U.S. Coast Guard Research and Development Center
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Report No. CG-D-04-03

FIRE TEST PROGRAM TO VERIFY THE CALCULATION METHOD OF DETERMINING THE A-3O AND A-15 THICKNESS OF APPROVED DECK AND BULKHEAD INSULATION MATERIALS

FINAL REPORT
FEBRUARY 2003

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National Technical Information Service, Springfield, VA 22161

Prepared for:

U.S. Department of Transportation
United States Coast Guard
Marine Safety and Environmental Protection (G-M)
Washington, DC 20593-0001

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Technical Report Documentation Page

1. Report No. CG-D-04-03	**2. Government Accession Number** ADA414235	**3. Recipient's Catalog No.**
4. Title and Subtitle Fire Test Program to Verify the Calculation Method of Determining the A-30 and A-15 Thickness of Approved Deck and Bulkhead Insulation Materials		**5. Report Date** February 2003 **6. Performing Organization Code** Project No. 3308.8
7. Author(s) Arthur J. Parker, Jesse J. Beitel, Craig L. Beyler		**8. Performing Organization Report No.** R&DC 565
9. Performing Organization Name and Address Hughes Associates, Inc. 3610 Commerce Drive, Suite 817 Baltimore, MD 21227-1652	U.S. Coast Guard Research and Development Center 1082 Shennecossett Road Groton, CT 06340-6096	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.**
12. Sponsoring Organization Name and Address U.S. Department of Transportation United States Coast Guard Marine Safety and Environmental Protection (G-M) Washington, DC 20593-0001		**13. Type of Report & Period Covered** Final Report **14. Sponsoring Agency Code** Commandant (G-MSE-4) U.S. Coast Guard Headquarters Washington, DC 20593-0001

15. Supplementary Notes

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16. Abstract (MAXIMUM 200 WORDS)

The United States Coast Guard (USCG) required data to either support a proposal to the International Maritime Organization (IMO) or to change existing policy regarding structural insulation materials. Historically, the USCG has required testing of insulation materials for use in an A-60 assembly (baseline thickness). Upon successful completion of this testing, a calculation method was applied to determine the insulation thickness required for A-30 and A-15 rated assemblies. The calculation method was that for an A-30 assembly, 75 percent of the A-60 insulation thickness was used and for an A-15 assembly, 50 percent of the A-60 insulation thickness was used.

A series of bulkhead and deck fire tests was conducted to develop the required test data to evaluate the validity of this calculation method. Each deck and bulkhead test assembly was comprised of six test samples: two baseline thickness, two 75 percent of baseline thickness, and two 50 percent of baseline thickness samples. All samples were nominally 0.9 m (3 ft) square. Comparison of the test results with calculated times to exceed the temperature limits using the underlying heat transfer principles indicated that the calculation method is adequate. Heat transfer modeling of the tested assemblies was conducted to numerically reduce the thickness of each insulation material to fit as closely as possible, the appropriate 60, 30, and 15 minutes of fire resistance requirements. Analysis of the reduced thicknesses using the basic heat transfer principles has determined that the calculation method is adequate.

17. Key Words IMO, insulation materials, A-60, A-30, A-15, bulkheads, decks, heat transfer testing		**18. Distribution Statement** This document is available to the U.S. public through the National Technical Information Service, Springfield, VA 22161	
19. Security Class (This Report) UNCLASSIFIED	**20. Security Class (This Page)** UNCLASSIFIED	**21. No of Pages** 99	**22. Price**

Form DOT F 1700.7 (8/72) Reproduction of form and completed page is authorized.

EXECUTIVE SUMMARY

Structural insulations are used to provide fire resistance properties to structural members (i.e., decks and bulkheads) so they will form barriers to prevent the spread of a fire. Historically, the U. S. Coast Guard (USCG) has required testing of insulation materials at the thickness needed for use in an A-60 assembly. Upon successful completion of this testing, a calculation method was applied to determine the insulation thickness required for A-30 and A-15 rated assemblies. The calculation method was that for an A-30 assembly, 75 percent of the A-60 insulation thickness can be used, and for an A-15 assembly, 50 percent of the A-60 insulation thickness can be used.

"A" class divisions are defined as divisions formed by suitably stiffened bulkheads and decks which are constructed of steel or other equivalent materials and are constructed so as to be capable of preventing the passage of smoke and flame for a minimum one-hour period. Specific bulkheads and decks are required to be insulated with an approved non-combustible material which will limit the average temperature rise on the unexposed side to no more than 140 ºC (250 ºF) above the original temperature. The insulation is also required to limit the temperature at any one point, including any joint, to no more than 180 ºC (325 ºF) above the original temperature. The insulated assemblies are required to demonstrate these characteristics for the following times: a class "A-60" for a minimum of 60 minutes, a class "A-30" for a minimum of 30 minutes, and a class "A-15" for a minimum of 15 minutes.

The calculation method for insulation thicknesses has its basis in the basic heat conduction equations. The concept was proposed to the International Maritime Organization (IMO) but it was not accepted because it appears that the test data to support this calculation method was not available. In order to proceed with the proposal to IMO, the necessary supporting data had to be generated.

Recent changes to the method of testing bulkheads and decks have been formalized in the International Code for Application of Fire Test Procedures (FTP Code). The FTP Code changed how the insulations were tested and greatly increased the number of required tests beyond what the USCG has required before.

The USCG needed to develop data to verify the calculation method under the International Code for Application of Fire Test Procedures (FTP Code) and provide the data in support for a proposal to IMO. To develop data specific to the testing of structural materials, four insulation materials (three batt/blanket type materials and one spray-applied fiber material) were installed on small-scale deck and bulkhead test samples. Each insulation material was applied to the test samples at the USCG approved baseline thickness. The calculation method was then applied to determine the reduced thicknesses needed for A-30 and A-15 divisions. Four bulkhead tests (vertical tests) and four deck tests (horizontal tests) were conducted for a total of eight tests. Each deck and bulkhead test assembly was comprised of six small-scale insulated test samples, each nominally 0.91 x 0.91 m (3 ft x 3 ft) in size and did not contain stiffeners. Each bulkhead and deck assembly included duplicate test samples of A-60, A-30 and A-15 insulation. By testing the three variations simultaneously, possible furnace control factors were eliminated from the test series. For the bulkhead tests, the uninsulated side of the small-scale assemblies was exposed to the fire (i.e., insulation on the unexposed face). In the deck tests, the insulated side was exposed to the fire. All testing was conducted in general accordance with Part 3 – Tests for "A," "B," and "F" Class Divisions of Annex 1 (Fire Test Procedures) of the FTP Code.

The results of the fire tests indicated that for bulkhead insulation materials tested at a thickness corresponding to 50 percent of the baseline thickness (i.e., expected to provide a minimum of 15 minutes of fire resistance), the average time to exceed the temperature limits was 24 ±6 minutes. For deck insulation materials, the average time to exceed the A-15 temperature limits was 44 ± 4 minutes. Bulkhead insulation materials tested at a thickness corresponding to 75 percent of the baseline thickness (i.e., expected to provide a minimum of 30 minutes of fire resistance) averaged a time to exceed the temperature limits of 44 ± 4 minutes. For the deck insulation materials, the average time to exceed the A-30 temperature limits was 56 ± 7 minutes. This indicated that application of the calculation method was adequate and conservative. Some A-60 thicknesses may pass the FTP Code tests with varying degrees of conservatism. For example, one manufacturer's insulation may pass the test at 62 minutes while another may pass at 69 minutes. In order to address the inherent conservatism due to the insulation thickness, an effort was undertaken using a finite difference heat transfer model to "optimize" the insulation thickness, based on the test results.

A one-dimensional heat transfer analysis was performed to calculate the unexposed surface temperature for each insulation sample. This analysis involved modeling the time-dependent temperature response of the insulation/steel sample to a thermal insult provided by the furnace (i.e., IMO time/temperature curve). The heat transfer model was initially calibrated using the baseline insulation thickness test data. Once an adequate simulation was achieved, the insulation thickness was modified to correspond to the testing thicknesses and the new time-dependent temperature calculated. No other model parameters were changed.

Examination of the predicted times to failure compared to the tested times to failure indicated that the computer model was capable of closely predicting the heat transfer through the insulation material. Adjustments to the insulation thickness were performed to achieve a balance between the insulation thickness and the predicted time to exceed the temperature limits. The goal of this part of the modeling effort was to determine the appropriate insulation thickness required to provide 15 minutes, 30 minutes, and 60 minutes of fire resistance. Application of the calculation method to the baseline 60 minutes insulation thickness (and assuming this value was a constant), the 50 percent and 75 percent insulation thickness were calculated. The calculated calculation method insulation thicknesses were within 10 mm (0.4 inch) of the “optimized” 50 percent and 75 percent of baseline insulation thicknesses, indicating that the calculation method remains adequate. The developed data shows that the current calculation method adequately predicts 50 percent and 75 percent of baseline insulation thickness, given an approved baseline insulation thickness and does not require any adjustment.

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LIST OF ACRONYMS

B.T.	USCG Approved Baseline Thickness (i.e., A-60)
FTP	Fire Test Procedures
IMO	International Maritime Organization
OPL	Omega Point Laboratories, Inc.
USCG	United States Coast Guard
75 percent of B.T.	75 percent of USCG Approved Baseline Thickness (i.e., A-30)
50 percent of B.T.	50 percent of USCG Approved Baseline Thickness (i.e., A-15)

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1.0 INTRODUCTION

Structural insulations are used to provide fire resistance properties to structural members (i.e., decks and bulkheads) so they will form barriers to prevent the spread of a fire. Historically, the U. S. Coast Guard (USCG) has required testing of insulation materials at the thickness needed for use in an A-60 assembly. Upon successful completion of this testing, a calculation method was applied to determine the insulation thickness required for A-30 and A-15 rated assemblies. The calculation method was that for an A-30 assembly, 75 percent of the A-60 insulation thickness can be used, and for an A-15 assembly, 50 percent of the A-60 insulation thickness can be used.

"A" class divisions are defined as divisions formed by suitably stiffened bulkheads and decks which are constructed of steel or other equivalent materials and are constructed so as to be capable of preventing the passage of smoke and flame for a minimum one-hour period. Specific bulkheads and decks are required to be insulated with an approved non-combustible material which will limit the average temperature rise on the unexposed side to no more than 140 ºC (250 ºF) above the original temperature. The insulation is also required to limit the temperature at any one point, including any joint, to no more than more than 180 ºC (325 ºF) above the original temperature. The insulated assemblies are required to demonstrate these characteristics for the following times: a class "A-60" for a minimum of 60 minutes, a class "A-30" for a minimum of 30 minutes, and a class "A-15" for a minimum of 15 minutes [IMO SOLAS, 1997].

This concept was proposed to the International Maritime Organization (IMO), but the test data to support this calculation method was not available. In order to proceed with the proposal to IMO, the necessary supporting data had to be generated.

The calculation method for insulation thicknesses has its basis in the basic heat conduction equations. The solutions for a one-dimensional heat transfer through an insulation thickness is primarily dependent upon the non-dimensional Fourier constant which is expressed as:

$$\frac{x}{\sqrt{\alpha t}} \tag{1}$$

where x is the thickness of the insulation, α is the thermal diffusivity (m^2/s), and t is time. The Fourier number allows for the comparison of a characteristic body dimension (i.e., thickness) with an approximate temperature wave penetration depth at a given time [Holman, 1990]. In the Fourier number given in Equation 1, the thermal diffusivity can be assumed constant for a given insulation material.

In this application of the calculation method, the unexposed surface temperature is reached at a constant value of the Fourier number; or for a single insulation material, a constant value for $x/\sqrt{t}$.

Application of the Fourier number to develop the calculation method is demonstrated below. Assuming $x/\sqrt{t}$ is constant, the ratio of an insulation thickness providing 30 minutes of thermal resistance to a baseline insulation providing 60 minutes can be expressed as:

$$\frac{x_{30}}{\sqrt{30}} = \frac{x_{60}}{\sqrt{60}} \tag{2}$$

Re-arranging terms, Equation 2 becomes:

$$\frac{x_{30}}{x_{60}} = \frac{5.477}{7.746} = 0.70 \text{ or } 70 \text{ percent} \tag{3}$$

Similarly, the ratio of an insulation thickness providing 15 minutes of thermal resistance to a baseline insulation providing 60 minutes can be expressed as:

$$\frac{x_{15}}{\sqrt{15}} = \frac{x_{60}}{\sqrt{60}} \tag{4}$$

Re-arranging terms, Equation 4 yields:

$$\frac{x_{15}}{x_{60}} = \frac{3.873}{7.746} = 0.50 \text{ or } 50 \text{ percent} \tag{5}$$

Presumably, the USCG conservatively adjusted the calculation method to require an A-30 insulation be 75 percent of the approved A-60 insulation thickness for ease of calculation. This illustrates that the calculation method is founded in the fundamentals of heat transfer theory and is not a mere ad-hoc notion.

Recent changes to the method of testing bulkheads and decks has been formalized via the International Code for Application of Fire Test Procedures (FTP Code) [IMO, 1993]. The FTP Code specifies limits with respect to temperatures on the unexposed surface, as well as test procedures whereby bulkheads are tested in the most onerous manner, i.e., with the insulation on the unexposed surface of the test sample. Decks currently remain tested with the insulation on the exposed surface of the test sample.

The USCG needed to develop data to verify the calculation method under the FTP Code test procedures and provide the data in support for their proposal. To meet this goal, a series of insulated bulkhead and deck tests was conducted to evaluate the thermal performance of various USCG approved insulation materials.

2.0 OBJECTIVE

The objective of this program was to develop data specific to the testing of structural insulation materials, applied on simulated decks and bulkheads, to assess the validity of the USCG calculation method for the thickness of insulation materials. Duplicate small-scale A-60 (referred to as baseline thickness"), A-30 (75 percent of the baseline thickness), and A-15 (50 percent of the baseline thickness) insulated test samples were tested in accordance with the FTP Code. The thermal performance of the insulation materials was determined by testing until thermal failure (temperature rise) of the insulation materials occurred. Analysis of these data determined the validity of the existing calculation method for insulation thickness currently being used by the USCG and proposed to IMO. A numerical heat transfer analysis was also conducted to verify the current calculation method for insulation thickness for the insulation materials used.

3.0 APPROACH

To meet the objectives stated above, four insulation materials (three batt/blanket type materials and one spray-applied fiber material) were installed on small-scale deck and bulkhead test samples. Each insulation material was applied to the test samples at the A-60 baseline thickness (B.T.), 75 percent of the baseline thickness (A-30), and 50 percent of the baseline thickness (A-15). All insulation thicknesses were tested in duplicate in a common test assembly. The test samples designated as bulkheads were tested with the insulation on the unexposed face. The test samples designated as decks were tested with the insulation on the exposed face. All tests were conducted for a minimum of 60 minutes or until the average failure temperature of the unexposed surface thermocouples was exceeded, whichever was greater. The test criterion (i.e., time to exceed the temperature limits) was as specified in the IMO Resolution A.754(18), Section 9.1.1. The temperature limits utilized in this program were: the average unexposed surface face temperature rise above the ambient starting temperature was 140 °C (250 °F) and a single point temperature rise by any unexposed surface face thermocouple was 180 °C (325 °F).

4.0 FIRE TESTING

4.1 Test Setup

This test program consisted of evaluating the performance of four insulation materials installed on simulated steel decks and steel bulkheads. The four thermal insulation materials evaluated in this test program are shown in table 1.

Table 1. Tested USCG approved thermal insulation materials.

Insulation Material	Classification	Configuration	Thickness mm (in)
Mineral fiber marine board	A-60	Bulkhead	76 (3)
Mineral fiber marine board	A-60	Deck	51 (2)
Ceramic fiber	A-30	Bulkhead	38 (1.5)
Ceramic fiber	A-60	Deck	38 (1.5)
Foil-faced mineral fiber	A-60	Bulkhead	76 (3)
Foil-faced mineral fiber	A-60	Deck	51 (2)
Spray-applied fiber	A-60	Bulkhead	51 (2)
Spray-applied fiber	A-60	Deck	38 (1.5)

Four bulkhead tests (vertical tests) and four deck tests (horizontal tests) were conducted for a total of eight tests. Each deck and bulkhead test assembly was comprised of six small-scale insulated test samples. The six small-scale test samples contained in each full-scale test assembly consisted of two samples insulated at the USCG baseline thickness, two samples insulated at 75 percent of the USCG approved baseline thickness, and two samples insulated at the 50 percent of the USCG approved baseline thickness. The specific test setup is shown in figure 1. The small-scale test samples were constructed using 4.8-mm (0.19-inch) thick steel plate, nominally 0.91 x 0.91 m (3 ft x 3 ft) in size and did not contain stiffeners. Perimeter reinforcement was included to facilitate mounting of the small-scale test samples into each full-scale test assembly. Each test sample was thermally protected with the insulation material applied to the appropriate face of each test sample.

Figure 1. Test Fixture.

Instrumentation of each of the small-scale test samples consisted of a total of ten thermocouples. Five thermocouples were placed on the steel surface at the interface between the steel and the insulation material. The remaining five thermocouples were installed on the unexposed face of the test sample in accordance with the IMO test procedures. The exact location of all thermocouples are provided in the OPL final report [OPL, 2002], which is available upon request.

For the bulkhead tests, the uninsulated side of the small-scale assemblies was exposed to the fire (i.e., insulation on the unexposed face). In the deck tests, the insulated side was exposed to the fire. All testing was conducted in general accordance with Part 3 – Tests for “A,” “B,” and “F” Class Divisions of Annex 1 (Fire Test Procedures) of the International Code for Application of Fire Test Procedures (FTP Code) [IMO, 1993]. The one exception to this test procedure was the use of smaller size samples than those specified in the FTP Code.

A letter/number designation system was utilized to identify each of the 48 small-scale test samples. Bulkhead samples were designated with a “B” followed by a sequential number. The bulkhead samples were identified as B1, … through B24. Similarly, the deck samples were designated with a “D” followed by a sequential number. The deck samples were identified as D1, … through D24. Each bulkhead and deck designation corresponded to a particular insulation material and thickness. Table 2 provides the sample designation, thickness tested, and corresponding insulation material.

