NIST IR 7471

Analysis of Inter-laboratory Testing of Non-loadbearing Gypsum/Steel-Stud Wall Assemblies

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December 2007

U.S. Department of Commerce
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ABSTRACT

This report summarizes the results of a test program conducted in 2006 and 2007 by the North American Fire Testing Laboratories (NAFTL) consortium. Gypsum/steel-stud wall assemblies, nominally rated at 1-h, were tested by six different organizations in North America employing ten different furnace facilities following the guidance provided in ASTM E119-00. The participating NAFTL laboratories arrived at an identical 1-h rating for the gypsum wall specimen tested according to their respective standard operating protocols. The average time to failure (defined by the temperatures reached on the unexposed side of the specimen) was 65 ± 2.8 minutes. The variability in individual peak thermocouple temperatures measured at similar locations on the different wall assemblies exceeded ± 50 ^{o}F around one hour into the test, and reached a maximum of close to ± 150 ^{o}F at the average time of failure. Differences in the time to failure for the ten close-to-identical wall assembly tests did not correlate at a statistically significant level with differences in average furnace temperature, the temperature-time integral, changes in ambient temperatures, or standard deviation among the furnace control thermocouple temperatures. Six inter-laboratory tests were also conducted by several Japanese organizations, yielding an average time to failure of 67.1 ± 1.1 minutes. The inter-laboratory program described in this report is the largest ever conducted for fire resistance testing and forms the basis for future programs aimed at testing additional structural materials, elements, and systems subjected to fire test standards referenced in building codes.

ACKNOWLEDGEMENTS

The authors acknowledge the essential contributions made by each of the North American laboratories who conducted the fire resistance tests for the wall assembly: Intertek, Underwriters Laboratories (UL), Southwest Research Institute (SwRI), NGC Testing Services, Western Fire Center, National Research Council of Canada (NRC-C), and U.S. Gypsum (USG). The authors would also like to acknowledge the participating Japanese laboratories: Center for Better Living, Japan Testing Center For Construction Materials, General Building Research Corporation of Japan, Japan Housing and Wood Technology Center, and Foundation Test Laboratory. U.S. Gypsum supplied 100 % of the gypsum board, created in a special factory run to ensure tight quality control. Western Fire Center is acknowledged for handling and shipping the gypsum board to the different laboratories, including to the participants in Japan. The assistance of the American Council of Independent Laboratories (ACIL) was essential to maintain the anonymity of the test results. Mr. Dale Bentz of NIST assisted with the thermal property measurements.

POLICY OF NIST REGARDING THE INTERNATIONAL SYSTEM OF UNITS

The policy of NIST is to use the International System of Units (metric units) in all publications. In this document, however, units are presented in metric units or the inch-pound system, whichever is prevalent to the discipline.

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LIST OF ACRONYMS

ACIL	American Council of Independent Laboratories
ATF	Bureau of Alcohol, Tobacco, Firearms and Explosives
ASTM	American Society for Testing and Materials
DSC	Differential Scanning Calorimeter
FM	Factory Mutual
ISO	International Organization for Standardization
NAFTL	North American Fire Testing Laboratories Organization
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NRC-C	National Research Council - Canada
SwRI	Southwest Research Institute
TC	Thermocouple
UL	Underwriters Laboratories

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BACKGROUND

In the aftermath of the World Trade Center collapse, a possible building code requirement that highrise structures withstand a complete burnout is being discussed in the U.S. Compartmentation and the integrity of bearing and non-bearing walls play a role in the severity and rate of spread of the fire, and thus the fate of the structure in a burnout scenario.

The ability of a structural element or system to withstand a fire is rated by subjecting the element, or a representative section of the system, to the heat of a furnace. Wall systems approximately 10 ft by 10 ft in area are evaluated by mounting them in a fixture and exposing them to a flame in a furnace with a prescribed temperature rise. ASTM E 119-00: *Standard Test Methods for Fire Tests of Building Construction Materials* is often cited in the U.S. model building codes; NFPA 251 and UL 263 are equivalent test methods. ISO 834-1 is the similar international standard, although it is never used in U.S. construction. Details on these and other test methods used to characterize the fire resistance of walls and other building elements are reviewed elsewhere (*e.g.*, Grosshandler, 2002; Grosshandler, 2006). While there are some differences among the test protocols, the general procedures and many of the measurements prescribed in all four test methods are similar.

The fire resistance of the wall assembly in an actual building fire is assumed to be related to the length of time necessary for the test specimen to meet any one of several failure criteria:

- The maximum temperature increase on the unexposed side of the wall exceeds 325 ^{o}F;
- The average temperature increase on the unexposed side of the wall exceeds 250 ^{o}F;
- A breach occurs in the wall that allows hot gases from the furnace to penetrate and ignite a cotton target on the unexposed side of the wall; or
- The wall is unable to maintain its design load.

The fire resistance rating of the wall system is defined as the time (to the next lowest half-hour increment for times up to two hours, and to the next lowest hour for longer times) when any of the criteria indicated are exceeded. It is expected that a 2-h rated wall would resist failure in a real fire for a longer period of time than a similarly functioning 1-h rated wall, and this is invariably the case. What can not be expected, however, is that a 2-h rated wall would necessarily withstand an actual fire in a building for two hours, or that the wall would necessarily fail after two hours. The inability of the fire resistance rating to act as an absolute predictor of performance in an actual fire was recognized from the beginning when the forerunner of ASTM E119 was published in 1918. Over the years, however, the reference to fire resistance ratings in common time units has become erroneously interpreted to relate closely (or at least conservatively) to the actual time that a wall would be expected to resist a fire.

The shortcomings of the current methods for rating the fire resistance of wall systems are numerous; some are obvious and have been recognized for years:

- The maximum size of the wall system is limited by the size of the furnace.
- The load conditions for the test article may not adequately mimic field use.
- The thermal environment of the furnace does not mimic a real fire.
- The tests reveal no fundamental information about the performance of the specimen and provide little guidance on how to improve performance.
- The furnaces themselves are not standardized; hence, the same specimen could receive different ratings if tested in two different facilities.
- Ratings are based upon a single test, with no way to quantify the uncertainty or safety factor.

In spite of severe shortcomings, these test methods continue to be used throughout the world because (i) a massive data base has been established and is in continual use, (ii) history suggests that the test methods are conservative, and (iii) alternative methods have not been developed yet that are acceptable to the major parties involved.

NAFTL TEST PROGRAM

Designing structures to withstand the hazard posed by an unconfined building fire requires that standard fire resistance tests be reliable and consistent, independent of the laboratory performing the test. Ascertaining the consistency of testing in North America is the focus of this report.

North American Fire Testing Laboratories Consortium[1]

The North American Fire Testing Laboratories (NAFTL) consortium was formed in 2004 to provide a forum for the exchange of technical information, to conduct studies, and to develop industry consensus positions relating to the full range of fire tests; e.g., reaction to fire, fire suppression, fire resistance and fire detection. The organization is open to any North American-based independent commercial laboratory engaged in fire testing or research. Current members include Southwest Research Institute (SwRI), Underwriters Laboratories (UL); FM Approvals, Intertek, NGC Testing Services, and Western Fire Center. The National Institute of Standards and Technology (NIST), the National Research Council of Canada (NRC-C), and the Fire Testing Laboratory of the Bureau of Alcohol, Tobacco, and Firearms (ATF) are non-voting associate members of NAFTL.

The operations of the member laboratories of NAFTL are certified according to ISO 17025, *General Requirements for the Competence of Testing and Calibration Laboratories*. As part of the certification process, organizations must demonstrate to a certifying body that they are proficient in conducting fire testing services offered to their customers, a task which is difficult for a test like ASTM E119. For this reason, and to gain a better understanding of the test itself as a means to overcome the shortcomings previously enumerated, NAFTL organized a test program for ASTM E119-00 using a common structural element: a gypsum/steel-stud wall assembly.

[1] http://www.naftl.org/

Participants and Objectives

A total of ten different laboratories representing seven different organizations participated in the test program. They included Intertek, UL, SwRI, NGC Testing Services, Western Fire Center, NRC-C, and U.S. Gypsum. All of these laboratories routinely operate large-scale furnaces that rate the fire resistance of structural elements such as building partitions and non-load-bearing walls. In addition, several Japanese organizations conducted their own inter-laboratory testing using the identical materials and wall design as used by NAFTL. The results of the Japanese program are presented in the appendix.

The guidance provided in ASTM E119-00 is imprecise with regard to the details on the design of the testing furnace, and the guidance allows some leeway in how the sample is to be prepared and instrumented, as well as the way the test is to be conducted. Thus, it is not surprising that different laboratories develop different standard operation procedures that are still within the constraints of the prescribed test method. In addition, the dimensions and materials used in constructing the test article often differ, and may not be within the control of the fire testing laboratory. When differences in ratings occur of ostensibly the same test article, it is not possible to discern whether the cause of the difference is the test article itself, the differences in furnace design and instrumentation, or the differences in operational procedures. In order to assess these differences and how they might lead to uncertainty in the fire resistance rating of a product, proficiency testing is necessary using a standardized product, with the results of the testing accumulated and analyzed by a qualified independent party.

The objective of the current testing program is to compare the behavior of different vertical furnaces and identify operational parameters that influence the performance of a generic non-load-bearing wall assembly undergoing an ASTM E119-00 resistance to fire test. The testing was conducted in accordance with the standard operating protocol of each participant.

The data from each test were collected in a common format and sent to the American Council of Independent Laboratories (ACIL), who acts as the secretariat for NAFTL. ACIL removed all identifying information from the data and delivered it to NIST, who was the qualified independent party responsible for analyzing and reporting the data.

The outcome from this test program is being used by the participating organizations to assess the relative performance of their furnaces. The data collected are also being used by NIST to help develop the needed relationship between furnace behavior and actual fires.

TEST PROCEDURES

Wall Assembly Description

The wall assembly was designed to be non-load bearing, nominally 1-h fire resistance rated, and consisting of a 5/8 inch thick type X gypsum board (ASTM C1396), 10 ft by 10 ft with taped, staggered vertical seams, on each side of steel studs located on 16 inch centers. The geometry of the wall specimen is shown in Fig. 1. The gypsum board was obtained by the individual laboratories in a single lot from the manufacturer since it was desired to have as little variation as possible in the test specimen. All laboratories used steel studs (25 gauge) and fasteners (1 ¼ in long Type S drywall screws) obtained from a single supplier.

The wall assembly was instrumented according to the provisions in ASTM E119-00. Additional thermocouples (type K) were located as indicated in Fig. 1 to measure the temperature within the wall cavity. The walls were constructed using each laboratories' established practice. Figure 2 shows a wall specimen being assembled.

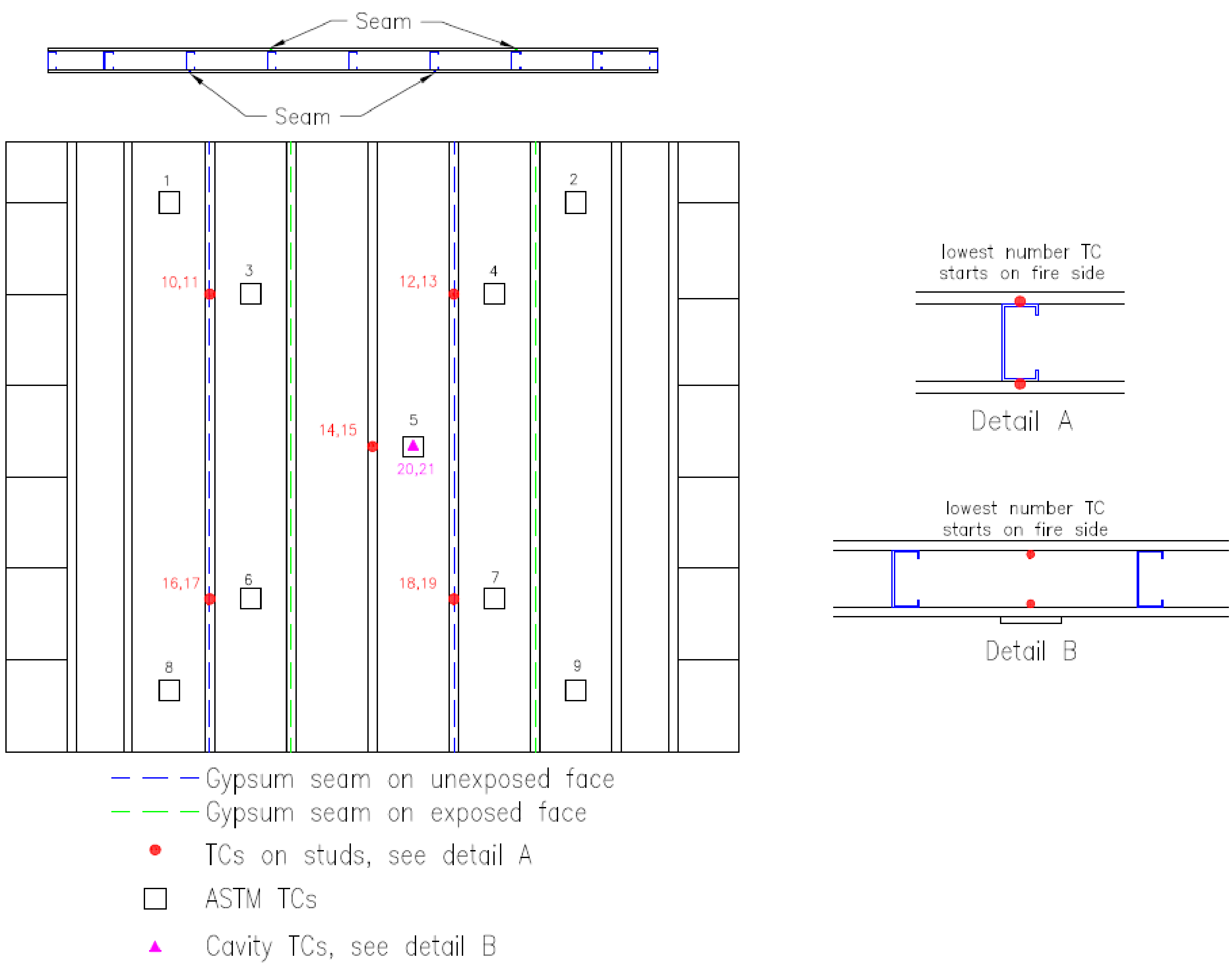

Figure 1. Gypsum/steel-stud wall assembly and location of thermocouples

Figure 2. Wall specimen being constructed

<u>Properties of Gypsum Board</u>

The properties of gypsum board can vary, even if extra care is taken by the manufacturer and the board is all cut from a single run. Because the performance of the wall assembly depends upon the thermal and physical properties of the gypsum board, the total weight and density of each specimen was recorded by the individual testing laboratory. Based upon the results obtained from each test laboratory, the room temperature density of the gypsum board was 47.40 lb/ft^3 ± 0.37 lb/ft^3 (mean ± standard deviation). For comparison, the density of the gypsum board samples used in the NAFTL series were also determined at NIST based upon measurements of the dimension and mass of individual 6 inch by 6 inch gypsum board samples. The measured density was 47.45 lb/ft^3 ± 0.47 lb/ft^3. The results obtained by NIST are in good agreement with those obtained by the test laboratories.

