughput of air. It has a larger exhaust opening, greater amount of inlet air venting and higher draw from its hood. This excess air would tend to minimize temperature changes. Also, more material is burned since the specimen is about 8 inches wide for AFRP-2 whereas it is 5 inches wide for AFRP-1.

5.1.1. Comparison of Rating Performance With Other Fire Test Methods

Despite the fact that AFRP-2 probably had a higher degree of energy feedback and thus conditions were more severe, the flame propagation distance still showed a high degree of correlation. This fact gives a boost to the radiant panel concept since it indicates that a high degree of reproducibility may be possible between two apparatus even if one is slightly more severe than the other. At this time it was decided to determine if any correlation existed between the Phase I results and results of other test methods. Chosen for comparison were UL992, E-84, E-162, and the model corridor of Man Made Fibers Producers Association (MMFPA). Graphs of the common data points are shown in figure 9 (the data is given in table 3). As would be expected, little correlation is indicated with any of these four test methods when all points are plotted. However, when only the data points with AFRP-2 values equal to or less than 100 are plotted, the correlation of MMFPA is better, but still not as good as the AFRP-1. The table below shows the correlation coefficient r calculated from the comparison data on the four graphs as well as for the comparison between AFRP-1 and 2.

	AFRP-1	E-84	E-162	Model Corridor (MMFPA)	UL992
All data	0.94	0.39	0.54	-0.57[a]	0.47
<100	0.94	0.45	0.29	-0.833[a]	0.14

Notice the high correlation between AFRP-1 and AFRP-2. The remainder of the comparisons seem relatively poor. In truth there may be little reason why a good correlation should be expected between any of the other four and the Flooring Radiant Panel Test owing to their basic differences.

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[a] A negative value of r indicates an inverse relationship, the strength of which is measured from low to high on a scale of 0.0 to -1.0.

5.2. Phase II - An Exploration of Various Test Heating Conditions and a Study of the Rating Method

Phase II was to study alternative test conditions and to improve the consistency of the test measurement and system characteristics. First, the present comparative rating system has raised questions. This is so, because it depends on the burning characteristics of red oak; and furthermore, is based on flame spread time or distance burned. The red oak standard can produce problems with reproducibility and the dual character of the measuring index yields two independent qualities of the material. Second, the level of radiant flux produced by the panel as well as extraneous heat transfer to the specimen from the chamber is an area that needs examination. In principle the external heat transfer to the specimen should be reasonably steady during a test.

Based on the fundamental ideas from which the test was designed, distance was chosen as the rating basis. The reason for this can be seen in a review of figure 1, the room fire situation. It is of more significance to know how far a fire will be propagated rather than how fast. Speed of flame front propagation will be a factor only if the flooring will propagate the fire a great distance. With this idea in mind, one criterion selected was that the test condition would be such that only flooring with the very worst surface flammability properties would propagate fire to the full sample length (100 cm). Other samples would burn some shorter distance and extinguish.

Another criterion was that of repeatability. In Phase I, of all replicate sets of samples tested, the average percent coefficient of variation was 9.9 if all data are considered and 8.8 if only those points under 100 are considered. This would be adequate repeatability and any changes in the test conditions should not cause the repeatability to be poorer.

Finally, the last criterion to be considered concerns relevance. As has been noted earlier, judging relevance can only be done fully with a knowledge of full scale results. However, a new test method should be at least qualitatively consistent with existing tests, common sense, and experience. For example, experience, and previous testing as well as common sense, says that a carpet in a flammability test should perform more poorly when used with an underlayment pad than when used directly over a substrate that has a relatively higher heat sink value, such as asbestos cement board. It should be expected, then, that carpets tested over underlayment pads should receive poorer ratings than the same carpets tested over asbestos cement board. In addition, the test conditions should generally reflect conditions that are typically encountered in a full scale fire situation with regard to energy inputs and sample configuration.

In summary, the three chosen criteria for Phase II were:

1. The flame front on all but the poorest flooring tested should extinguish before reaching the end of the sample. Furthermore, assuming that the samples selected for this study were randomly chosen, there should be a normal distribution among extinguishment points from about 10 cm to 100 cm.
2. The repeatability of the test under any new set of conditions should be no worse than that found in Phase I.
3. The test results should be at least qualitatively consistent with experience, previous testing, and common sense, or any major deviations accounted for.

Criterion 1 would be the immediate goal with the remaining ones to be tested subsequently.

5.2.1. Test Operation at Several Thermal Conditions

The underlying plan in this phase of work was to select three sets of test conditions which would include one set that was very severe and one set that was rather mild. Testing a skeleton series of flooring on each of these sets would allow a further narrowing of the field to one set of conditons. Next, the complete series of flooring would be tested at these conditions. If the results of this testing met the chosen criteria, the Phase II goals would be met. However, minor changes may be indicated and these would be made with some minimum amount of retesting for confirmation. If at this time the criteria could not be met, then the entire process would be repeated using conditions obtained by varying different sets of parameters.

Chosen initially to be varied were the following three parameters (see figure 10):

1. Panel temperature
2. Panel to sample angle
3. Panel to sample distance (minimum)

In order to have some guidelines in the selection of the three trial sets of conditions, seven different preliminary sets of conditions were set up on the apparatus and sample surface radiant flux measurements taken. The results of those measurements are shown in figure 10.

Before the test conditions were determined, the exhaust port was changed from its original opening of 4 in x 12 in (48 sq in) as used in Phase I to 4-3/4 in x 16 in (76 sq in) as designed. This opening was used for all subsequent tests in AFRP-2.

On a set of experimental tests in the MMFPA Model Corridor, a typical carpet sample requires about 0.3 watts/cm^2 to maintain a flame front [5]. In addition, in Phase I testing, the average distance where flame front extinguishment occurred corresponds to an incident flux of around 0.3 watts/cm^2. This fact provided a benchmark in the choice of conditions.

The three sets of conditions chosen are shown as A, B, and C on figure 10. The reasons for their choice centered around their relationship to the 0.3 watts/cm^2 line. Condition A has almost no points below 0.3 watts/cm^2; thus it is quite severe. Condition C has over 50 percent of the sample surface receiving less than 0.3 watts/cm^2 and this condition should be mild enough so that very few samples will burn to the full sample length. Condition B is some midpoint between A and C having about 40% of the sample surface under 0.3 watts/cm^2.

Notice that Condition A differs from Condition D apparently only in panel to sample distance. Condition D was that condition tested in Phase I. It was at this point that the importance of another parameter became evident, that of initial chamber temperature as measured by the chamber thermocouple. Originally it was thought that steady state initial chamber temperature was a function only of the panel temperature. However, under Condition D in Phase I the initial chamber temperature was about 227°C, while under Condition A, the chamber temperature was only 197°C. The reason for the difference is in the total air-gas flow volume to the panel. In order to keep the same panel temperature and increase the chamber temperature, all that needs to be done is to increase the total volume flow to the panel without altering significantly the air to gas ratio, which essentially determines the panel temperature.

The next step in Phase II was to test a selection of flooring covering a wide range of flammability under all conditions for comparison. At first eight samples were chosen and tested under Condition A - panel temperature at 670°C, initial chamber temperature at 197°C. For Condition B - panel temperature at 550°C and chamber temperature at 172°C, and Condition C - panel temperature at 490°C and chamber temperature at 144°C, a few more samples were added to make a more complete comparison. The results of this testing are shown in table 4. Notice that all ratings are in terms of distance burned (in centimeters) except in the case of those samples which burned the full distance (100 centimeters) for which the elapsed time to burn the full distance is given. The incident heat flux at extinguishment is also shown. Also, on this table the Phase I results are included in similar terms.

A graphical representation of the data, figure 11, compares all the conditions as to distribution of ratings. The bar graph shows the number of times a rating fell in the range listed on the abscissa. The graph indicates that Condition C has a distribution of ratings that is reasonably spaced over the range of possible ratings. In addition, under this condition, only two samples out of 19 burned the full 100 centimeters. For this reason, Condition C was chosen for complete testing and the remainder of the series of 36 tests was run under this condition. The results are shown in figure 12.

The last step in Phase II was to find out if the test results met the three criteria stipulated. First, out of 36 different constructions tested, only four burned the full 100 centimeters. Two of these four consisted of the only polypropylene carpet tested (0-1), with and without an underlayment; the other two were a nylon (N-4) and a polyester (P-1), both with underlayment. The table below shows data from other types of tests on these materials. No data were available for the polyester.

	AFRP-2 Time to Burn 100 cm	UL992 Index	E-162 Index
0-1	84 minutes	2.1	616
0-1/pad	36 minutes	24.0	764
N-4/pad	73 minutes	11.8	253
Average of all others	---	1.55[a]	240[a]
Hi/Lo all others	---	0.9/2.6	64/400

These data indicate that these carpets have been considered poor, with the exception of specimen 0-1 by UL-992, by the other test methods. Thus the first criteria has been considered to have been met. All but the poorest flooring in the series extinguished before burning 100 cm.

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[a] Arithmetic mean of the results of all tests except those on 0-1, 0-1 with underlayment pad, and N-4 with underlayment pad.

5.2.2. An Examination of Test Repeatability

During testing at conditions A, B, and C a number of duplicate samples were run for the purpose of testing repeatability. A summary of that testing is shown in table 5. The average percent coefficient of variation has been calculated for replicate tests for each temperature. The average for the entire set under a particular condition is found at the bottom.

The repeatability appears to be excellent for this type of test. At 670°C the average percent coefficient of variation is 5.5 and at 550°C the average percent coefficient of variation is 5.8. Notice that in the replicate testing at 550°C on wool (W-1), there is one value that is grossly inconsistent. There were no reported problems with this test. However, the W-1 carpet has repeatedly performed unusually. For example, when W-1 is tested under the panel at 490°C, it will not propagate any flame front without a three minute and thirty second preheat, whereas under a 670°C panel, it will propagate quite readily. Perhaps 550°C is at a critical point between preheat necessary and preheat not necessary. If the unusual value is discounted, the average percent coefficient of variation for 550°C panel temperature drops to 3.1.

The average percent coefficient of variation for all samples is 5.3 if the unusual condition B W-1 Test is included and 4.4 if it is not. This is well within the 9.9% achieved for all samples in Phase I, and below the 8.8 percent for the partial sample. This data indicates that the repeatability criterion of Phase II has also been met.

Criterion 3 states that the results should be at least qualitatively consistent with experience, previous testing, and common sense. A number of events point toward the fulfillment of this goal. First, in all cases, the addition of a rubberized hair jute underlay increased the flame spread distance of the carpet under test. Second, as can be seen in a comparison of Condition C with the other three conditions tested (A, B, and D, table 4), a reduction of the panel and chamber temperature reduces the flame spread distance in every case but two, and one of these is the erratic specimen, W-1. Finally, a comparison of Condition C with other test methods, while not necessarily showing good correlation, should show general agreement on flooring materials that are very good or very bad. Figure 13 and table 6 show these comparisons along with the regression line and correlation coefficients. It is evident that the results of AFRP-2 are at least qualitatively consistent with the four flammability tests listed. In addition, comparing the correlation coefficients obtained in Phase I and Phase II (figures 9 and 13) shows that the modifications made in Phase II have significantly improved the correlation with E-84 and UL-992, whereas, it was worse for E-162 and about the same for MMFPA.

	E-84	E-162	Model Corridor (MMFPA)	UL-992
Phase I	0.39	0.54	-0.57	0.47
Phase II	0.73	0.24	-0.65	0.91

5.3. Smoke Generation

Although the Flooring Radiant Panel Test is primarily a flame spread measurement test, nevertheless, a smoke density measurement capability was designed into the apparatus. During all testing, smoke generation, as measured by the smoke meter located in the chimney, was recorded. Discussion of that data is outside the scope of this paper. However, the data is on file at the Armstrong Cork Company's Research and Development Center.

5.4. Phase III - A Study of the Effects of Variations in Test Procedures and Test Conditions

Phase III is a study to determine what effect changes in some of the more important test parameters would have upon the results. Toward this end, Phase III was divided into five parts to effect the following studies:

Part 1 Study of the effect of changes in initial chamber air temperature.

Part 2 Study of the effect of changes in ignition procedure.

Part 3 Study of the effect of changes in air throughput.

Part 4 Study of the effect of sample conditioning.

Part 5 Study of the effect of changes in substrate.

These studies will give an indication of the ruggedness of the Flooring Radiant Panel Test or how sensitive the results are to some of the expected daily variations in test environment. These tests would also allow a prediction of how some deviations in test operation procedure will affect the results.

5.4.1. Effect of Changes in Initial Chamber Air Temperature

In Phase I and II, the only temperature measuring instrument in operation during the tests was the chamber air temperature thermocouple centrally located 10 inches from the cold end and four inches from the ceiling of the chamber. Also, during Phase II it was discovered that, as has been mentioned above, the chamber air temperature was not solely a function of the panel temperature but varied with the total air gas mixture throughput to the panel as well. Furthermore, the results of the test also varied with the chamber air temperature. In order to monitor the actual chamber wall temperatures, ten additional thermocouples were added to the chamber before the start of Phase III. These thermocouples were embedded in the outside of the walls deep enough to be within 1/16" from the inside but not exposed. The locations are shown in figure 14.

To study the effect of differing chamber and panel temperatures a test schedule was set up which would allow testing under two or three different initial chamber temperatures. The schedule is shown in table 7. It covers essentially the entire operating range of the apparatus in its present design. For example, it is not possible to achieve a steady state chamber air temperature as low as 172°C when the panel itself is at 670°C.

A test was conducted on each of the five materials under each set of conditions in the schedule.[1] The flame spread distance results of that testing are shown in table 8. These results show that the radiant panel is by far the most powerful influence upon flame spread distance while the initial chamber air temperature, which itself is influenced in part by the initial chamber wall temperature, has a small but definite effect.

Notice that there is a consistent anomaly in the results which occurs under conditions 490/172 and 490/197[2] in four out of five materials. The flame spread distance is less with condition 490/197 when that condition should be more severe. Plots of chamber air and wall temperatures for the tests in question do not show why flame spread distance should be more under 490/172; nor do plots of heat flux versus location. The answer may lie in the greatly increased panel "exhaust" flow

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[1] Some of these tests had previously been conducted in Phase I or II and, in order to save time, were not repeated in this study, but the earlier results used instead.

[2] Since the test conditions are defined by two temperatures, the panel temperature and the initial chamber air temperature, the two numbers separated by the slash represent those temperatures. Thus, for a panel temperature of 550°C and an initial chamber air temperature of 197°C, the designation 550/197 is used.

under 490/197 which may upset normal air patterns in the chamber and cause localized cooling on the sample. This theory has not been tested.

During this study, the embedded chamber wall thermocouple outputs were recorded. This allowed another study of the involvement of the chamber walls in each individual test. In the following table are given comparison temperature rise difference data for four thermocouple locations under four different conditions listed in order of increasing severity.

Thermocouple Location	Conditions 490/144	490/172	550/144	550/197
Air	max ΔT_p=8°C	32°C	130°C	130°C
#1	0°C	10°C	27°C	38°C
#3	7°C	9°C	14°C	22°C
#10	2°C	8°C	26°C	38°C

The numbers in each column are the differences between the highest and lowest maximum temperature rises recorded at that thermocouple in the first six minutes among all the tests run under the conditions listed at the head of the column. With increasing severity, all locations show wider differences between the lowest and highest maximum. Since chamber energy feedback has been estimated to contribute approximately 10% of the incident energy falling upon the sample,[1] the chamber feedback can have a significant effect upon the flame spread distance of a sample. Probably, however, the effect is only noticeable under conditions at least as severe as 550/144, above which the chamber temperature is significantly affected by a burning sample.

5.4.2. Effect of Changes in the Ignition Procedure

In the next part of Phase III, the ignition procedure was studied. As was mentioned before, during Phase II under conditions 550/144 the wool carpet (W-1) would not ignite without a three minute and thirty second preheat. It was thought that perhaps preheating could have a drastic effect on the flame spread results of other materials as well. Also, to be studied in this section was the effect of the initial rapid burn zone

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[1] Based on radiant energy "view factor" considerations.

on the final flame spread results. As can be seen in the graphs of chamber air temperature in the previous section, with most materials there is an initial time, usually 0 to 7 minutes, where the burning is completely under the influence of the large output from the panel. This burning consumes a larger percentage of the material and releases a much larger amount of heat than under steadier state conditions later. The question to be answered here is how would the material perform if this initial stage were eliminated.

To conduct the first part of the study, six flooring materials were selected and put through preheat tests. In these tests, run under conditions 490/144 (panel temperature 490°C, chamber temperature 144°C) all conditions for a normal test were set. However, to prevent ignition with the introduction of the sample, the pilot burner was raised four inches off the sample surface. At the end of the predetermined preheat period, the pilot burner was lowered until ignition occurred and normal flame spread distance versus time readings taken.

A number of different preheat times for each sample were used. Figures 15 and 16 are a graphical representation of two typical series of tests showing the effects of preheating. Preheating appears to have only one obvious effect. It increases the rate of burning in the initial rapid burn zone. (In some of the series, preheating does consistently increase the total flame spread distance, but this is not true in every case.)

There does appear to be a pattern to the preheating effect. After the initial rapid burn zone, the burning attempts to follow a set pattern which is the extension of the line representing no preheat.

One possible explanation for this behavior is found by considering elements of the sample far from the panel in the region of typical extinguishment. During a normal (no preheat) test, the flame front takes a definite amount of time to reach this area. In this time, the area has received a given amount of energy from the panel and from the flame front and has exchanged energy with the chamber walls as well. However, in a preheat test, the flame front movement is delayed. By the time the flame front reaches the area, it has received more energy than before and is more likely to burn. The net result is that areas further from the burner will receive enough energy to burn. Of course, there is a limit to this effect as the sample areas heat up and begin to come to equilibrium with their surroundings.

This explanation has not been verified since it would take a detailed analysis and energy balance of the system and that is beyond the scope of this work. However, work in Phase IV was done to provide heat transfer data that may allow an energy balance to be made.

The testing of carpet A-5 (figure 16) brought about some other interesting phenomena. Carpet A-5 is a white plush acrylic that can be rated average to poor (as to flammability) in relation to the entire series of flooring tested. When the preheating of carpet A-5 was attempted, on two different occasions the same phenomenon was noticed: at 5.0 minutes heavy localized smoking occurred directly under the pilot burner which also is the part of the sample receiving the most energy. At 5.7 minutes, the gases from this region ignited as they reached the pilot burner. The flame flashed back to the carpet and sample ignition occurred. These two tests were the only tests where auto ignition occurred and their flame spread versus time plots are identical.

In order to keep auto ignition from occurring, the pilot burner was moved 2 inches further from the sample. Another A-5 test was run with a planned 12 minute preheat. At 5.0 minutes the smoking again occurred, and at 5.7 minutes, pyrolysis products were igniting around the pilot burner but no flame found its way back to the sample. A few minutes later, the smoking ceased.