Table 2. Bulkhead and deck sample designations.

Sample Designation		Sample Rating	Insulation Material
Bulkhead	Deck		
B1, B2	D1, D2	A-60	Spray-applied material
B3, B4	D3, D4	A-30	Spray-applied material
B5, B6	D5, D6	A-15	Spray-applied material
B7, B8	D7, D8	A-60	Mineral fiber marine board
B9, B10	D9, D10	A-30	Mineral fiber marine board
B11, B12	D11, D12	A-15	Mineral fiber marine board
B13, B14	D13, D14	A-60	Foil-faced mineral fiber marine board
B15, B16	D15, D16	A-30	Foil-faced mineral fiber marine board
B17, B18	D17, D18	A-15	Foil-faced mineral fiber marine board
B19, B20	D19, D20	A-60	Ceramic fiber insulation material
B21, B22 [1]	D21, D22	A-30	Ceramic fiber insulation material
B23, B24	D23, D24	A-15	Ceramic fiber insulation material

[1] USCG approved baseline thickness for ceramic fiber bulkhead only

Determination of the thickness for each sample was based on starting with an existing baseline thickness (i.e., A-60), as recommended by the insulation manufacturers and developed by conducting a full-scale bulkhead or deck test in accordance with IMO Resolution A.754 (18). The calculation method for insulation thickness was then applied to determine the A-30 and A-15 insulation thickness for each insulation material.

The ceramic fiber material utilized in this test program was only tested and certified for use as an A-30 bulkhead at 38 mm (1.5 inches). To determine the "A-60" (133 percent of the baseline thickness) insulation thickness, the calculation method was applied assuming that the 38 mm (1.5 inches) thickness was 75 percent of the required A-60 thickness. A test thickness of 51 mm (2 inches) was calculated and used for the A-60 test samples designated B19 and B20. Application of the calculation method in this manner (increasing thickness) provided an opportunity to determine if the calculation method was applicable for increasing thicknesses, not only decreasing thicknesses, as it has been historically applied.

Prior to conducting the testing, samples were obtained from extra mineral fiber marine board, foil-faced mineral fiber marine board, and ceramic fiber insulation materials to document sample thicknesses and densities. Samples of the spray-applied fiber insulation material were not able to be collected prior to testing. The insulation thickness was, however, weighed and measured prior to testing. The weight of the installed spray-applied insulation was initially calculated by determining the weight of the installed insulation. This was calculated as the pre-test weight of the steel sample and insulation minus the post-test weight of the cleaned steel sample. Using these data and the measured thickness of the insulation, the actual density was calculated. Table 3 provides the nominal and calculated density and thicknesses for all four insulation materials tested.

Review of table 3 indicated the measured thicknesses of the spray-applied materials were very close to the nominal thickness for all samples. The average density of the materials, however, ranged from 319 to 460 kg/m^3 (20 to 29 pcf), approximately 2 to 3 times the nominal density of 160 kg/m^3 (10 pcf). The reason for the high sample densities has not been determined. However, the intent of this test program was to provide relative performance data for approved insulation materials; therefore, these significant density differences were not expected to adversely impact the quality of the generated data.

The measured thicknesses and densities for the mineral fiber marine board and foil-faced mineral fiber marine board samples were determined to be very close to the nominal thicknesses and densities. These materials are essentially rigid and machine manufactured, therefore, these values were expected. The slightly higher average measured densities for the foil-faced mineral fiber marine board samples included the 0.05 mm (2 mil) aluminum foil-facing, which contributed to the increased sample weight and density.

Table 3. Calculated sample thicknesses and densities.

Insulation Material	Sample Orientation	Nominal Thickness mm (in)	Nominal Density kg/m^3 (pcf)	Measured Sample Size			Measured Weight kg (lbs.)	Calculated Density kg/m^3 (pcf)
				Width mm (in)	Length mm (in)	Thickness mm (in)		
Spray-applied fiber[1]	Deck	38 (1.5)[2]	160 (10)	897 (35.3)	895.4 (35.25)	35.6 (1.4)	13.1 (29.0)	460.1 (28.7)
Spray-applied fiber[1]	Deck	29 (1.125)	160 (10)	897 (35.3)	895 (35.25)	30 (1.16)	8.2 (18.0)	344.8 (21.5)
Spray-applied fiber[1]	Deck	19 (0.75)	160 (10)	897 (35.3)	895 (35.25)	18 (0.72)	6.6 (14.5)	448.6 (28.0)
Spray-applied fiber[1]	Bulkhead	51 (2)[2]	160 (10)	897 (35.3)	895 (35.25)	50 (1.97)	12.8 (28.3)	319.5 (20.0)
Spray-applied fiber[1]	Bulkhead	38 (1.5)	160 (10)	897 (35.3)	895 (35.25)	41 (1.61)	10.8 (23.8)	328.7 (20.5)
Spray-applied fiber[1]	Bulkhead	25 (1)	160 (10)	897 (35.3)	895 (35.25)	26 (1.02)	8.4 (18.4)	402.0 (25.1)
Mineral fiber marine board	Deck	51 (2)[2]	112 (7)	203 (8)	203 (8)	51 (2)	0.3 (0.6)	125.0 (7.8)
Mineral fiber marine board	Deck	38 (1.5)	112 (7)	254 (10)	254 (10)	35 (1.38)	0.3 (0.6)	113.7 (7.1)
Mineral fiber marine board	Deck	25 (1)	112 (7)	254 (10)	254 (10)	25 (1)	0.2 (0.4)	105.7 (6.6)
Mineral fiber marine board	Bulkhead	76 (3)[2]	112 (7)	152 (6)	203 (8)	76 (3)	0.3 (0.6)	120.2 (7.5)
Mineral fiber marine board	Bulkhead	57 (2.25)	112 (7)	254 (10)	152 (6)	57 (2.25)	0.3 (0.6)	126.6 (7.9)
Mineral fiber marine board	Bulkhead	38 (1.5)	112 (7)	254 (10)	254 (10)	35 (1.38)	0.3 (0.6)	129.8 (8.1)
Foil-faced mineral fiber	Deck	51 (2)[2]	112 (7)	914 (36)	914 (36)	51 (2)	4.9 (10.9)	116.9 (7.3)
Foil-faced mineral fiber	Deck	38 (1.5)	112 (7)	914 (36)	914 (36)	35 (1.375)	4.0 (8.8)	136.2 (8.5)
Foil-faced mineral fiber	Deck	25 (1)	112 (7)	914 (36)	914 (36)	25 (1)	2.5 (5.5)	116.9 (7.3)
Foil-faced mineral fiber	Bulkhead	76 (3)[2]	112 (7)	889 (35)	914 (36)	76 (3)	7.7 (16.9)	123.4 (7.7)
Foil-faced mineral fiber	Bulkhead	57 (2.25)	112 (7)	902 (35.5)	914 (36)	57 (2.25)	5.5 (12.2)	116.9 (7.3)
Foil-faced mineral fiber	Bulkhead	38 (1.5)	112 (7)	914 (36)	914 (36)	35 (1.38)	4.0 (8.8)	136.2 (8.5)
Ceramic fiber	Deck	38 (1.5)[2]	96 (6)	254 (10)	254 (10)	45 (1.75)	0.3 (0.6)	91.3 (5.7)
Ceramic fiber	Deck	25 (1)	96 (6)	254 (10)	254 (10)	32 (1.25)	0.2 (0.4)	83.3 (5.2)
Ceramic fiber	Deck	19 (0.75)	96 (6)	197 (7.75)	210 (8.25)	19 (0.75)	0.1 (0.2)	104.1 (6.5)
Ceramic fiber	Bulkhead	51 (2)	128 (8)	152 (6)	152 (6)	57 (2.25)	0.2 (0.4)	133.0 (8.3)
Ceramic fiber	Bulkhead	38 (1.5)[2]	128 (8)	203 (8)	254 (10)	48 (1.19)	0.2 (0.5)	99.3 (6.2)
Ceramic fiber	Bulkhead	25 (1)	128 (8)	254 (10)	254 (10)	30 (1.19)	0.3 (0.6)	142.6 (8.9)

[1] Average of two samples

[2] USCG approved baseline thickness

The reported measured thicknesses and densities for the ceramic fiber material were made on relatively small samples (nominally 254 mm (10 inches) square). Discussions with test laboratory personnel, familiar with verifying production material properties, indicated that the typical method for verifying the manufactured ceramic fiber material properties (thickness and density) was to weigh entire rolls of blanket, not small samples, and to measure the insulation thickness at numerous places along the length and width of the roll. The rolling and handling process may have an effect on the thickness of the sample, translating into variability in the end product density when the small-scale sample was weighed and measured. The ceramic fiber insulation material utilized in this test program was obtained from a manufacturer who participates in a recognized listing and labeling program. The variability in the measured density and thickness would have negligible effect on the test results.

4.2 Fire Test Results

All eight tests were conducted during the weeks of 14 January and 21 January 2002. Testing was organized such that each insulation material was tested as a bulkhead and deck insulation material on the same day. Table 4 provides the test order for both bulkhead and deck testing as well as the associated insulation material.

Table 4. Insulation material test order.

Bulkhead Test No.	Deck Test No.	Insulation Material	Test Date
1	1	Mineral fiber marine board	14 January 2002
2	2	Foil-faced mineral fiber marine board	16 January 2002
3	3	Ceramic fiber insulation	18 January 2002
4	4	Spray-applied insulation	22 January 2002

The spray-applied fiber insulation material samples were prepared in mid-December, 2001 and allowed to cure for a minimum of 28 days prior to testing. The remaining three insulation materials were installed onto the test samples prior to testing using welded copper pins and speed washers, as described in the OPL final report [OPL, 2002].

4.2.1 Mineral Fiber Marine Board Bulkhead Test Results (Bulkhead Test 1)

The mineral fiber marine board insulation material bulkhead test was conducted on 14 January 2002. The ambient temperature at the start of the test was 14 °C (57 °F). Based on the ambient temperature, the average unexposed face temperature limit was calculated as 154 °C (309 °F), and the single point temperature limit was calculated as 194 °C (381 °F). The test was continued until all unexposed face temperatures exceeded the average temperature limit.

The mineral fiber marine board currently had a USCG Certificate of Approval at a baseline thickness of 76 mm (3 inches) to provide a minimum of 60 minutes of fire resistance. Application of the calculation method using the approved baseline insulation thickness resulted in the evaluation of an insulation thickness of 57 mm (2.25 inches), corresponding to 75 percent of the baseline thickness, and an insulation thickness of 38 mm (1.5 inches), corresponding to 50 percent of the baseline thickness. Table 5 provides the times to exceed the temperature limits for the six bulkhead samples (designated B7 through B12) tested. The test was terminated after 105 minutes of fire exposure.

Table 5. Mineral fiber marine board bulkhead test results.

Sample Designation	Tested Thickness mm (in)	Time to Exceed Temperature Limits (min)	Average Time to Exceed Temperature Limits (min)
B7	76 (3) [1]	80.1	79.8
B8	76 (3) [1]	79.4	
B9	57 (2.25)	56.7	54.7
B10	57 (2.25)	52.7	
B11	38 (1.5)	23.8	22.6
B12	38 (1.5)	21.4	

[1] USCG Approved Baseline Thickness

A plot of the average unexposed face temperatures as a function of time is provided in figure 2. Each of the three trendlines represent the average unexposed face temperatures for each pair of samples (i.e., average of the ten unexposed face thermocouples total for each pair of samples). Near the end of the test, the test laboratory experienced minor furnace control difficulties. Just prior to a drop in furnace temperature, test sample B8 had exceeded the temperature limit and test sample B7 was approximately 1 to 2 degrees from exceeding the temperature limit. It was determined that if the furnace temperature had not dropped, the time to failure for test sample B7 would have been 80.1 minutes.

4.2.2 Mineral Fiber Marine Board Deck Test Results (Deck Test 1)

The mineral fiber marine board insulation material deck test was conducted on 14 January 2002. At the start of the test, the ambient temperature was 19 °C (66 °F). Based on the ambient temperature, the average unexposed face temperature limit was calculated as 159 °C (318 °F), and the single point temperature limit was calculated as 199 °C (390 °F). The test was continued until all unexposed face temperatures exceeded the average temperature limit.

The mineral fiber marine board currently had a USCG Certificate of Approval as a deck insulation material at a baseline thickness of 51 mm (2 inches) to provide a minimum of 60 minutes of fire resistance. Application of the calculation method using the approved baseline insulation thickness resulted in the evaluation of an insulation thickness of 38 mm (1.5 inches), corresponding to 75 percent of the baseline thickness, and an insulation thickness of 25 mm (1.0 inch), corresponding to 50 percent of the baseline thickness.

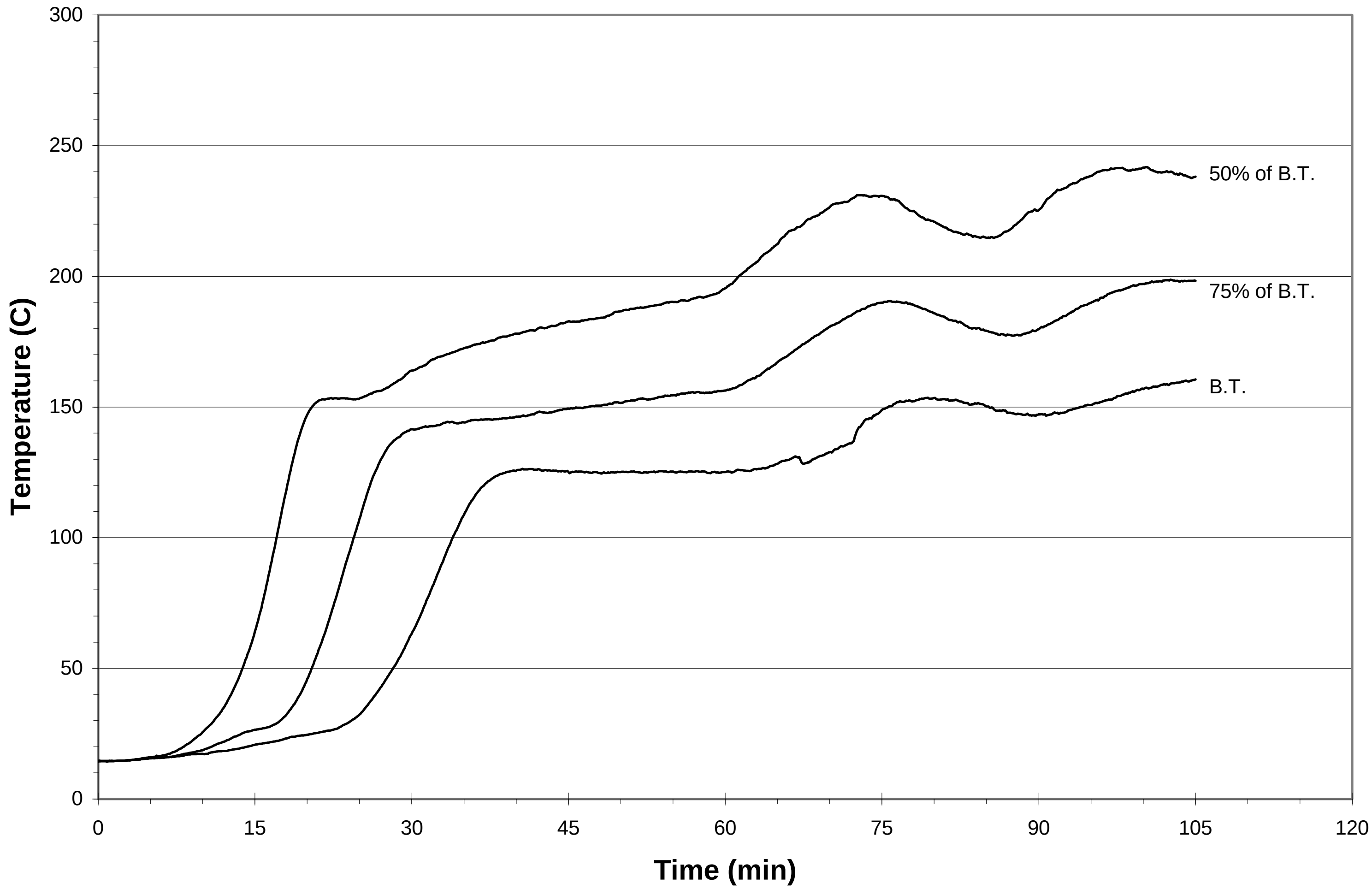

Figure 2. Mineral fiber bulkhead average unexposed surface temperatures.

Table 6 provides the times to exceed the temperature limits for the six deck samples (designated D7 through D12) tested. The test was terminated after 105 minutes of fire exposure.

Table 6. Mineral fiber marine board deck test results.

Sample Designation	Tested Thickness mm (in)	Time to Exceed Temperature Limits (min)	Average Time to Exceed Temperature Limits (min)
D7	51 (2) [1]	98.8	99.5
D8	51 (2) [1]	100.2	
D9	38 (1.5)	59.6	60.2
D10	38 (1.5)	60.8	
D11	25 (1)	43.3	42.0
D12	25 (1)	40.6	

[1] USCG Approved Baseline Thickness

A plot of the average unexposed face temperatures as a function of time is provided in figure 3. Each of the three trendlines in figure 3 represent the average unexposed face temperatures for each pair of samples (i.e., average of the ten unexposed face thermocouples total for each pair of samples).

4.2.3 Foil-faced Mineral Fiber Bulkhead Test Results (Bulkhead Test 2)

The foil-faced mineral fiber insulation material bulkhead test was conducted on 16 January 2002. At the start of the test, the ambient temperature was 14 °C (59 °F). Based on the ambient temperature, the average unexposed face temperature limit was calculated as 154 °C (309 °F), and the single point temperature limit was calculated as 194 °C (381 °F). The test was continued until all unexposed face temperatures exceeded the average temperature limit.