In addition to determining the room temperature density, measurements were performed using the Hot Disk Thermal Constants Analyzer® (TPS 2500) to determine the room temperature thermal conductivity and specific heat of representative samples of gypsum board. The Hot Disk determines thermal properties using the transient plane source technique (TPS). As the Hot Disk provides the volumetric heat capacity, the room temperature density was used to determine the specific heat on a mass basis. The sizes of the gypsum board samples used were 6 inches by 6 inches. These measurements were performed with the paper in place and with the paper removed from the gypsum board samples. For the paper in place, experiments were conducted with the brown paper side in contact with the probe as well as the grey paper side in contact with the probe. The results are summarized in Table 1; the uncertainty in these results is ± 10 %. The uncertainty is dependent upon material variability as well as the uncertainty of the analyzer used. As can be seen, the effect of removing the paper does not have a significant effect on the measured thermal conductivity at room temperature. For the specific heat, it appears that the specific heat of the paper backing is higher than the gypsum material.

Table 1. Thermal conductivity and specific heat at 70 ºF taken with hot disk (virgin material)

Thermal Conductivity (Btu/h-ft°F) Grey Paper	Thermal Conductivity (Btu/h-ft°F) Brown Paper	Thermal Conductivity (Btu/h-ft°F) No Paper	Specific Heat (Btu/lb°F) Grey Paper	Specific Heat (Btu/lb°F) Brown Paper	Specific Heat (Btu/lb°F) No Paper
0.16	0.16	0.16	0.26	0.24	0.21

The thermal conductivity and specific heat were also determined as a function of temperature for representative gypsum board samples. The thermal conductivity as a function of temperature was determined using the Slug Calorimeter (Bentz *et al*., 2006). The slug calorimeter is comprised of a square central stainless steel plate (6 inches by 6 inches by ½ inch). A set of 6 inch by 6 inch gypsum board samples (with paper carefully removed) was installed in a 'sandwich' configuration (i.e. steel slug in the center); this provided an adiabatic boundary condition at the central axis of the slug plate. This entire configuration was then placed at the bottom of an electrically heated box furnace and the temperatures of the metal slug and exterior gypsum board surfaces were recorded during multiple heating and cooling cycles. The effective thermal conductivity was estimated knowing the heat capacities and densities of the steel slug and gypsum board samples (determined for the gypsum board using the Hot Disk measurements above).

During the first heating cycle, the gypsum dehydrated, absorbed some of the energy, and delayed the temperature rise of the slug. As a result, the thermal conductivity was determined based upon the second heating/(natural) cooling cycle and is displayed in Fig. 3. The thermal conductivity exhibits a slight decrease with temperature then steadily increases with temperature; similar behavior has been observed in thermal conductivity measurements for other gypsum board types (Bénichou and Sultan, 2005).

To determine the specific heat as a function of temperature, Differential Scanning Calorimetry (DSC) was used. DSC specific heat measurements were taken following the procedure outlined in ASTM E 1269-2001 at a scanning rate of 36 °F/min. The gypsum board samples used were 0.02 lb in initial mass. To accommodate the gas generation incurred from dehydration, the sample, reference and standard measurements utilized pans that were sealed except for a 0.002 inch pinhole in the lid.

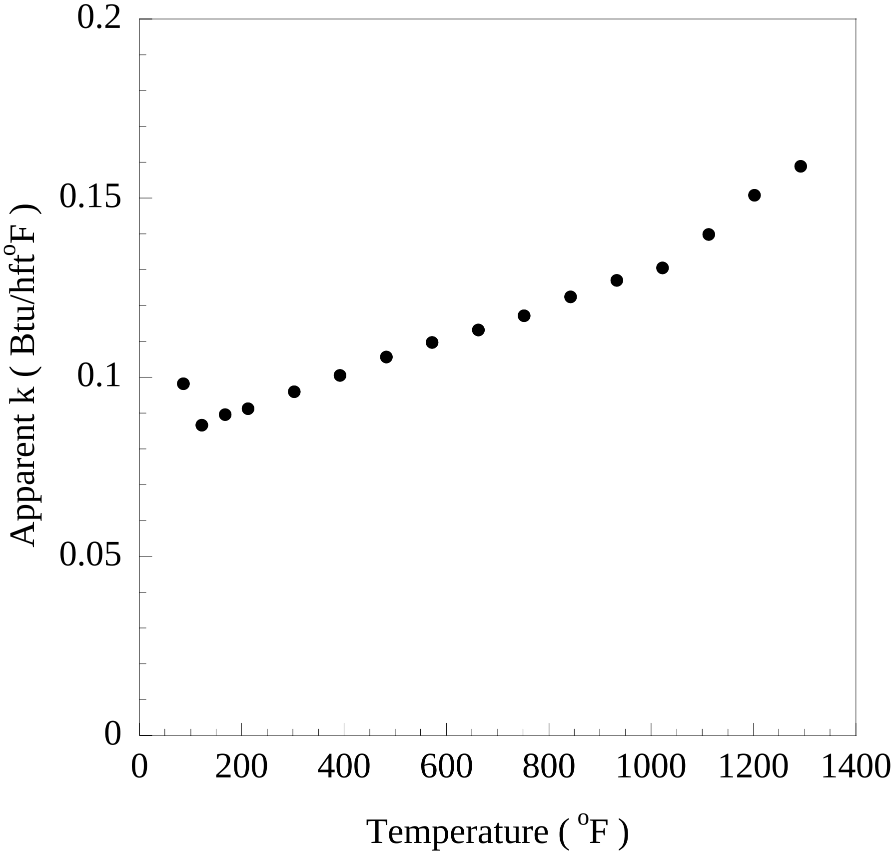

Figure 3. Thermal conductivity of gypsum board (previously heated) as a function of temperature determined with slug calorimeter

The core material of gypsum board is a porous solid composed primarily of calcium sulfate dihydrate ($CaSO_4 2H_2O$), a naturally occurring mineral in which two water molecules are chemically bound for every one calcium sulfate molecule within the crystal matrix. The presence of the water molecules is a key feature in establishing the fire resistance properties of gypsum. When heated, crystalline gypsum dehydrates and water is liberated, typically in two separate, reversible chemical reactions (Ramachandran *et al*., 2003):

$$CaSO_4 2H_2O + Q \leftrightarrow CaSO_4(1/2)H_2O + (3/2)H_2O \quad (1)$$

$$CaSO_4(1/2)H_2O + Q \leftrightarrow CaSO_4 + (1/2)H_2O \quad (2)$$

Both of these dehydration reactions are endothermic and generally occur at temperatures between 257 °F and 437 °F.

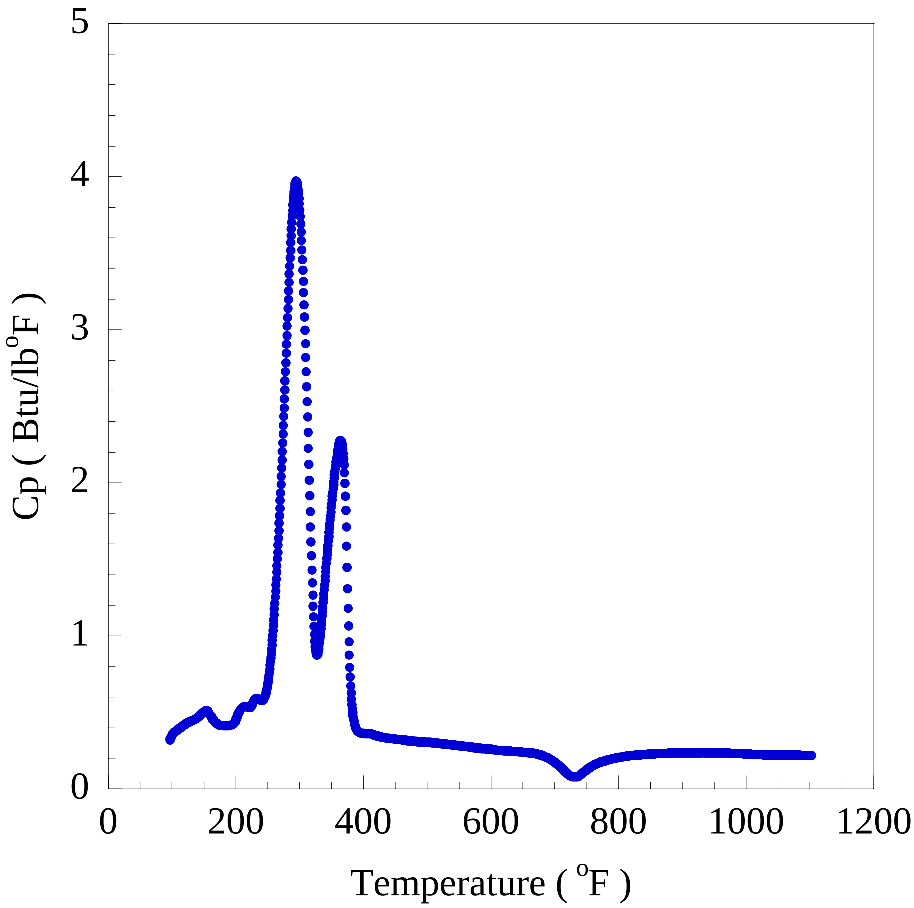

Figure 4. Specific heat of gypsum board as a function of temperature

At a temperature around 752 °F, a third, exothermic reaction occurs, in which the molecular structure of the soluble crystal reorganizes itself into a lower insoluble energy state (hexagonal to orthorhombic):

$$CaSO_4\ (\text{sol}) \rightarrow CaSO_4\ (\text{insol}) + Q \qquad (3)$$

These reactions can be observed in the Differential Scanning Calorimetry (DSC) traces presented in figure 4. The first two reactions are strongly endothermic while the third reaction is slightly exothermic. The DSC traces show that significant reaction, and thus water loss, is completed by the time the board reaches 400 °F. Similar findings for specific heat as a function of temperature have been reported for other gypsum board types (Bénichou and Sultan, 2005; Manzello *et al.*, 2007).

<u>Conduct of Test</u>

The instrumented specimen was mounted on the vertical wall furnace and prepared for testing using the standard procedure of the respective laboratory. The furnace was controlled to follow the standard time-temperature curve specified in ASTM E119-00. Temperatures of the specimen and furnace were collected at least once a minute. A video record of the entire test was made, along with photos of observed damage to the specimen when it occurred. A thermal imaging camera was used in several of the tests to view the unexposed side of the wall assembly. Figure 5 is a thermal image of a wall specimen during one of tests. The actual instrumentation employed and its placement on the specimen was recorded by each laboratory. The tests were documented and, in several cases, witnessed by NIST research staff.

The test was designed to continue until all of the following conditions were met:

- The average temperature of thermocouples used in standard practice by the laboratory on the unexposed side of the specimen reached 250 ^{o}F above its initial average temperature;
- At least one thermocouple used in standard practice by the laboratory on the unexposed side of the specimen reached a temperature 325 ^{o}F above its initial temperature; and
- A crack opens up in the specimen large enough and hot enough to ignite cotton waste.

The hose stream test (which is specified in ASTM E119-00) was not applied to the specimen.

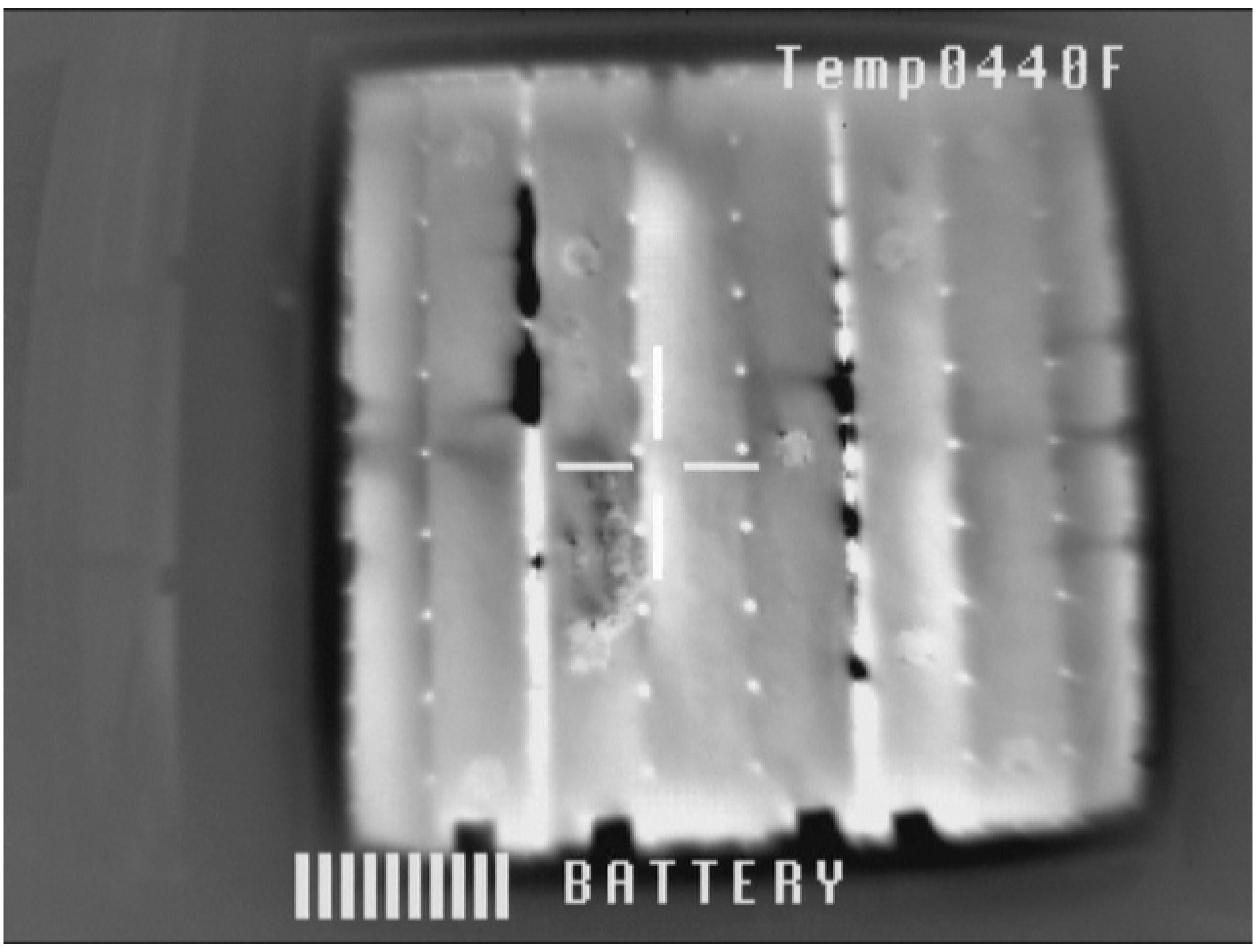

Figure 5. Thermal image of unexposed side of wall assembly during test

Each laboratory prepared a standard ASTM E119-00 data sheet for the tests conducted. In addition, data were compiled for the temperature vs. time for all specimen thermocouples and temperature vs. time for the furnace control thermocouples.