At the 12 minute mark, the pilot was lowered to the sample but no ignition took place. Evidently enough of the combustibles had been pyrolyzed in the pilot ignition zone so that there were none left to burn. A piece of rolled up chart paper was ignited and touched to locations successively further from the pilot in an attempt to cause ignition. Finally at 12.9 minutes and at 28 centimeters, the sample ignited and burned as shown in figure 16. This is the only flooring that exhibited this behavior; however, under more extreme preheating, others may be expected to perform similarly.

The second part of this study dealt with the effect of moving the location of the ignition source. Taking a typical curve from one of the graphs, for example, A-5, figure 16, the plan was to cut off the bottom half of the curve and ignite the carpet at 30 cm instead of 0 cm; after a 6.6 minute preheat. For these tests, that portion of the sample from the ignition area to the pilot burner was removed. Comparison of the resulting flame spread versus time curve with that of the original test would give an indication of the importance of the initial rapid burning zone.

The curves for these results are shown in figures 17-19. Also on these figures are the preheat tests to which these results should be compared. In the case of carpet N-2, the initial rapid burning zone appears to have the effect of increasing the total flame spread (even though this zone has finished burning for a number of minutes). However, with the resilient flooring R-3, the effect of the initial burning zone does not increase final burn length. This was even more puzzling since R-3 releases more heat than any of the other floorings tested in Phase II.

In summary, it appears as though the Flooring Radiant Panel Test results are affected to a small extent by preheating. In addition, at the low radiant heat input conditions that were standard for the test, some amount of preheat may be desirable. The reason lies in the difference in severity between the panel and the pilot burner. Under more severe conditions such as Condition A in Phase II, the panel was contributing a high enough energy input to the sample to rapidly bring the area near the pilot burner to pyrolysis before the pilot-induced flame extinguished. However, under the reduced operating level of 490°C, some materials (W-1) may not reach pyrolysis near the pilot before the pilot-induced flame extinguishes. In this case, when pyrolysis is finally reached near the pilot, there is no ignition source and thus no ignition. However, a preheat would bring the pilot burner region up to pyrolysis before extinguishment of the pilot-induced flame.

Unfortunately, different materials heat up at different rates; thus a universal preheat time is nonexistent. Moreover, experience shows that a particular flooring material can warm at a fast or slow rate depending upon the fiber composition. It could be stipulated that if a material does not ignite and burn to at least 4 cm upon introduction into the chamber, it should be retested with a preheat of either 5 or 15 minutes based upon whether it is a fast or slow "warmer". The time factors given here are based upon the limited experience of testing under the program. Further work on the Flooring Radiant Panel may change these numbers or, in fact, eliminate the need for any consideration of preheating.

In summarizing the displaced ignition tests, it can be repeated that the initial rapid burning area does have an effect on total flame spread distance although the mechanism for this effect is not known.

5.4.3. A Study of Induced Air Flow Patterns

The third study in Phase III was a relatively minor study aimed at the charting of air patterns within the chamber and determining the effects produced by a gross change in the exhaust draft.

The first part of the study involved the use of titanium tetrachloride to produce an indicator smoke that was sparse enough to not disturb the natural air patterns but dense enough to be easily seen. With the panel in operation and a piece of asbestos cement board replacing the sample, indicator smoke was traced in its path from a point at the 90 cm location on the asbestos cement (point 1, figure 20) until it exited the chamber. The incoming air at the end of the sample was found to move along the sample, reaching the 50 cm point (point 3) in about eight seconds. It continued along the sample until it was under the panel, where it was picked up by convection currents, followed the face of the panel and went out the chimney (point 2). The entire journey from point 1 to the chimney took about 25 seconds.

The top view on figure 20 shows how the smoke drifts toward the back wall side of the panel. This phenomenon is in accord with other occurrences noticed in earlier testing. For example, after about 100 tests, the samples began to burn more readily on the side toward the wall. In an attempt to determine why this was happening, it was discovered that the effluent from the pilot burner strikes the panel on the near wall side and hinders burning. As a result the back wall side of the panel is hotter.

Next, air and smoke patterns were observed under actual testing conditions. Duplicate samples underwent the test. In the first test, the exhaust hood was in normal operation. Air flow velocity was intermittently monitored in the center of the chimney. In the second test, the exhaust hood gate was partially closed reducing the velocity of the air in the chimney about 12 percent. During this test, the titanium tetrachloride indicator was applied at the 90 cm point and its progress monitored. After both tests, a velocity profile was taken across the chimney. Figure 21 shows the results of air velocity measurements as well as the comparison of flame spread, maximum chamber temperature, and maximum smoke generation[1] results for each test. The material tested was the acrylic carpet A-5 which normally will burn out to 60± 2 cm. Thus it is

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[1] The smoke generation number is calculated as follows:

$S = \log \frac{I_I}{I_O}$ where I_I, I_O is the output from the smokemeter without and with smoke present, respectively.

evident that the decreased air flow had an almost negligible effect upon the burning characteristics. It is true that 63 is outside of the previously established error limits; however, it is only 5% from the mean value and therefore the difference is not considered significant.

In figure 22 are observations of the air and smoke patterns during the second test. An unusual aspect was observed at 3:30 when the flame front had reached 40 cm. The $TiCl_4$ indicator gas, after flowing down the sample, appeared to pass straight through the flame front plume without altering its direction in any way. This phenomenon continued for the remainder of the test. Although the smoke produced by the flame front followed its normal pattern of heading toward the panel and then out to the chimney, the $TiCl_4$ indicator flow seemed to be unaffected by the existence of the flame front.

5.4.4. Effect of Specimen Conditioning and Wear

Approximately one month before these tests were to be conducted, two sets of five samples each were selected for moisture content testing and a set of three samples set aside for wear testing. One set of the moisture content samples was placed in a sealed bag containing calcium sulfate drying crystals and the other set placed in a sealed bag containing a beaker of water. Also into the bags were placed 2 in x 2 in squares of each sample that had been previously weighed. The bags were undisturbed for 30 days. At the end of that time, the bags were opened, the small squares weighed and the samples tested. The percent moisture content[1] by weight based on weight of bone dry sample as well as the flame spread results of the testing are shown in table 9. Notice that the percent moisture content of the samples did not vary drastically.

The results of this testing indicate quite clearly that moisture content within the range studied is not a factor in the flame spread of these samples.

A limited study of the effect of specimen wear characteristics was conducted. The three samples set aside for wear testing were mounted side by side on the floor of the room housing the radiant panel apparatus in a high traffic area. After two weeks, the samples were quite dirty but were left down for an additional two weeks. At that time, they were removed from the floor and tested, and the results are also shown in table 9. Samples N-3 and A-4 showed no difference in flame spread results but A-5 actually increased in flame spread.

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[1] Percent moisture content = $\dfrac{\text{weight of moisture}}{\text{weight of bone dry sample}} \times 100.$

It was thought that soiling of the flooring would lower the flammability simply by physical hindrance of heat transfer to the unburned parts of the sample. Of course, this depends upon the composition of the soiling agent, but since all three samples received the same exposure to foot traffic, this is probably not the factor. Another possibility is that some samples are not as highly emissive as is commonly thought. In this case, addition of soiling may change the emissivity and thus energy absorption.

5.4.5. Substrate Study

The final part of Phase III was a study of the effect of substrate variation. This study is important inasmuch as it is commonly known that substrate has an effect upon surface flammability due to the amount of energy that the surface may lose through the backing and also in some cases, by the fuel that it contributes. In effect, a different "substrate" had already been tested in Phase II when underlayment was used. In this section, studies involved the use of substrates that should have more subtle effects.

A series of tests were run using four different flooring samples. Three of the four were tested over two different substrates, 3/8 inch plywood and 3/8 inch asbestos cement board, with and without adhesive.[1] For these three samples, then, there were actually six different substrate systems including the regular substrate used in Phase II and that substrate with an underlayment. The fourth flooring, due to lack of sufficient number of samples, was only tested over plywood without use of adhesive.

The results are shown in table 10. As had been predicted, the substrate did make a difference. The plywood, being a poor heat sink, kept the heat on the surface. In addition, depending upon the time duration of the test, the plywood actually became involved in the burning and contributed heat. Both of these factors result in greater flame spread. Notice, however, that carpet A-5 did not show an increase in flame spread as did the others. In addition, with the use of asbestos-cement board, A-4 and P-1 reacted as expected and had lower flame spread; however, again A-5 was not affected. An understanding of this phenomenon may be gained by looking at the test duration time column on table 10. In this column are

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[1] The adhesive used was a latex base floor covering adhesive. It was applied to the substrate at 50 grams/ft^2 wet coverage. The carpet was then applied. The samples were allowed to air dry for 1 week and then put into a 110°C oven for 24 hours after which they were allowed to come to equilibrium in a controlled environment room 75°F, 50% RH for 72 hours.

listed the test duration times for the norm test. In the next two columns are listed the minimum difference between results for the various substrates. The longer the test duration time the more the flooring is affected by the substrate. There is much support for this idea. If a material burns rapidly, chances are that the heat flow has not had an opportunity to penetrate a great distance. Thus the composition of the substrate would tend not to be a factor. On the other hand, where test duration time is long, more of the sample will be heated down to the substrate, making the substrate itself important.

Finally, consider the effect that use of the adhesive has upon results. Except for A-5, use of the adhesive results in 10 to 20 percent reduction in flame spread. To a great degree, this is probably the result of the better surface contact between the sample and the substrate provided by the adhesive and also, to a smaller degree, it is the result of the moisture content of the adhesive. The moisture content may not be important in the initial rapid burning zone, but out near the end of the burning region, when the flame front is small, it may be a factor.

5.4.6. Summary of Phase III

Phase III was a study of changes in test conditions. The purpose of this study was not to determine how gross changes in the apparatus or sample will affect the results. Rather its purpose was to see how sensitive the test is to minor fluctuations that may be encountered in day-to-day testing. It was assumed that if the Flooring Radiant Panel Test gains acceptance in the field, with it must come a typically stringent set of test procedures, specimen conditioning procedures, reporting procedures, etc. We assume that under proper conditions, these procedures will be followed. Therefore, all that can be asked of a test method is that if the proper procedures are followed, the test should be accurate in its measurements. It must not be overly sensitive to test condition variations that can occur even if the procedures are followed.

Therefore, this phase was aimed at those smaller scale changes such as humidity changes of the conditioning room from 35% to 65%, small (±5°C) changes in panel or chamber air temperatures, or soiling of the sample. These variations can occur and the Flooring Radiant Panel Test has shown that even with these variations, a high degree of repeatability can be expected.

Finally, the matter of the substrate was studied. It was found that the substrate can have a drastic effect upon the results. Therefore, in light of the fact that the Flooring Radiant Panel Test is a relatively inexpensive test to run, it is reasonable to expect that flooring should be considered as existing in a system, and not alone; and that the entire system should be tested, not the surface portion alone. This would mean that in order to be rated properly, a flooring material would have to be tested over all the possible substrates over which it is typically used. This would be something completely new in fire hazard testing but it is easily seen how much confidence it would give to fire hazard ratings. Of course, after a log of testing had been built up, knowledge of heat transfer mechanisms and constants related to the substrates would allow predictions and interpolations to reduce the number of required tests. This approach would be similar to that used now in fire endurance testing of floor and roof-ceiling structures.

5.5. Phase IV - Study of Thermal Conditions During Burning

The original plan for Phase IV called for a wrap up of the one year testing program in addition to any supplemental work that may have been found to be needed during the year. Fortunately, the program was completed by the end of the third phase. Therefore, the fourth phase was involved in making measurements on the apparatus during testing for the purpose of providing data for research on surface flammability and also for possible correlation with current corridor work. These measurements consisted largely of heat flux measurements through the sample, through the walls, and to the sample surface. The analysis of this data is largely outside the scope of this work; however, some of the more general results will be presented here.

5.5.1. Heat Flow

The first work done in this phase involved measurement of conductive heat flow through the chamber walls and sample. For this study six ceramic heat flux meters were used. These heat flux meters are the differential thermopile type with temperature correction. Two of them were cemented to the wall directly between thermocouples 1 and 3 and between 3 and 6 (on figure 23). Another one was cemented in the middle of the ceiling 12 inches from the cold end. These three were spray painted flat black to match the emissivity of the surroundings. Another three were cemented to the 3/8 inch asbestos board (which is the standard substrate) at the 30, 50 and 70 cm locations so that with the installation of the flooring, they would be in place between the flooring and the substrate.

Recordings of heat flux and temperature were taken every 5 seconds for the duration of four tests. The heat flux data for one of these tests on A-5 is graphed on figure 24.

The phenomenon of importance here is the significance of heat transfer through the substrate. At 30 cm, the sample is receiving about 0.76 watts/cm^2. From the graph it is evident that the transfer through the substrate at this point levels off at about 0.17 watts/cm^2 until the flame front passes over. Then it can shoot up to four or five times this value. (Unfortunately the data at the peak was lost.) However, if this curve is similar to the curve for the heat flux meter at 50 cm, the peak might have reached as high as 0.85 watts/cm^2. Even when the flame front passes to within 4 inches of the wall heat flux meter, the transfer to the wall only reaches 0.12 watts/cm^2. This fact reinforces earlier conclusions about effect of chamber involvement as well as the effect of substrate involvement.

In the second series, use was made of three Schmidt-Boelter type total incident heat flux sensors. These sensors, which record all incident heat flux no matter what the mechanism of transfer, were located at 30, 50, and 70 cm at the sample surface (see figure 23). In addition to these, the pyrometer used to monitor the panel temperature readings was relocated to the back of the chamber (location P, figure 23) so that panel temperature readings could be made during the test.

Figure 25 shows graphs of the results of one of the tests (Carpet A-5). Notice that the temperature of the panel appears to skyrocket with ignition. Actually, it has been noticed that upon removal of the sample tray immediately after a normal test, in Phase II, the panel was settling down from higher temperatures, as much as 20°C higher as measured by the pyrometer. However, skepticism arises as to whether the panel temperature was actually reading 660°C.

One check of the panel temperatures lies in the reaction of the heat flux sensors to the panel. The energy exchange between the panel and the heat flux sensors varies according to the formula

$$q_{net} = \sigma A_s \varepsilon_{ps} F_{ps} (T_p{}^4 - T_s{}^4).$$

where,

q_{net} is the net transfer of energy from the panel to the heat flux sensor,

σ is the Stefan-Boltzman constant

A_s is the area of the sensor

ε_{ps} is the interchange emissivity (related to the surface characteristics of both the panel and the heat flux sensor).

F_{ps} is the view factor (related to the geometry of the system).

T_p, T_s are the temperatures (absolute) of the panel and the heat flux sensor, respectively.

Fortunately, the product $A_s\varepsilon_{ps}$ is nearly constant throughout the test and T_s is small enough when compared to T_p that its fluctuations can be discounted, since the senors are water cooled. In addition, F_{ps} is constant for a particular location. Thus,

$$q_{net} \sim kT_p{}^4 \text{ where } k = A_s\varepsilon_{ps}F_{ps}$$

If the panel is actually reaching a maximum, then the energy transfer to the heat flux meters should increase according to the ratio:

$$\frac{[T_{p,\ \text{max (or min)}}]^4}{[T_{p,\ \text{steady state}}]^4} = \frac{q_{T_{p,\ \text{max (or min)}}}}{q_{T_{p,\ \text{steady state}}}} = \text{HFS}^1 \text{ Ratio}$$

The actual ratios for the three tests at points where the apparent panel temperature went through a maximum or minimum (and the flame front had not reached the first heat flux meter) are as follows:

Test	T_p Steady State	T_p Maximum	$(T_p \text{ Ratio})^4$	Ratio HFS@30	Ratio HFS@50	Ratio HFS@707
193	773°K	943°K	2.13	1.77	1.49	1.45
194	773°K	713°K	0.73	0.93	0.95	1.00
195	773°K	838°K	1.39	1.41	1.32	1.37

Obviously, the three tests show three different situations. Test 195 shows consistent results. The apparent panel temperature went through a maximum with buildup of the flame front and this maximum was reflected in the energy transfer to the heat flux meters. However, in test 193 the apparent panel temperature went through a maximum that was not followed by

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[1] HFS - Schmidt-Boelter type heat flux sensor

the heat flux meters while in test 194, a minimum was reached by the apparent panel temperature which also the heat flux meters did not follow. As for the maximum seen in test 193, a check of the log book for that test shows the operator noted a plume which was high enough to be in the pyrometer's view. This may have resulted in a false high reading for the panel and, in fact, the inconsistently high reading for the HFS ratio at 30 cm could also have been the result of the plume's proximity.

The low values noticed in test 194 are a little more difficult to explain. Smoke obscuration is one possibility, but the smoke charts show that the W-1 carpet in test 194 produced almost no visible smoke. However, the effect of CO and CO_2 which is present in most hydrocarbon burning, may have been overpowered in tests 193 and 195 by the heavy particulate smoke production which, when it reached the face of the panel, became a thermal emitter. But in test 194, the particulate production being absent, the absorbing affect of CO and CO_2 would become evident and cause the pyrometer to read a lower temperature.

In any case, the question can be much deeper than we have presented here and is thus beyond the scope of this work.

One other phenomenon of importance from this graph is indicated by the line representing heat flux to the sample at 70 cm. Although this point is never reached by the flame front, it is nevertheless affected by the burning that does take place. Even toward the end of the test, the incident heat flux at this point is 20% higher than that at the start of the test. This supports the observation in Phase III that the initial stages of burning do affect the latter stages.

Again, the work of Phase IV was much more extensive than is described here. On file with the author is the bulk of the raw data which includes chamber wall temperature and heat flux readings, sample temperature and heat flux readings and panel temperature readings taken on a number of samples. This data will be put to use in more detailed analyses of the Flooring Radiant Panel Test some time in the future.

6. REVIEW

With the completion of Phase IV, the year long development program at NBS was brought to a close. The primary goals of the program were met. The Flooring Radiant Panel Test, originally developed by Armstrong Cork Company, was brought further along in its development to the point where it has been considered by NBS as a possible successor to E-84 and E-162 as the standard test for floor covering. In addition, developmental work on the test has provided a wealth of data that can be of value in the general understanding of flooring flammability.

6.1. Test Apparatus

Of course, the project should not stop here. In any program not brought to total completion, there must be plans for future work. During this year, a number of situations and problems arose which were side-stepped for the benefit of the overall program. Generally, these problems were not of a nature significant enough to warrant program delays, but their solution can easily be incorporated into future work.

Perhaps the most significant of these problems is the radiant panel itself. At present, the panel is a gas fired refractory mounted into a steel housing. This arrangement leads to the following problems:

1. It is a delicate structure easily damaged, and difficult, expensive, and time-consuming to repair.
2. Panel warm-up takes from 1/2 to 1 hour even after the proper gas/air intake settings are known.
3. There is a limited range of operating temperatures.
4. The quality of the burning, i.e., temperature variations with location on the surface is affected by events within the chamber such as sample burning and pilot burner effluent.
5. The temperature is difficult to control and measure.
6. Extensive safety equipment is required.