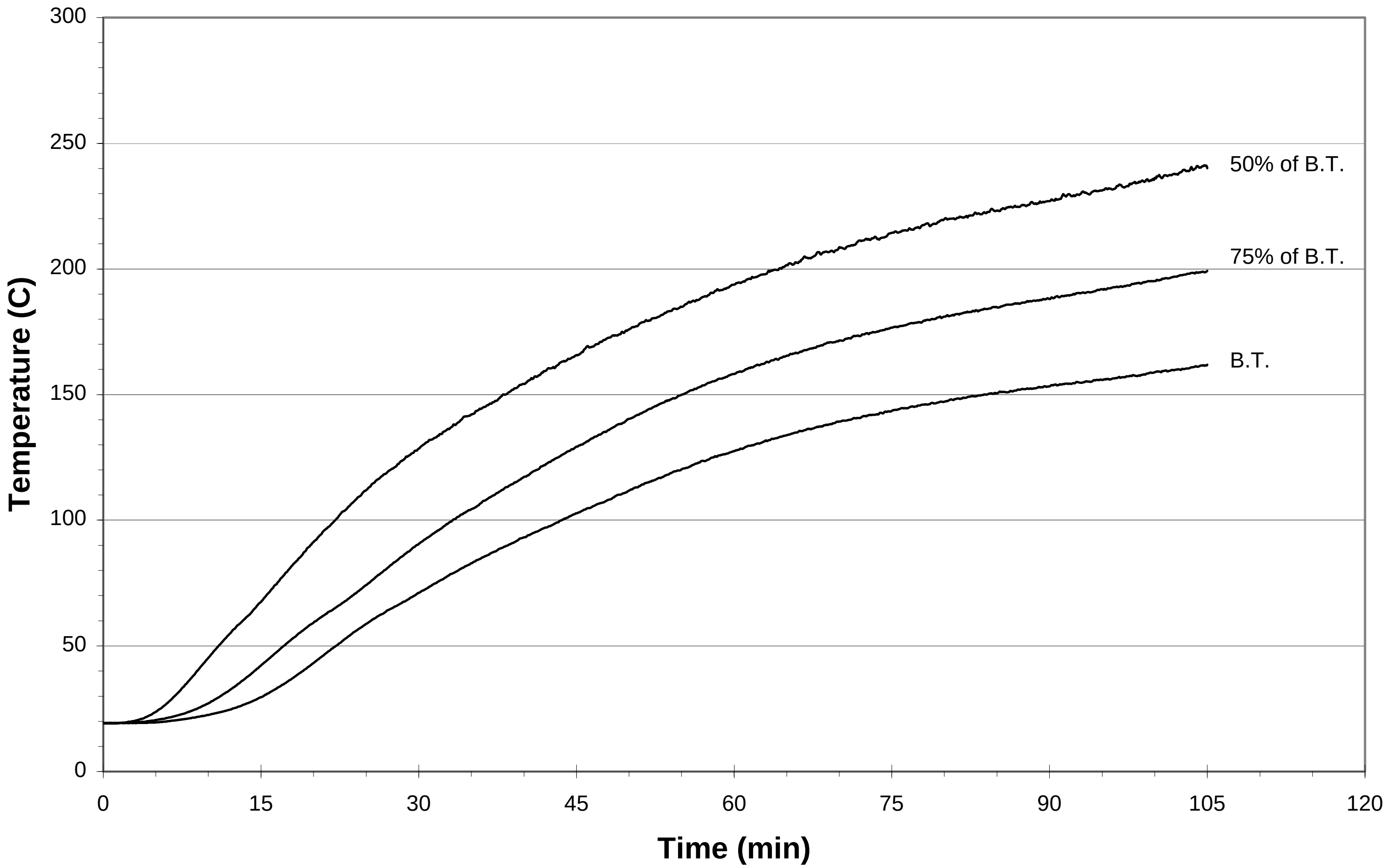

Figure 3. Mineral fiber deck average unexposed surface temperatures.

The aluminum foil-faced mineral fiber marine board did not have a USCG Certificate of Approval for use as a bulkhead insulation material. The base insulation material was, however, identical to the approved unfaced mineral fiber marine board insulation. The USCG approved baseline thickness of 76 mm (3 inches) was used for this test. Application of the calculation method using the baseline insulation thickness of 76 mm (3 inches) resulted in the evaluation of an insulation thickness of 57 mm (2.25 inches), corresponding to 75 percent of the baseline thickness, and an insulation thickness of 38 mm (1.5 inches), corresponding to 50 percent of the baseline thickness. In the bulkhead tests, the insulation material was installed with the foil-face on the unexposed face of the test specimens. Table 7 provides the times to exceed the temperature limits for the six bulkhead samples (designated B13 through B18) tested. The test terminated after 105 minutes of fire exposure.

Table 7. Foil-faced mineral fiber marine board bulkhead test results.

Sample Designation	Tested Thickness mm (in)	Time to Exceed Temperature Limits (min)	Average Time to Exceed Temperature Limits (min)
B13	76 (3) [1]	51.0	52.4
B14	76 (3) [1]	53.7	
B15	57 (2.25)	32.3	32.7
B16	57 (2.25)	33.0	
B17	38 (1.5)	21.0	22.0
B18	38 (1.5)	23.0	

[1] USCG Approved Baseline Thickness

A plot of the average unexposed face temperatures as a function of time is provided in figure 4 for all three pairs of samples (i.e., average of the ten unexposed face thermocouples total for each pair of samples). Approximately 30 minutes into the test, the temperatures on the unexposed face of the baseline and 75 percent of baseline thickness test samples were observed to be noticeably hotter than compared to the previous bulkhead test of the mineral fiber marine board test at the same times. The insulation materials were composed of the same base material, with the only difference being the addition of the foil-facing. Figures 5, 6, and 7 provide a comparison of the average unexposed surface temperatures, for 50 percent of baseline thickness samples, 75 percent of baseline thickness, and, respectively, the baseline thickness for Bulkhead Test No. 1 (unfaced mineral fiber marine board) and Bulkhead Test No. 2 (foil-faced mineral fiber marine board).

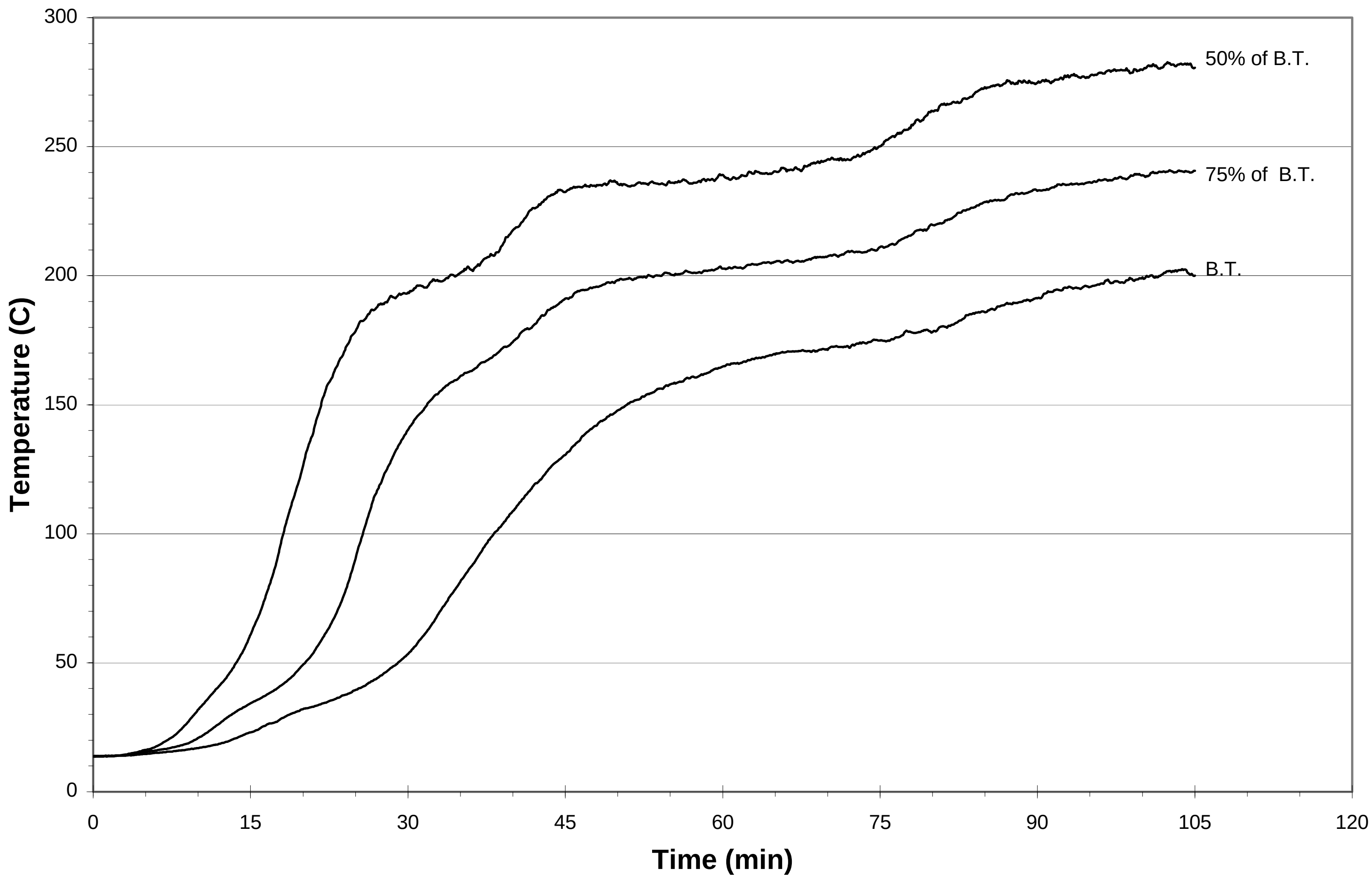

Figure 4. Foil-faced mineral fiber bulkhead average unexposed surface temperatures.

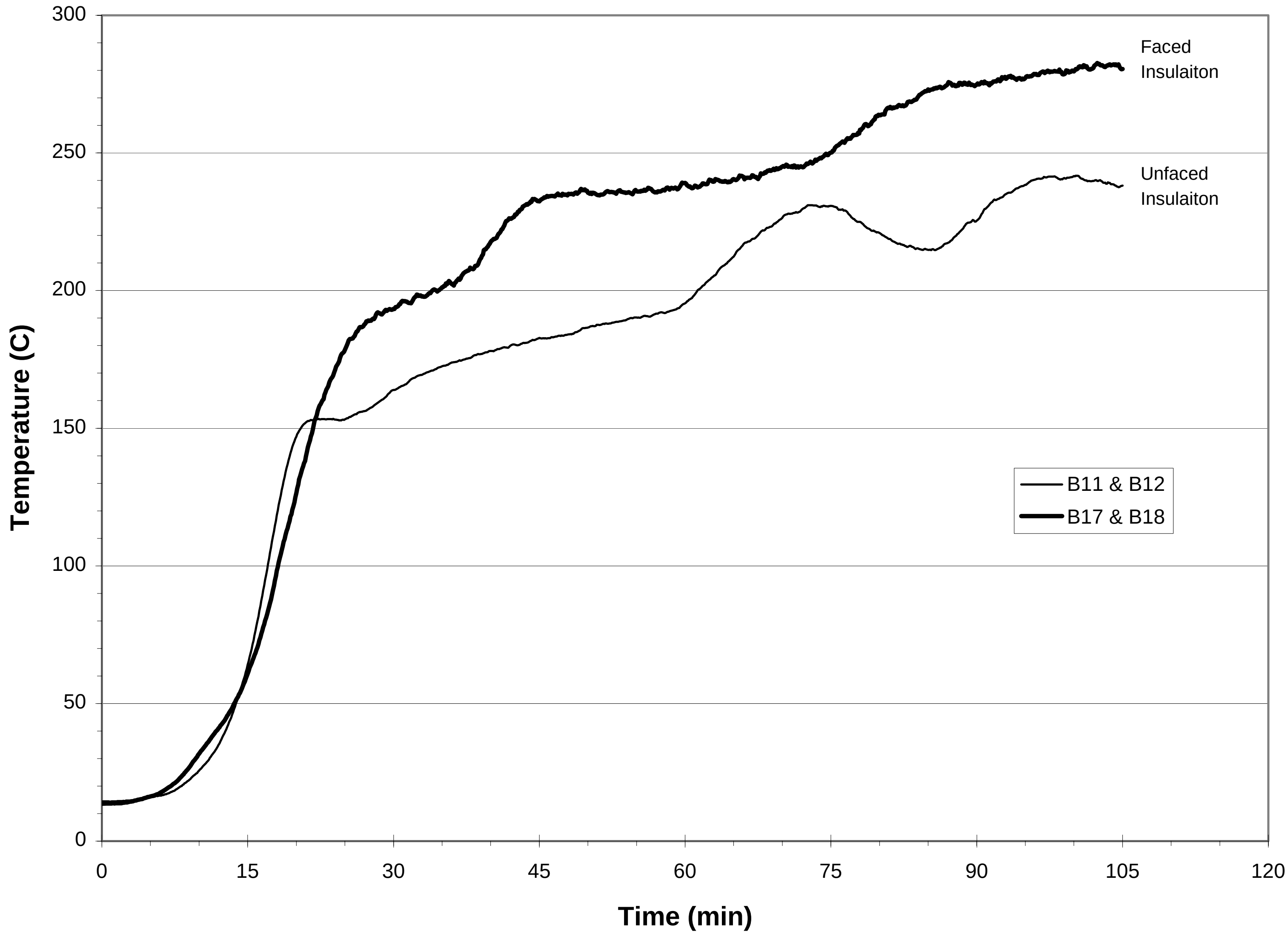

Figure 5. 50 percent of baseline thickness average unexposed surface temperatures (faced & unfaced bulkhead insulation).

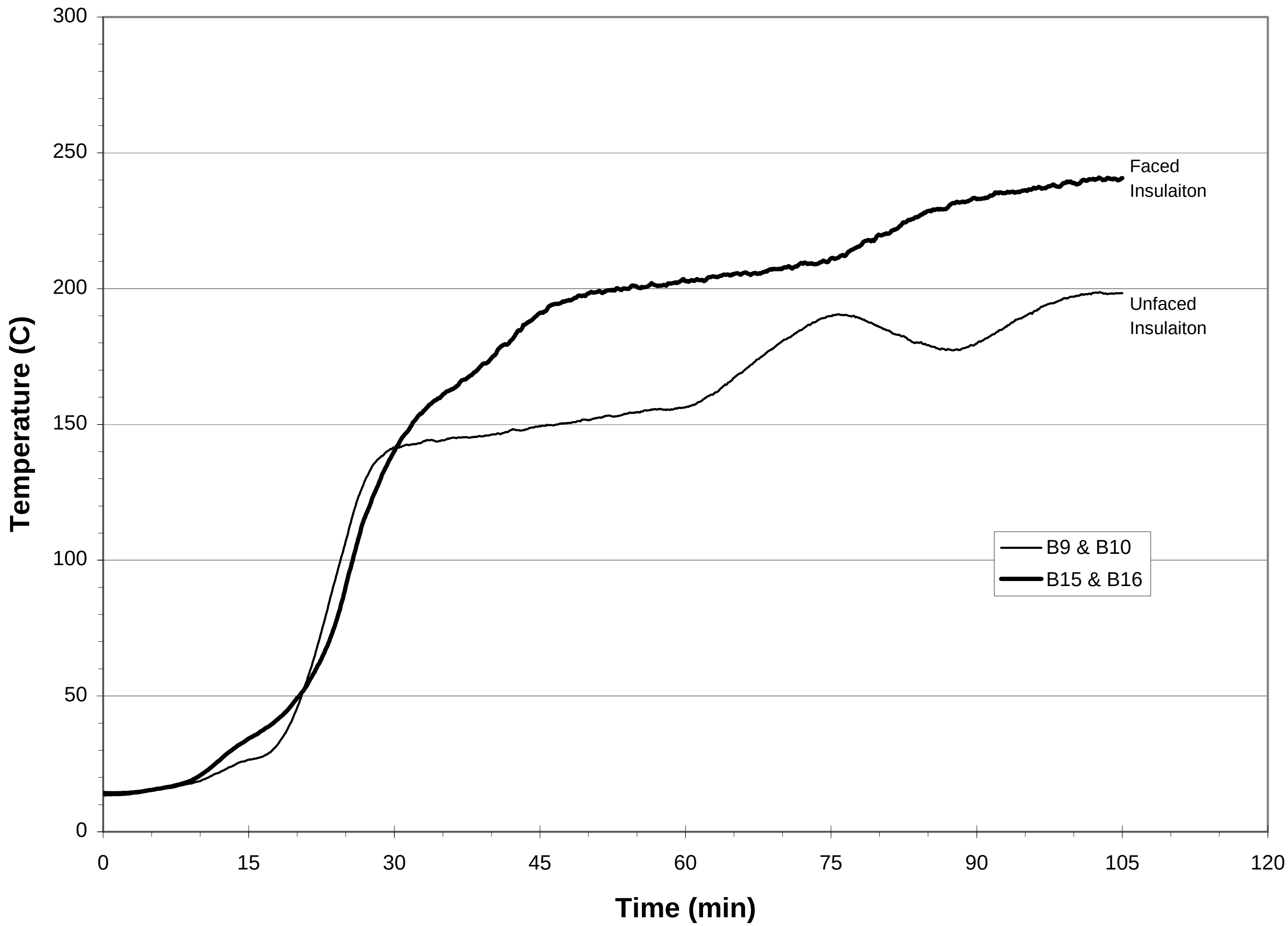

Figure 6. 75 percent of baseline thickness average unexposed surface temperatures (faced and unfaced bulkhead insulation).