These data sheets were collected by ACIL and sent to NIST for analysis, without identifying which data set belonged to which laboratory. The assessment is based upon how much an individual laboratory differed from the following composite results of the group:

- Time for the average temperature to reach 250 ^{o}F above its initial average
- Time for the first thermocouple to reach 325 ^{o}F above its initial temperature
- Time for a crack to open up sufficient to ignite a cotton swab
- T vs. t for the peak temperature
- T vs. t for the average temperature

TEST RESULTS

<u>Average Furnace Temperatures</u>

The temperature of the furnace is determined from the average of multiple shielded, slow time-response thermocouples located within the furnace cavity. Most furnaces are controlled manually, with an experienced operator increasing or decreasing the fuel flow to different burners to maintain uniformity at the temperature specified in ASTM E119-00. At five minutes, the furnace temperature is required to be 1000 ^{o}F; at fifteen minutes it must be 1399 ^{o}F; the target temperature at one hour is 1700 ^{o}F; and at two hours the temperature is 1850 ^{o}F.

The temperatures of the laboratory furnace tests, designated A1 through A10, are plotted in Fig. 6. The dotted red line represents the average of the ten tests and the vertical red bars represent one standard deviation around the mean of the ten tests. During the start-up period, several of the furnaces tend to either lag or over-correct, but by fifteen minutes into the test, eight of the ten furnaces fall close to a single curve. Furnace A3 lags the group until about 40 minutes into the test.

Figure 7 demonstrates how closely the furnace temperatures follow the standard temperature curve. The times specified to reach a given temperature in the standard test are shown on the top axis of Fig. 7. One can see that during the first five minutes of warm-up, the test furnaces deviate by as much as 400 ^{o}F from the E119 temperature, and are most often on the low side. At temperatures above 1400 ^{o}F, all ten furnace temperatures are clustered close to the specified E119 temperature. The Standard requires that the integral of the temperature over time be within 7.5 % of the specified curve for tests lasting more than one hour. The areas under the temperature curves, listed in Table 2, were all within 2 % of the area specified in ASTM E119-00 (82 330 ^{o}F-min). Also shown in Table 2 are the initial ambient laboratory temperatures, which ranged between 62 ^{o}F and 92 ^{o}F. The Standard assumes, but does not require, that the initial laboratory temperature is 68 ^{o}F

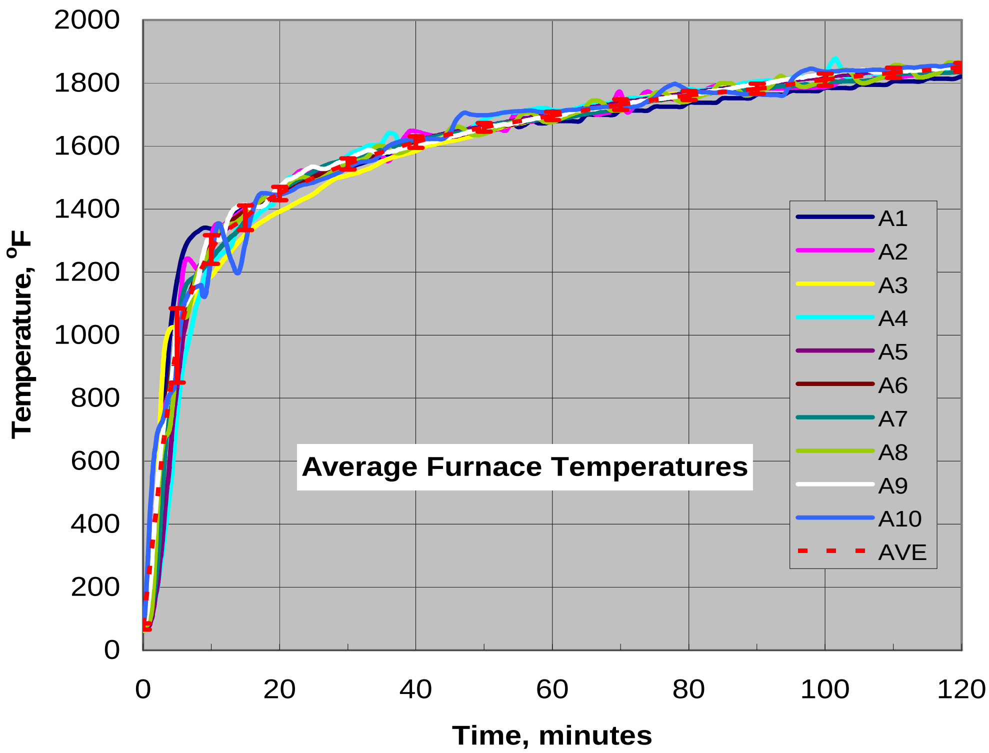

Figure 6. Average temperature of each of ten furnaces as a function of time

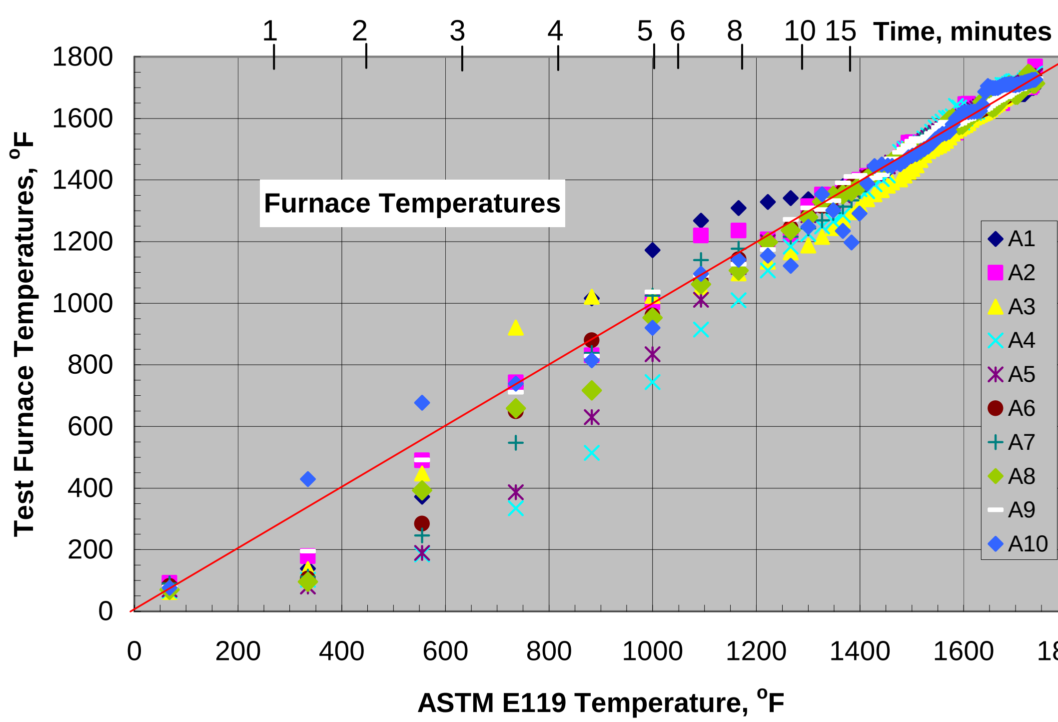

Figure 7. Individual furnace temperatures vs. prescribed ASTM E119 temperature

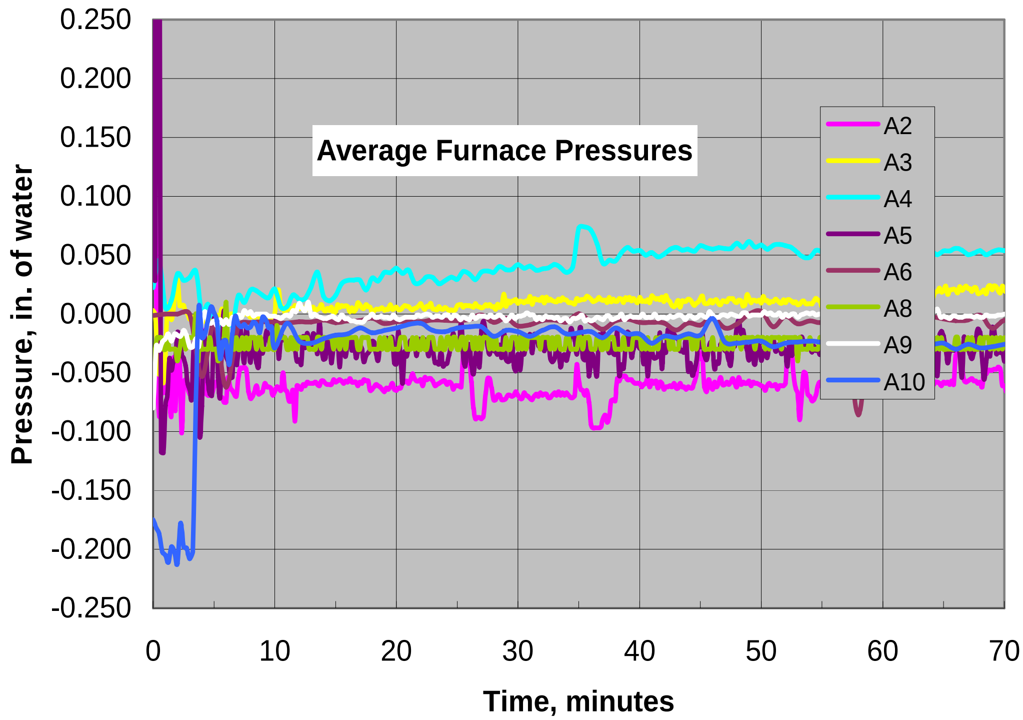

Figure 8. Furnace pressure as a function of time

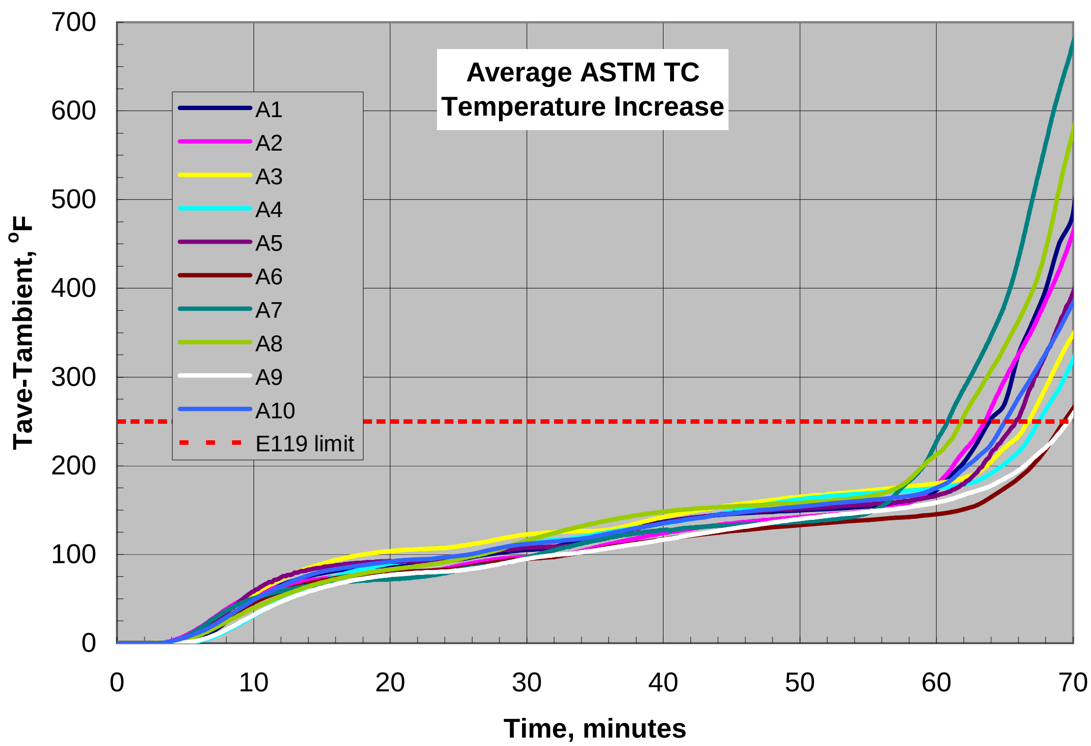

Figure 9. Average ASTM TC increase on unexposed face

Table 2. Ambient temperature and temperature-time integrals for the inter-laboratory tests

Laboratory	Ambient Temperature, ^{o}F	T-t Integral, ^{o}F-min	Deviation from ASTM E119
A1	68	82 880	0.7 %
A2	92	82 980	0.7 %
A3	62	80 650	2.0 %
A4	66	80 860	1.8 %
A5	70	81 480	1.0 %
A6	82	81 790	0.6 %
A7	90	81 880	0.5 %
A8	70	81 960	0.4 %
A9	78	82 550	0.3 %
A10	76	82 430	0.1 %

Furnace Pressure

The furnace pressure was recorded continuously for eight of the ten tests, and these are plotted in Fig. 8. The pressures (relative to the surrounding laboratory) remained fairly constant and around zero after an initial transient that lasted less than five minutes. The measured relative pressures ranged from about -0.07 in. H_2O for test A2 (where the pressure probe was located 24 in. above the bottom of the wall) to +0.05 in. H_2O in test A4 (location of the pressure probe was unspecified). Proper interpretation of these pressure data requires knowing the location of the probe in the furnace.

Average Temperature of Unexposed Wall

Appendix A contains the temperature-time plots for all of the individual thermocouples on the unexposed wall for tests A-1 through A-10. The average temperature increase on the unexposed wall for each laboratory test is shown in Fig. 9. Note that the ambient temperature (which varied between 62 ^{o}F and 92 ^{o}F as listed in Table 2) has been subtracted from the average temperatures. As mentioned earlier, one of the criteria for rating the fire resistance of a wall assembly is the time when the average temperature of the thermocouples on the unexposed side of the specimen reaches 250 ^{o}F above its initial average temperature. This limit is shown as the dotted red line in Fig. 9. The temperature profiles are closely grouped for the first 56 minutes and then begin to diverge. None of the average temperature increases exceed the threshold before 60 minutes, and all have exceeded the threshold by 70 minutes.