The above problems did not prevent the completion of the program, rather they caused delays, lowered the total number of tests that could be run on a daily basis, limited the scope of the program, and possibly increased the repeatability error limits. The author feels that an electrically heated panel would solve many of the above problems and create no significant new ones. It would be more versatile and definitely an overall asset for experimental and developmental work.

Another problem area is the wall material. At present, the two Flooring Radiant Panel Tests in existence make use of a mineral-base acoustical material. This material, while being an excellent ceiling material, is rather unsuited for use as a test enclosure. Its main drawback is its brittleness and susceptibility to damage. Replacement of this material with asbestos cement board, gypsum, or some combination thereof, would surely solve this problem.

There are some other construction changes which can be made in the apparatus. For example, a smaller door would allow easier sample mounting techniques. Perhaps a quick clamp mechanism would help.

6.2. Flame Spread Index

The above-mentioned problems all involve changes in the apparatus. Future work may also lead to improvements in the method of flame spread rating.

At this point, the suggested flame spread index is the distance the material burns until extinguishment. In order to attach more physical significance to the rating it was suggested that, since each point along the sample surface corresponds to a given incident flux, the ratings be converted into flux readings. The physical significance of this idea is that the flux value corresponding to the extinguishment point for a particular material can be said to be the material's minimum required (critical) flux for flame front propagation.

This approach requires that the true total incident heat flux be known at every point along the sample surface just before extinguishment in all tests. Let us assume, for example, that the true flux is known for a blank test, under steady-state conditions. Then, the only factors that will alter that flux are changes in the panel temperature, changes in the chamber wall and air temperatures, or physical obscuration of the energy sources (smoke).

First of all, we can eliminate physical obscuration as a factor since in no cases has it been reported in a Flooring Radiant Panel Test that there was even a trace of smoke at the time of flame front extinguishment. Smoke production always happens well ahead of extinguishment. By the same token, changes in panel temperature can be discounted by similar arguments. What remains then is the accurate determination of how incident flux to the sample is affected by changes in the chamber wall and air temperatures. This can be determined either by empirical measurement or by calculation. In fact, as a check on the incident flux measurements of Phase II, the theoretical flux measurement at 25 cm under Conditions C of Phase II were calculated. This calculation took into consideration panel and wall temperatures and their appropriate emissivities and view factors. While the measured value at that location was 0.66 watts/cm^2, the calculated value was 0.65 watts/cm^2 of which about 5% was contributed by the chamber walls.

Thus, when the actual flux is known for any chamber temperature, then the "critical" flux can be determined by running a standard Flooring Radiant Panel Test. And, in addition, we have not allowed for the possibility that the chamber wall temperature fluctuations are not significant enough to affect the test. Since the chamber contributes only about 5% to 10% of the total energy under conditions of a low (490°C) panel temperature, this may be true.

As a check on the above idea, this "critical" flux of seven different materials (neglecting wall temperature effects) was found under conditions 670/197, 550/172, and 490/144 (Phase III).

Conditions	Critical Radiant Flux W/cm^2 A-2	A-4	A-5	N-3	N-4	W-1	R-3
T_p=670, T_{ca}=197	0.28	0.36	0.24	1.40	0.35	1.35	0.36
T_p=490, T_{ca}=172	0.31	0.43	0.23	1.10	0.27	0.61	0.35
T_p=490, T_{ca}=144	0.29	0.38	0.23	0.85	0.25	0.60	0.42

These data show surprising correlation except for N-3 and W-1 for which no explanation is offered, indicating that a true critical flux may be a simple value to measure in the Flooring Radiant Panel Test.

Of course, critical flux is only one factor in the flammability of a material. Also to be considered are heat release and speed of flame front propagation, and at this point no one can say which facet is most important or what is the relative importance of each.

APPENDIX A. THE ARMSTRONG CORK COMPANY FLOORING RADIANT PANEL DEVELOPMENT

A.1. Test Parameter and Apparatus Design Criteria

Since fire is very complex, some difficulty was encountered in selecting the proper parameters for the test. The selection of the temperature at the hot end of the specimen offered some problems, since it was desired that the temperature be hot enough to ignite all specimens and also high enough to equal flame temperatures encountered in a full-scale fire. Therefore, a temperature of 950°F without a pilot burner was selected. The selection of this temperature was based in part upon a corridor test performed by the Forest Products Laboratories reported in a paper, "Effect of Wall Linings on Fire Performance with a Partially Ventilated Corridor," where maximum temperatures on hardwood floors in three tests were recorded at 630°, 805°, and 780°F. A paper by L. W. Sayers in Textile Institute and Industry [1], 1965, (Eng) reported ignition temperatures of fibers determined by a hot-plate method such as: cotton, 400°C (725°F); nylon, 530°C (987°F); triacetate, 540°C (1,004°F); acrylic, 560°C (1,040°F); polypropylene, 570°C (1,058°F; and wool, 600°C (1,112°F). C. H. Yuill also reported in his paper "Floor Coverings--What is a Hazard?" maximum floor temperatures in the range of 1,100° to 1,400°F in some room burnout tests. Based on this information, with the use of a pilot light, the maximum temperature at the hot end of our test specimen would be 1,600°F.

It was also desired that there be a uniform temperature gradient down the full length of the test specimen. This was found by measuring the temperature every one inch with thermocouples attached to the surface of an asbestos millboard and setting the angle of the panel at 30°. The radiation intensity at the sample surface (at the hot end) was also measured and found to be 8,150 Btu/ft^2 hr (2.55 W/cm^2).

Preliminary tests showed that draft control is important for reproducibility and the burning of the specimen. In enclosing the apparatus, make-up air is required; but it should not cause excessive drafts, yet it should be sufficient to supply enough oxygen for complete combustion of all specimens. Available literature indicated that polypropylene would require the most oxygen for combustion. Therefore, 4 inch high openings were made at both ends of the chamber, supplying air at a velocity of approximately 50 ft/min. Since the width of the chamber (20 in) is wider than the specimen (5 in) this air is easily dispersed within the chamber without causing a direct draft in one direction across the flaming specimen.

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[1] Sayers, L. W., Flammability of Fibers, Fabrics and Garments, Textile Institute and Industry, Vol. 3, No. 7, 168-171 (July 1965).

The opening in the top is large enough to remove all of the smoke and heat without causing abnormal draft across the specimen.

A.2. Armstrong Test Apparatus

The apparatus consists of a 12 in x 18 in gas fired refractory radiant panel (same as in E-162) inclined at a 30° angle over the exposed 5 in x 25 in portion of the horizontally mounted test specimen, see figure 2. The specimen surface is 3-3/8 in below the lower edge of the panel. The panel and adjustable height specimen transport system are enclosed in a 19-1/2 in x 26-1/2 in x 45 in, 5/8 in thick asbestos millboard sheathed chamber with provisions for a free flow of draft-free air to simulate natural burning conditions, see figure 3. The end openings are 4 in x 19-1/2 in. The exhaust port (top) at the cold end is a 7 inch diameter semi-circular hole. There is a 4 in x 36 in VYCOR glass test viewing window in the front face of the chamber. Below the window is a panel which can be opened to facilitate placement and removal of the test specimen via a drawer-like transport assembly.

The gas fired radiant panel is capable of operating at temperatures up to 1,500°F with natural gas (nominal 1,000 Btu/ft^3/min). The gas and air are mixed at approximately atmospheric pressure in a venturi. Air is supplied by a centrifugal blower capable of delivering 100 ft^3/min at 3.2 inches of water. When properly adjusted the burner has a blue flame 1/8 inch long with only a few short flashes of luminous flame. The operation and adjustment of this burner is identical to the one described in ASTM E-162. A radiation pyrometer is used to monitor the black body temperature of the panel. A chromel-alumel thermocouple 4 inches from the top and 10 inches from the cold end of the chamber measures temperatures during a test.

A 48 in x 36 in x 11 in exhaust hood with a 6 inch diameter duct removes smoke and heat from the chamber. Its volumetric capacity is approximately 3,000 ft^3/min.

A.3. Armstrong Test Procedure

1. Ignite the gas/air mixture passing through the radiant panel and allow the unit to heat up for approximately 1/2 hour. Before each test, the panel should be checked to maintain a temperature of 1,238°F ±7°F and adjustments made to the gas if necessary.

2. Ignite the pilot burner and adjust the flame to its proper length. The pilot burner is not extinguished between tests.

3. The temperature in the chamber before each test should be approximately 460°F, but this may vary slightly from one apparatus to another. This temperature will be established after a number of tests have been conducted. Adjustments are made with the sample base removed from the apparatus.

   NOTE: It is recommended that a sheet of asbestos millboard be used to cover the opening when a hinged portion of the front panel is raised and the base of the chamber removed. The millboard is used to prevent heating of the base and the operator when the front panel is open.

4. Invert the sample holder on a workbench and insert the specimen, then the desired underlayments and substrates, and finally the millboard. Place the five channel-iron clamps provided across the back of the assembly and tighten firmly into place with the wing nuts. Raise the sample holder with the specimen assembly, vacuum the surface to remove any foreign particles; and if the specimen is a carpet, brush the surface of the carpet to raise the fibers to their normal position. Place the assembly onto the base and fasten the assembly using the four threaded studs in the base.

5. Remove the millboard sheet, slide the base containing the specimen into the chamber, close the hinged flap, and immediately start the timer.

6. Record the flame spread by noting the time and flame front passes each 1 inch mark and any other observations such as melting, blistering, penetration of the flame to the substrate exposing backing, etc.

7. The test is continued until the flame front reaches the end of the specimen or the flames extinguish themselves.

8. When the test is completed, the hinged flap is raised, the base and specimen are pulled out of the chamber and the millboard shield is put into place. The specimen and rack can be cooled with wet towels or water. The sample holder is removed from the base and preparation made for the next test. Allow the chamber to cool to 460°F or to the base temperature determined for the particular apparatus.

9. Since the temperature of the radiant panel will increase slightly during the test, its temperature must be checked and a slight adjustment made to the gas. Fifteen to twenty minutes are required to cool the chamber and the radiant

panel between tests. This will depend upon the length of the previous test.

10. Calculate the flame spread index as follows:

    a. If the specimen burns the full sample length in less time than it takes red oak to burn that distance

$$FSI = \frac{T_{RO}}{T_s} \times 100$$

    b. If the specimen burns the full sample length in a longer period of time than it takes red oak, or if the specimen does not burn the full sample length

$$FSI = \frac{D_s}{L} \times 100$$

where FSI = flame spread index

L = specimen length

T_{RO} = time for red oak to burn full sample length

T_s = time for specimen to burn full sample length

D_s = distance specimen burns in time T_{RO}, or flame spread length

11. Report the results, the observations with a complete description of the test specimen, and also the test assembly.

APPENDIX B. STATISTICAL ANALYSIS

B.1. Correlation of Test A with Test B

In this paper, in discussing the correlation of one test result with another, least squares regression is used. To determine the best straight line approximation of the data points, the following formula is used

$$y = \beta_1 x + \beta_2$$

$$\beta_1 = \frac{n \sum_{i=1}^{n} x_i y_i - \left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{n \sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}$$

$$\beta_2 = \bar{y} - \beta_1 \bar{x}$$

$\bar{y}$, $\bar{x}$ are mean values of y and x respectively
n is the number of data points (sample size)

To determine the value of the correlation coefficient, r, which is a measure of linear correlation, the following formula is used

$$r = \frac{\sum_{i=1}^{n} (x_1 - \bar{x})(y_i - \bar{y})}{\left[\sum_{i=1}^{n} (x_1 - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2\right]^{1/2}}$$

The correlation coefficient is of significant value in this work because, as can be seen from the formula used to calculate r, it does not depend upon whether x or y is plotted on the horizontal axis. Physically, this means that the correlation coefficient is not concerned with dependency of y upon x but only with relationship. And since in this paper, we are interested in relationship, r is a useful quantity.

This coefficient varies from -1.0 to +1.0 and the strength of correlation is equal to the absolute value of r regardless of sign. In other words, a value of 0 for r indicates no correlation whereas a value of -1.0 or +1.0 indicates perfect correlation. A negative sign merely indicates that the correlation is inverse.

References

[1] Surface Flammability of Materials: A Survey of Test Methods and Comparison of Results, Symposium on Fire Test Methods, ASTM Special Technical Publication, No. 301, 1961.

[2] Z. Zabawsky, Private communication.

[3] Z. Zabawsky, Private communication.

[4] Denyes, W. and Raines, J., A Model Corridor for the Study of the Flammability of Floor Coverings, Nat. Bur. Stand. (U.S.), NBSIR 73-200 (May 1973).

[5] Denyes, W. and Quintiere, J., Experimental and Analytical Studies of Floor Covering Flammability with a Model Corridor, Nat. Bur. Stand. (U.S.), NBSIR 73-199 (May 1973).

TABLES

Table 1. Sample Identification

Carpets

Code	Fiber	Type	Backing	Weight		Pile Height Inches
				Pile oz/yd^2	Total oz/yd^2	
N-1	BCF Nylon	Level Loop	PP/Foam	20	89	1/8
N-2	Nylon	Shag	Jute/Jute	24	64	1-1/8
N-3	BCF Nylon	Level Loop	Jute/Jute	25	69	1/4
N-4	Nylon	Shag	Jute/Jute	28	75	7/8
N-5	NCF Nylon	Multi-level Loop	Jute/Jute	16	64	1/8 - 5/16
A-1	100% Acrylic	Woven Level Loop	Jute & Cotton	38	55	1/4
A-2	100% Acrylic	Random Shear	PP/Jute	32	69	1/16 - 5/16
A-3	100% Acrylic	Level Loop	PP/PP	36	65	1/8
A-4	100% Acrylic	Random Shear	Jute/Jute	36	80	1/8 - 3/8
A-5	100% Acrylic	Plush	PP/Jute	30	66	3/8
A-6	100% Acrylic	Level Loop	PP/Jute	35	92	1/4
0-1	BCF Olefin	Level Loop	PP/Jute	13	55	1/8
W-1	Wool	Woven Level Loop	Jute & Cotton	38	76	7/32
W-2	Wool	Woven Saxony	Jute & Cotton	40	76	9/16
P-1	Polyester	Level Loop	PP/Jute	38	70	1/4
P-2	Polyester	Random Shear	Jute/Jute	32	73	1/4 - 3/8
P-7	Polyester/ Modacrylic (70/30)	Level Loop	PP/Jute	42	85	1/2

PP-Polypropylene

Resilent Flooring, Red Oak and Pad

Code	Wear Layer (in)	Backing (in)
R-1	.010 Vinyl Surface	.035 Vinyl Foam -- .030 Inorganic Felt Back
R-2	.035 Vinyl Surface	Glass Strands and PVC Film -- .100 PVC Foam Back
R-3	.050 Linoleum	.040 Cellulosic Film Back
R-4	.050 Vinyl Surface	.040 Inorganic Felt Back
R-5	.036 Vinyl Surface	.012 Vinyl -- .125 Vinyl Foam
R-6	Urethane	PVC -- Inorganic Felt
RO	3/4 Red Oak Flooring	
Underlayment	55 oz/yd^2 rubberized - hair/jute pad	

Table 2. Flame Spread Index and Chamber Temperature Rise Results and Comparison Between AFRP-1 and AFRP-2

Flooring	Flame Spread		Chamber Temp Rise°F	
	AFRP-1	AFRP-2	AFRP-1	AFRP-2
A-1	82	85	76	284
A-2	331	290	77	252
A-3	94	98	71	273
A-4	83	100	74	230
A-5	-	493	-	351
N-1	70	89	118	396
N-2	-	65	-	243
N-3	50	52	87	253
N-4	-	88	-	405
N-5	76	89	63	286
O-1	-	148	-	347
W-1	47	39	60	221
RO	100	100	-	-
A-1/pad	225	167	147	345
A-2/pad	410	580	148	439
A-3/pad	253	229	122	282
A-4/pad	275	-	111	-
A-5/pad	-	682	-	473
N-2/pad	-	90	-	333
N-3/pad	72	72	110	311
N-4/pad	-	172	-	473
N-5/pad	97	106	120	324
O-1/pad	-	457	-	570
W-1/pad	43	46	89	255

Table 3. Flame Spread Ratings and Comparison

Flooring	AFRP-1	AFRP-2	Model Corridor (MMFPA) (Btu/min)	UL-992	E-162	E-84
A-1	82	85	750	0.9	145	43
A-2	331	290	750	1.2	263	50
A-3	94	98	600	-	225	-
A-4	83	100	750	1.3	262	-
A-5	-	493	300	-	309	-
N-1	70	89	600	1.1	284	237
N-2	-	65	1,000	-	210	179
N-3	50	52	1,000	-	140	-
N-4	-	88	500	1.9	173	-
N-5	76	89	750	1.1	241	-
0-1	-	148	300	2.1	616	71
W-1	47	39	1,250	-	64	50
A-1/pad	225	167	300	2.6	150	298
A-2/pad	410	580	400	2.3	445	279
A-3/pad	253	229	<300	-	265	-
A-4/pad	275	-	400	-	291	-
A-5/pad	-	682	<300	-	400	-
N-2/pad	-	90	600	-	289	-
N-3/pad	72	72	750	-	185	-
N-4/pad	-	172	<300	11.8	253	-
N-5/pad	97	106	300	-	332	-
0-1/pad	-	457	<300	24.0	764	-
W-1/pad	43	46	750	-	119	-
R-1	-	43	1,250	-	400	-
R-2	-	66	1,000	-	-	-
R-3	-	98	500	-	-	-

Table 4. Flame Spread Rating Results and Heat Flux at Extinguishment For Several Thermal Conditions

Flooring	Condition D T_p = 670 °C T_c = 227 °C				Condition A T_p = 670 °C T_c = 197 °C				Condition B T_p = 550 °C T_c = 172 °C				Condition C T_p = 490 °C T_c = 144 °C			
	No Pad		W/Pad		No Pad		W/Pad		No Pad		W/Pad		No Pad		W/Pad	
	Rating	W/cm^{2}[a]	Rating	W/cm^{2}	Rating	W/cm^{2}	Rating	W/cm^{2}	Rating	W/cm^{2}	Rating	W/cm^{2}	Rating	W/cm^{2}	Rating	W/cm^{2}
A-1	85	0.35	(13.00)	<0.27	-	-	-	-	49	0.45	(44.50)	<0.20	44	0.35	-	-
A-2	(7.52)[b]	<0.27	(3.75)	<0.27	92	0.30	-	-	63	0.25	84	0.20	55	0.30	-	-
A-4	100	0.27	-	-	76	0.35	-	-	52	0.40	-	-	46	0.35	-	-
A-5	(4.46)	<0.27	(3.19)	<0.27	97	0.27	-	-	73	0.20	88	0.20	61	0.20	-	-
N-1	89	0.30	-	-	-	-	-	-	60	0.30	-	-	45	0.35	-	-
N-2	65	0.50	90	0.30	-	-	-	-	66	0.25	-	-	55	0.25	-	-
N-3	52	0.75	72	0.40	35	0.30	-	-	24	1.10	-	-	4	0.85	-	-
N-4	88	0.30	(12.62)	<0.27	77	0.35	-	-	67	0.25	(61.60)	<0.20	59	0.25	(73.23)	<0.10
N-5	89	0.30	(20.52)	<0.27	-	-	-	-	66	0.25	-	-	-	-	-	-
W-1	39	1.20	46	0.90	36	1.30	-	-	41	0.65	44	0.55	30	0.65	32	0.70
W-2	-	-	-	-	-	-	-	-	61	0.30	-	-	-	-	-	-
P-1	-	-	-	-	-	-	-	-	86	0.20	-	-	74	0.20	-	-
0-1	(14.73)	<0.27	(4.75)	<0.27	(27.32)	<0.27	-	-	(64.76)	<0.20	-	-	(83.65)	<0.10	-	-
R-1	43	1.00	-	-	-	-	-	-	23	1.10	-	-	10	0.80	-	-
R-3	98	0.30	-	-	75	0.35	-	-	58	0.75	-	-	43	0.40	-	-