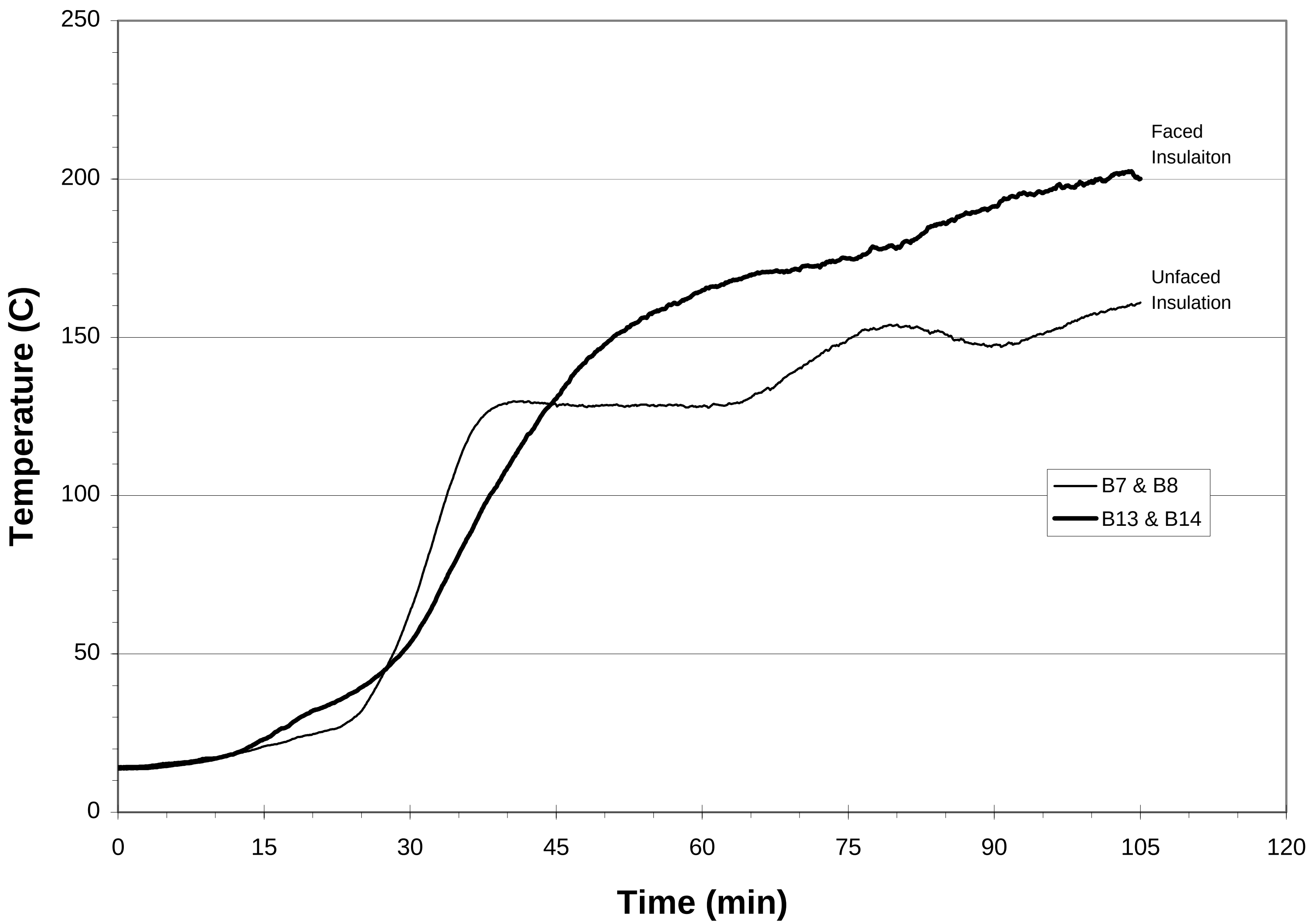

Figure 7. Baseline thickness average unexposed surface temperatures (faced & unfaced bulkhead insulation).

Examination of the temperature traces for the 50 percent of baseline thickness insulation material shown in figure 5 indicates that prior to the average unexposed surface temperatures approaching the average temperature limit of 154 °C (309 °F), the foil-facing has no appreciable effect on the insulation performance. In the test of the 75 percent of baseline thickness insulation materials (figure 6), the temperature rise on the unexposed surfaces of both samples was similar up to approximately 140 °C (284 °F). Above this temperature, the average unexposed temperatures began to significantly deviate. The unfaced insulation material began a somewhat steady-state heat soak phase (as indicated by a period of slower increase of the unexposed face temperatures) while the foil-faced unexposed face temperatures continued to rise dramatically. The foil-faced mineral fiber marine board samples reached the average A-30 temperature limit at approximately 33 minutes, compared to the unfaced mineral fiber marine board which reached the average A-30 temperature limit at approximately 55 minutes. In the test of the A-60 baseline thickness insulation materials (figure 7), the temperature deviations between the average unexposed surface temperatures was evident approximately 28 minutes into the test. At this point in the test, the average unexposed surface temperature of the foil-faced insulation material was slightly lower than measured on the unfaced insulation. The average unexposed surface temperatures of the two materials crossed at approximately 130 °C (266 °F) approximately 45 minutes into the test. Similar to the A-30 thickness, the unfaced insulation material began a more pronounced steady-state heat soak phase while the foil-faced unexposed face temperatures continued to rise dramatically. The foil-faced insulation material exceeded the temperature limits at approximately 52 minutes compared to the unfaced insulation material at approximately 80 minutes.

The effect of the foil-facing on the average unexposed surface temperature is evident from the comparison of results of Bulkhead Test Nos. 1 and 2. It appears that as the insulation thickness increased, to provide the required thermal insulation for a more severe (i.e., longer duration) fire exposure, the foil-facing prevented the heat from dissipating and reflected the heat back into the insulation material, effectively trapping the heat in the sample.

During Bulkhead Test No. 2, a small 100 mm x 100 mm (4 inches x 4 inches) section of foil was cut from the B18 test sample (50 percent of baseline thickness). This was done in an attempt to understand why the times to reach the limiting temperatures were reached quicker in Bulkhead Test No. 2 than in Bulkhead Test No. 1. A portable thermocouple was placed over the now unfaced mineral fiber insulation material to monitor the surface temperatures. It was observed that the temperatures of the unfaced section of mineral fiber was approximately 38 °C (100 °F) cooler than when measured on the foil-facing. This verified that the foil-facing was trapping the heat and not allowing it to dissipate on the unexposed face.

These results indicated that the foil-facing had a pronounced effect on the thermal performance of the insulation material, especially at the longer exposure durations and thicker insulation materials.

4.2.4 Foil-faced Mineral Fiber Deck Test Results (Deck Test 2)

The foil-faced mineral fiber insulation material deck test was conducted on 16 January 2002. At the start of the test, the ambient temperature was 23 °C (72 °F). Based on the ambient temperature, the average unexposed face temperature limit was calculated as 163 °C (325 °F), and the single point temperature limit was calculated as 203 °C (397 °F). The test was continued until all unexposed face temperatures exceeded the average temperature limit.

The foil-faced mineral fiber marine board did not have a USCG Certificate of Approval for use as a deck insulation material. The base insulation was, however, identical to the approved unfaced mineral fiber marine board insulation. The USCG approved baseline thickness of 51 mm (2 inches) was used for this test. Application of the calculation method using the approved baseline insulation thickness of 51 mm (2 inches) resulted in the evaluation of an insulation thickness of 38 mm (1.5 inches), corresponding to 75 percent of the baseline thickness, and an insulation thickness of 25 mm (1.0 inch), corresponding to 50 percent of the baseline thickness. In the deck tests, the material was installed such that the foil-faced was exposed to the fire. Table 8 provides the times to exceed the temperature limits for the six deck samples (designated D13 through D18) tested. The test was terminated after 105 minutes of fire exposure.

Table 8. Foil-faced mineral fiber deck test results.

Sample Designation	Tested Thickness mm (in)	Time to Exceed Temperature Limits (min)	Average Time to Exceed Temperature Limits (min)
D13	51 (2) [1]	90.4	90.2
D14	51 (2) [1]	90.0	
D15	38 (1.5)	63.3	63.8
D16	38 (1.5)	64.3	
D17	25 (1)	46.2	47.9
D18	25 (1)	49.5	

[1] USCG Approved Baseline Thickness

A plot of the average unexposed face temperatures as a function of time is provided in figure 8. Each of the three trendlines in figure 8 represent the average unexposed face temperatures for each pair of samples (i.e., average of the ten unexposed face thermocouples total for each pair of samples). Comparison of the average unexposed surface temperatures of the faced and unfaced mineral fiber marine board insulation tested as deck insulation materials for each of the three pairs of samples is provided in figures 9, 10, and 11, respectively. The temperature traces shown in figures 9, 10, and 11 show only slight temperature variations. This indicated the foil-facing on the exposed face of test samples D13 through D18 had negligible effect on the insulation performance (i.e., foil burned off). The slight variations shown in the average surface temperature traces are likely due to slight variations within the test samples themselves (i.e., variations in steel thickness, insulation thickness and density, etc.) and in the conduct of the fire exposure test (i.e., average furnace temperature, pressure, etc.).

4.2.5 Ceramic Fiber Bulkhead Test Results (Bulkhead Test 3)

The ceramic fiber blanket insulation material bulkhead test was conducted on 18 January 2002. At the start of the test, the ambient temperature was 12 °C (54 °F). Based on the ambient temperature, the average unexposed face temperature limit was calculated as

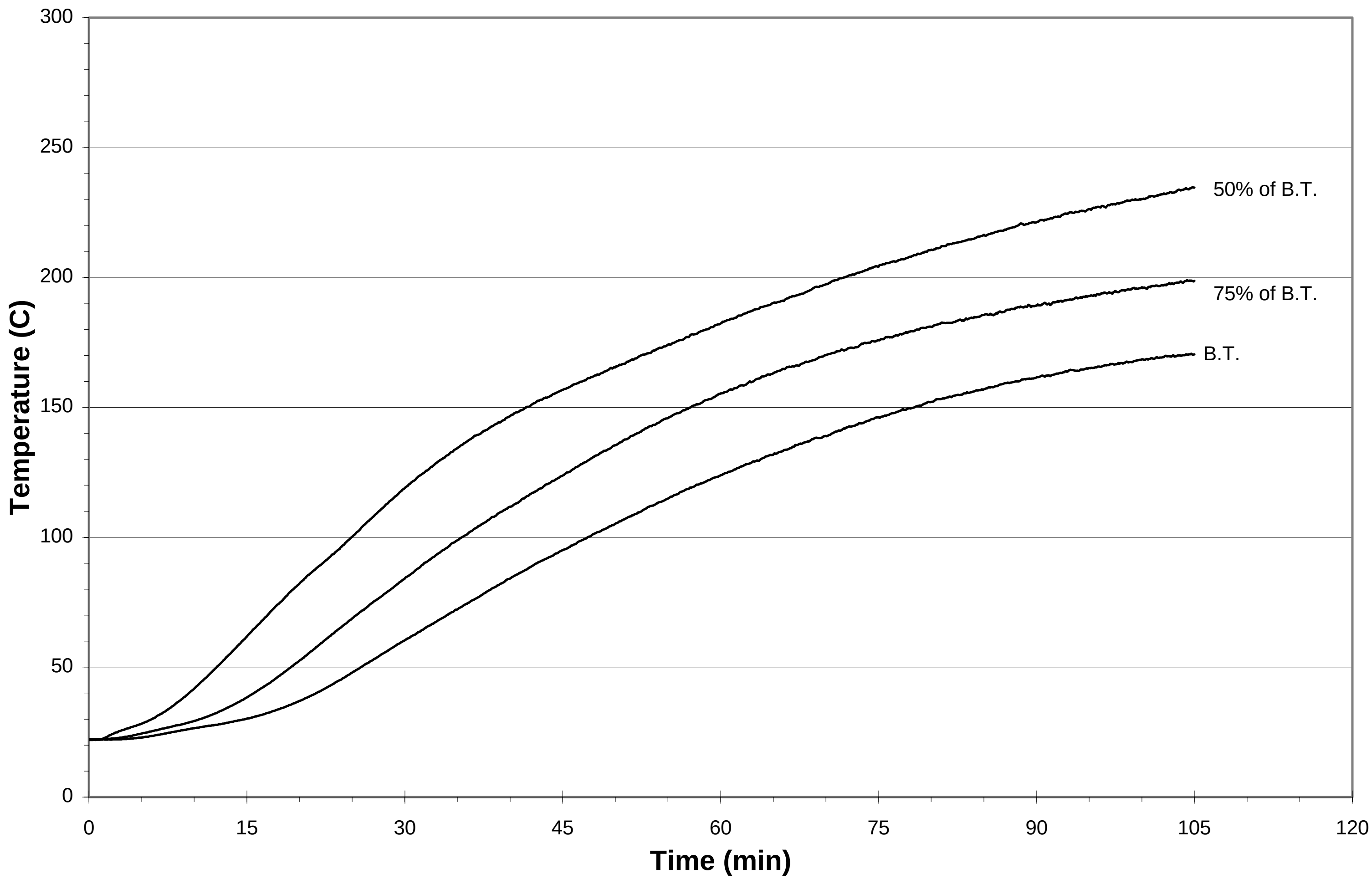

Figure 8. Foil-faced mineral fiber deck average unexposed surface temperatures.

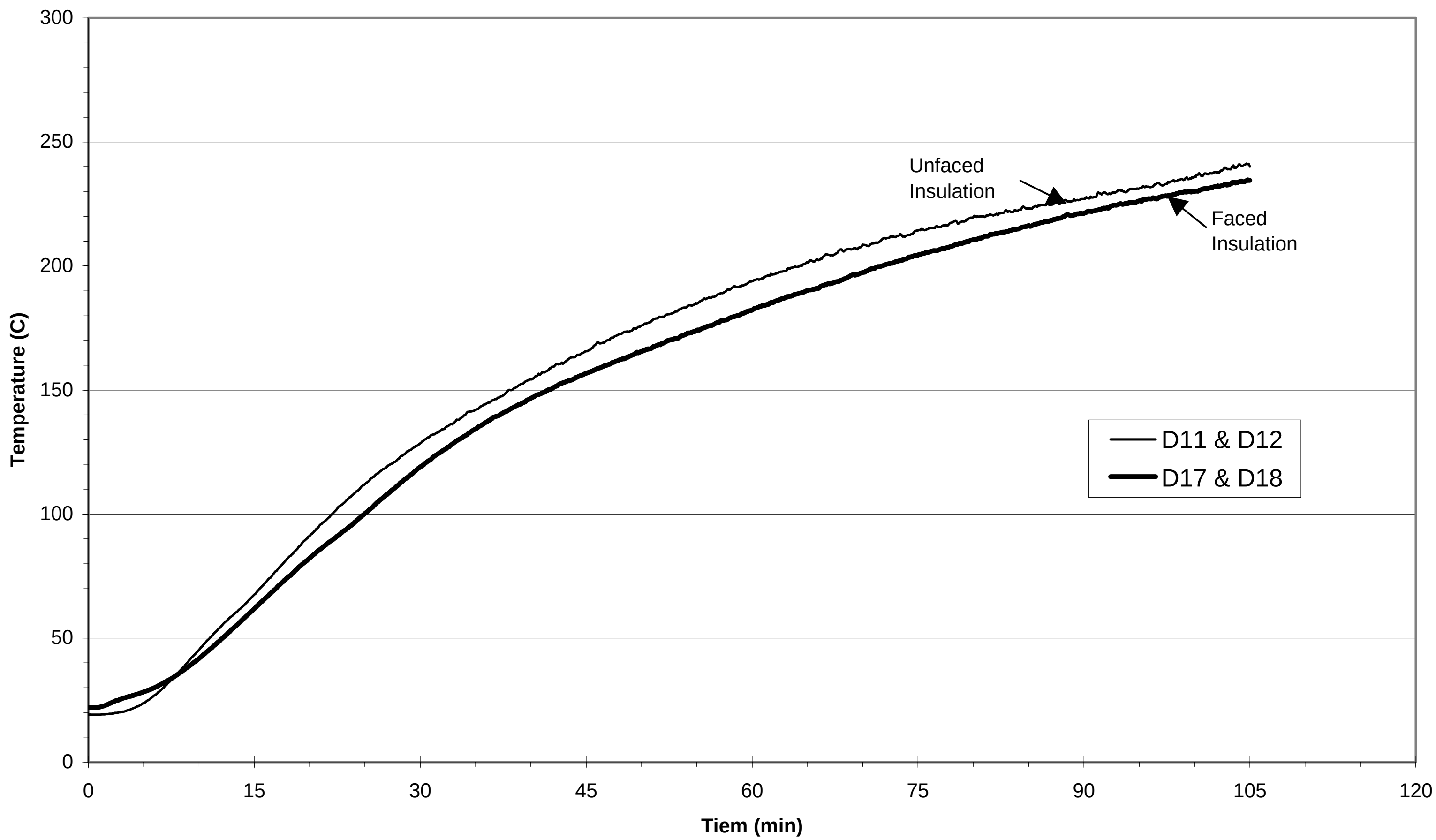

Figure 9. 50 percent of baseline thickness average unexposed surface temperatures (faced and unfaced deck insulation).