Figure 10 is a plot of the standard deviation of the curves graphed in Fig. 9. The standard deviation remains less than 20 ^{o}F until the time approaches the 60 minute mark, when the

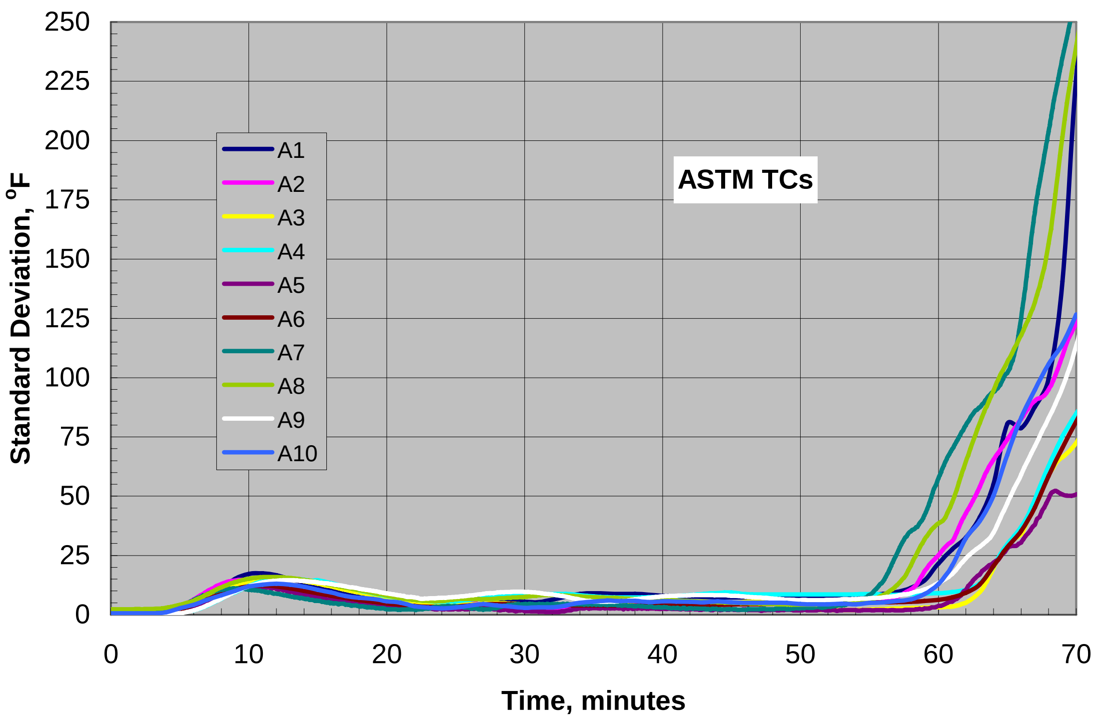

Figure 10. Standard deviation among 9 ASTM TCs on unexposed side of each specimen tested

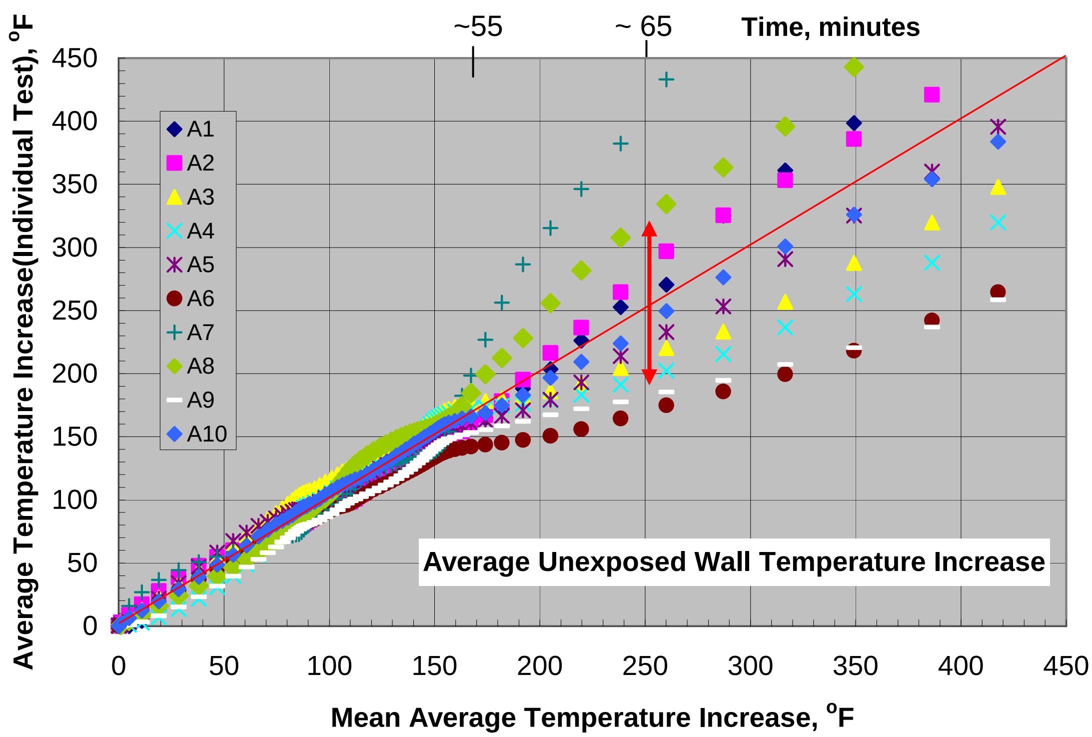

Figure 11. Individual test unexposed surface average temperature vs. mean of all ten tests

standard deviation grows rapidly for all of the tests, especially for A1, A7 and A8, which reach standard deviations in excess of 200 ^{o}F. This divergence is shown even more graphically in Fig. 11, which is a plot of the average temperature increase on the unexposed wall for the individual specimen versus the mean value for the temperature increase of all of the tests. The spread in temperatures among the ten samples begins at around 170 ^{o}F. At the 250 ^{o}F threshold, the standard deviation (shown as the double-ended red arrow in Fig. 11) is +/- 66 ^{o}F, and the maximum spread is almost 250 ^{o}F.

Peak Wall Temperatures

The temperature histories of all nine ASTM E119 thermocouples on the wall not exposed to the furnace are included in the appendix for the ten tests conducted. Because each furnace has a unique design and method of temperature control, it is not possible to predict which of the thermocouples positioned on the side of the wall that is unexposed to the flames will be the hottest. For most of the current testing, the temperature increase indicated by TC6 was within one minute of being the hottest, and for ease of comparison, this temperature increase is plotted in Fig. 12 for the ten furnace tests. The first laboratory for which TC6 reaches the criteria for failure, 325 ^{o}F (dotted line in Fig. 10), is A7, at 62 minutes; laboratory A9 is the last, with TC6 reaching 325 ^{o}F more than 10 minutes later. Note, however, that TC6 is not representative of the hottest temperature for this test; TC5 reaches the limit in A9 at 65 min.

The highest temperature increases measured on the unexposed surface of the wall assembly at any given time (regardless of thermocouple location) are plotted on the vertical axis in Fig. 13 against the average of the ten tests on the horizontal scale. If all of the tests were identical, the data would fall on the solid line. Up to a temperature increase of about 175 ^{o}F, the tests are well correlated; however, at higher values the maximum temperature increases at any given time diverge greatly, with a standard deviation of +/- 100 ^{o}F for mean high temperature increases equal to the limiting temperature in ASTM E119-00 (the vertical red line at 325 ^{o}F indicates the limit). The range in peak temperature increases at this point is from 220 ^{o}F to 580 ^{o}F.

Fire Resistance Ratings

The key output of ASTM E119-00 is the fire resistance rating. In all ten furnace tests, this wall design received a rating of 1-h. For five of the laboratories, the failure time was based upon the average temperature increase on the unexposed face exceeding 250 ^{o}F. The maximum allowed individual temperature on the backside of the wall (325 ^{o}F) was the failure limit for four laboratories, and one laboratory exceeded both criteria simultaneously (within the limit of their data rate). In no case was the wall breached in less than 70 minutes. The wall was not designed to be loaded; hence, the failure to maintain a load was not examined.

Table 3 displays these times, as well as the failure criteria. The overall average time to failure was 65.0 minutes, with a standard deviation of 2.8 minutes. Laboratory A6 exceeded the average by more than one standard deviation, and laboratories A7 and A8 were less that the average by more than one standard deviation. The far right column indicates additional temperature failure criteria that occurred within one minute of the first failure. Note that the fire resistance rating, shown in the second column, is the same for all nine laboratories: 1-h.

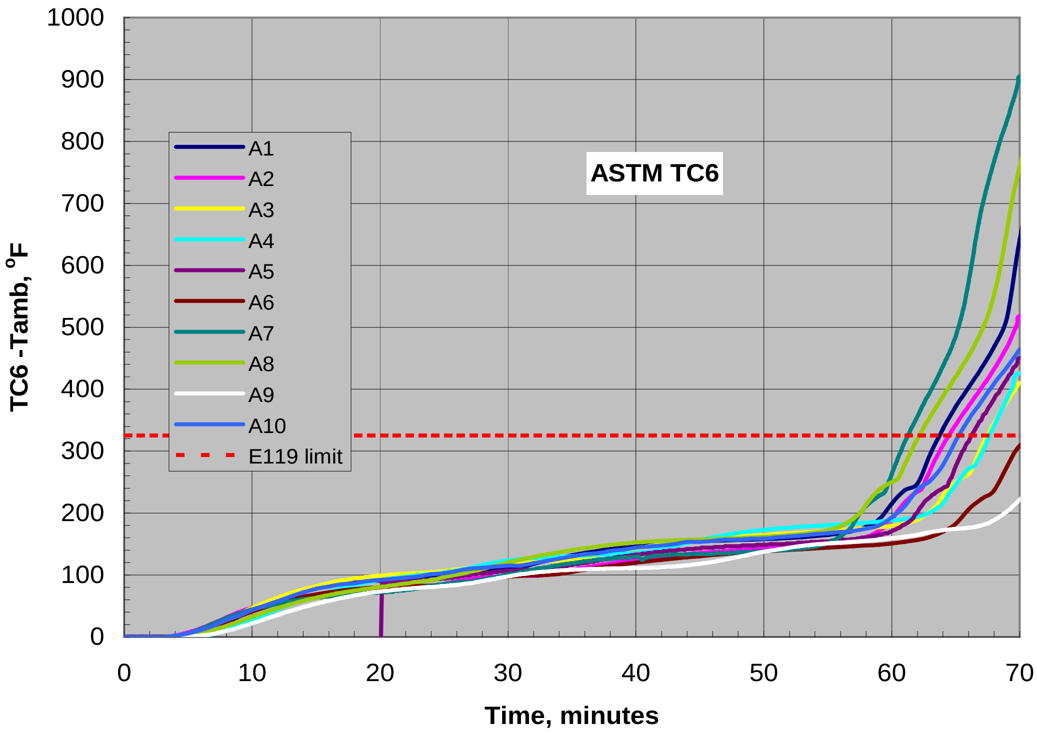

Figure 12. Temperature increase of TC6 on unexposed side of each specimen tested

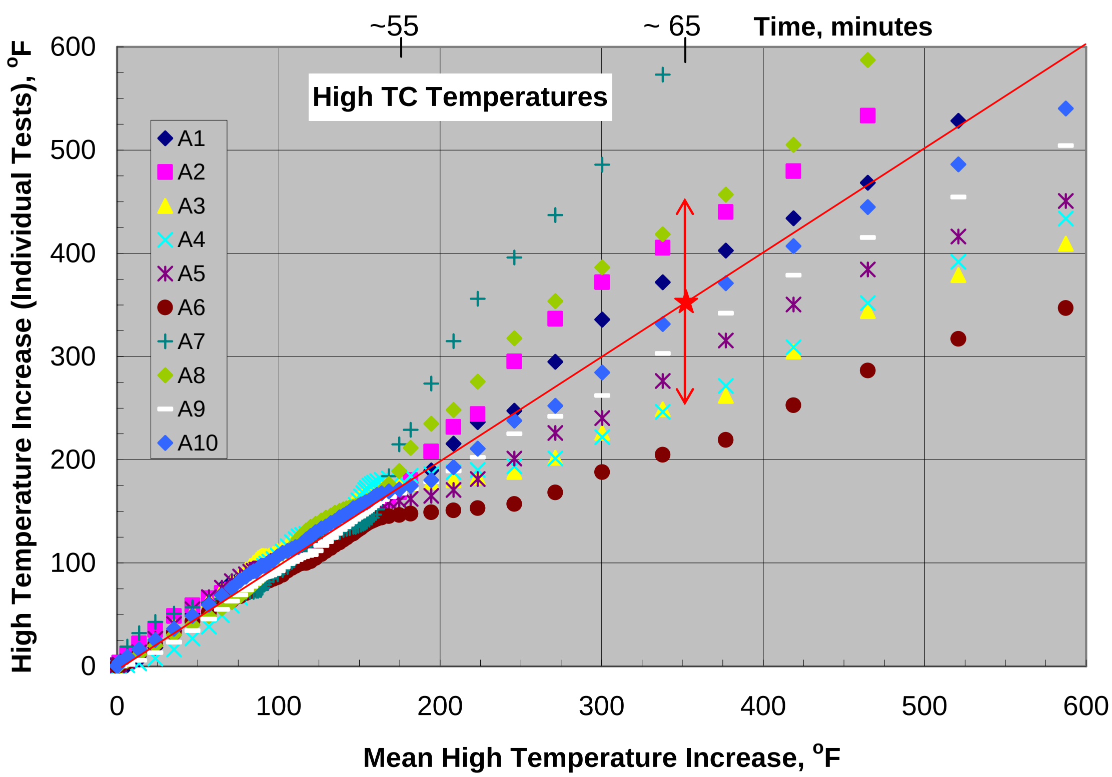

Figure 13. Individual test unexposed surface peak temperature vs. mean of all ten tests

Table 3. Summary of Failure Criteria

Laboratory	Fire Resistance Rating	Time to First Failure, minutes	Failed Thermocouple Reading	Other TC's Failing within 1 minute
A1	1 hour	64	average	TC3, 5, 7
A2	1 hour	62.8	TC3	average
A3	1 hour	66.8	average	TC4, 6, 8
A4	1 hour	67.5	average	TC3, 6, 8
A5	1 hour	65.8	average	TC6
A6	1 hour	70	TC3	TC4, 5, 6, 7, average
A7	1 hour	60.6	TC7	TC3, 5, 6, average
A8	1 hour	61.9	average	TC3, 4, 6
A9	1 hour	65.8	TC5	none
A10	1 hour	65	average, TC5	TC4, 6, 7
average	1 hour	65.0 +/- 2.8	average	--

ANALYSIS OF RESULTS

Even though all ten tests resulted in the same fire resistance rating for this generic wall assembly (1 h), it is important to identify the possible causes for the range of times to failure for this set of tests, especially considering how close to the minimum time (60 min) that several of the laboratories reported. The relationship between time to failure and the following parameters has been examined: average furnace temperature, temperature-time integral, peak furnace temperature, and standard deviation of furnace temperature.