[a] critical radiant flux

[b] ( ) indicates rating in time, minutes

Table 5. Repeatability Results

	Condition A			Condition B			Condition C		
	Rating	Ave.	% Coeff. Var.	Rating	Ave.	% Coeff. Var.	Rating	Ave.	% Coeff. Var.
A-2				64, 62	63	2.2			
A-4	76, 82, 71	76.3	7.2	52, 50, 54	52	3.8			
A-5	98, 95, 99	97.3	2.1	72, 73, 74	73	1.4			
N-3	32, 37, 35	34.7	7.3	24, 24	24	0.0			
N-4				64, 70	67	6.3			
W-1				39, 43, 26, 41 (39, 43, 41)	37.25 (41)	21.0 (4.9)	31, 29	30	4.7
Average			5.5		W/O W-1	5.8 (3.1)			4.7

Total Average = 5.3%
W/O W-1 = (4.4%)

Table 6. Flame Spread Ratings and Comparison

Flooring	Condition C AFRP-2 (cm)	Model Corridor (MMFPA) (Btu/min)	UL-992	E-162	E-84
A-1	44	750	0.9	145	43
A-2	55	750	1.2	263	50
A-3	48	600	-	225	-
A-4	46	750	1.3	262	-
A-5	61	300	-	309	-
A-6	34	1,250	-	-	-
N-1	45	600	1.1	284	237
N-2	55	1,000	-	210	179
N-3	4	1,000	-	140	-
N-4	59	500	1.9	173	-
O-1	>100	300	2.1	616	71
W-1	30	1,250	-	64	50
W-2	53	1,250	-	-	-
P-1	74	500	-	-	-
P-2	47	1,000	-	-	-
P-7	48	1,000	-	-	-
A-1 pad	99	300	2.6	150	298
A-2 pad	70	400	2.3	445	279
A-3 pad	93	<300	-	265	-
A-4 pad	63	400	-	291	-
A-5 pad	70	<300	-	400	-
A-6 pad	47	1,000	-	-	-
N-2 pad	86	600	-	289	-
N-3 pad	35	750	-	185	-
N-4 pad	>100	<300	11.8	253	-
O-1 pad	>100	<300	24.0	764	-
W-1 pad	32	750	-	119	-
W-2 pad	55	1,250	-	-	-
P-1 pad	>100	<300	-	-	-
R-1	10	1,250	-	400	-
R-2	24	1,000	-	-	-
R-3	43	500	-	-	-
R-4	18	1,250	-	-	-
R0	60	1,250	-	-	-

Table 7. Test Schedule

Chamber Temperature	Panel Temperature		
	490°C	550°C	670°C
1 - 144°C	A-2, A-5 N-3, W-1, R-3	A-2, A-5 N-3, W-1, R-3	
2 - 172°C	A-2, A-5 N-3, W-1, R-3	A-2, A-5 N-3, W-1, R-3	
3 - 197°C	A-2, A-5 N-3, W-1, R-3	A-2, A-5 N-3, W-1, R-3	A-2, A-5 N-3, W-1, R-1
4 - 227°C			A-2, A-5, N-3, W-1, R-3

Table 8. Flame Spread Results

Sample	Chamber Temperature	Panel Temperature		
		490°C	550°C	670°C
A-2	1 - 144°C	55	65	
	2 - 172°C	57	63	
	3 - 197°C	59	73	92
	4 - 227°C			>100
A-5	1 - 144°C	61	69	
	2 - 172°C	74	73	
	3 - 197°C	68	80	97
	4 - 227°C			>100
N-3	1 - 144°C	4	22	
	2 - 172°C	18	24	
	3 - 197°C	16	30	35
	4 - 227°C			51
W-1	1 - 144°C	30	37	
	2 - 172°C	37	41	
	3 - 197°C	35	43	36
	4 - 227°C			39
R-3	1 - 144°C	43	51	
	2 - 172°C	52	58	
	3 - 197°C	47	56	75
	4 - 227°C			98

Table 9. Humidity and Wear Tests

Humidity Tests

Conditioning RH Samples	Moisture Content % 30%	 50%	 65%	Results in cm 30%	 50%	 65%
W-1	6.0	6.5	9.7	30	30	29
N-3	1.9	2.2	3.3	5	4	4
A-5	1.0	1.2	1.7	61	61	59
A-6	0.9	1.0	1.1	30	34	31
R-2	1.4	1.4	1.4	26	24	26

$$\% \text{ Moisture Content} = \frac{\text{Wt Moisture} \times 100}{\text{Wt Bone Dry Sample}}$$

Results - Flame Spread Distance

Wear Tests

Samples	Results Normal	Dirty
N-3	4	5
A-4	46	46
A-6	61	69

Table 10. Effect of Substrate on Flame Spread Distance

Carpet	Flame Spread Distance, cm						Test Duration No Pad min.	Difference in Flame Spread Distance, cm (minimum)	
	Substrate								
	ACB 1 no pad	ACB 1 W/pad	ACB 2 W/glue	ACB 2 no glue	Plywood W/glue	Plywood no glue		W/pad	no pad
A-4	46	63	36	40	40	51	13	27	15
A-5	61	70	63	59	63	59	7	11	4
P-1	74	100	54	70	83	100	100	46	46
A-2	55	70				57	10	15	(2)

Note: ACB = 3/8 inch asbestos-cement board

ILLUSTRATIONS

Figure 1. Room Fire Situation

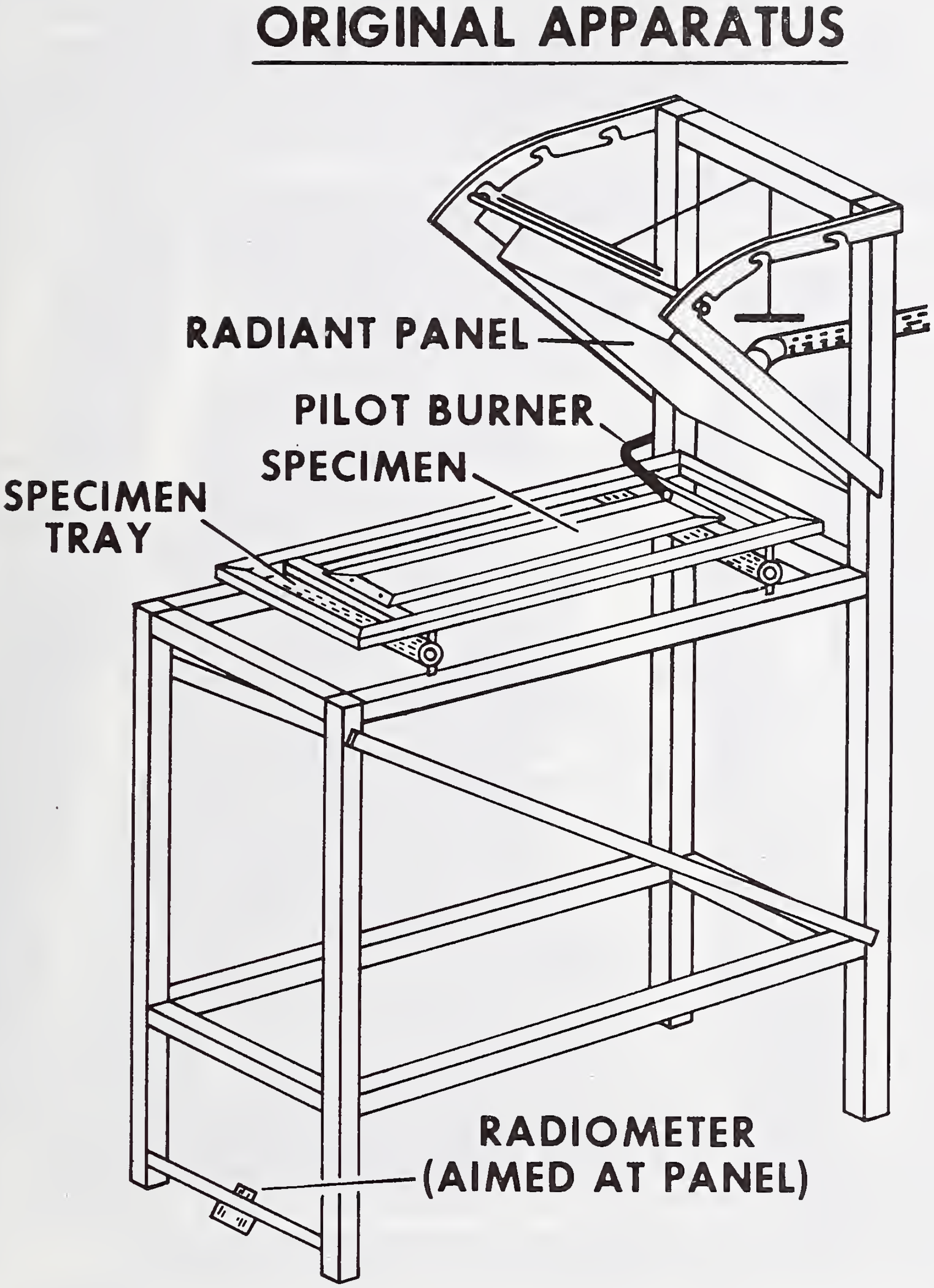

Figure 2. Original Apparatus.

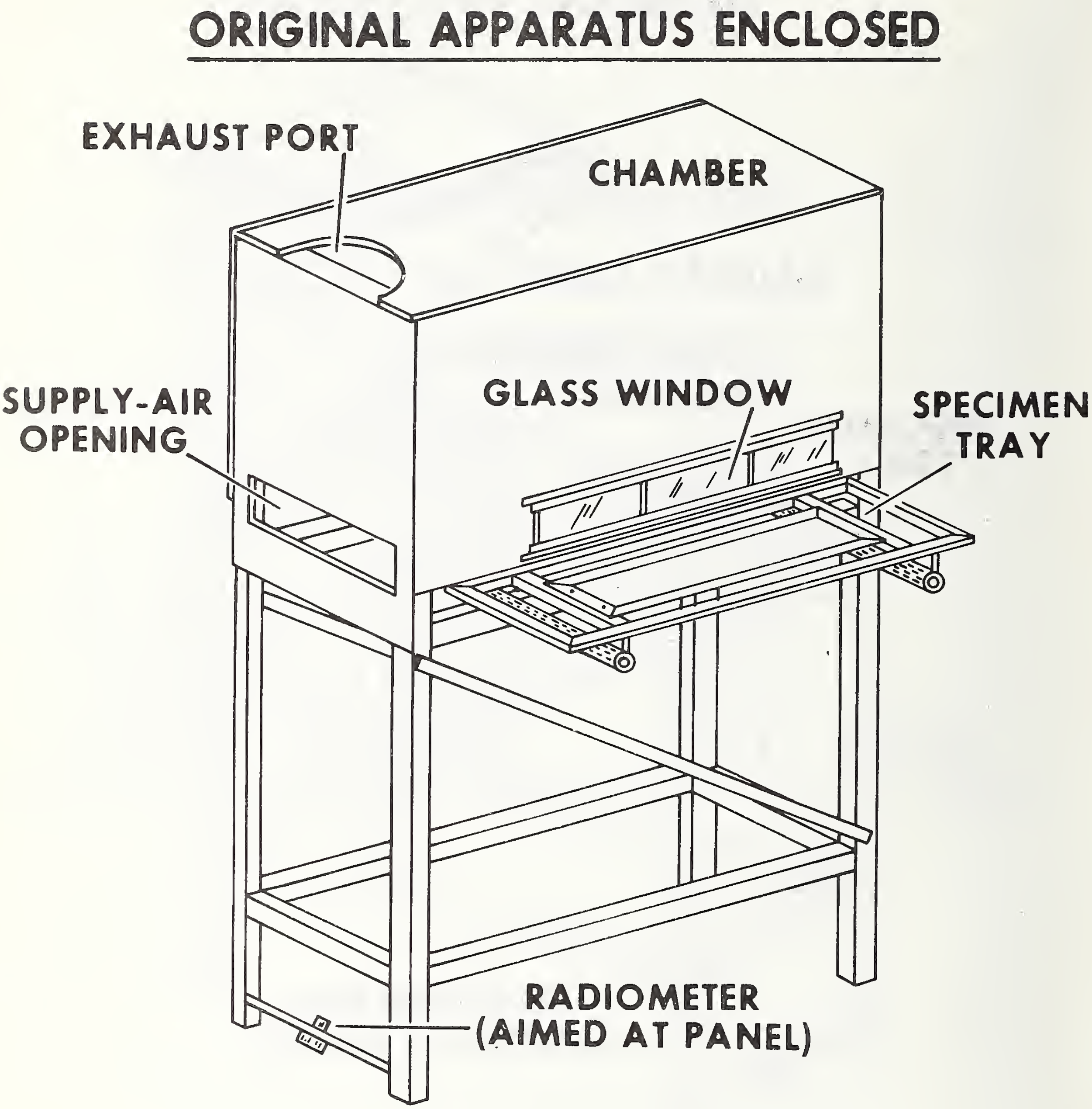

Figure 3. Original Apparatus Enclosed.

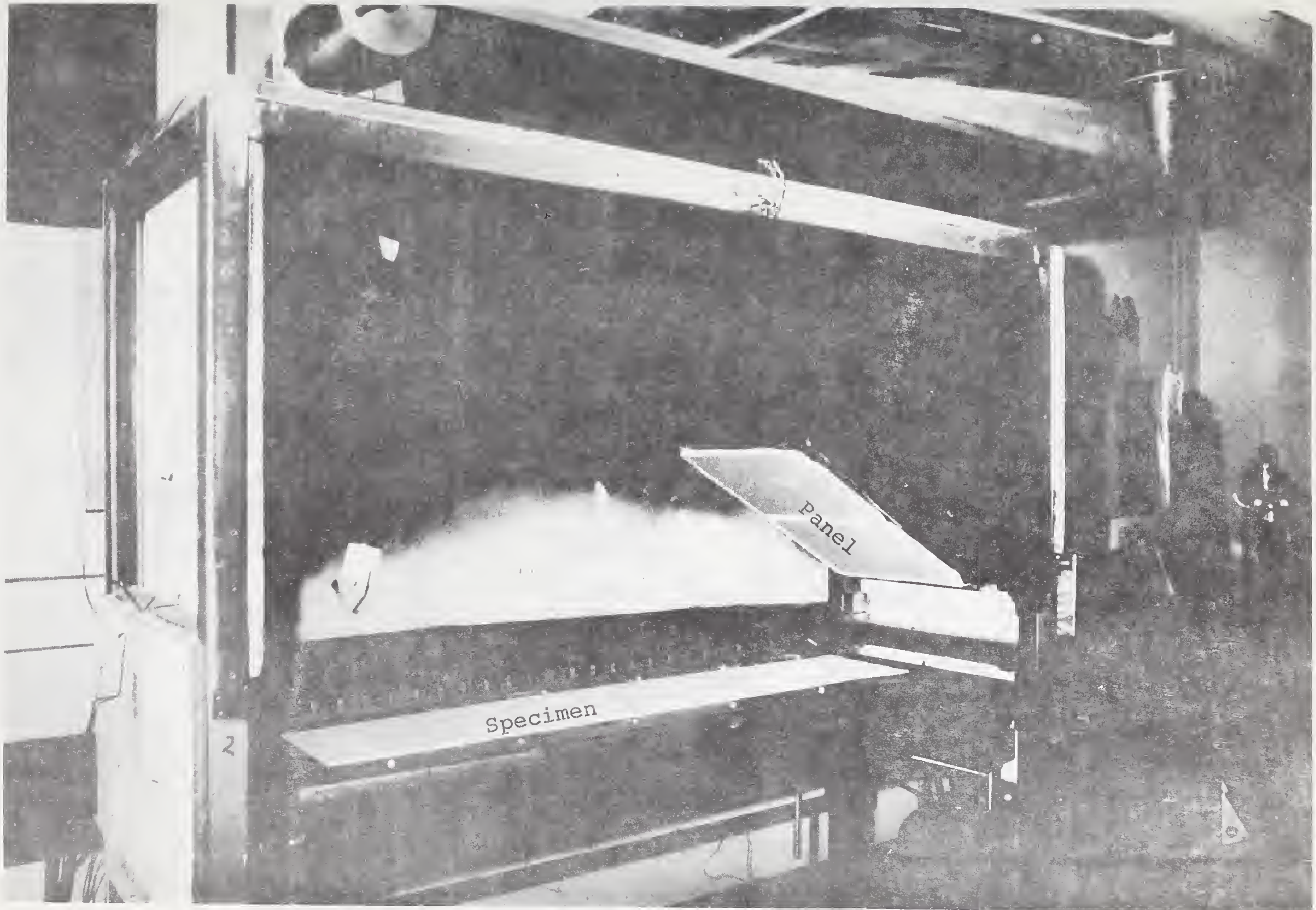

Figure 4. Radiant Panel Apparatus With Front Wall Removed.