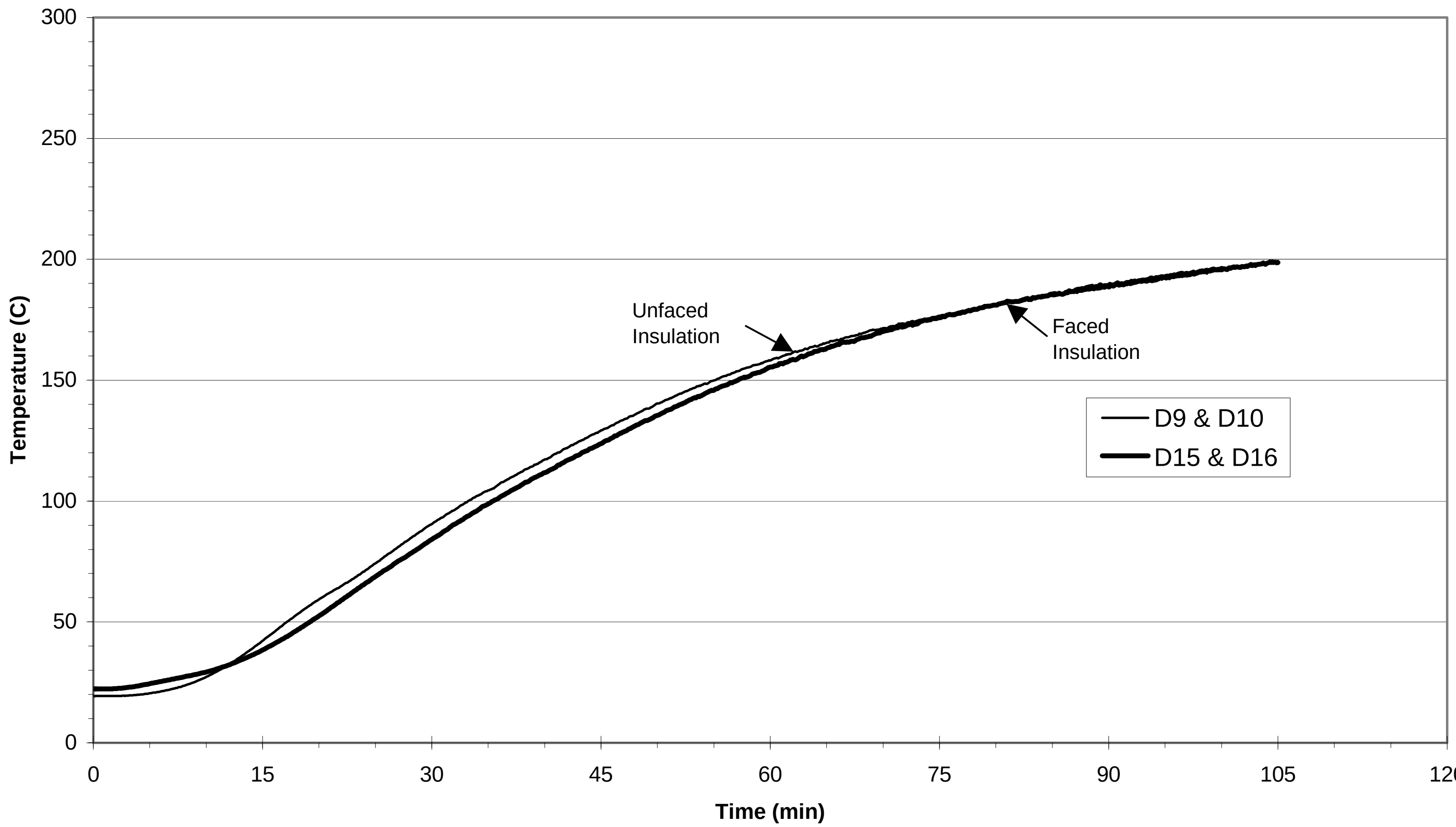

Figure 10. 75 percent of baseline thickness average unexposed surface temperatures (faced and unfaced deck insulation).

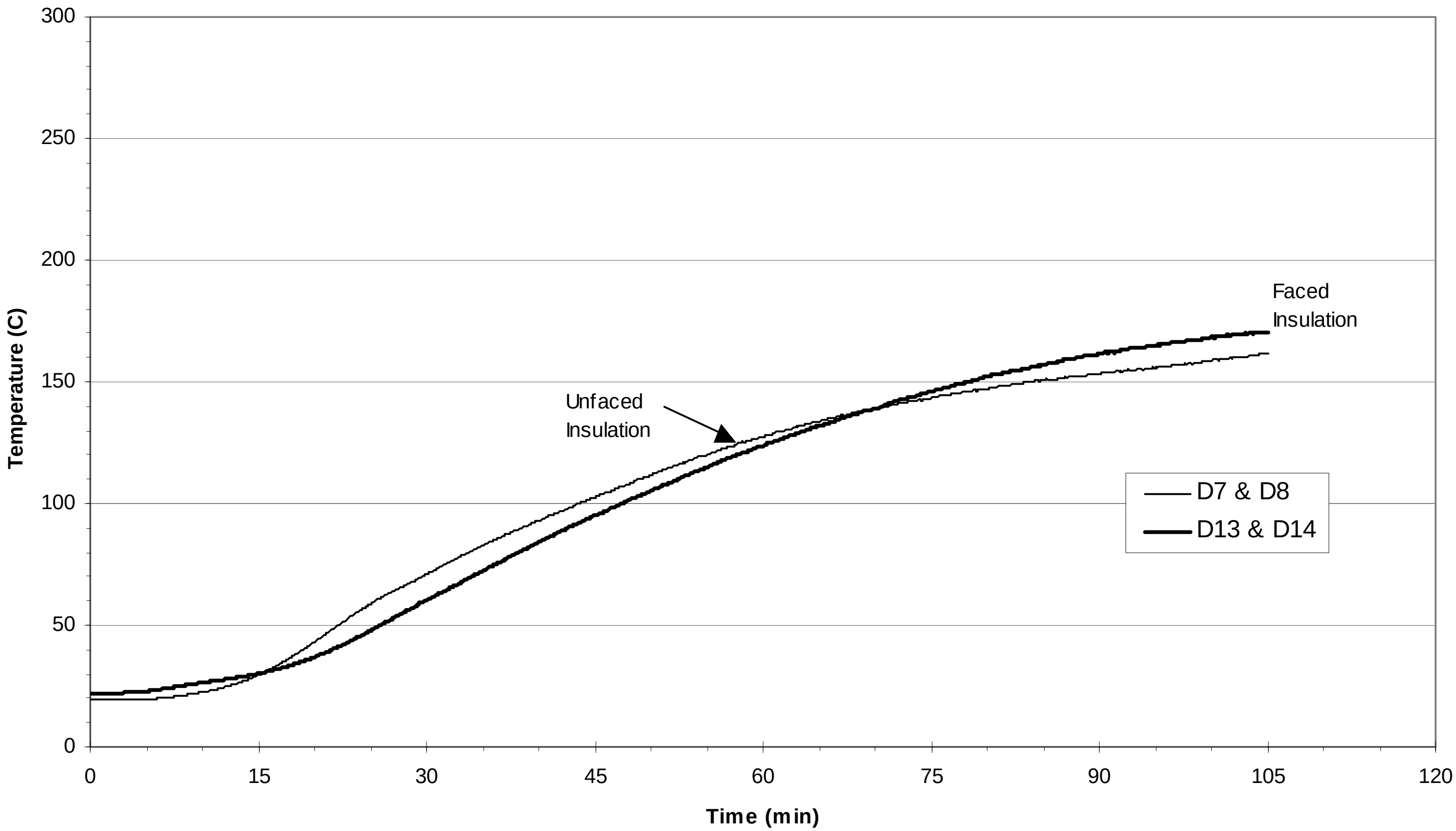

Figure 11. Baseline thickness average unexposed surface temperatures (faced and unfaced deck insulation).

152 °C (306 °F), and the single point temperature limit was calculated as 192 °C (378 °F). The test was continued until all unexposed face temperatures exceeded the average temperature limit.

The ceramic fiber insulation material currently had a USCG Certificate of Approval as a bulkhead insulation material at a baseline thickness of 38 mm (1.5 inches) to provide a minimum of 30 minutes of fire resistance. Application of the calculation method using the approved baseline 30 minutes insulation thickness resulted in the evaluation of an increased insulation thickness of 51 mm (2 inches) corresponding to the minimum 60 minutes insulation (i.e., A-60 or 133 percent of baseline thickness) and an insulation thickness of 25 mm (1.0 inch) corresponding to 66 percent of the baseline thickness. The rationale for utilizing the current calculation method to determine an increased insulation thickness has been previously discussed in Section 4.1. Table 9 provides the times to exceed the temperature limits for the six bulkhead samples (designated B19 through B24) tested. The test was terminated after 67 minutes of fire exposure.

Table 9. Ceramic fiber blanket bulkhead test results.

Sample Designation	Tested Thickness mm (in)	Time to Exceed Temperature Limits (min)	Average Time to Exceed Temperature Limits (min)
B19	51 (2)	51.0	51.8
B20	51 (2)	52.5	
B21	38 (1.5)[1]	31.7	34.1
B22	38 (1.5)[1]	36.4	
B23	25 (1)	19.7	19.9
B24	25 (1)	20.1	

[1] USCG Approved Baseline Thickness

Examination of the data from table 9 indicated that 133 percent of the A-30 baseline thickness deck assemblies did not meet the expected one-hour duration. The approved A-30 baseline thickness assembly and the 50 percent of baseline thickness met the expected test duration. As discussed above, this particular manufacturer had a USCG Certificate of Approval to provide a minimum of 30 minutes of fire resistance; however, the approval had been granted for use with aluminum bulkheads. Because of the low melting temperature of aluminum, the approval tests were conducted with the insulation mounted on the exposed side of the test bulkhead. Since these tests were performed with the insulation or the unexposed side of the steel assembly, correlation with the approved A-30 thickness may not be possible. A plot of the average unexposed face temperatures as a function of time is provided in figure 12 for all three pairs of samples (i.e., average of the ten unexposed face thermocouples total for each pair of samples).

4.2.6 Ceramic Fiber Blanket Deck Test Results (Deck Test 3)

The ceramic fiber blanket insulation material deck test was conducted on 18 January 2002. At the start of the test, the ambient temperature was 15 °C (61 °F). Based on the ambient temperature, the average unexposed face temperature limit was calculated as 155 °C (311 °F), and the single point failure temperature was calculated as 195 °C (383 °F). The test was continued until all unexposed face temperatures exceeded the average temperature limit.

The ceramic fiber insulation material currently had a USCG Certificate of Approval as a deck insulation material at a baseline thickness of 38 mm (1.5 inches) to provide a minimum 60 minutes of fire resistance. Application of the calculation method using the approved baseline insulation thickness resulted in the evaluation of an insulation thickness of 25 mm (1.0 inch), corresponding to 75 percent of the baseline thickness, and an insulation thickness of 19 mm (0.75 inch), corresponding to 50 percent of the baseline thickness. The 19 mm (0.75 inch) thick insulation material was not available for this test due to supply issues. A piece of 38 mm (1.5 inches) thick blanket was carefully cut in half to yield a nominally 19 mm (0.75 inch) thick piece of insulation for testing. Two separate pieces of 38 mm (1.5 inches) thick insulation blankets were cut in half to make the two 19 mm (0.75 inch) thick test samples. Table 10 provides the times to exceed the temperature limits for the six deck samples (designated D19 through D24) tested. The test was terminated after 75 minutes of fire exposure.

A plot of the average unexposed face temperatures as a function of time is provided in figure 13. Each of the three trendlines in figure 13 represent the average unexposed face temperatures for each pair of samples (i.e., average of the ten unexposed face thermocouples total for each pair of samples).

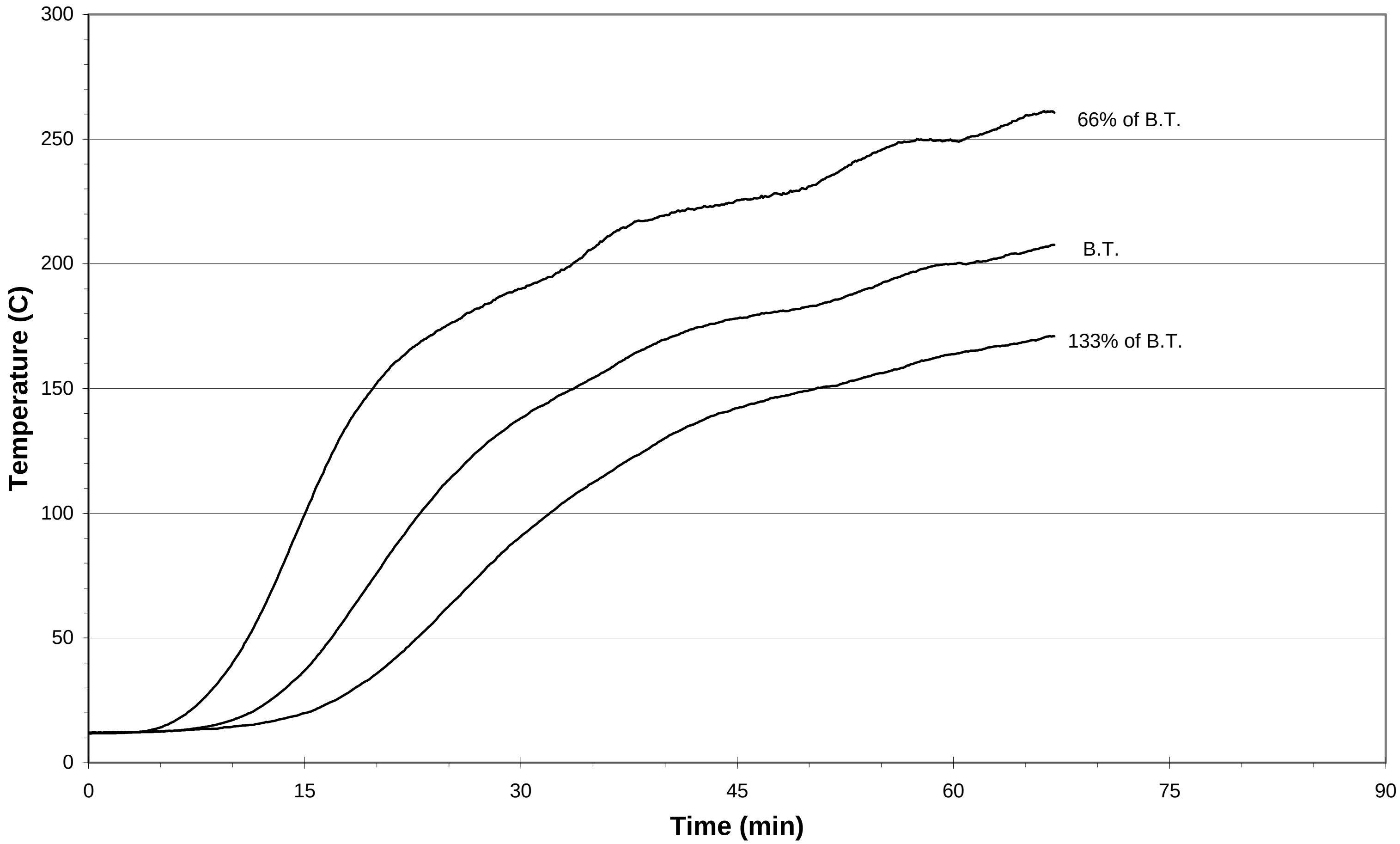

Figure 12. Ceramic fiber bulkhead average unexposed surface temperatures.

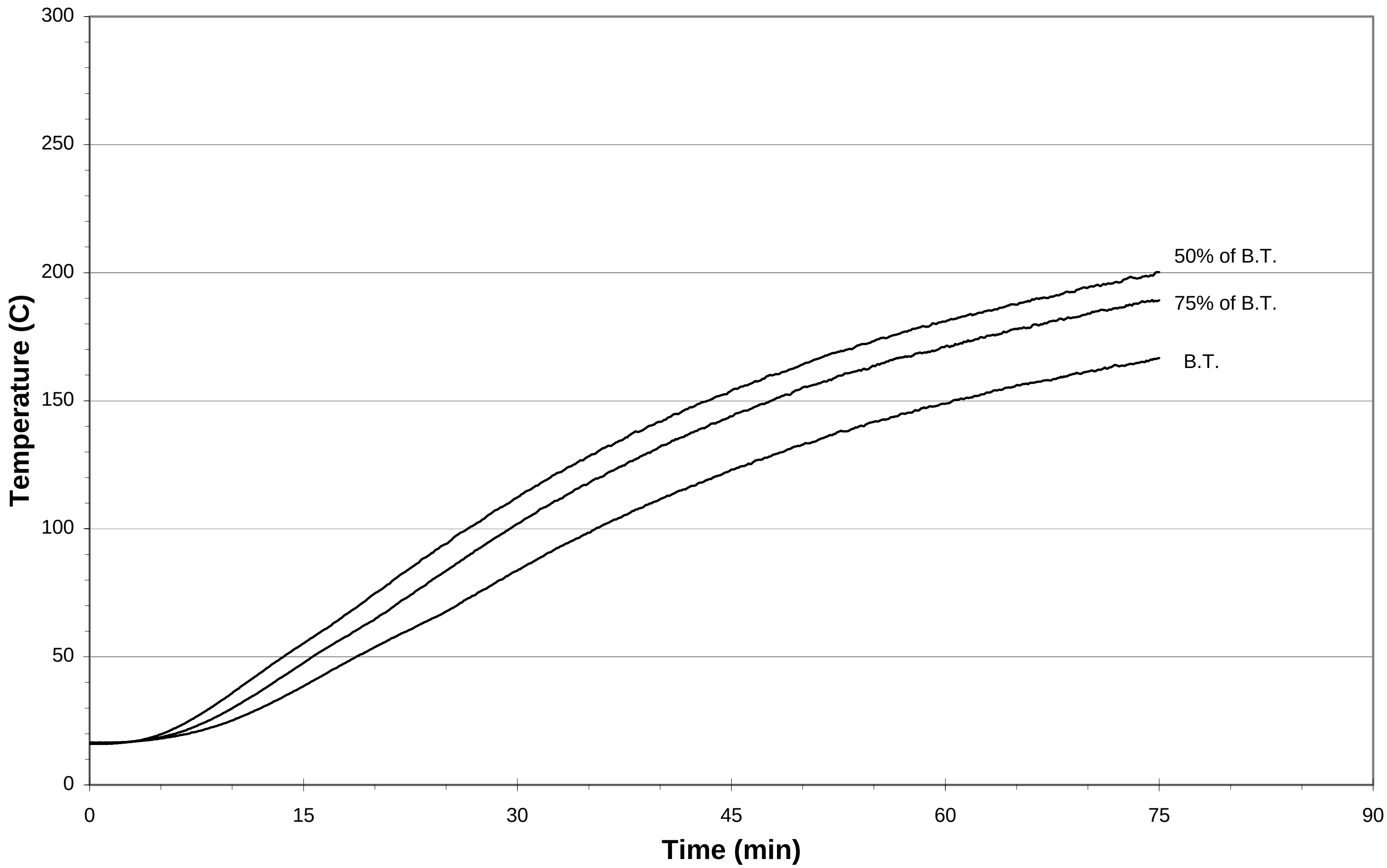

Figure 13. Ceramic fiber deck average unexposed surface temperatures.

Table 10. Ceramic fiber blanket deck test results.