Figure 14 is a plot of the difference between the average time-to-failure and the time-to-failure for a specific test, and the furnace temperature averaged over time for the control thermocouples. The failure time trends downward with increasing average furnace temperature, but the correlation is too small to be significant. The negative correlation between time-to-failure and the integral of temperature over time (Fig. 15) is also too small to be significant

The difference between the average time-to-failure and the time-to-failure for a specific test, and the time-average of the highest temperature furnace control thermocouple exhibits a correlation coefficient of R^2=0.36; too small to be significant. This is shown in Fig. 16. The average of the standard deviation across the furnace control thermocouples also has a correlation with time-to-failure (Fig. 17) too small to be significant.

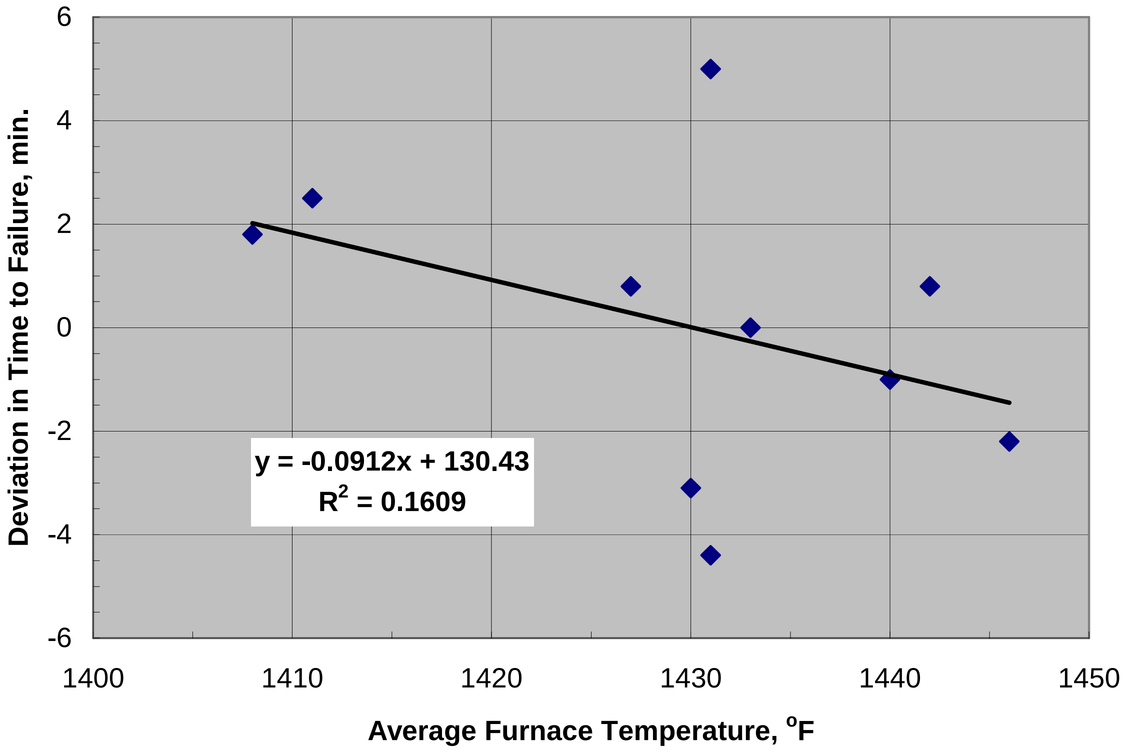

Figure 14. Correlation of deviation with average furnace temperature

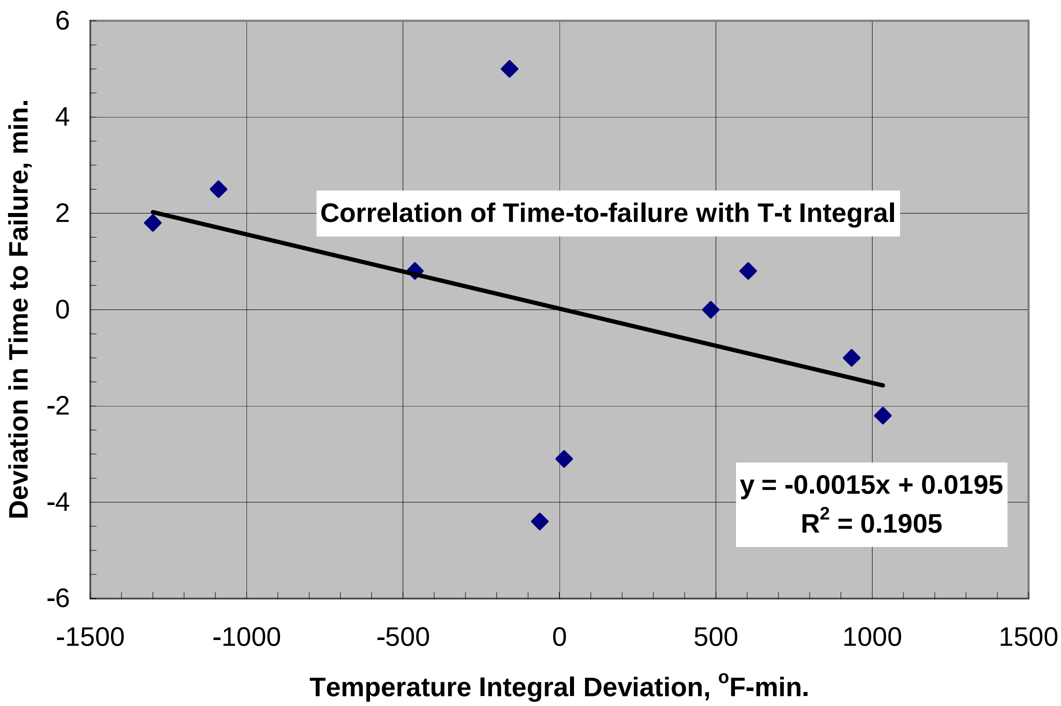

Figure 15. Correlation of deviation with temperature integral

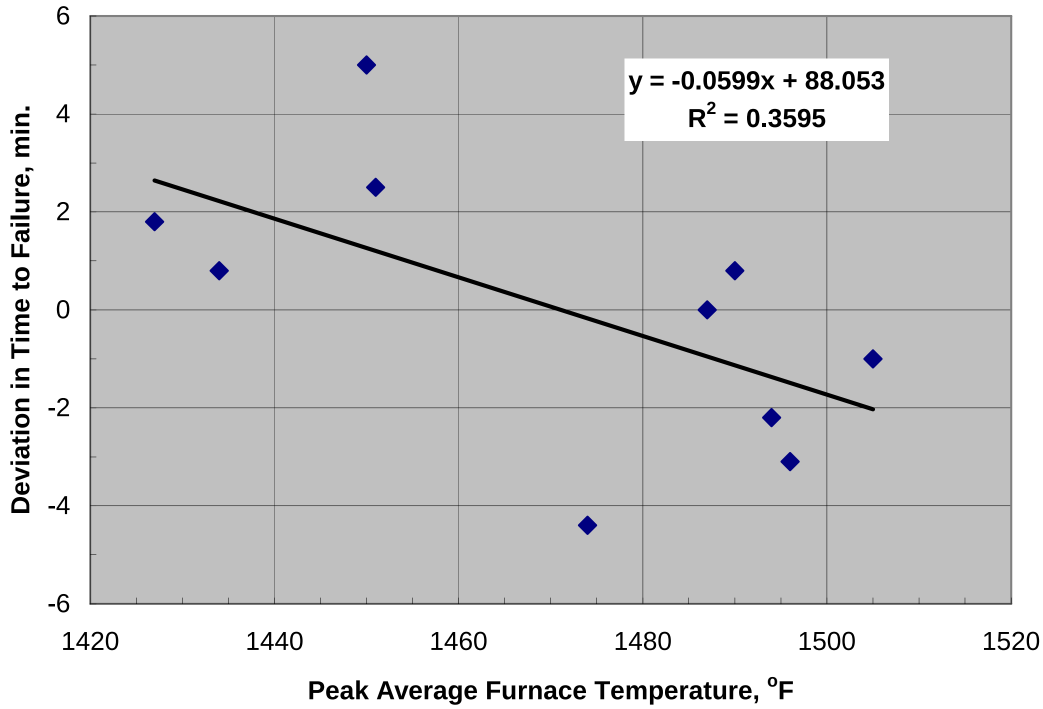

Figure 16. Correlation of deviation with peak average furnace temperature

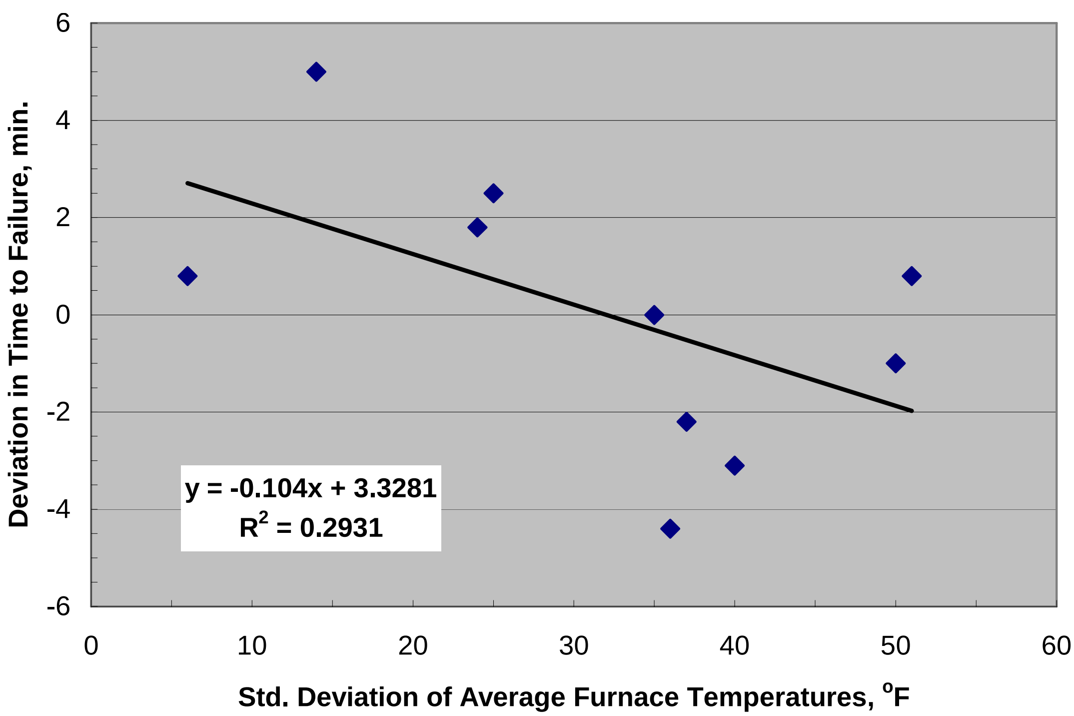

Figure 17. Correlation of deviation with standard deviation of average furnace temperature

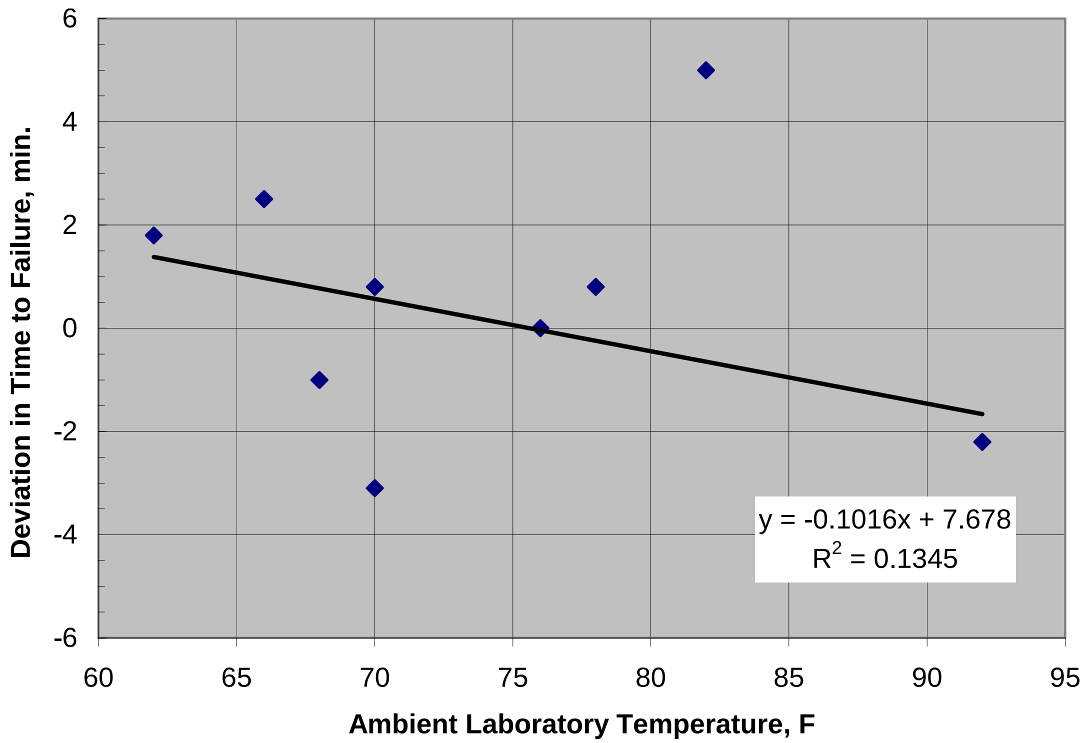

Figure 18. Correlation of deviation with laboratory ambient temperature

Figure 18 shows that the initial ambient temperature does not correlate, to any significant degree, with the time-to-failure. Furnace pressure was not considered since the furnace pressures were not all taken at the same location in the furnace. Table 4 summarizes the results of these correlation studies, indicating that none of the correlations reached a statistically meaningful level of significance.

Table 4. Summary of correlations of failure time with furnace conditions

Furnace Parameters	Slope	R^2
overall average of TCs	-0.09 min/^{o}F	0.16
T-t deviation	-0.0015 min/^{o}F-min	0.19
peak ave. TC	-0.06 min/^{o}F	0.36
std. dev. of ave. TCs	-0.10 min/^{o}F	0.29
ambient temperature	-0.10 min/^{o}F	0.13

In addition to the furnace parameters mentioned above, the time to failure in a given test can be influenced by the variations in the specimen materials, differences in specimen preparation and operating procedures, the furnace design, the instruments used to make the measurements, and their placement on the specimen and in the furnace.

SUMMARY OF RESULTS

A test program was conducted to examine the laboratory-to-laboratory variations associated with determining the fire resistance rating of a gypsum wall assembly using the test method prescribed in ASTM E119-00. The test program undertaken by the NAFTL consortium and described in this report is the first ever to target a fire test of this magnitude.