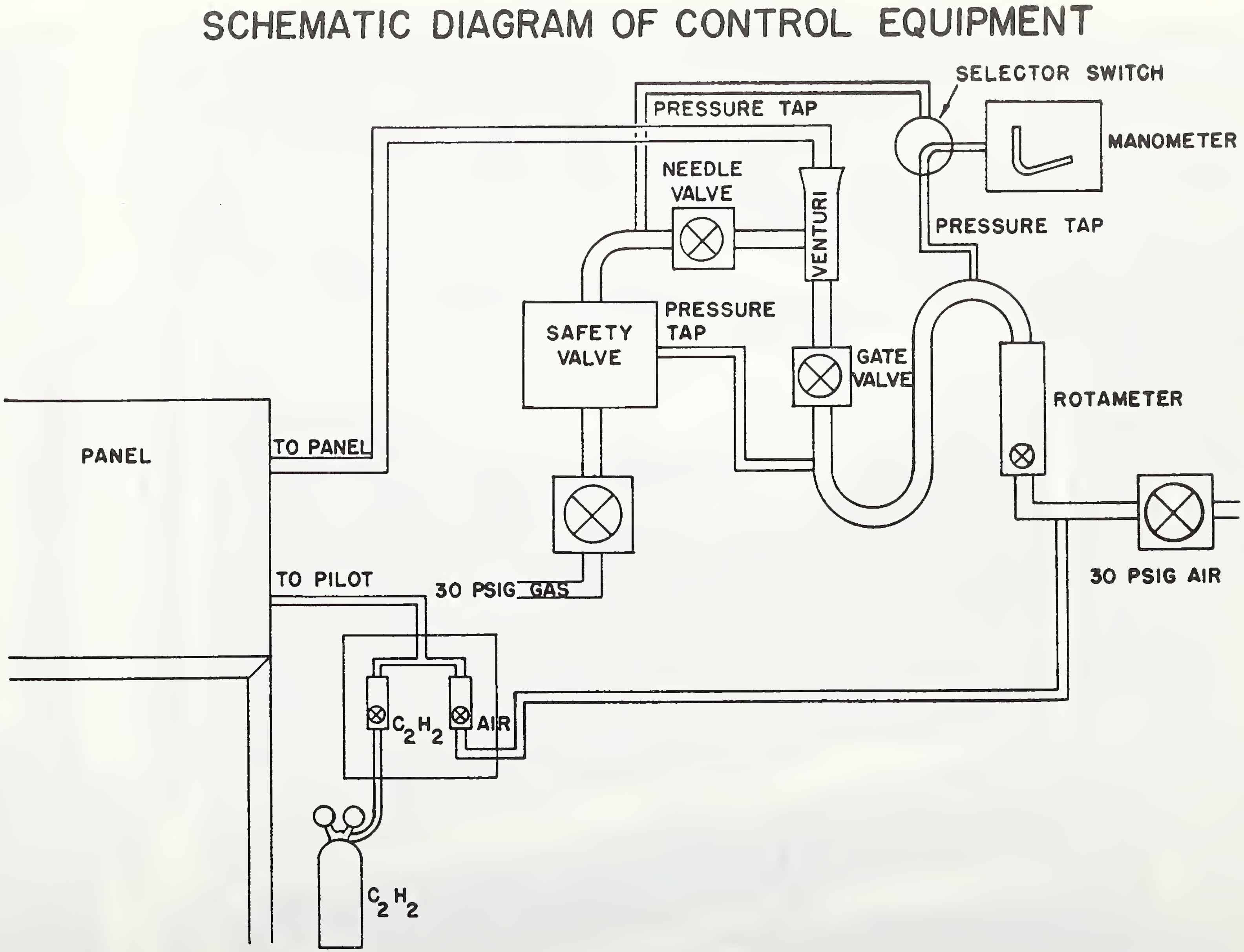

Figure 5. Schematic Diagram of Control Equipment.

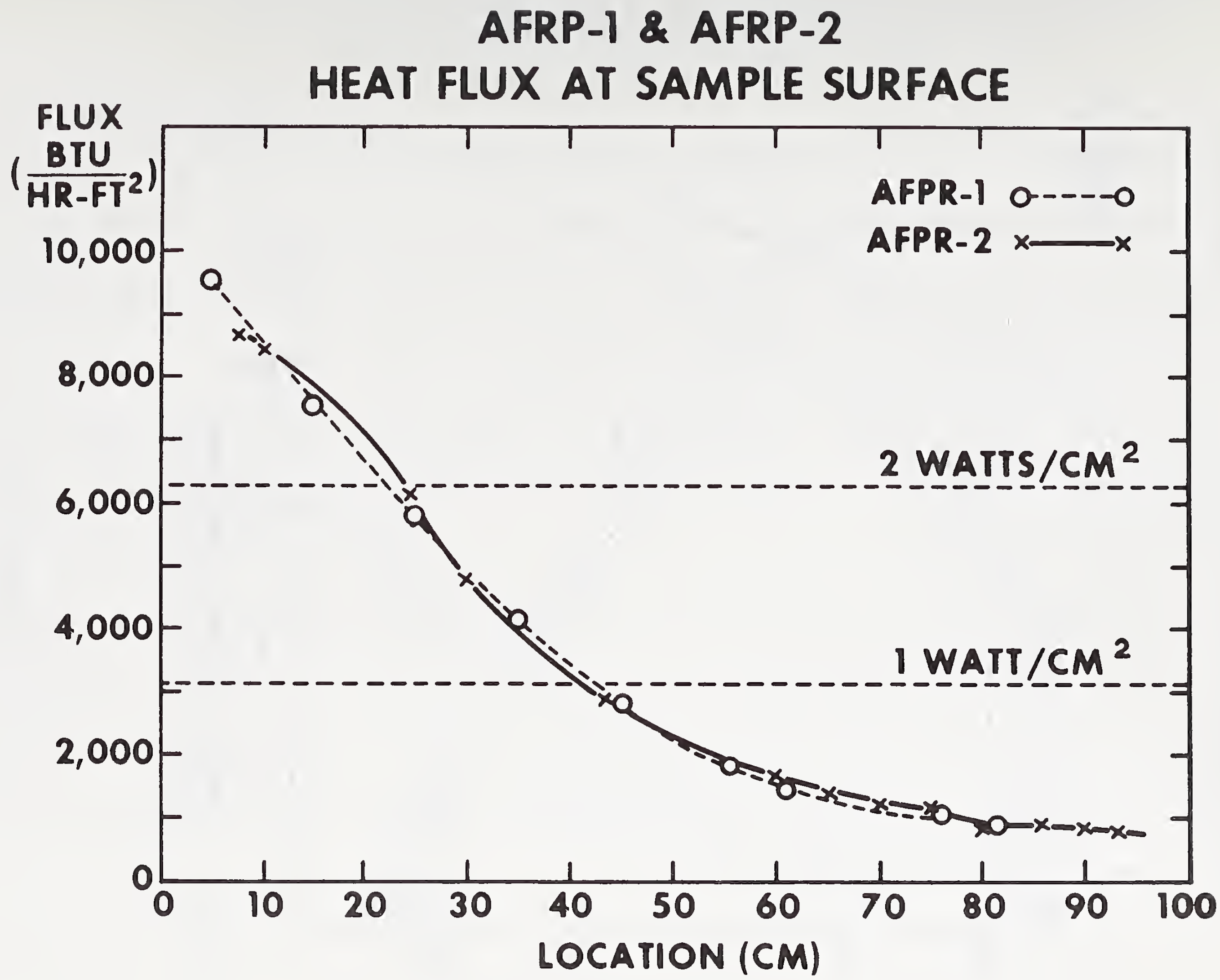

Figure 6. Phase I -- AFRP-1 and AFRP-2 -- Heat Flux at Sample Surface.

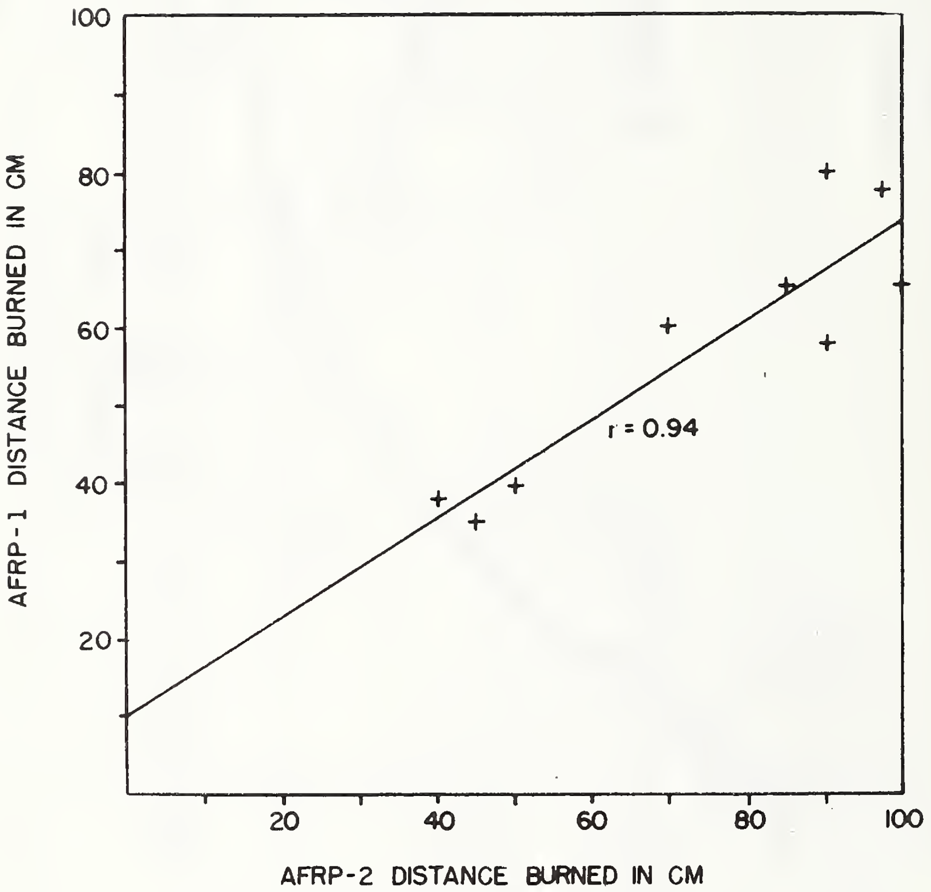

Figure 7. Comparison, AFRP-1 Vs. AFRP-2 (less than 100 only) Least Squares Fit (Correlation Coefficient, r).

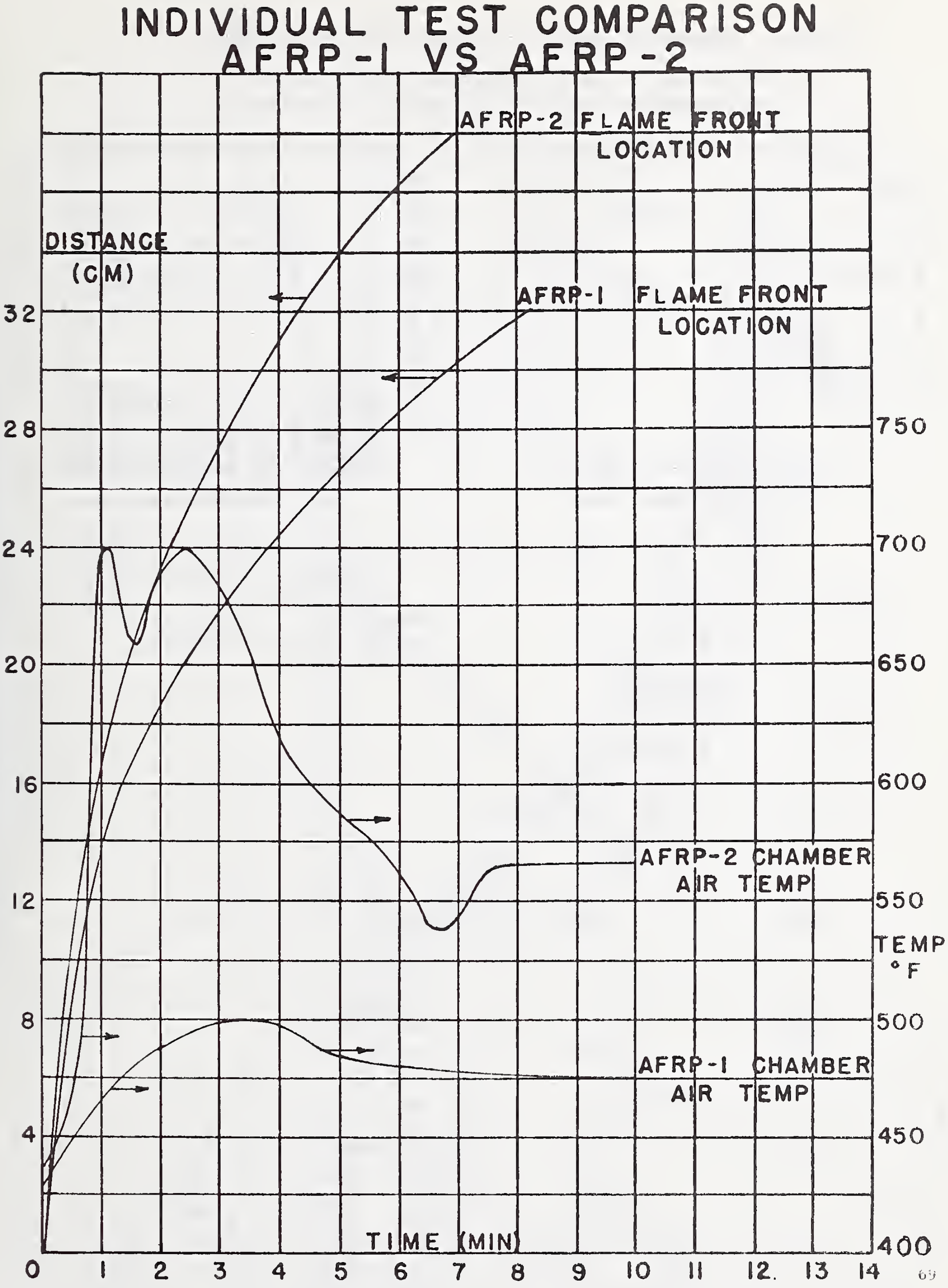

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Figure 8. Phase I -- Individual Test Comparison -- AFRP-1 Vs. AFRP-2.

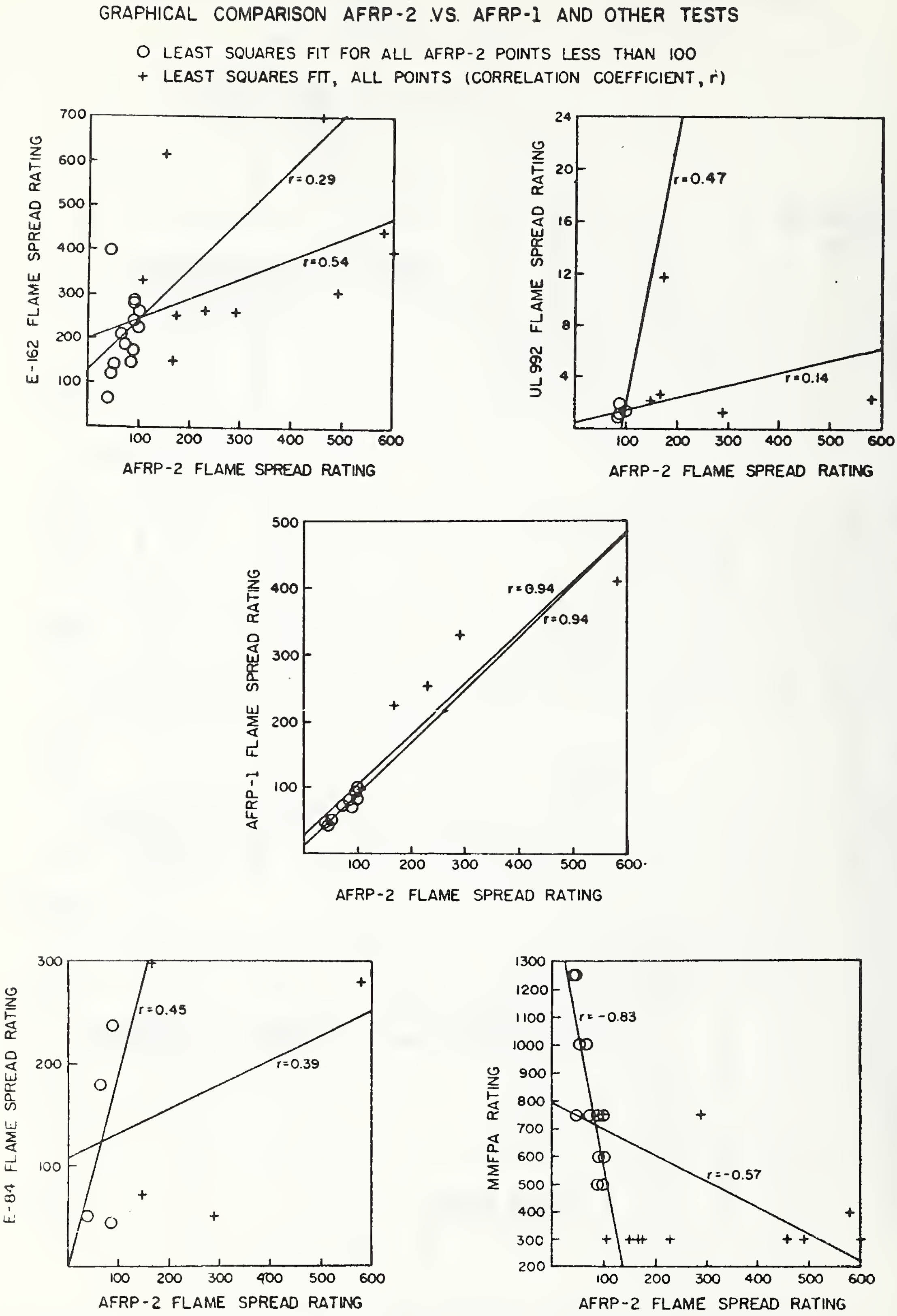


Figure 9. Phase I -- Graphical Comparison -- AFRP-2 Vs. AFRP-1 and other tests.