Sample Designation	Tested Thickness mm (m)	Time to Exceed Temperature Limits (min)	Average Time to Exceed Temperature Limits (min)
D19	38 (1.5)[1]	64.1	64.7
D20	38 (1.5)[1]	65.3	
D21	25 (1)	53.6	50.7
D22	25 (1)	47.8	
D23	19 (0.75)	46.7	45.8
D24	19 (0.75)	44.9	

[1] USCG Approved Baseline Thickness

4.2.7 Spray-Applied Fiber Bulkhead Test Results (Bulkhead Test 4)

The spray-applied fiber insulation material bulkhead test was conducted on 22 January 2002. At the start of the test, the ambient temperature was 16 °C (54 °F). Based on the ambient temperature, the average unexposed face temperature limit was calculated as 156 °C (313 °F), and the single point temperature limit was calculated as 196 °C (385 °F). The test was continued until all unexposed face temperatures exceeded the average temperature limit.

The spray-applied fiber insulation material had a USCG Certificate of Approval as a bulkhead insulation material at a baseline thickness of 51 mm (2 inches) to provide a minimum 60 minutes fire resistance. Application of the calculation method using the approved baseline insulation thickness resulted in the evaluation of an insulation thickness of 38 mm (1.5 inches) corresponding to 75 percent of the baseline thickness and an insulation thickness of 25 mm (1.0 inch) corresponding to 50 percent of the baseline thickness. The test was terminated after 92 minutes of fire exposure.

During the conduct of the test, bound water in the insulation material was released, resulting in a number of the unexposed face thermocouples falling off during the test. This resulted in erroneous temperature readings. Post-test analysis of the individual temperature traces determined that a number of thermocouples needed to be discarded from the calculation of the unexposed face average. Table 11 provides a listing of the thermocouples discarded prior to calculating the final average unexposed face temperatures.

Table 11. Discarded unexposed face thermocouples.

Sample Designation	Discarded Unexposed Face Thermocouples	TC Location
B1	10	Lower, right corner
B2	17	Upper, right corner
B3	29	Lower, left corner
B4	36	Upper, left corner
	40	Lower, right corner
B5	49	Lower, left corner
	50	Lower, right corner
B6	None	N/A

After discarding the above thermocouples, the sample averages were calculated and the times to exceed the temperature limits determined. Table 12 provides the times to exceed the temperature limits for the six bulkhead samples (designated B1 through B7) tested.

Table 12. Spray-applied fiber bulkhead test results.

Sample Designation	Tested Thickness mm (in)	Time to Exceed Temperature Limits (min)	Average Time to Exceed Temperature Limits (min)
B1	51 (2)[1]	71.2	75.4
B2	51 (2)[1]	79.5	
B3	38 (1.5)	60.6	55.0
B4	38 (1.5)	49.3	
B5	25 (1)	32.0	32.3
B6	25 (1)	32.6	

[1] USCG approved baseline thickness

A plot of the average unexposed face temperatures as a function of time is provided in figure 14. Each of the three trendlines in figure 14 represent the average unexposed face temperatures for each pair of samples (i.e., average of the ten unexposed face thermocouples total for each pair of samples).

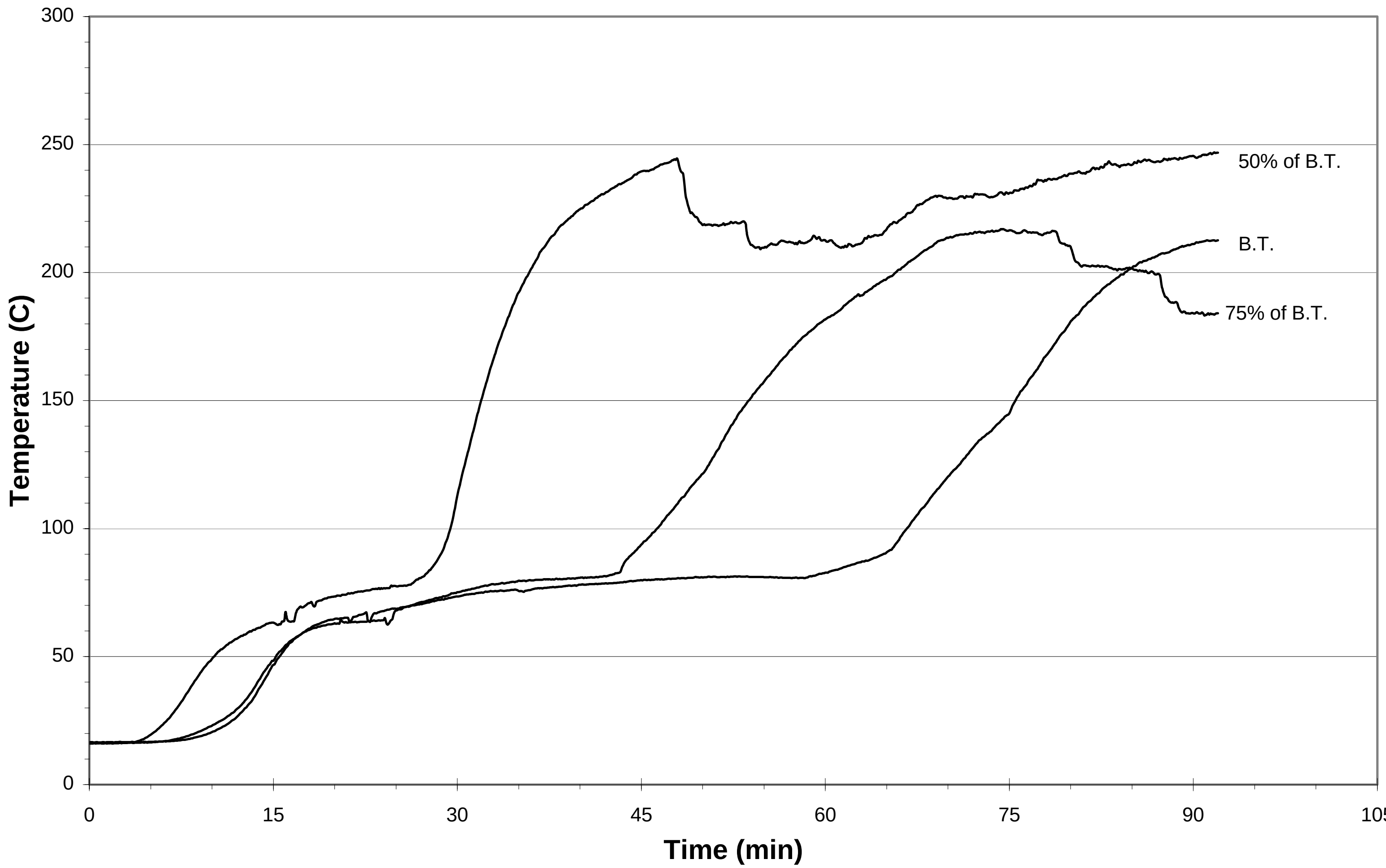

Figure 14. Spray-applied fiber bulkhead average unexposed surface temperatures.

Additional thermocouples continued to fall off the unexposed surface of the test sample after the average unexposed face temperature of each test sample exceeded the temperature limits. Since the test sample had technically “failed” at this point in the test, therefore these temperature readings were not discarded from the average. This effect is demonstrated by the decrease in the temperature traces in figure 14.

4.2.8 Spray-Applied Fiber Deck Test Results (Deck Test 4)

The spray-applied fiber insulation material deck test was conducted on 22 January 2002. At the start of the test, the ambient temperature was 22 °C (72 °F). Based on the ambient temperature, the average unexposed face temperature limit was calculated as 162 °C (324 °F), and the single point temperature limit was calculated as 202 °C (396 °F). The test was continued until all unexposed face temperatures exceeded the average temperature limit.

The spray-applied fiber insulation material had a USCG Certificate of Approval as a deck insulation material at a baseline thickness of 38 mm (1.5 inches) to provide a minimum 60 minutes of fire resistance. Application of the calculation method using the approved baseline insulation thickness resulted in the evaluation of an insulation of 29 mm (1.125 inches), corresponding to 75 percent of the baseline thickness, and an insulation thickness of 19 mm (0.75 inch), corresponding to 50 percent of the baseline thickness. Table 13 provides the times to exceed the temperature limits for the six deck samples (designated D1 through D6) tested. The test was terminated after 90 minutes of fire exposure.

Table 13. Spray-applied fiber deck test results.

Sample Designation	Tested Thickness mm (in)	Time to Exceed Temperature Limits (min)	Average Time to Exceed Temperature Limits (min)
D1	38 (1.5)[1]	75.4	79.1
D2	38 (1.5)[1]	82.7	
D3	29 (1.125)	49.2	48.4
D4	29 (1.125)	47.6	
D5	19 (0.75)	38.1	38.3
D6	19 (0.75)	38.5	

[1] USCG Approved Baseline Thickness

A plot of the average unexposed face temperatures as a function of time is provided in figure 14. Each of the three trendlines in figure 15 represent the average unexposed face temperatures for each pair of samples (i.e., average of the ten unexposed face thermocouples total for each pair of samples). No problems were encountered with the unexposed surface temperature measurements as the spray-applied fiber was exposed to the fiber and the surface thermocouples were mounted to the unexposed steel surface.

4.3 Fire Test Analysis

4.3.1 Bulkhead Test Analysis

The summarized test results for the four USCG approved bulkhead insulation materials are presented in table 14. The 50 percent of the baseline (A-15) insulation material thickness resulted in an average time to exceed the temperature limits of 24 minutes ± 6 minutes. The 75 percent of the baseline (A-30) insulation thicknesses tested exceeded the temperature limits an average of 44 minutes ± 12 minutes. All ± time values were calculated as one standard deviation from the calculated mean value.

The test results generated during the bulkhead tests were normalized with the baseline thickness insulation performance. This permitted an evaluation of the insulation material performance for each of the three insulation thicknesses for all insulation materials evaluated. For each of the four insulation materials tested, the corresponding $x/\sqrt{t}$ value was calculated using the tested insulation thickness (x) and the average time to exceed the temperature limits (t). For the same insulation material, the baseline and 75 percent of the baseline thickness calculated $x/\sqrt{t}$ values were similar in magnitude. The calculated $x/\sqrt{t}$ values for the 50 percent of baseline thickness insulation material were, however, noticeably lower. In a perfect scenario, all three calculated $x/\sqrt{t}$ values for a given insulation material should be the same. The lower calculated $x/\sqrt{t}$ value indicated some degree of conservatism.

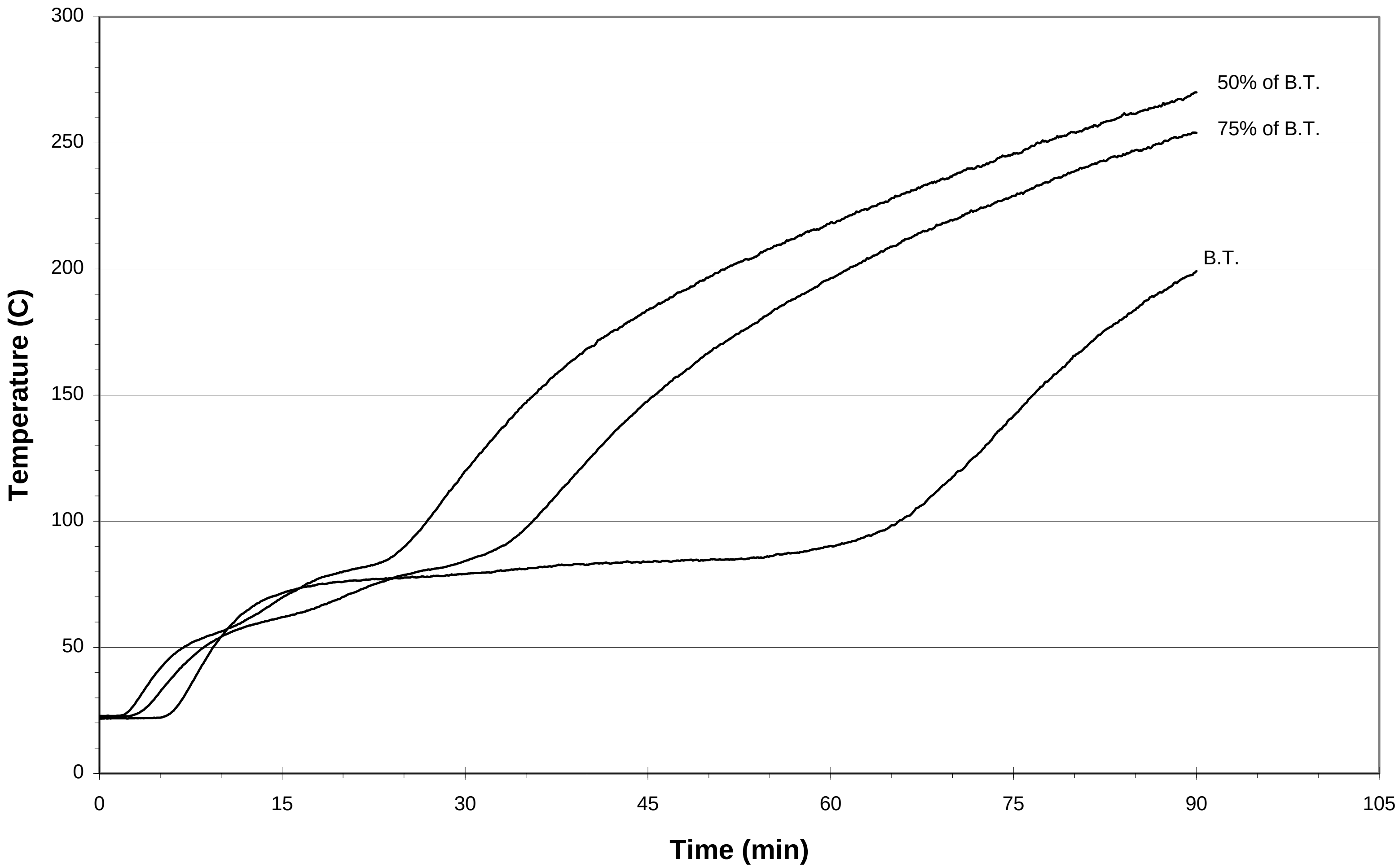

Figure 15. Spray-applied fiber deck average unexposed surface temperatures.

Table 14. Bulkhead insulation material test results.

Sample Designation	USCG Approved Thickness mm (in)	Insulation Material	Time to Exceed Temperature Limits (min)	Average Time to Exceed Temperature Limits (min)
B1	51 (2) [1]	Spray-applied	71.2	75.4 (A-60)
B2	51 (2) [1]	Spray-applied	79.5	
B3	38 (1.5)	Spray-applied	60.6	55.0 (A-30)
B4	38 (1.5)	Spray-applied	49.3	
B5	25 (1)	Spray-applied	32.0	32.3 (A-15)
B6	25 (1)	Spray-applied	32.6	
B7	76 (3) [1]	Unfaced Mineral Fiber	80.1	79.8 (A-60)
B8	76 (3) [1]	Unfaced Mineral Fiber	79.4	
B9	57 (2.25)	Unfaced Mineral Fiber	56.7	54.7 (A-30)
B10	57 (2.25)	Unfaced Mineral Fiber	52.7	
B11	38 (1.5)	Unfaced Mineral Fiber	23.8	22.6 (A-15)
B12	38 (1.5)	Unfaced Mineral Fiber	21.4	
B13	76 (3) [1]	Foil-faced Mineral Fiber	51.0	52.4 (A-60)
B14	76 (3) [1]	Foil-faced Mineral Fiber	53.7	
B15	57 (2.25)	Foil-faced Mineral Fiber	32.3	32.7 (A-30)
B16	57 (2.25)	Foil-faced Mineral Fiber	33.0	
B17	38 (1.5)	Foil-faced Mineral Fiber	21.0	22.0 (A-15)
B18	38 (1.5)	Foil-faced Mineral Fiber	23.0	
B19	51 (2)	Ceramic Fiber Blanket	51.0	51.8 (A-60)
B20	51 (2)	Ceramic Fiber Blanket	52.5	
B21	38 (1.5) [1]	Ceramic Fiber Blanket	31.7	34.1 (A-30)
B22	38 (1.5) [1]	Ceramic Fiber Blanket	36.4	
B23	25 (1)	Ceramic Fiber Blanket	19.7	19.9 (A-15)
B24	25 (1)	Ceramic Fiber Blanket	20.1	

[1] USCG Approved Baseline Thickness

To quantify the degree of conservatism, the baseline thickness $x/\sqrt{t}$ value was considered constant. The basic heat transfer equation $x/\sqrt{t} = C$ was rearranged to solve for time ($t = (x/C)^2$). Using the baseline thickness $x/\sqrt{t}$ value as the constant, the predicted times to exceed the temperature limits for the remaining insulation thicknesses (based on the calculation method) were calculated. Table 15 presents the tested insulation thickness and corresponding average times to exceed the temperature limits from the testing. Also included are the $x/\sqrt{t}$ values and the calculated time to exceed the temperature limits based on the calculation method. The calculated time to exceed the temperature limits calculated for the 75 percent of the baseline thickness using the calculation method were increased 5 percent, corresponding to the 5 percent increase implemented by the USCG in the application of the calculation method. Figure 16 provides a plot of the test-determined time to exceed the temperature limits compared to the times calculated using the calculation method. All of the insulation materials tested show some degree of conservatism in that the predicted time to exceed the temperature limits using the calculation method was less than the tested time to exceed the temperature limits (i.e., lies above the 45° line).

4.3.2 Deck Test Analysis

Test results for the four deck insulation materials are summarized in table 16. Testing of the 50 percent of the baseline insulation thickness resulted in an average time to exceed the temperature limits of 44 minutes ± 4 minutes. The test results for the 75 percent of the baseline insulation thickness indicated the average time to exceed the temperature limits was 56 minutes ± 7 minutes. These test data indicated that the currently applied calculation method for deck insulation materials is very conservative. From the data analysis of the deck insulation materials tested, the USCG A-60 baseline approved thicknesses averaged a time to exceed the temperature limits of 83 minutes ± 15 minutes.

Table 15. $x/\sqrt{t}$ calculated values for bulkhead insulation materials.