The key results of the test program are summarized below:

- The participating NAFTL laboratories arrived at an identical 1-h rating for the gypsum wall specimen tested according to ASTM E119-00 and using their respective standard operating protocols.
- The variability among laboratories using their individual standard operating procedures and as close-to-identical as possible 1-h rated gypsum wall specimens was found to be 65 ± 2.8 minutes.
- The variability in individual peak thermocouple temperatures measured at similar locations on different 1-h rated gypsum wall assemblies exceeded ± 50 ºF about one hour into the tests.
- Individual thermocouples on the unexposed side of the 1-h rated gypsum wall differed in temperature by as much as 300 ^{o}F at the average time of failure.
- Differences in the time to failure for ten close-to-identical ASTME E119 wall assembly tests did not correlate at a statistically significant level with differences in average furnace temperature, the temperature-time integral, changes in ambient temperatures, or standard deviation among the furnace control thermocouple temperatures.
- The six inter-laboratory tests conducted by the Japanese organizations yielded an average time to failure (based upon either the average unexposed wall temperature or the peak temperature measured by TC 6 or TC7) of 67.1 ± 1.1 minutes.

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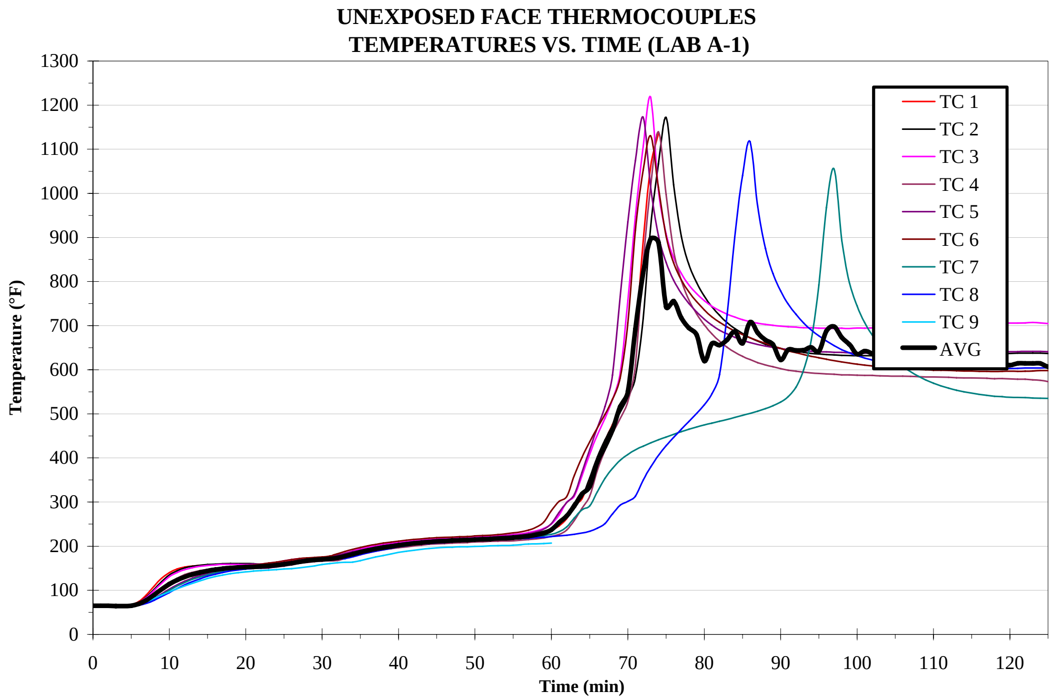
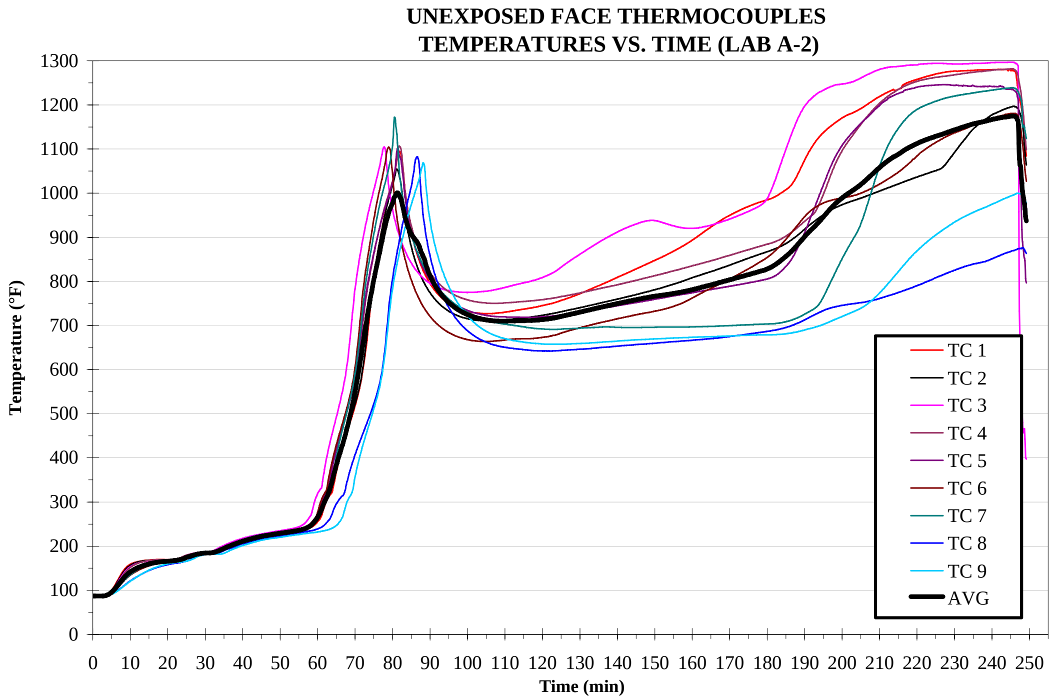
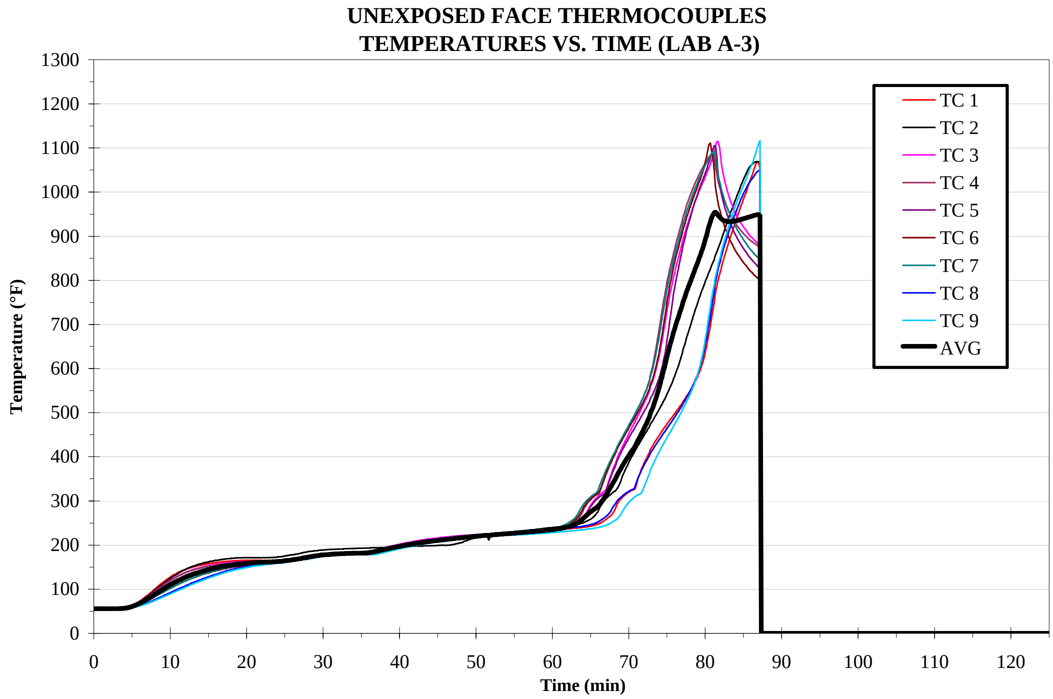
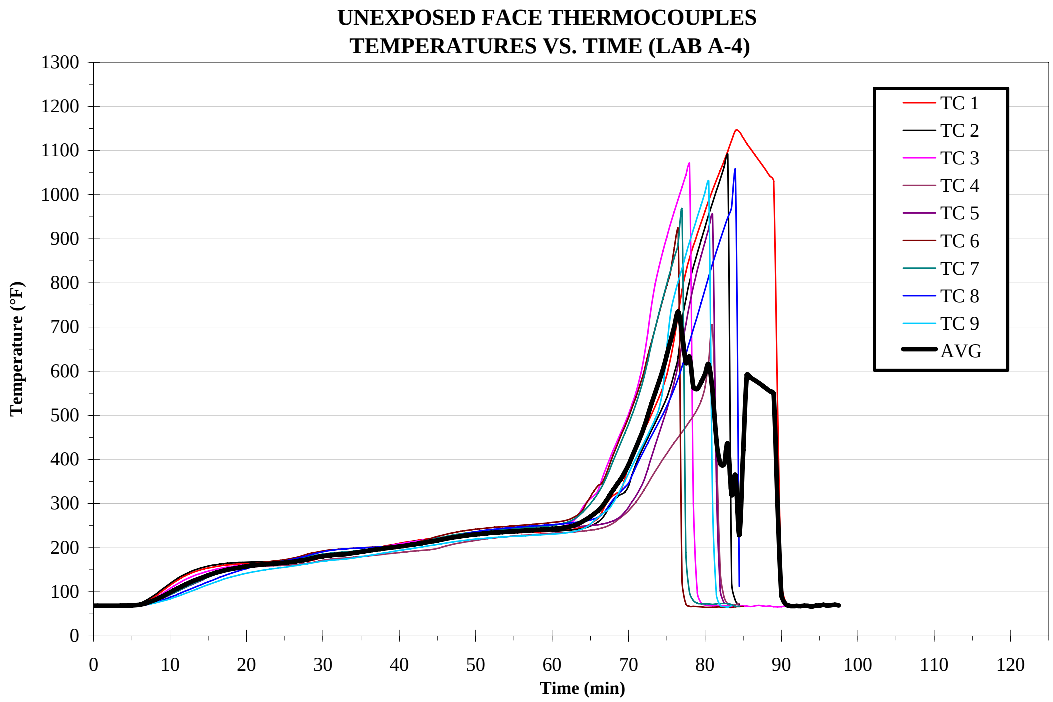
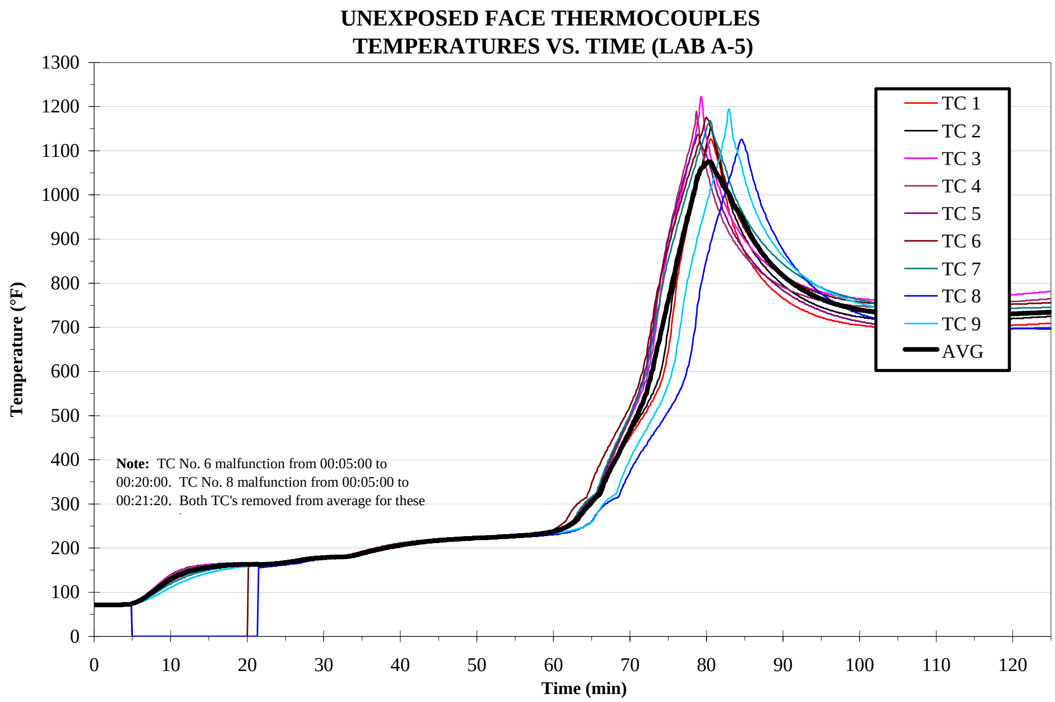
APPENDIX A. Plots of unexposed face thermocouples for laboratories A-1 through A-10