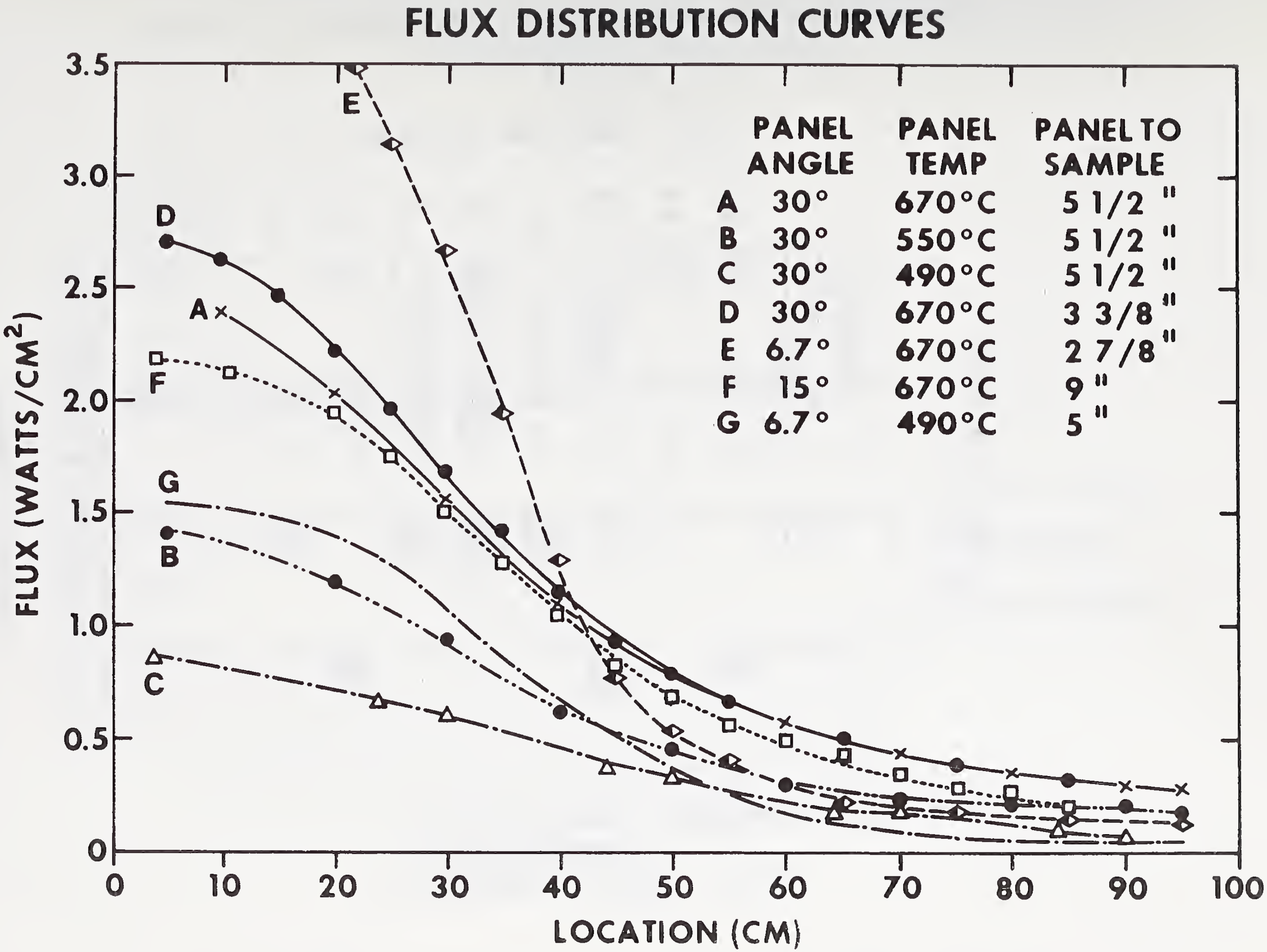


Figure 10. Phase II -- Flux Distribution Curves.

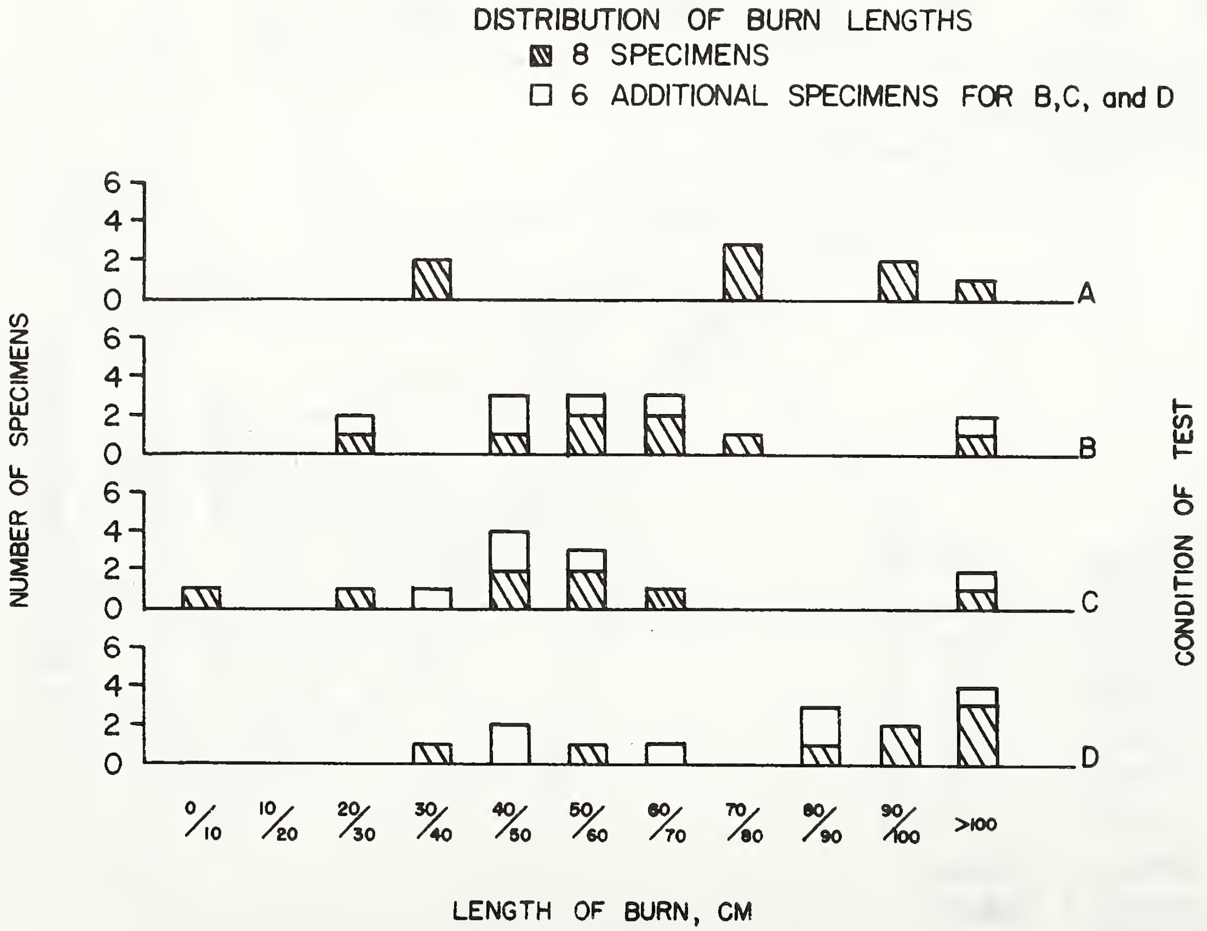


Figure 11. Phase II -- Distribution of Burn Lengths.

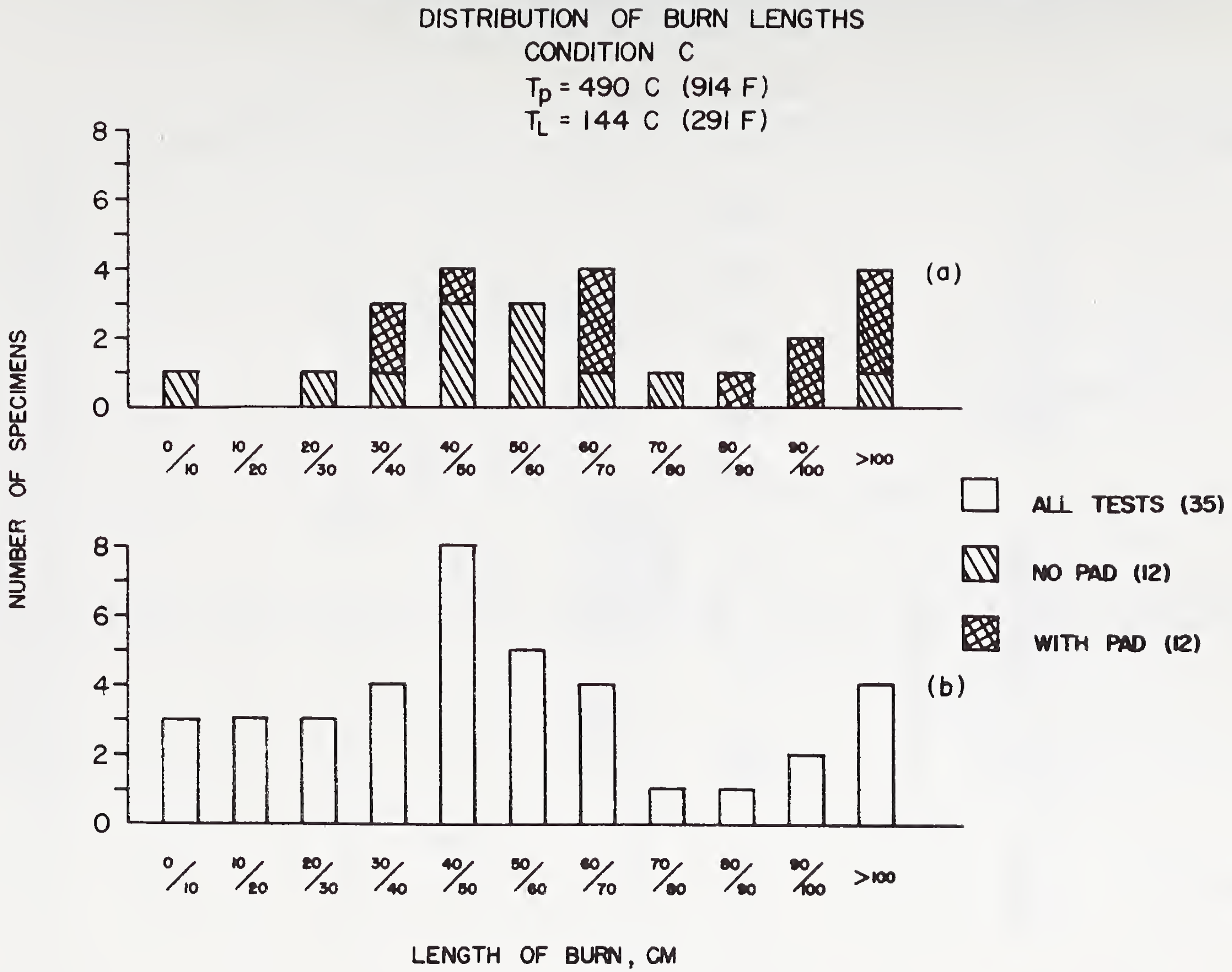


Figure 12. Phase II -- Distribution of Burn Lengths, Condition C.

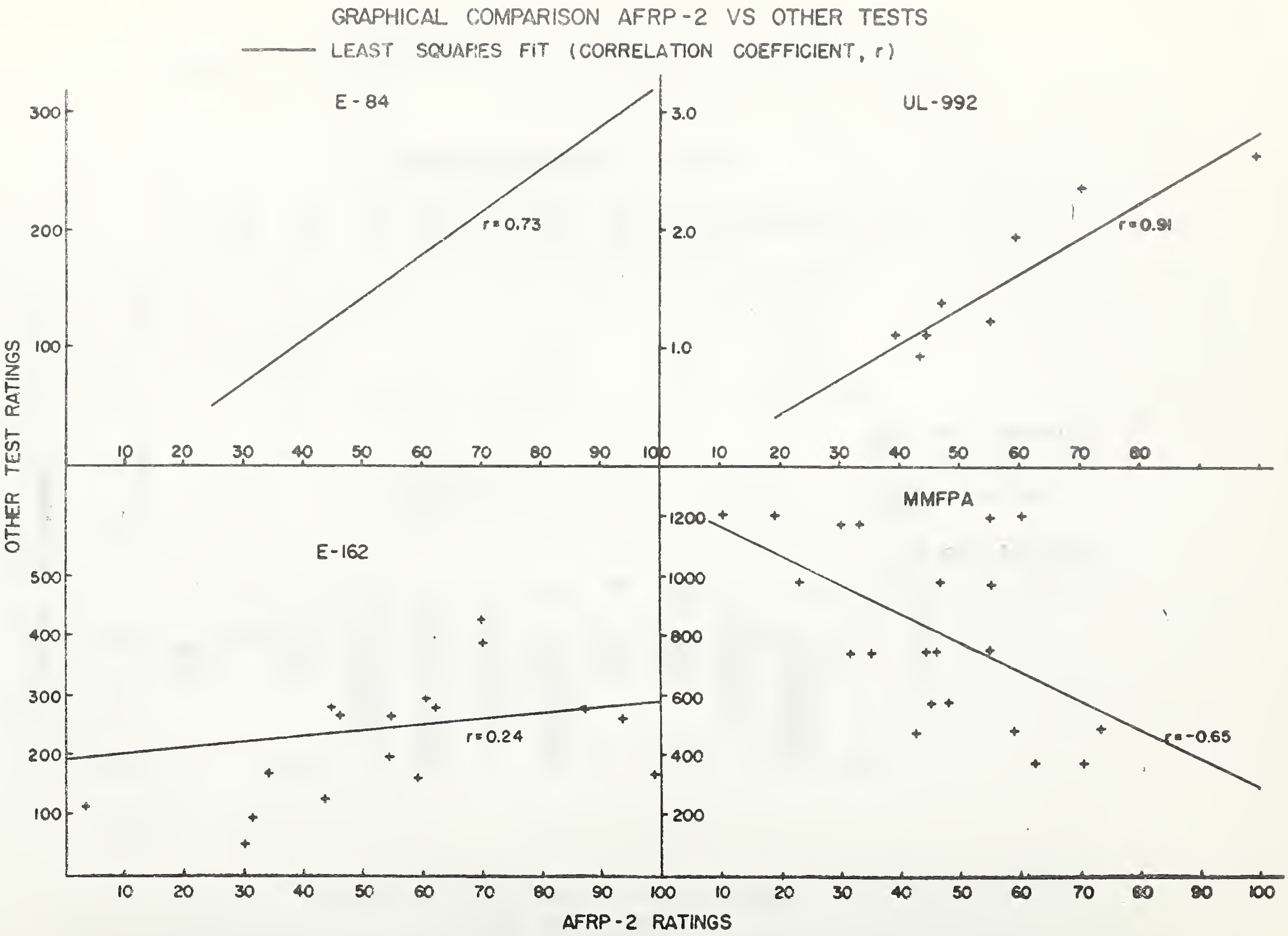


Figure 13. Phase II -- Graphical Comparison -- AFRP-2 Vs. other tests.

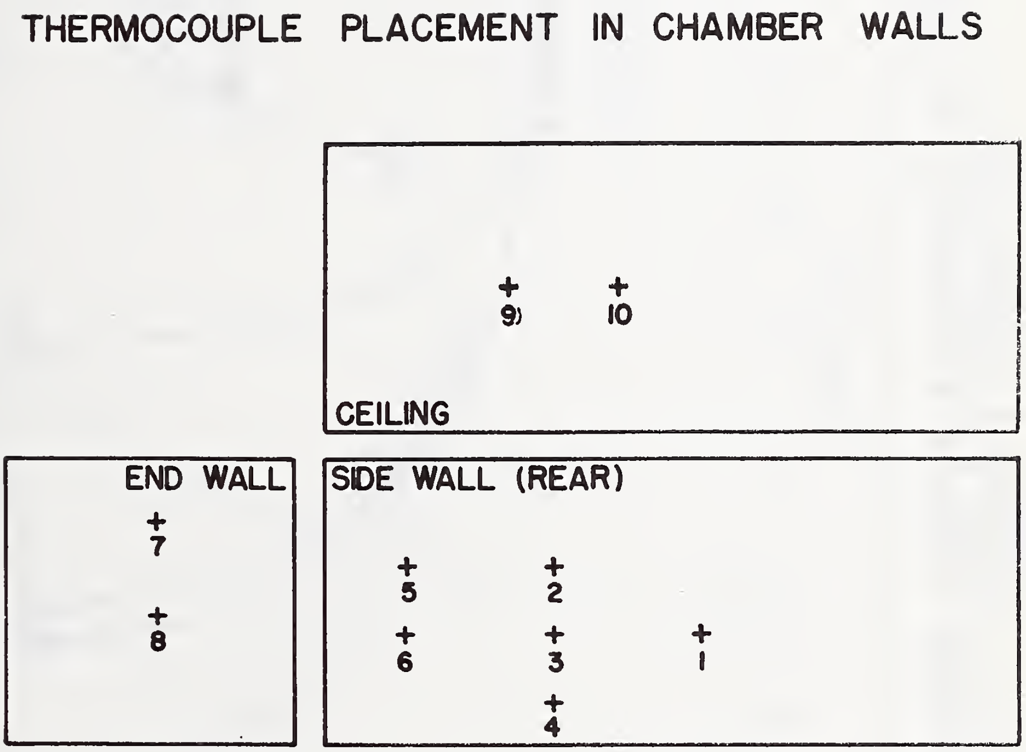


Figure 14. Phase III -- Thermocouple Placement in Chamber Walls.

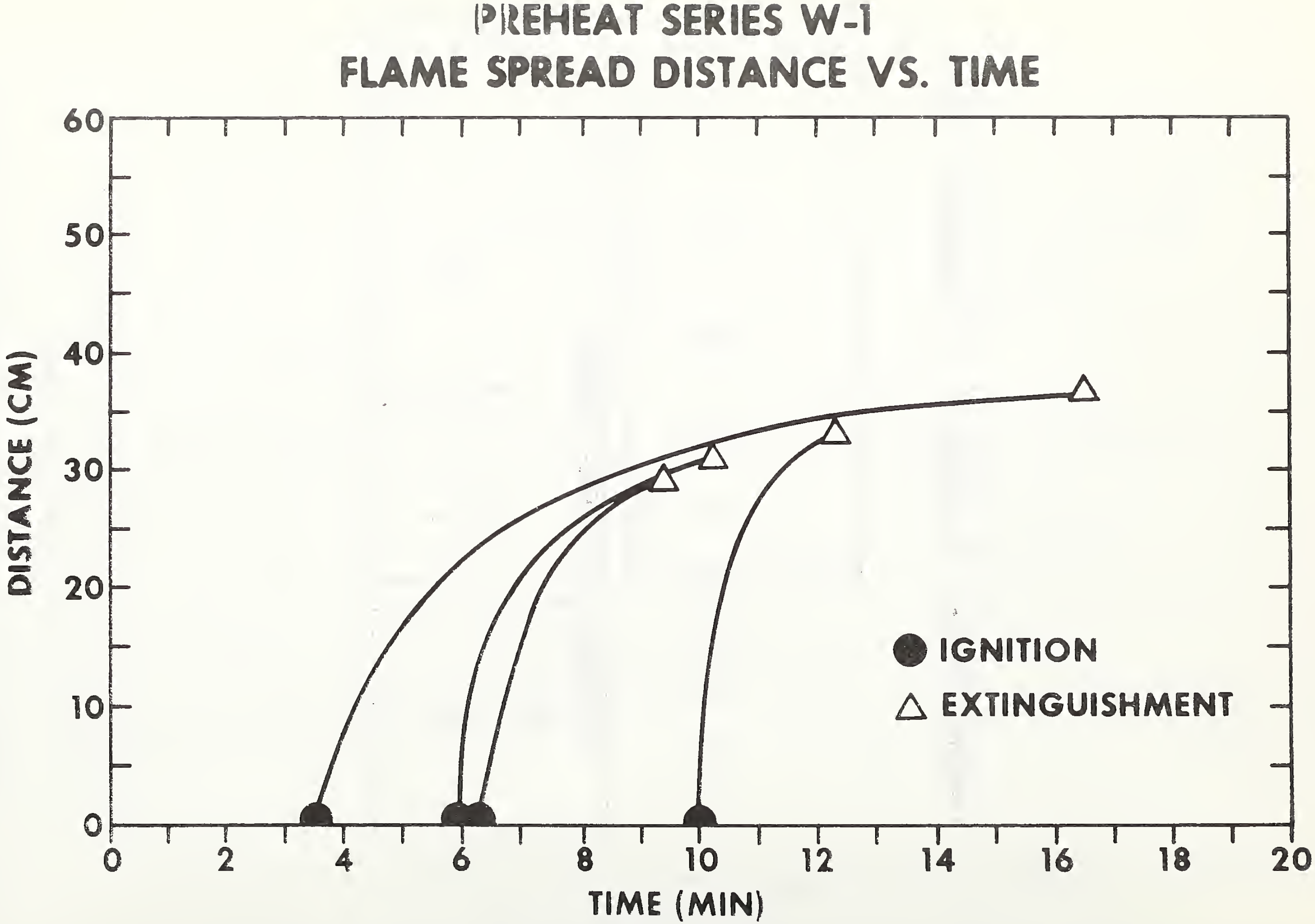


Figure 15. Phase III Part 1 -- Preheat Series W-1 Flame Spread Distance Vs. Time.