Insulation Material	Test Sample Designation	Tested Thickness mm (in)	Average Time to Exceed Temperature Limits (min)	$x/\sqrt{t}$	Calculated Time to Exceed Temperature Limits (min)
Spray-applied	B.T.	51 (2) [1]	75.4	5.87	N/A
Spray-applied	75 percent of B.T.	38 (1.5)	55.0	5.12	44.0 [2,3]
Spray-applied	50 percent of B.T.	25 (1)	32.3	4.4	18.1 [4]
Mineral Fiber	B.T.	76 (3) [1]	79.8	8.51	N/A
Mineral Fiber	75 percent of B.T.	57 (2.25)	54.7	7.71	47.1 [2,3]
Mineral Fiber	50 percent of B.T.	38 (1.5)	22.6	7.99	19.9 [4]
Foil-faced mineral fiber	B.T.	76 (3) [1]	52.4	10.5	N/A
Foil-faced mineral fiber	75 percent of B.T.	57 (2.25)	32.7	9.97	31.0 [2,3]
Foil-faced mineral fiber	50 percent of B.T.	38 (1.5)	22.0	8.1	13.1 [4]
Ceramic fiber	100 percent of B.T.	51 (2)	51.8	7.09	50.5 [5]
Ceramic fiber	B.T.	38 (1.5) [1]	34.1	7.18 [6]	N/A
Ceramic fiber	50 percent of B.T.	25 (1)	19.9	5.6	12.41 [4]

[1] USCG approved baseline thickness

[2] Time calculated using B.T. $x/\sqrt{t}$, assuming B.T. $x/\sqrt{t}$ is constant, re-arranging to solve for t, and using the 75 percent of B.T. tested thickness

[3] 5 percent added to calculated time to include for 5 percent increase in USCG applied calculation method

[4] Time calculated using B.T. $x/\sqrt{t}$, assuming B.T. $x/\sqrt{t}$ is constant, re-arranging to solve for t, and using the 50 percent of B.T. tested thickness

[5] Time calculated using B.T. $x/\sqrt{t}$, assuming B.T. $x/\sqrt{t}$ is constant, re-arranging to solve for t, and using the 100 percent of B.T. tested thickness

[6] 5 percent added to $x/\sqrt{t}$ to account for 5 percent added to USCG calculation method

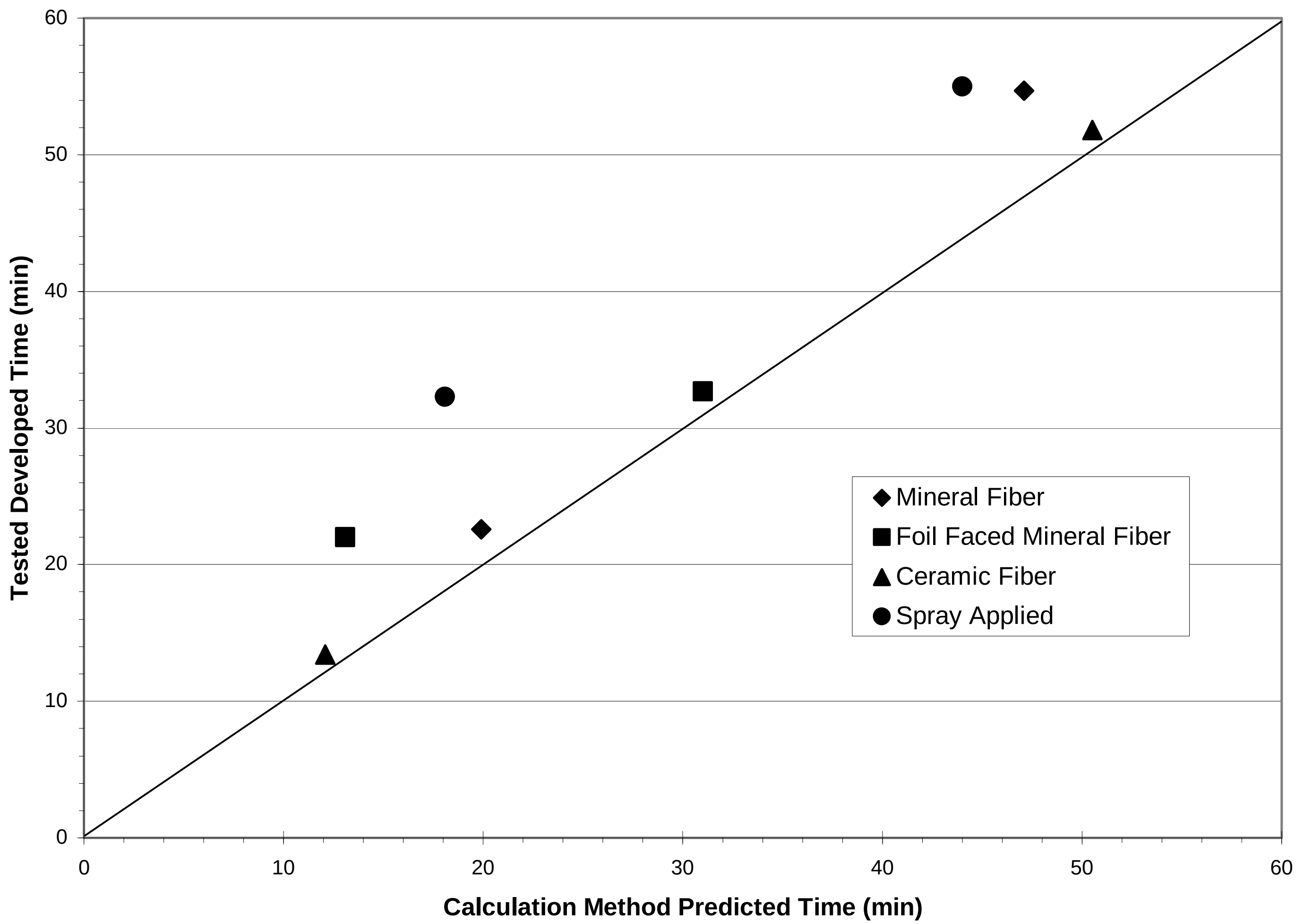

Figure 16. Tested versus calculation method predicted failure times-bulkhead insulation materials.

Table 16. Deck insulation material test results.

Sample Designation	Tested Thickness mm (in)	Insulation Material	Time to Exceed Temperature Limits (min)	Average Time to Exceed Temperature Limits (min)
D1	38 (1.5)[1]	Spray-applied	75.4	79.1 (A-60)
D2	38 (1.5)[1]	Spray-applied	82.7	
D3	29 (1.1)	Spray-applied	49.2	48.4 (A-30)
D4	29 (1.1)	Spray-applied	47.6	
D5	19 (0.75)	Spray-applied	38.1	38.3 (A-15)
D6	19 (0.75)	Spray-applied	38.5	
D7	51 (2)[1]	Unfaced Mineral Fiber	98.8	99.5 (A-60)
D8	51 (2)[1]	Unfaced Mineral Fiber	100.2	
D9	38 (1.5)	Unfaced Mineral Fiber	59.6	60.2 (A-30)
D10	38 (1.5)	Unfaced Mineral Fiber	60.8	
D11	25 (1)	Unfaced Mineral Fiber	43.3	42.0 (A-15)
D12	25 (1)	Unfaced Mineral Fiber	40.6	
D13	51 (2)[1]	Foil-faced Mineral Fiber	90.4	90.2 (A-60)
D14	51 (2)[1]	Foil-faced Mineral Fiber	90.0	
D15	38 (1.5)	Foil-faced Mineral Fiber	63.3	63.8 (A-30)
D16	38 (1.5)	Foil-faced Mineral Fiber	64.3	
D17	25 (1)	Foil-faced Mineral Fiber	46.2	47.9 (A-15)
D18	25 (1)	Foil-faced Mineral Fiber	49.5	
D19	38 (1.5)[1]	Ceramic Fiber Blanket	64.1	64.7 (A-60)
D20	38 (1.5)[1]	Ceramic Fiber Blanket	65.3	
D21	25 (1)	Ceramic Fiber Blanket	53.6	50.7 (A-30)
D22	25 (1)	Ceramic Fiber Blanket	47.8	
D23	19 (0.75)	Ceramic Fiber Blanket	46.7	45.8 (A-15)
D24	19 (0.75)	Ceramic Fiber Blanket	44.9	

[1] USCG approved baseline thickness

The test results generated during the deck tests were normalized with the baseline thickness insulation performance. This permitted an evaluation of the insulation material performance for each of the three insulation thicknesses for each material tested. For each of the four insulation materials tested, the corresponding $x/\sqrt{t}$ value was calculated using the tested insulation thickness (x) and the average time to exceed the temperature limits (t). For the same insulation material, the baseline and 75 percent of the baseline thickness calculated $x/\sqrt{t}$ values were similar in magnitude. The calculated $x/\sqrt{t}$ values for the 50 percent of baseline thickness insulation material were, however, noticeably lower. In a perfect scenario, all three calculated $x/\sqrt{t}$ values for a given insulation material should be the same. The lower calculated $x/\sqrt{t}$ value indicated some of conservatism.

To quantify the degree of conservatism, the baseline thickness $x/\sqrt{t}$ value was considered constant. The basic heat transfer equation $x/\sqrt{t} = C$ was rearranged to solve for time ($t = (x/C)^2$). Using the baseline thickness $x/\sqrt{t}$ value as the constant, the predicted times to exceed the temperature limits for the two remaining insulation thicknesses (based on the calculation method) were calculated. Table 17 presents the tested insulation thickness and corresponding average times to exceed the temperature limits from the testing. Also included are the $x/\sqrt{t}$ values and the calculated time to exceed the temperature limits based on the calculation method. The calculated time to exceed the temperature limits calculated for the 75 percent of the baseline thickness using the calculation method were increased 5 percent, corresponding to the 5 percent increase implemented by the USCG in the application of the calculation method. Figure 17 provides a plot of the test determined time to exceed the temperature limits compared to the times calculated using the calculation method. All of the insulation materials tested show some degree of conservatism in that the predicted time to exceed the temperature limits using the calculation method is less than the tested time to exceed the temperature limits (i.e., lies on or above the 45° line).

Table 17. $x/\sqrt{t}$ calculated values for deck insulation materials.

Insulation Material	Test Sample Designation	Tested Thickness mm (in)	Average Time to Exceed Temperature Limits (min)	$x/\sqrt{t}$	Calculated Time to Exceed Temperature Limits (min)
Spray-applied	B.T.	38 (1.5)[1]	79.1	5.11	N/A
Spray-applied	75 percent of B.T.	29 (1.125)	48.4	4.9	48.4[2,3]
Spray-applied	50 percent of B.T.	19 (0.75)	38.3	3.86	19.8[4]
Mineral Fiber	B.T.	51 (2)[1]	99.5	5.37	N/A
Mineral Fiber	75 percent of B.T.	38 (1.5)	60.2	4.76	58.1[2,3]
Mineral Fiber	50 percent of B.T.	25 (1)	42.0	3.61	23.9[4]
Foil-faced mineral fiber	B.T.	51 (2)[1]	90.2	4.72	N/A
Foil-faced mineral fiber	75 percent of B.T.	38 (1.5)	63.8	3.51	52.6[2,3]
Foil-faced mineral fiber	50 percent of B.T.	25 (1)	47.9	2.81	21.7[4]
Ceramic fiber	B.T.	38 (1.5)[1]	64.7	4.27	N/A
Ceramic fiber	75 percent of B.T.	25 (1)	50.7	4.17	29.5[2,3]
Ceramic fiber	50 percent of B.T.	19 (0.75)	45.8	3.51	16.2[4]

[1] USCG approved baseline thickness

[2] Time calculated using B.T. $x/\sqrt{t}$, assuming B.T. $x/\sqrt{t}$ is constant, re-arranging to solve for t, and using the 75 percent of B.T. tested thickness

[3] 5 percent added to calculated time to include for 5 percent increase in USCG applied calculation method

[4] Time calculated using B.T. $x/\sqrt{t}$, assuming B.T. $x/\sqrt{t}$ is constant, re-arranging to solve for t, and using the 50 percent of B.T. tested thickness

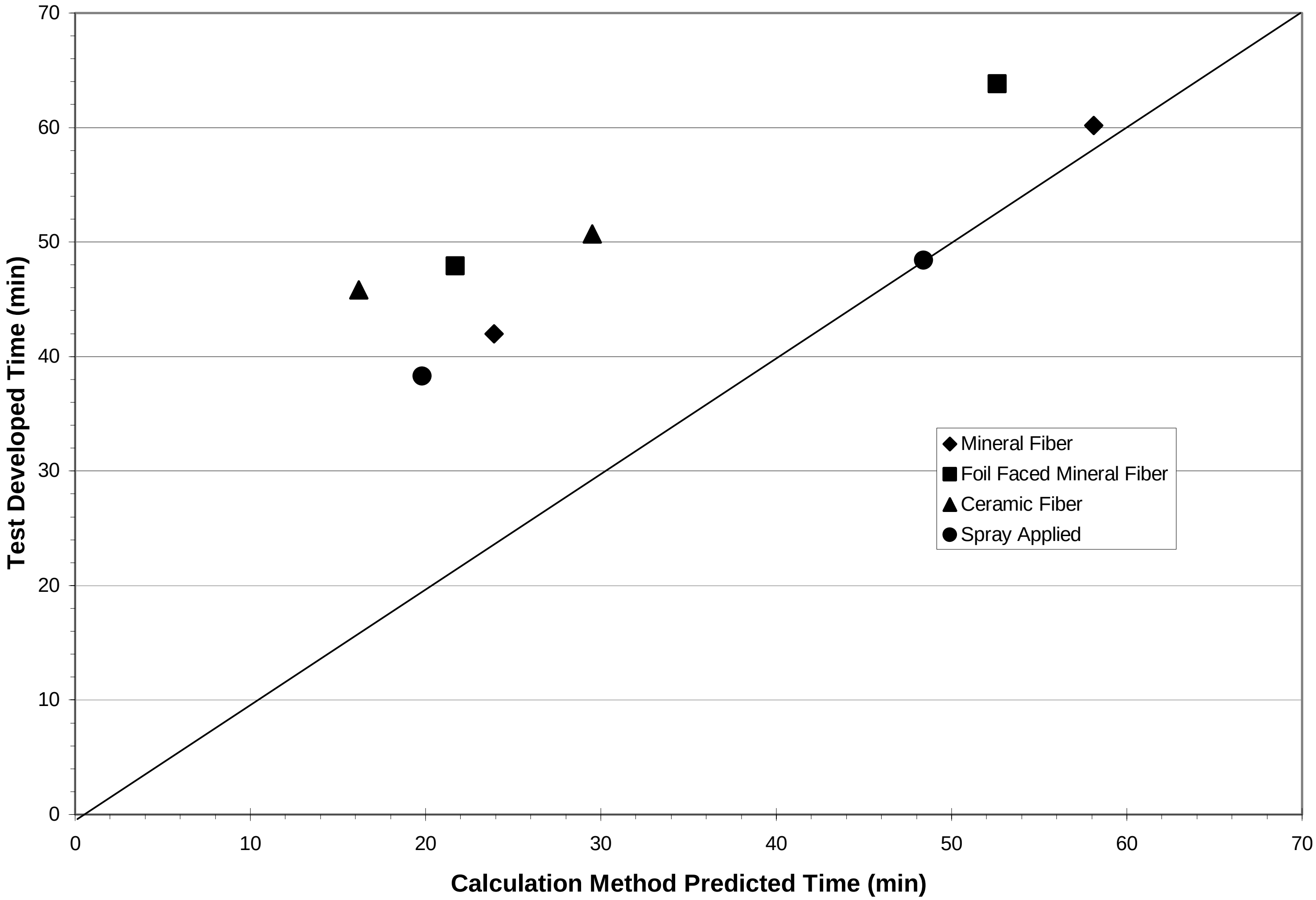

Figure 17. Tested versus calculation method predicted failure times – deck insulation materials.

The calculation method was determined to be conservative when applied to bulkhead insulation materials tested in the most onerous manner, with the insulation material on the unexposed face of the test sample, and for deck insulation materials where the insulation material was exposed to the fire. There does, however, exist some degree of conservatism inherent in the insulation materials. The full-scale baseline insulation thickness qualification tests previously conducted by the manufacturers continued for longer than 60 minutes (in some cases to nearly 75 minutes) before the time to exceed the temperature limits was reached [Private Communications]. Carrying this conservatism through application of the calculation method for insulation materials resulted in longer test durations, primarily due to the increased insulation thickness. To address this inherent conservatism, an effort was undertaken using a finite difference heat transfer model to predict the test results and "optimize" the insulation thicknesses.

5.0 NUMERICAL MODELING

5.1 Introduction

A numerical modeling effort was undertaken to determine if some of the conservatism demonstrated during the qualification testing conducted by the insulation manufacturers could be removed. Test data generated from the fire tests reported herein was utilized to initially model the tested insulation samples ("calibrate" the model) and then "optimize" the insulation thickness for each division classification time (15, 30, and 60 minutes). Once the optimized insulation thickness and time to exceed the temperature limits was predicted, the calculation method heat transfer principle was applied. The predicted values were compared to the tested values to evaluate the degree of conservatism in the calculation method.

5.2 Numerical Modeling Setup and Procedure

A one-dimensional heat transfer analysis was performed to calculate the unexposed surface temperature for each insulation sample. This analysis involved a computer simulation of the time-dependent temperature response of the insulation/steel sample to a thermal insult provided by the furnace (i.e., IMO time/temperature curve). This type of analysis has been used previously to conservatively predict the fire resistance of various structural and non-structural bulkhead and deck assemblies when test data are not available. The equations that describe this process are well documented and widely employed. The factors that determine how quickly a solid will exchange heat with the surroundings are the thermal properties for the materials and the boundary conditions.

This heat transfer analysis was performed using HEATING, Version 7.3 [ORNL, 1998]. HEATING 7 is a finite difference numerical heat transfer program developed at Oak Ridge National Laboratories (ORNL) Radiation Safety Information Computation Center to analyze the thermal impact of various high energy research projects. It has one of the longest development histories among various computational heat transfer software packages. ORNL has published numerous validation studies for this software that show that the mechanics of the software are implemented as intended.