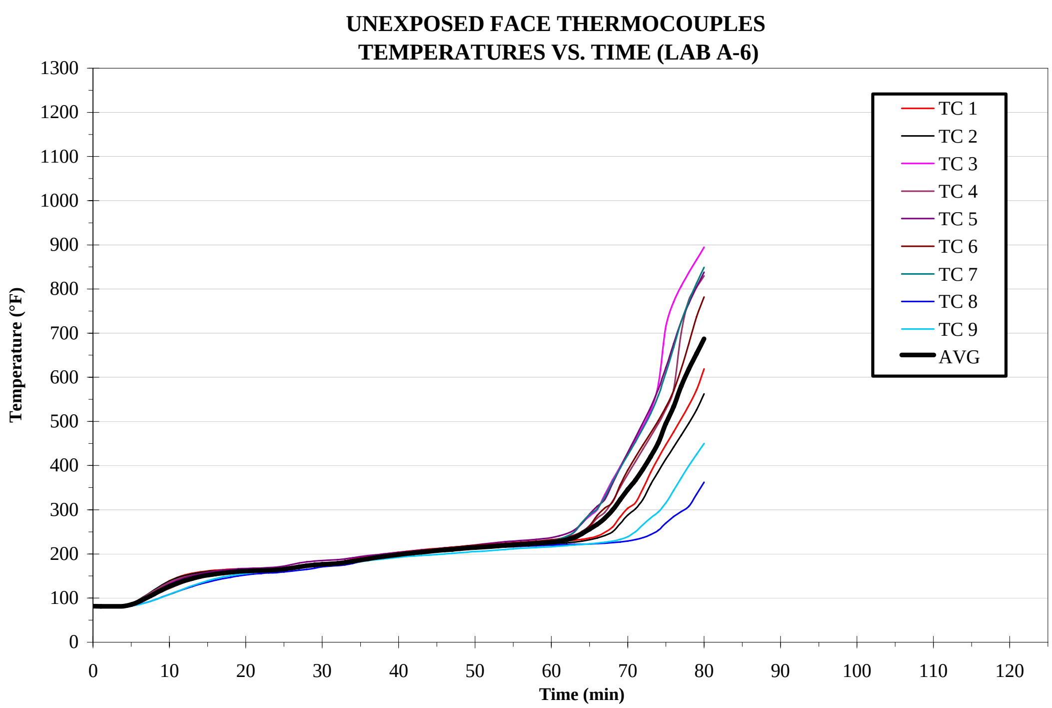




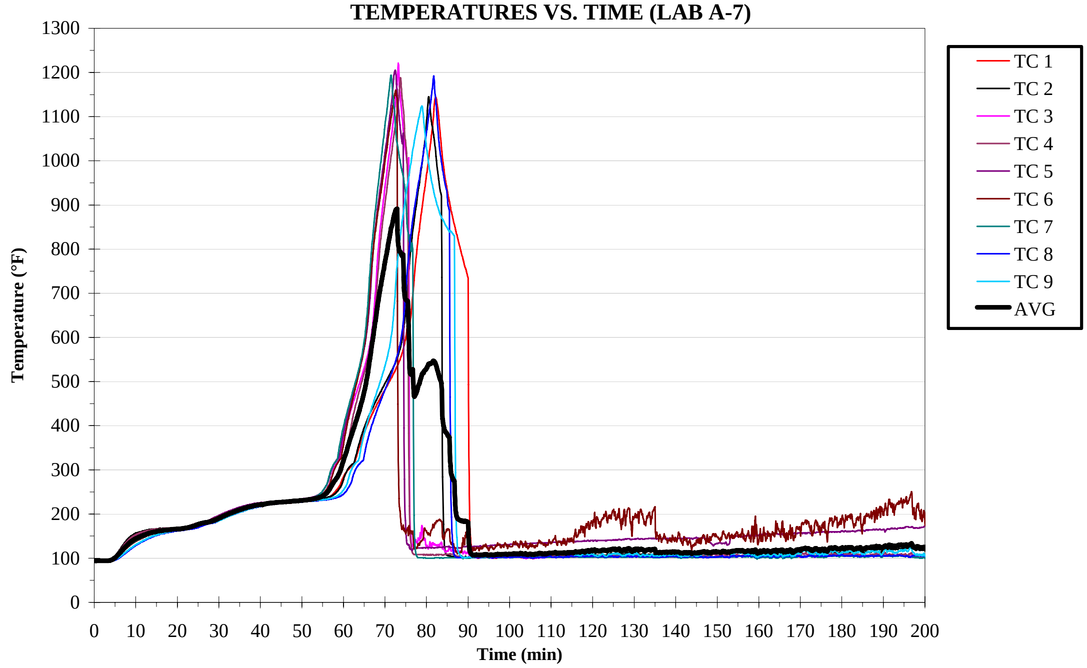

UNEXPOSED FACE THERMOCOUPLES
TEMPERATURES VS. TIME (LAB A-3)
Temperature (°F)
Time (min)
TC 1
TC 2
TC 3
TC 4
TC 5
TC 6
TC 7
TC 8
TC 9
AVG


UNEXPOSED FACE THERMOCOUPLES
TEMPERATURES VS. TIME (LAB A-4)
Temperature (°F)
Time (min)
TC 1
TC 2
TC 3
TC 4
TC 5
TC 6
TC 7
TC 8
TC 9
AVG

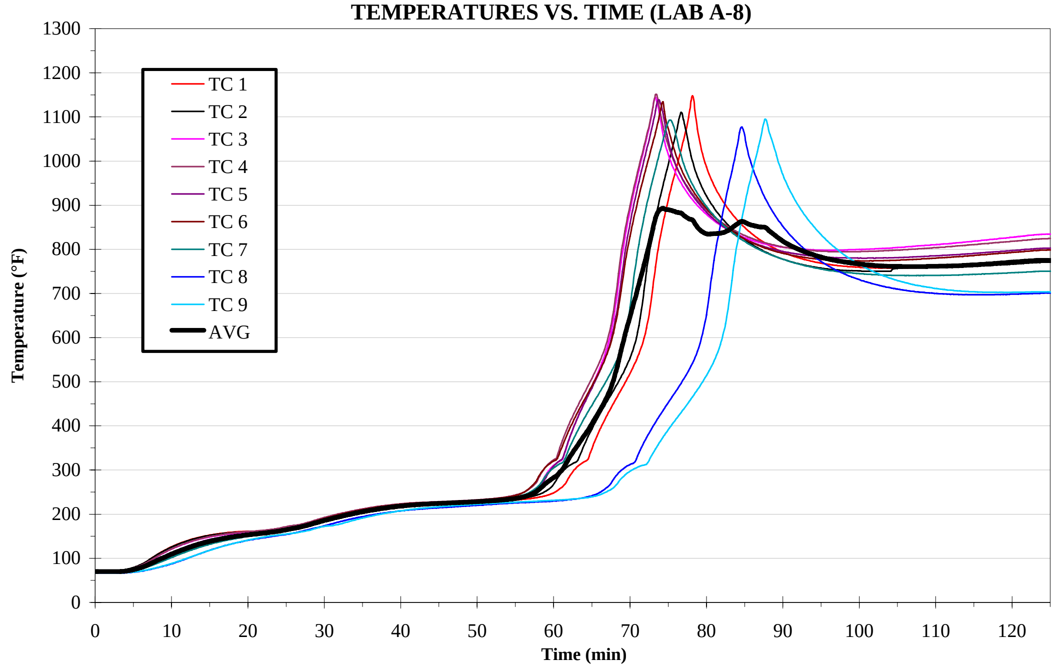

UNEXPOSED FACE THERMOCOUPLES
TEMPERATURES VS. TIME (LAB A-5)
Temperature (°F)
Time (min)
TC 1
TC 2
TC 3
TC 4
TC 5
TC 6
TC 7
TC 8
TC 9
AVG
Note: TC No. 6 malfunction from 00:05:00 to 00:20:00. TC No. 8 malfunction from 00:05:00 to 00:21:20. Both TC's removed from average for these

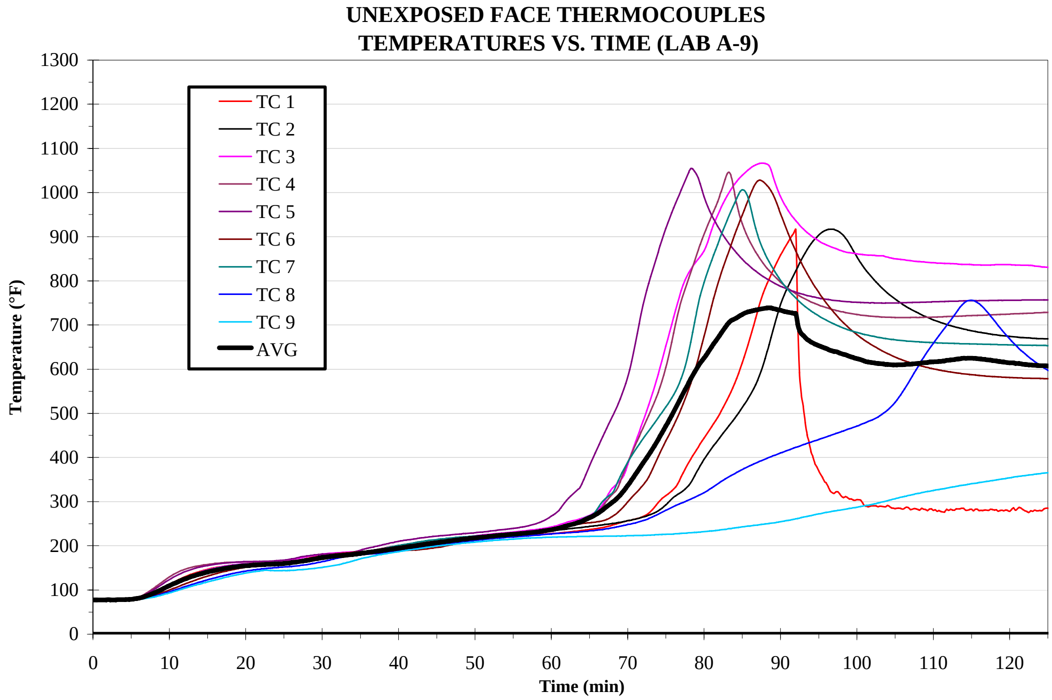

UNEXPOSED FACE THERMOCOUPLES
TEMPERATURES VS. TIME (LAB A-6)
Temperature (°F)
Time (min)
TC 1
TC 2
TC 3
TC 4
TC 5
TC 6
TC 7
TC 8
TC 9
AVG

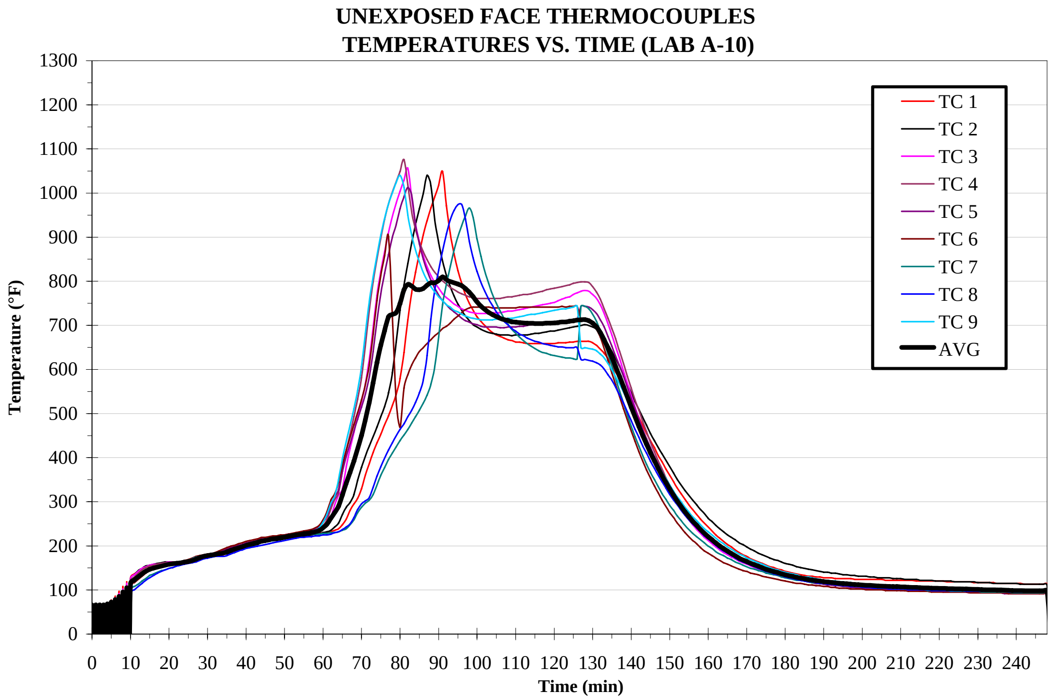
UNEXPOSED FACE THERMOCOUPLES TEMPERATURES VS. TIME (LAB A-7)



UNEXPOSED FACE THERMOCOUPLES TEMPERATURES VS. TIME (LAB A-8)




UNEXPOSED FACE THERMOCOUPLES
TEMPERATURES VS. TIME (LAB A-9)
Temperature (°F)
Time (min)
TC 1
TC 2
TC 3
TC 4
TC 5
TC 6
TC 7
TC 8
TC 9
AVG


UNEXPOSED FACE THERMOCOUPLES
TEMPERATURES VS. TIME (LAB A-10)
Temperature (°F)
Time (min)
TC 1
TC 2
TC 3
TC 4
TC 5
TC 6
TC 7
TC 8
TC 9
AVG

APENDIX B. Results from Japanese inter-laboratory test program

In addition to the NAFTL members that participated in this effort, four Japanese laboratories joined in the testing. These include: The Center for Better Living, Japan Testing Center for Construction Materials, General Building Research Corporation of Japan, and Japan Housing and Wood Technology Center. The Japanese testing was coordinated through The Center for Better Living by Tensei Mizukami. Mr. Mizukami contacted several Japanese laboratories and worked with Dr. Manzello of NIST to have all necessary materials (gypsum board/steel studs) used for the NAFTL program exported from the USA to Japan. Dr. Manzello was also able to observe some of the tests that were conducted in Japan. A summary of data collected from the Japanese laboratories is included below. Although four laboratories participated, the Japan Testing Center for Construction Materials maintains more than one vertical furnace. Consequently, six tests were conducted in Japan.

Table 1B. Summary of failure criteria for Japanese laboratories

Laboratory	Fire Resistance Rating	Time to First Failure, minutes	Failed Thermocouple Reading	Other TC's Failing within 1 minute
B1	1 hour	67.7	TC7	Ave., TC6
B2	1 hour	67.3	TC7	Ave., TC6
B3	1 hour	66.0	TC6	Ave.
B4	1 hour	65.5	Ave.	TC3, TC4, TC5, TC6, TC7
B5	1 hour	68.0	Ave., TC6	TC4, TC5, TC7
B6	1 hour	68.0	TC7	Ave.
average	1 hour	67.1 ± 1.1	TC7, TC6, Ave	--

The temperatures of the Japanese laboratory furnace tests, designated B1 through B6, are plotted in Fig. 1B. The dotted line represents the time-temperature curve specified in the ASTM E119-00 standard. As can be seen, furnace B1 failed at approximately 20 minutes into the test. The furnace was subsequently brought on-line again within three minutes of the failure; the cause of failure is not known.

Fig. 2B demonstrates how closely the furnace temperatures follow the standard temperature curve. One can see that during warm-up, the test furnaces deviate by as much as 300 ^{o}F from the E119-00 temperature, and are most often on the low side. Very similar behavior was observed for the furnaces in North America. Due to failure of furnace B1, a large discrepancy was observed between the E119-00 temperature and furnace B1.