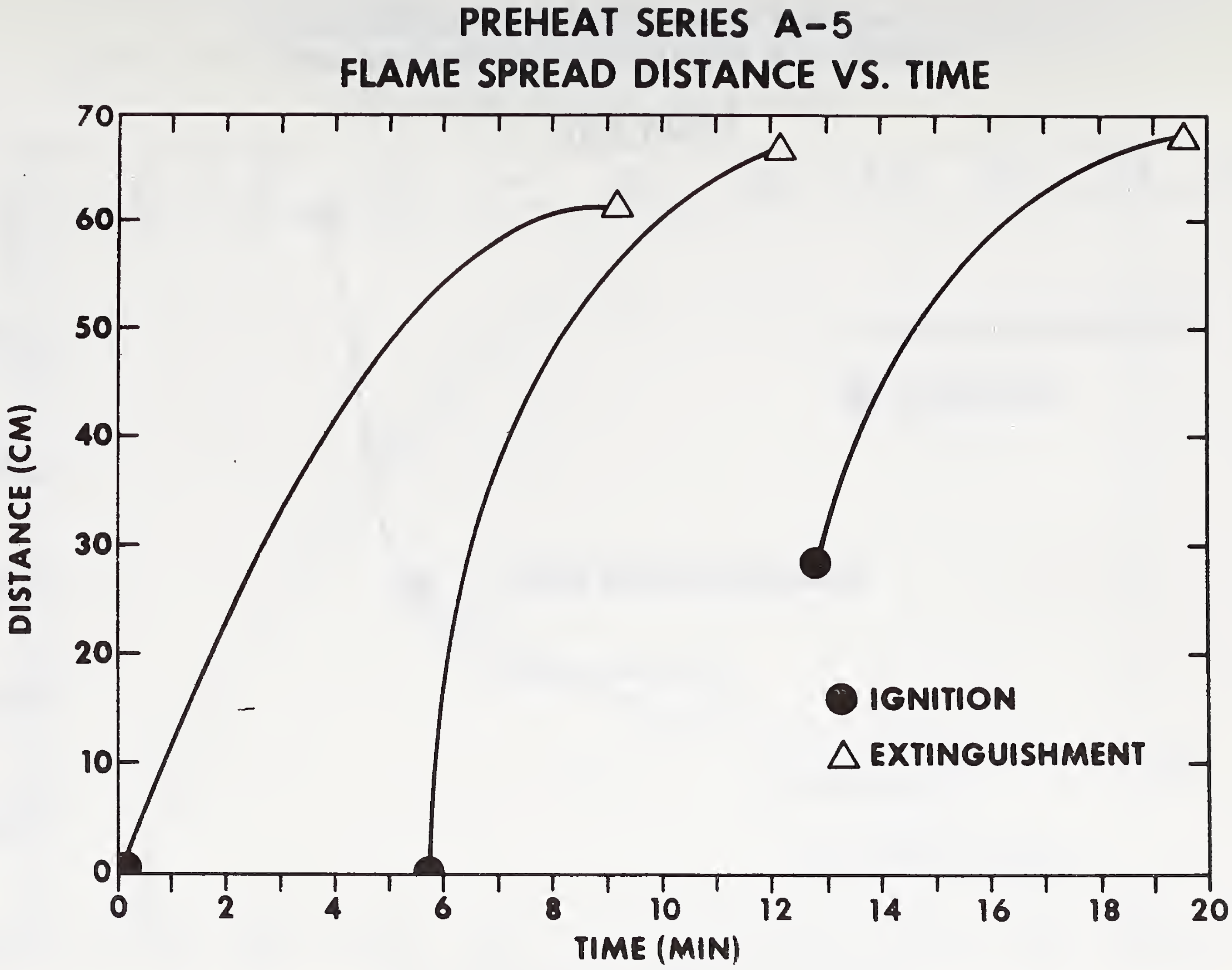
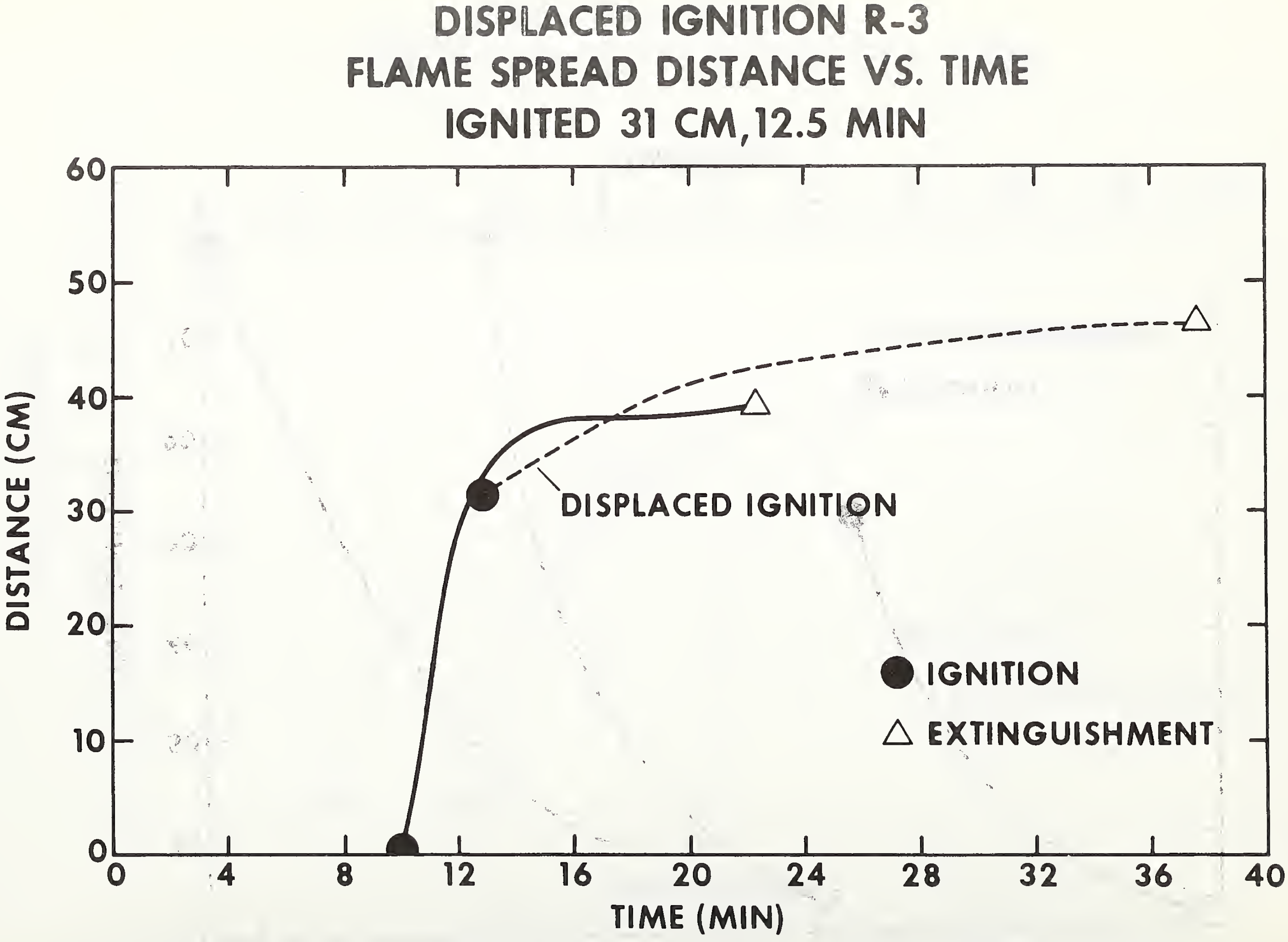


Figure 16. Phase III Part 1 -- Preheat Series A-5 Flame Spread Distance Vs. Time.



DISPLACED IGNITION R-3
FLAME SPREAD DISTANCE VS. TIME
IGNITED 31 CM,12.5 MIN

Figure 17. Phase III Part 2 -- Displaced Ignition R-3 Flame Spread Distance Vs. Time Ignited 31 cm, 12.5 min.

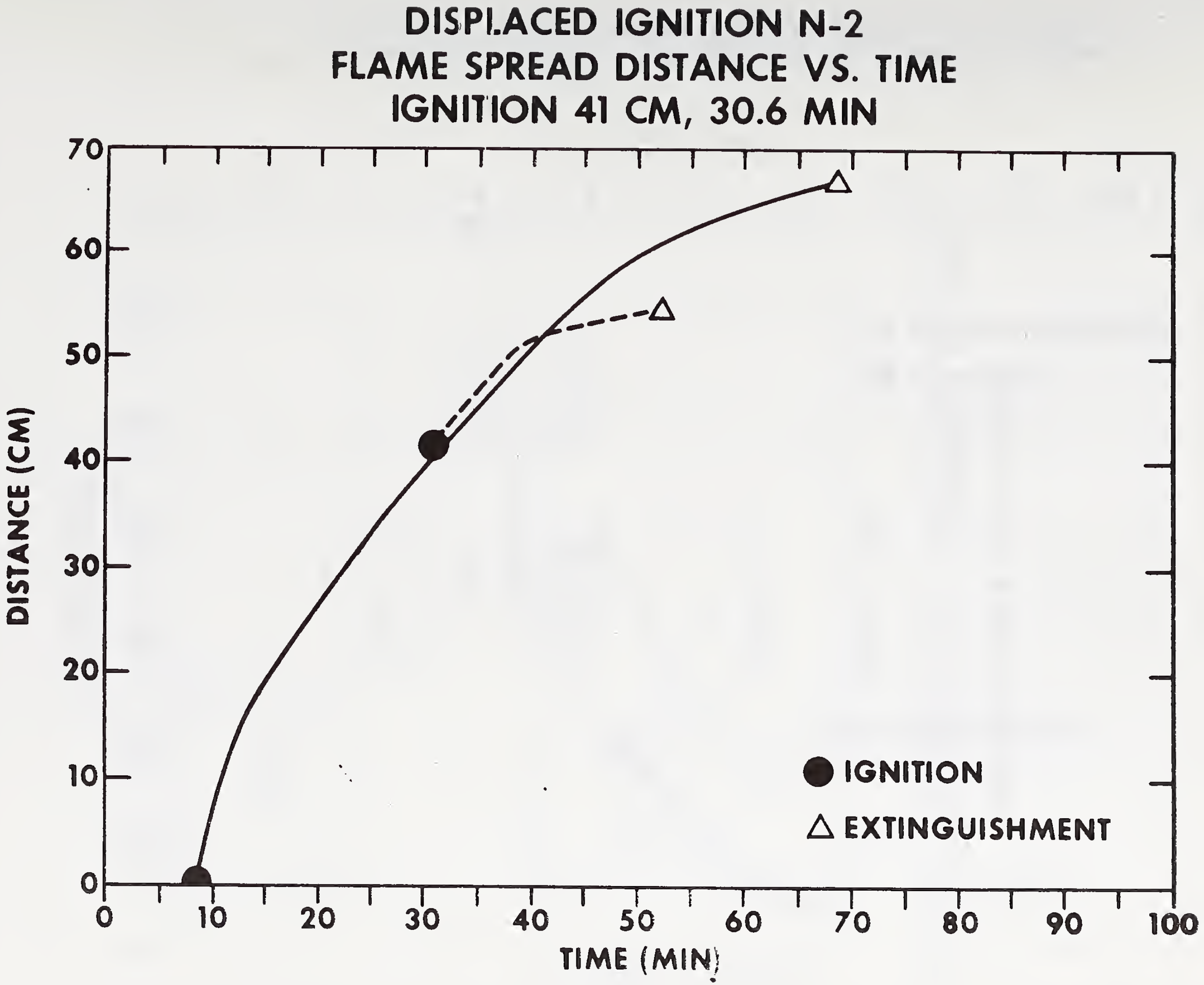


Figure 18. Phase III Part 2 -- Displaced Ignition N-2 Flame Spread Distance Vs. Time Ignition 41 cm, 30.6 min.

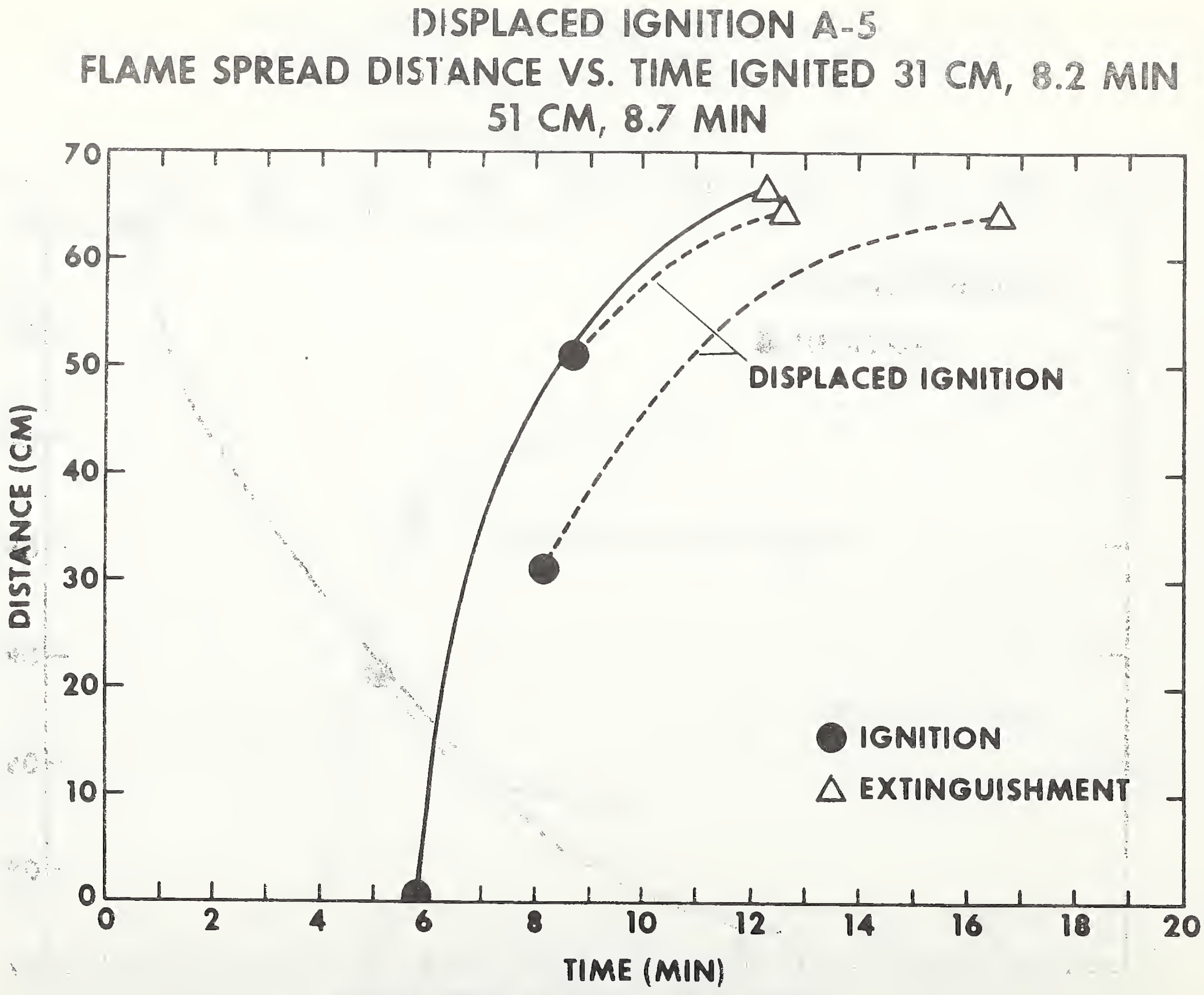


Figure 19. Phase III Part 2 -- Displaced Ignition A-5 Flame Spread Distance Vs. Time Ignited 31 cm, 8.2 min.

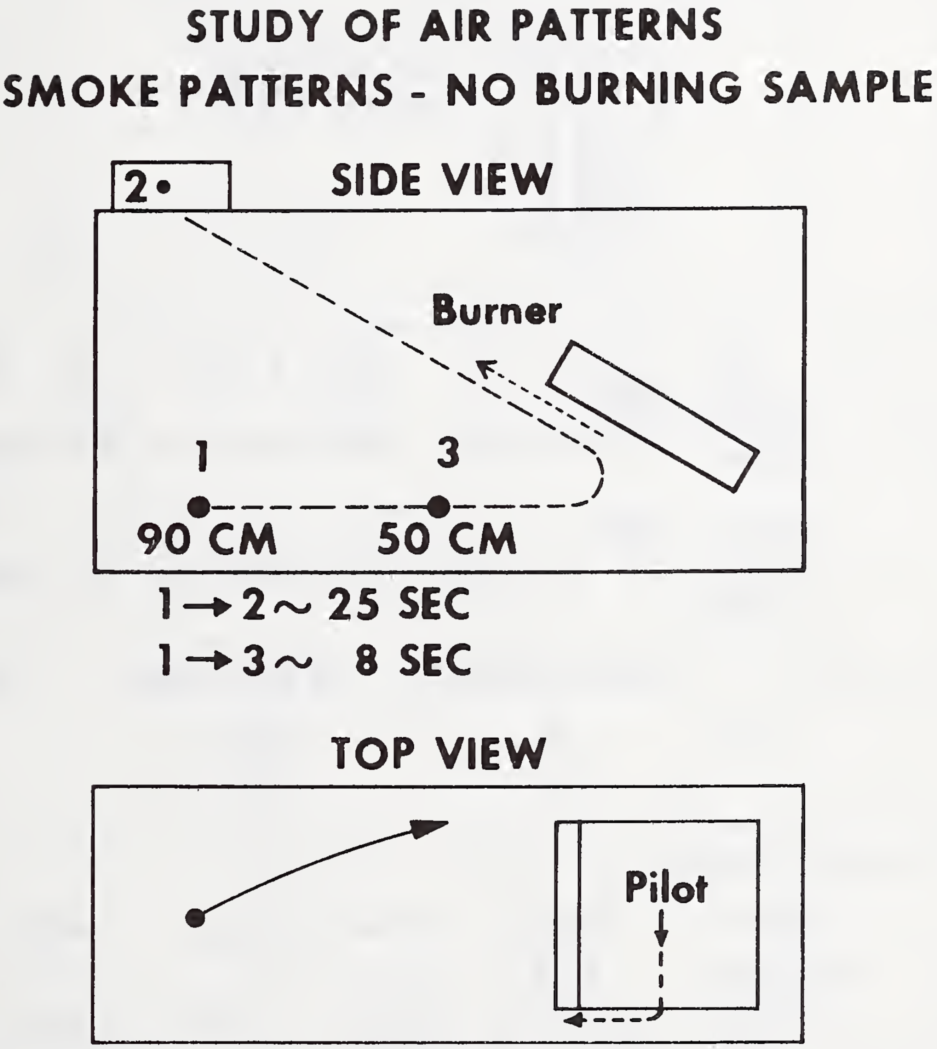
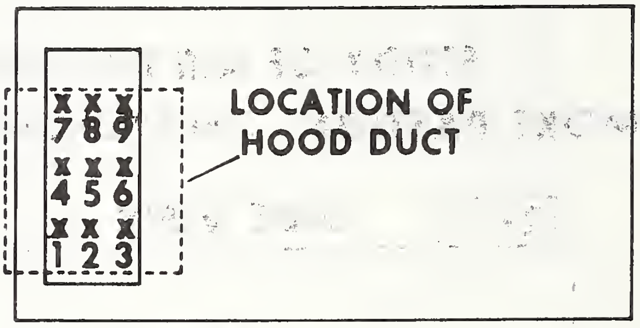


Figure 20. Phase III Part 3 -- Study of Air Patterns Arrows Indicate Flow Directions.

STUDY OF AIR PATTERNS

AIR VELOCITY MEASUREMENTS



TEST		1	2	3	4	5	6	7	8	9	AVE
		FPM									
191	DUCT OPEN	425	380	280	490	600	650	400	200	155	400
		FPM									
192	DUCT PART CLOSED	330	270	250	450	450	550	370	200	230	350

RESULTS	FLAME SPREAD	MAX. TEMP.	MAX. SMOKE
191	58	204°C	.20
192	63	204°C	.24

DURING TEST 191

TIME	–1:00	+0:48	+2:18	+4:30	8:00
VELOCITY (X5)	FPM 450	600	700	600	600

Figure 21. Phase III Part 3 -- Study of Air Patterns Air Velocity Measurements.

STUDY OF AIR PATTERNS

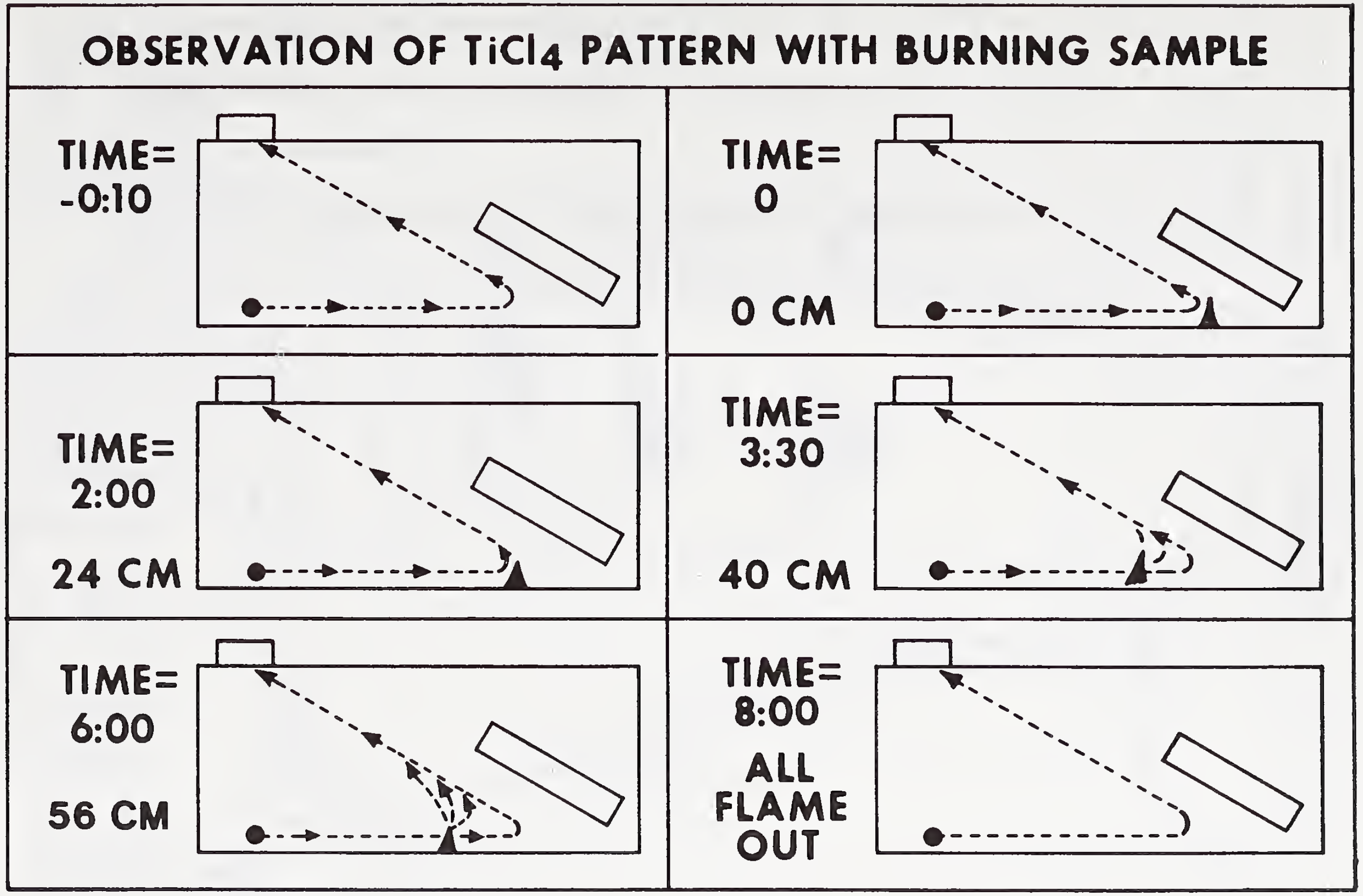


Figure 22. Phase III Part 3 -- Study of Air Patterns Observation of T_iCl_4 Pattern With Burning Sample.

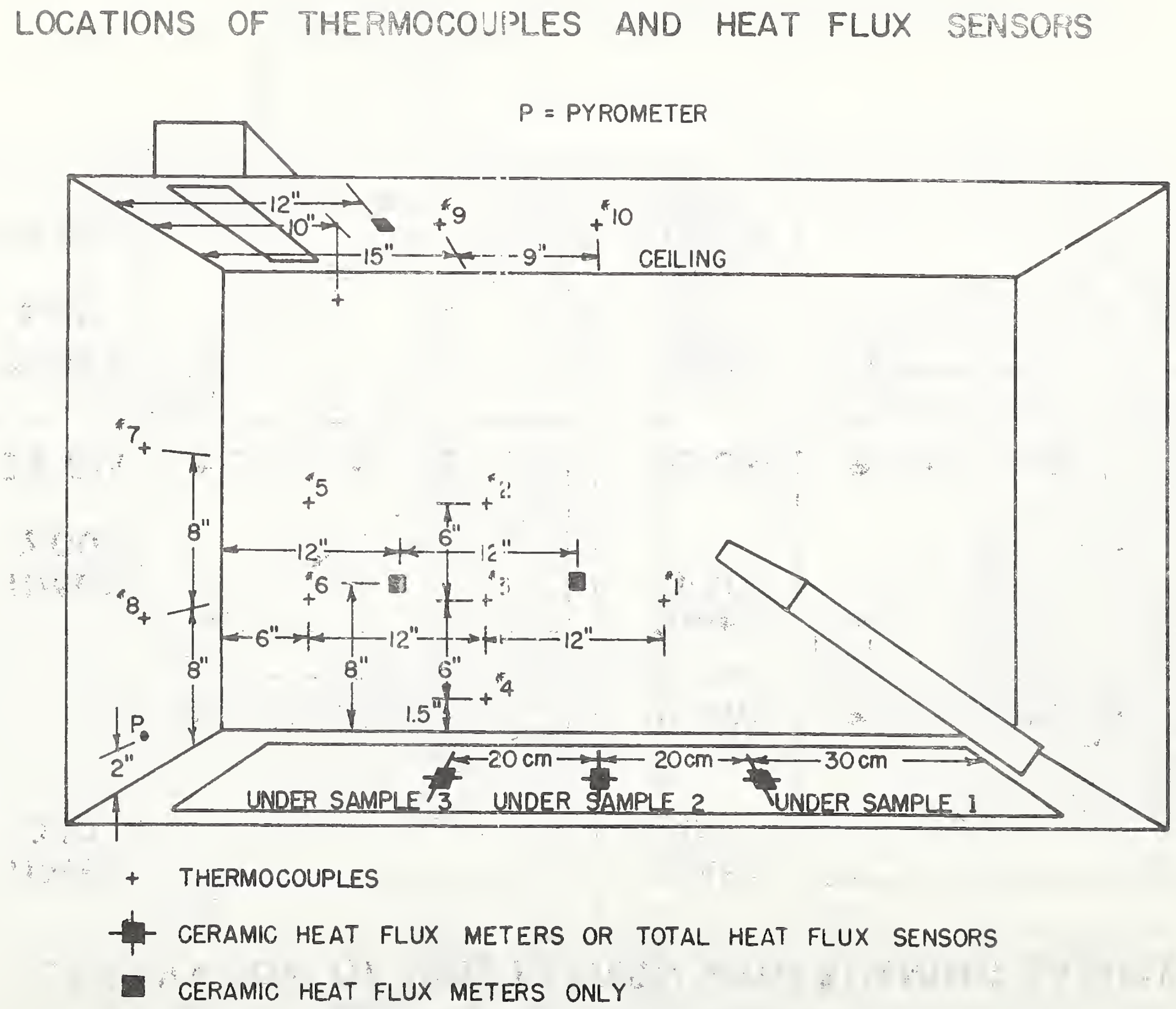


Figure 23. Phase IV -- Locations of Thermocouples and Heat Flux Sensors.

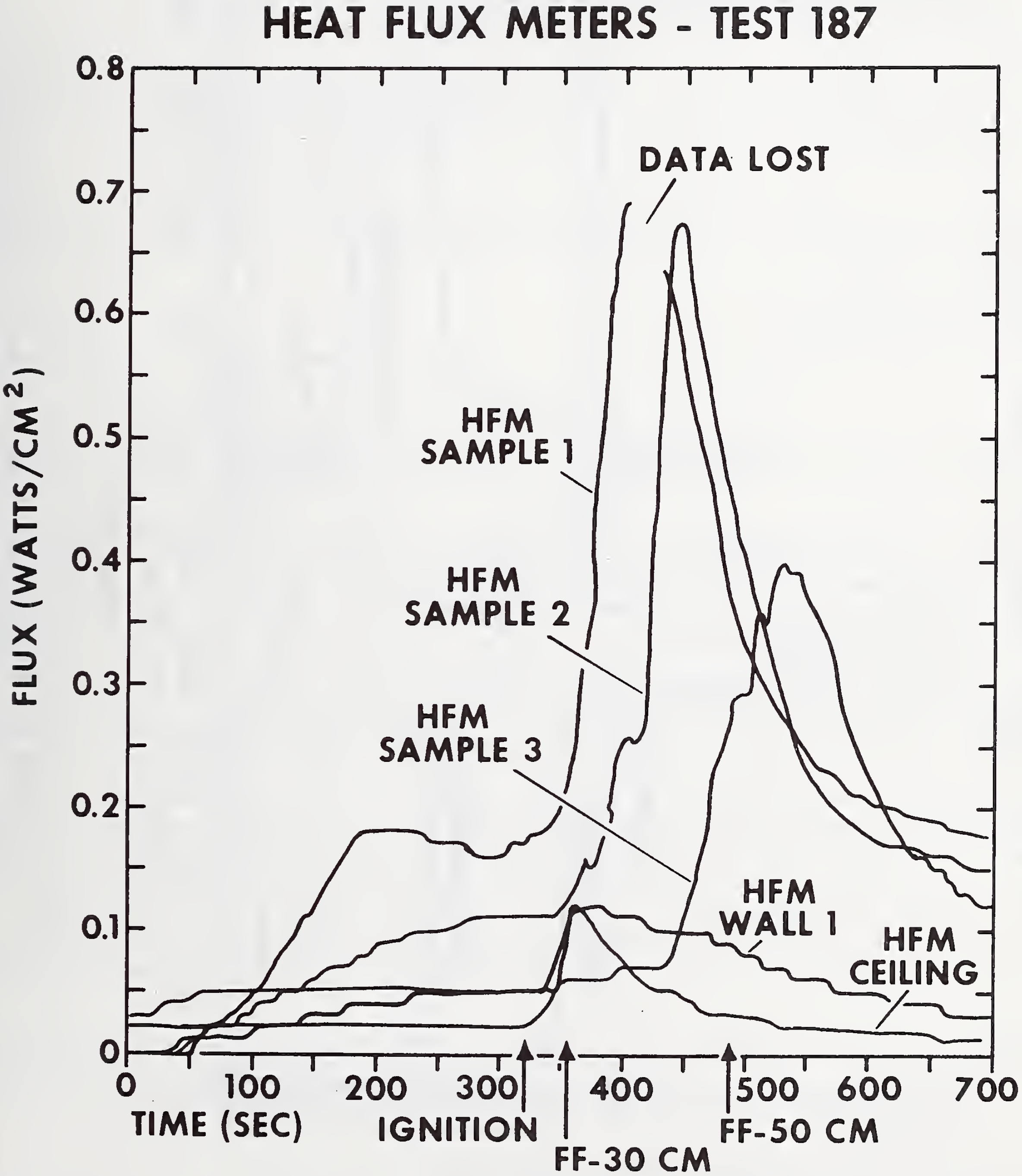


Figure 24. Phase IV -- Heat Flux Meters -- Test 187

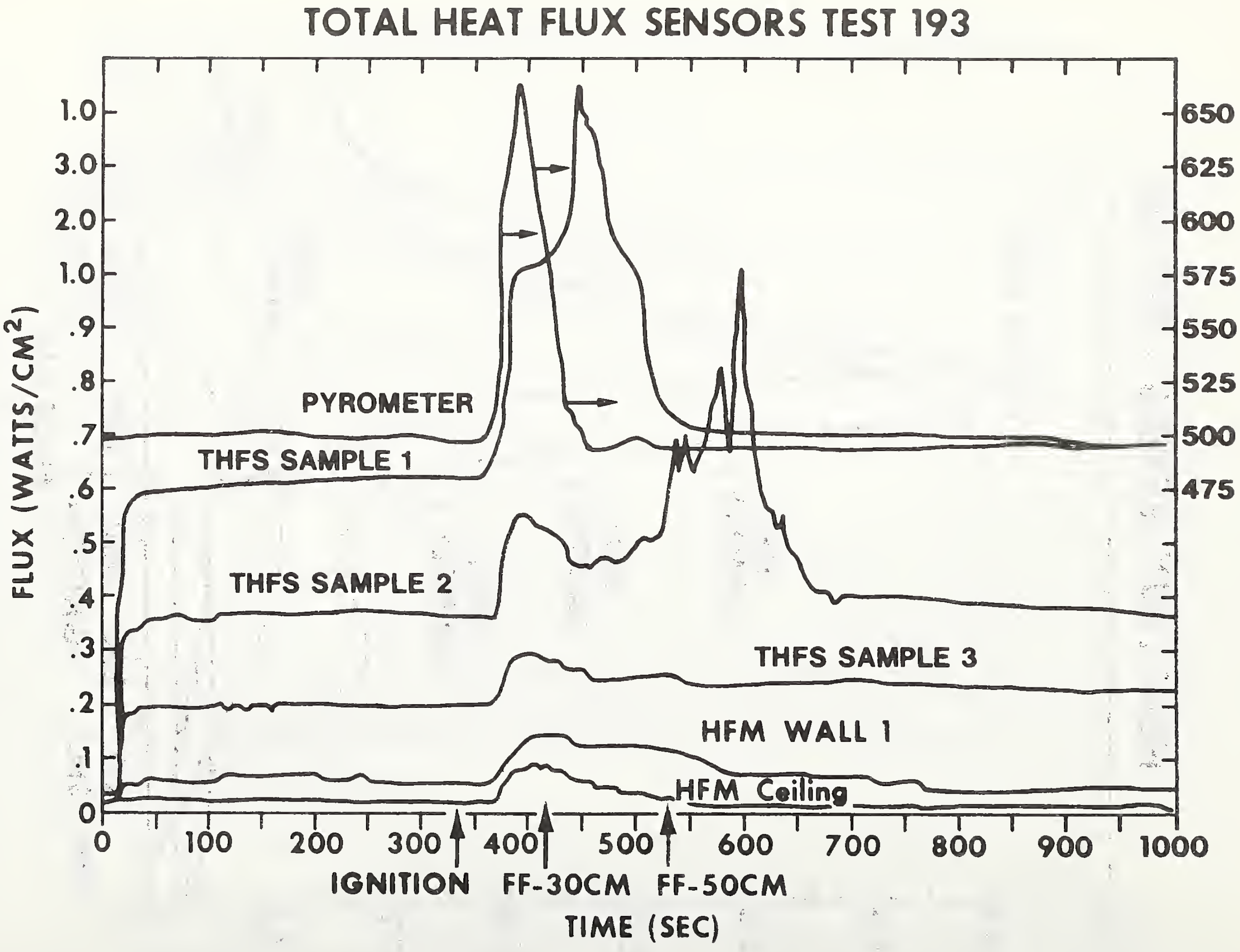


Figure 25. Phase IV -- Total Heat Flux Sensors -- Test 193.

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

This paper summarizes the work of a year long program to continue the development of a radiant panel type test for flooring materials, the original concept of which was developed at the Armstrong Cork Company's Research and Development Center in Lancaster, Pennsylvania. This program at the National Bureau of Standards had as its goal, the further development of the test for possible adoption as a standard ASTM test method.

The program work was divided into five phases. During the first phase, an attempt was made to duplicate the performance of the original apparatus in a similar one at the National Bureau of Standards Laboratory. The proof of this duplication was shown in replicate testing using a wide range of flooring on both apparati.

In the second phase of the program, a new set of test conditions were found in an attempt to eliminate some of the more serious equipment and procedural problems of the test. These new conditions provided the test with the ability to rate flooring materials according to their ability to resist the surface spread flames.

Under the third and fourth phases of the program, the effects of changes in some test parameters was investigated and other test characteristics were measured. Phase V, the data analysis and report, concluded the program.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Carpet; fire test; flammability; flooring; heat flux; ignition; radiant panel.

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