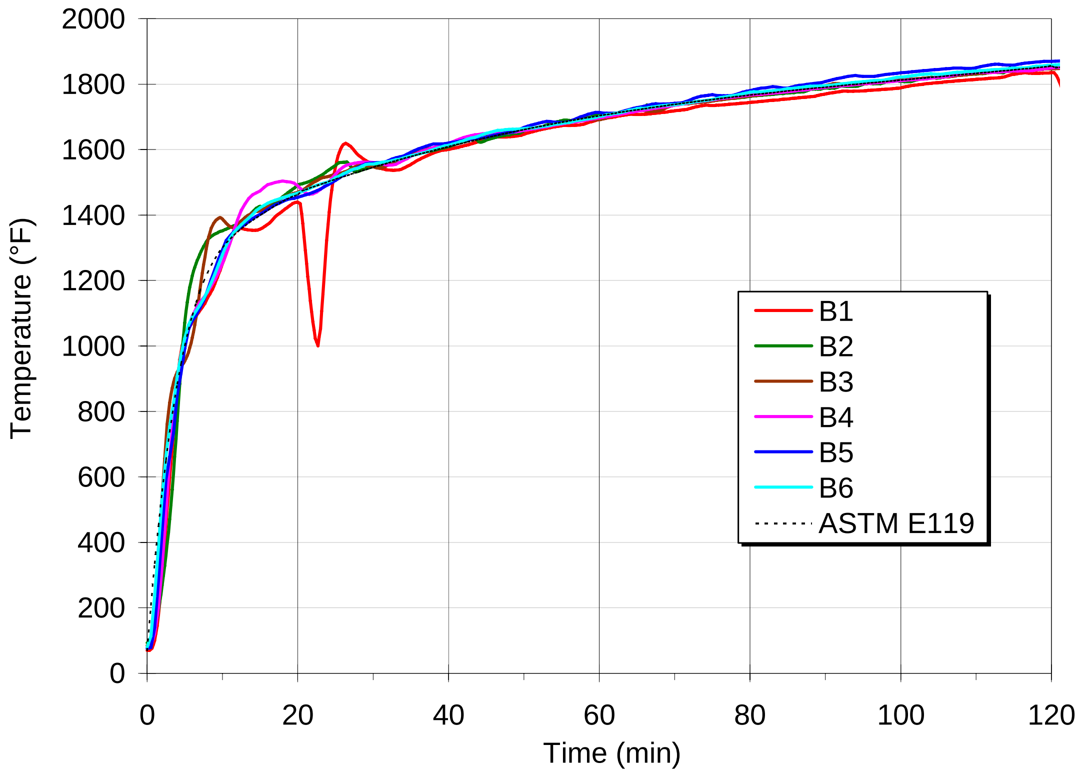


Figure 1B. Average temperature of each of six Japanese furnaces as a function of time

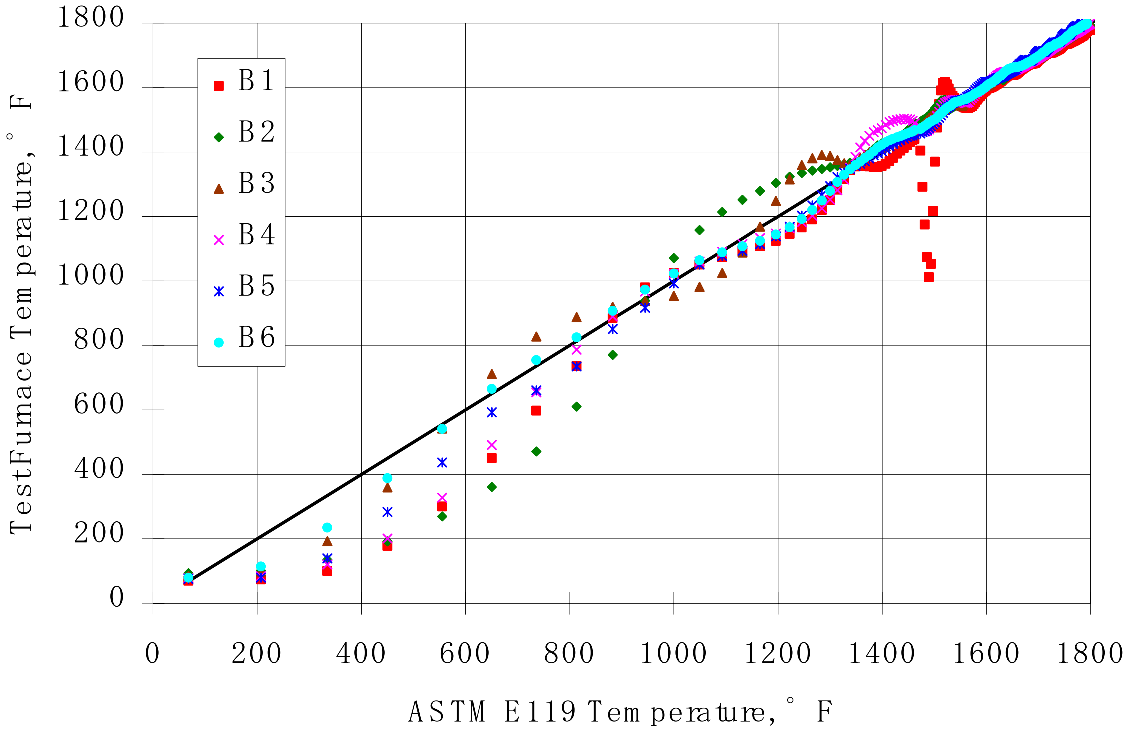


Figure 2B. Individual Japanese furnace temperatures vs. prescribed ASTM E119 temperature

The furnace pressure was recorded continuously for all of the six tests conducted by the Japanese laboratories, and these are plotted in Fig. 3B. The pressures (relative to the surrounding laboratory) remained fairly constant and slightly positive (except for furnace B1). This was in contrast to the North American furnace pressures which remained fairly constant and around zero during the tests. In any event, proper interpretation of these pressure data requires knowing the location of the probe in the furnace.

The average temperature increase on the unexposed wall for each Japanese furnace test is shown in Fig. 4B. Note that the ambient temperature has been subtracted from the average temperatures. As mentioned earlier, one of the criteria for rating the fire resistance of a wall assembly is the time when the average temperature of the thermocouples on the unexposed side of the specimen reaches 250 ^{o}F above its initial average temperature. This limit is shown as the dotted red line in Fig. 4B. Similar to the North American furnaces, the temperature profiles are closely grouped for the first 60 minutes and then begin to diverge. None of the average temperature increases exceed the threshold before 60 minutes, and all have exceeded the threshold by 70 minutes.

Fig. 5B is a plot of the average temperature increase on the unexposed wall for the individual specimen versus the mean value for the temperature increase of all of the tests. The spread in temperatures among the six samples begins at around 170 ^{o}F, which was very similar to the North American tests. Above these temperatures, the deviation among furnaces is quite large; more than 200 ^{o}F at later times.

The key output of ASTM E119-00 is the fire resistance rating (Table 1B). For one of the Japanese furnaces, the failure time was based upon the average temperature increase on the unexposed face exceeding 250 ^{o}F. The maximum allowed individual temperature on the backside of the wall (325 ^{o}F) was the failure limit for four Japanese furnaces; one furnace exceeded both criteria simultaneously (within the limit of their data rate). In no case was the wall breached in less than 70 minutes. The wall was not designed to be loaded; hence, the failure to maintain a load was not examined.

It is useful to compare these results to the North American furnaces. For five of the North American furnaces, the failure time was based upon the average temperature increase on the unexposed face exceeding 250 ^{o}F. The maximum allowed individual temperature on the backside of the wall (325 ^{o}F) was the failure limit for four North American furnaces, and one North American furnace exceeded both criteria simultaneously (within the limit of their data rate).

In summary, Table 1B displays these times for the Japanese furnaces, as well as the failure criteria. The overall average time to failure was 67.1 minutes, with a standard deviation of 1.1 minutes. For comparison, the North American furnaces resulted in an overall average time to failure was 65.0 minutes, with a standard deviation of 2.8 minutes. Similar to the North American furnace tests, the fire resistance rating, shown in the second column, is the same for all six Japanese furnaces: 1-h.

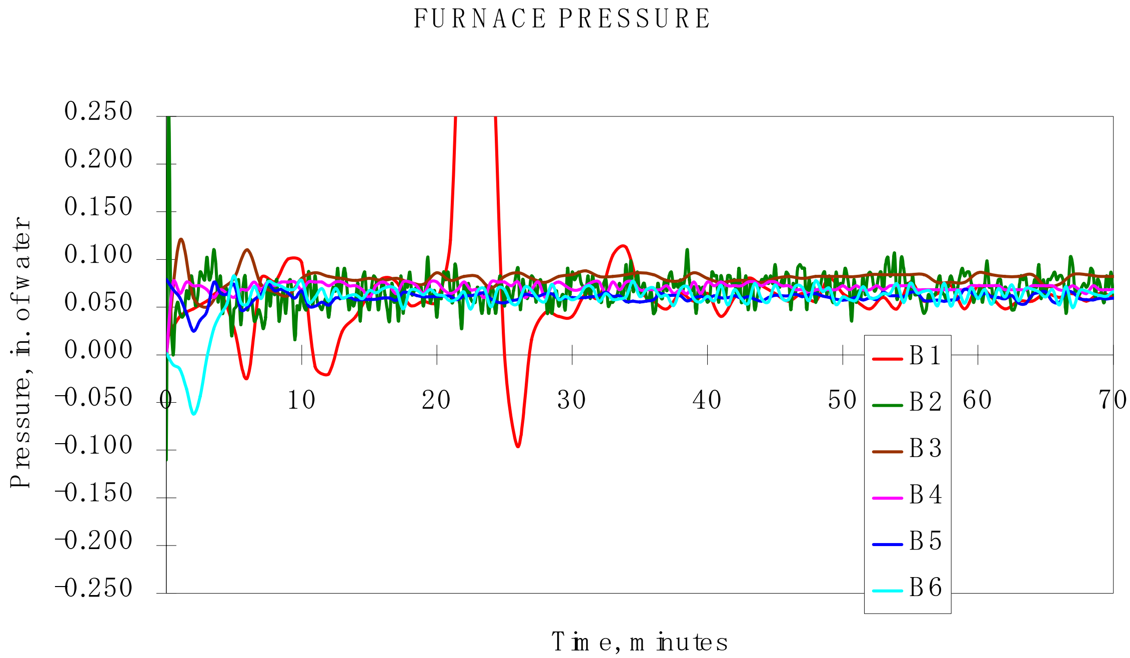


Figure 3B. Japanese furnace pressures as a function of time

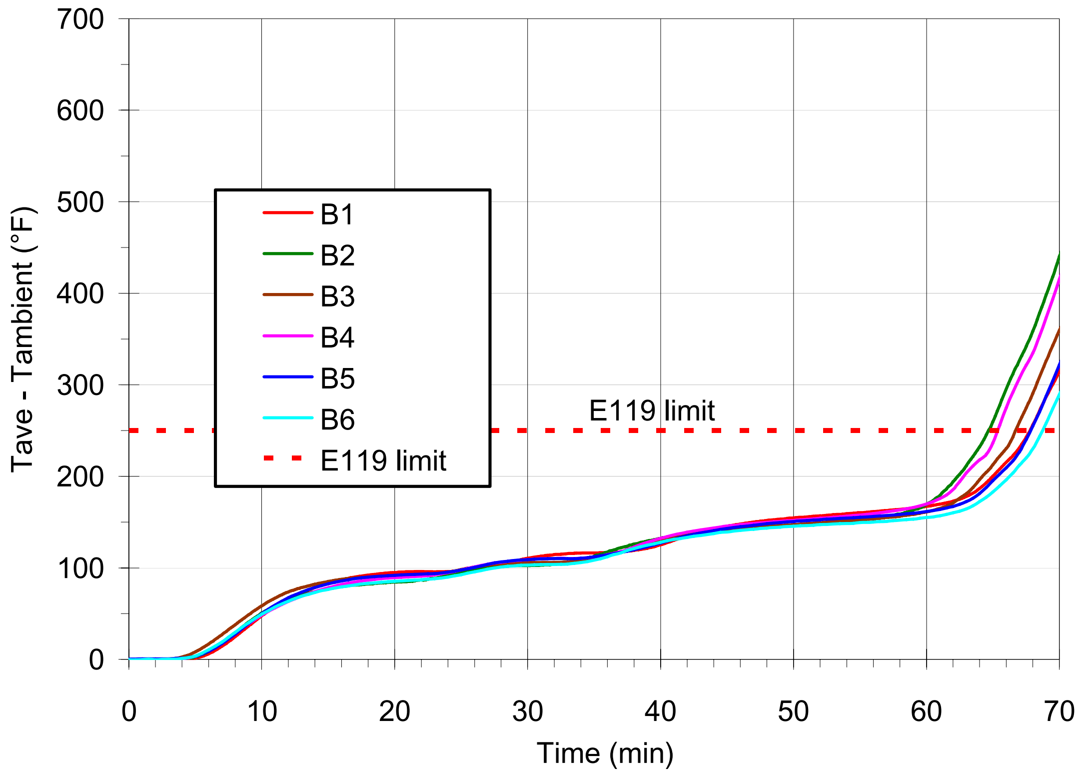


Figure 4B. Average ASTM TC increase on unexposed face of Japanese specimens

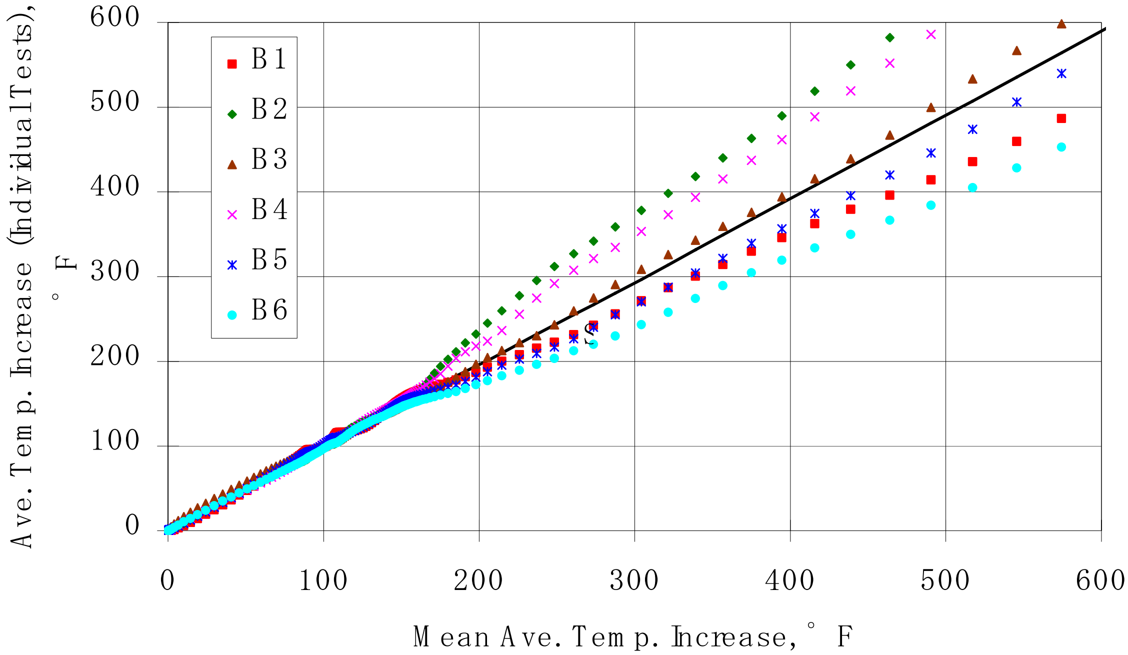


Figure 5B. Individual test unexposed surface average temperature vs. mean of six Japanese tests