The program is based on the Conservation of Energy equation. By numerically solving this equation, the temperature of a solid as a function of time may be calculated. The equation is summarized in a general form by the following expression [Bird,et al.,1960; Childs,1998]:

$$c_P(T)\,\rho(T)\frac{\partial T}{\partial t} = \nabla\, k(T)\nabla T \qquad (6)$$

Where $c_p(T)$ is the temperature dependent heat capacity (J/kg-K), $\Delta\ (T)$ is the temperature dependent density (kg/m^3), T is the spatially dependent temperature (K), t is the time (s), and $k(T)$ is the temperature dependent thermal conductivity (W/m-K).

The temperature distribution within a solid is determined using Equation 6 and a given set of boundary conditions or assumptions regarding the energy flow between the solid and its surroundings. For this analysis, two types of boundary conditions between the insulation sample and the furnace exposure were used: radiation and convection. The radiation boundary condition is summarized by the following equation [Childs, 1998; Siegel and Howell, 1992]:

$$q''_r = \left(\frac{1}{\frac{1}{\varepsilon_S} + \frac{1}{\varepsilon_f} + 1} \right) F\,\sigma\,(T_f^{\,4} - T_S^{\,4}) \tag{7}$$

Where q''_r is the net radiant heat flux at the boundary surface (W/m^2), ε_s is the emissivity of the boundary surface, ε_f is the emissivity of the exposure fire, *F* is the configuration factor between the surface and the fire, σ is the Stefan-Boltzman constant (5.67 x 10^{-8} W/m^2-K^4), T_f is the temperature of the fire (K), and T_s is the temperature of the material surface (K). For this analysis, it was assumed that the configuration factor and the emissivity of the furnace were unity. Also, it was assumed that the emissivities for the steel and insulation were 0.6 and 0.8, respectively [Siegel and Howell, 1992].

The convection heat transfer boundary condition is summarized by the following equation [Holman, 1990; Childs,1998]:

$$q''_c = h(T_f - T_s) \tag{8}$$

Where q''_c is the convective heat flux at the boundary surface (W/m^2) and *h* is the convection heat transfer coefficient (W/m^2-K). The convection coefficient for forced conditions is typically between 5 and 15 W/m^2-K for fire exposures [Babrauskas and Williamson, 1979; Walton and Thomas, 1995]. Values used in this analysis ranged between 5 and 20 W/m^2-K.

The fixed inputs for sample type included the exposure (furnace curve) and some of the material properties. Each sample consisted of the insulation (with appropriate thickness), 5 mm (0.188 inch) thick steel, and the 2 mm (0.08 inch) thick insulating thermocouple pad. The density, thermal conductivity, and specific heat for the steel and the insulating pad for the thermocouple remained constant for each of the runs. A complete set of thermal properties was not available for each type of insulation material from the manufactures. In each case, the density and a partial thermal conductivity curve were provided. The thermal conductivity values did not, however, cover the entire range of applicable temperatures. As a result, the unknown thermal conductivity and specific heat values were adjusted within the range of conventional values for other insulation materials. The criteria of "calibrating" the model to the baseline insulation thickness performance was to accurately predict a time to exceed the unexposed surface temperature limits. The response of the insulation material prior to reaching the end point was considered secondary during the modeling effort. The use of this criteria resulted in some deviations between the tested and predicted thermal response of the insulation material prior to reaching the end point. These deviations were not considered to effect the final modeling performance. The convective heat transfer coefficient on the exposed and unexposed sides was then adjusted to regulate the amount of energy that was contained within the sample.

The model was calibrated using the baseline insulation test data. Once satisfactory results were obtained for the time to exceed the temperature limits and overall transient response, the model was used to predict the time to exceed the temperature limits for the 75 percent and 50 percent of the baseline thickness tests (133 percent and 50 percent for the ceramic fiber bulkhead configuration) using the same insulation properties and boundary conditions. The heat transfer model was utilized to predict the time to exceed the temperature limits for the mineral fiber marine board and ceramic fiber deck and bulkhead insulation materials, and the foil-faced mineral fiber bulkhead insulation material. The foil-faced mineral fiber deck insulation material was not modeled due to the similar performance observed during the fire tests (see Section 4.2.4). Modeling was not conducted on the spray-applied fiber insulation material due to the water evaporation issues encountered during the fire tests, specifically in the bulkhead test.

The model inputs (thermal conductivity, thickness, density, and specific heat capacity) utilized for each modeling effort are contained in Appendix A.

5.3 Modeling Limitations

The heat transfer modeling effort utilized test results generated from the small-scale tests conducted and described herein. The test data were based on a small sample that did not include stiffeners as would be required in the full-scale testing of bulkhead and deck insulation materials. The purpose of the modeling effort was only to evaluate the heat flow through the insulation/steel assembly. The effect of stiffeners was not considered, as would be a factor in the full-scale tests conducted in accordance with IMO A.754 (18).

5.4 Numerical Modeling Results

The heat transfer model was “calibrated” to the baseline thickness test results generated for each bulkhead and deck test. Test parameters input into the baseline thickness model included the thermal conductivity and heat capacity of the insulation material at various temperatures, tested insulation thickness, cross-section of the insulated steel test sample, IMO time/temperature curve, initial temperatures, boundary conditions, and thermocouple/pad. The model was determined to be “calibrated” when the tested and predicted times to exceed the average temperature limit for the baseline thickness matched as closely as possible. After calibration of the model against the baseline thickness test results, the insulation thickness was adjusted corresponding to the tested 50 percent and 75 percent of the baseline insulation thicknesses (133 percent and 50 percent for the ceramic fiber bulkhead insulation). New predicted times to exceed the temperature limits for the 75 percent and 50 percent of the baseline thickness test sample were also determined based on the adjusted thicknesses. No other model parameters were changed, apart from the insulation thickness.

Both the bulkhead and deck configurations were modeled for the mineral fiber marine board and the ceramic fiber insulation materials, and the foil-faced mineral fiber marine board used as a bulkhead insulation material. The foil-faced mineral fiber insulation used as a deck insulation material was not modeled, as the foil-facing was directly exposed to the fire and melted away shortly after the start of the test. Once the foil-facing melted away, the insulation material was similar to the unfaced mineral fiber marine board and similar unexposed surface temperatures were obtained. Figures 9, 10, and 11 provide a comparison of the foil-faced and unfaced mineral fiber deck insulation materials average unexposed surface temperatures, demonstrating the minimal variance in measured temperature.

Upon completion of the modeling of the tested configurations, the model was re-run to optimize the insulation thickness to obtain as close as possible a 60, 30, and 15 minutes insulated boundary. The thickness was determined to the nearest 3 mm (1/8 inch).

5.4.1 Mineral Fiber Marine Board Bulkhead Tests

The mineral fiber marine board insulation material evaluated had a USCG Certificate of Approval for use as a bulkhead insulation material at a baseline thickness of 76 mm (3 inches). Application of the calculation method for insulation thickness provided an insulation thickness of 57 mm (2.25 inches), corresponding to 75 percent of the baseline thickness, and an insulation thickness of 38 mm (1.5 inches), corresponding to 50 percent of the baseline insulation thickness. The model was “calibrated” for the baseline test results and then re-configured to predict the time to exceed the temperature limits for the reduced sample thicknesses (insulation thicknesses only adjusted accordingly). Table 18 provides the initial model results for the three tested configurations. For the modeling of the mineral fiber marine board bulkhead insulation, the initial ambient temperature was taken as 14 °C (57 °F) and the average unexposed face temperature limit was 154 °C (309 °F).

Table 18. Mineral fiber marine board bulkhead results.

Tested Insulation Thickness mm (in)	Tested Time to Exceed Temperature Limits (min)	Predicted Time to Exceed Temperature Limits (min)
76 (3)[1]	79.8	76.3
57 (2.25)	54.1	47.3
38 (1.5)	23.0	22.7

[1] USCG Approved Baseline Thickness

In the fire test, the average unexposed surface temperatures of the baseline thickness test samples exceeded the temperature limits at 79.8 minutes. The "calibrated" HEATING 7 model predicted the insulation material would exceed the temperature limit at 76.3 minutes, approximately 3.5 minutes early. Figure 18 provides a plot of the average unexposed temperatures for the baseline thickness compared to the predicted temperatures. The deviation between the predicted and tested unexposed surface temperatures in figure 18 are a result of the modeling effect procedure as discussed in Section 5.2. The insulation thickness was then adjusted down from the baseline thickness of 76 mm (3 inches) to 57 mm (2.25 inches), corresponding to 75 percent of the baseline insulation thickness, and the model re-run. The model predicted a time to exceed the temperature limits of 47.3 minutes compared to the test result of 54.1 minutes. Adjustment of the insulation thickness to 38 mm (1.5 inches), corresponding to 50 percent of the baseline insulation thickness, yielded a predicted time to exceed the temperature limits of 22.7 minutes (compared to 23.0 minutes from the test). The predicted 75 percent of baseline insulation thickness time to exceed the temperature limits was approximately 7 minutes before to the tested value, however, the model accurately predicted the time to exceed the temperature limits for the 50 percent of the baseline insulation thickness sample.

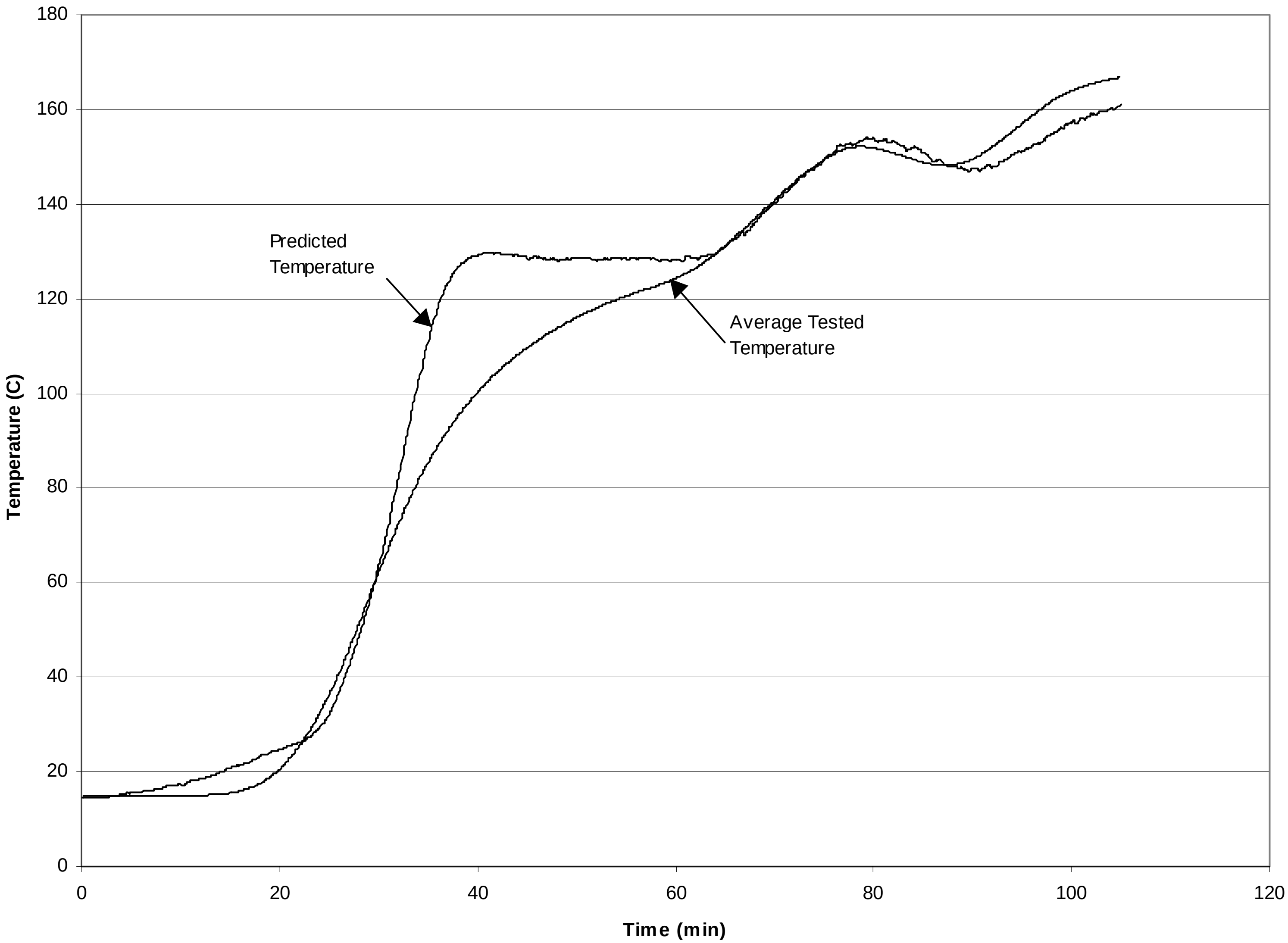

Figure 18. Mineral fiber bulkhead predicted and tested baseline thickness unexposed surface temperatures (calibration run).

Figures 19 and 20 provide plots of the average unexposed temperatures measured during the test compared to the predicted temperatures for the 75 percent and 15 percent of baseline insulation thickness test samples, respectively. In figure 20, after the temperature limits were exceeded, the predicted unexposed surface temperatures noticeably diverged from the tested temperatures. The insulation materials had effectively “failed” by this point, therefore, the divergence of the two lines was ignored. Further refinement of the insulation thicknesses was then conducted to determine the “optimized” thickness for this insulation material.

The insulation thickness was iteratively changed in the model in 3 mm (1/8 inch) increments until insulation thicknesses corresponding to the times to exceed the 15, 30 and 60 minutes temperature limits were obtained. These thicknesses represented the “optimum” insulation thickness. Table 19 provides the numerical modeling results. Included in table 19 (and all subsequent numerical modeling tables) is a column labeled “Calculation Method Insulation Thickness.” This column provided the calculated 50 percent and 75 percent insulation thickness based on the new, optimized baseline insulation thickness using the calculation method.

Table 19. Optimized mineral fiber marine board bulkhead insulation material.

Tested Insulation Thickness mm (in)	Optimized Time to Exceed Temperature Limits (min)	Optimized Insulation Thickness mm (in)	Calculation Method Insulation Thickness mm (in)
76 (3)	63.3	67 (2.625)	N/A
57 (2.25)	30.0	45 (1.75)	50 (2.0)
38 (1.5)	15.9	29 (1.125)	34 (1.3)

[1] USCG Approved Baseline Thickness

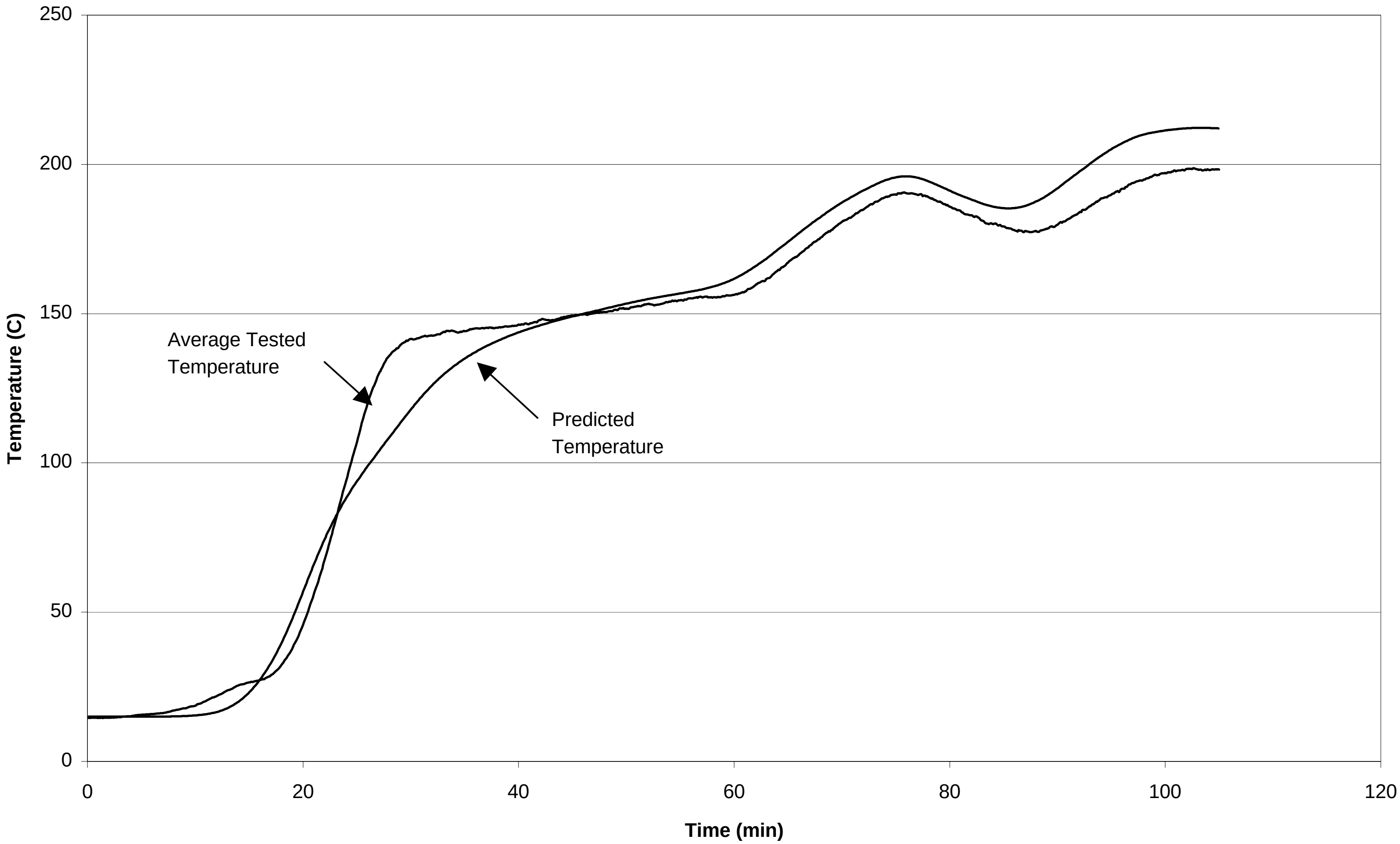

Figure 19. Mineral fiber bulkhead predicted and tested 75 percent of baseline thickness unexposed surface temperatures.

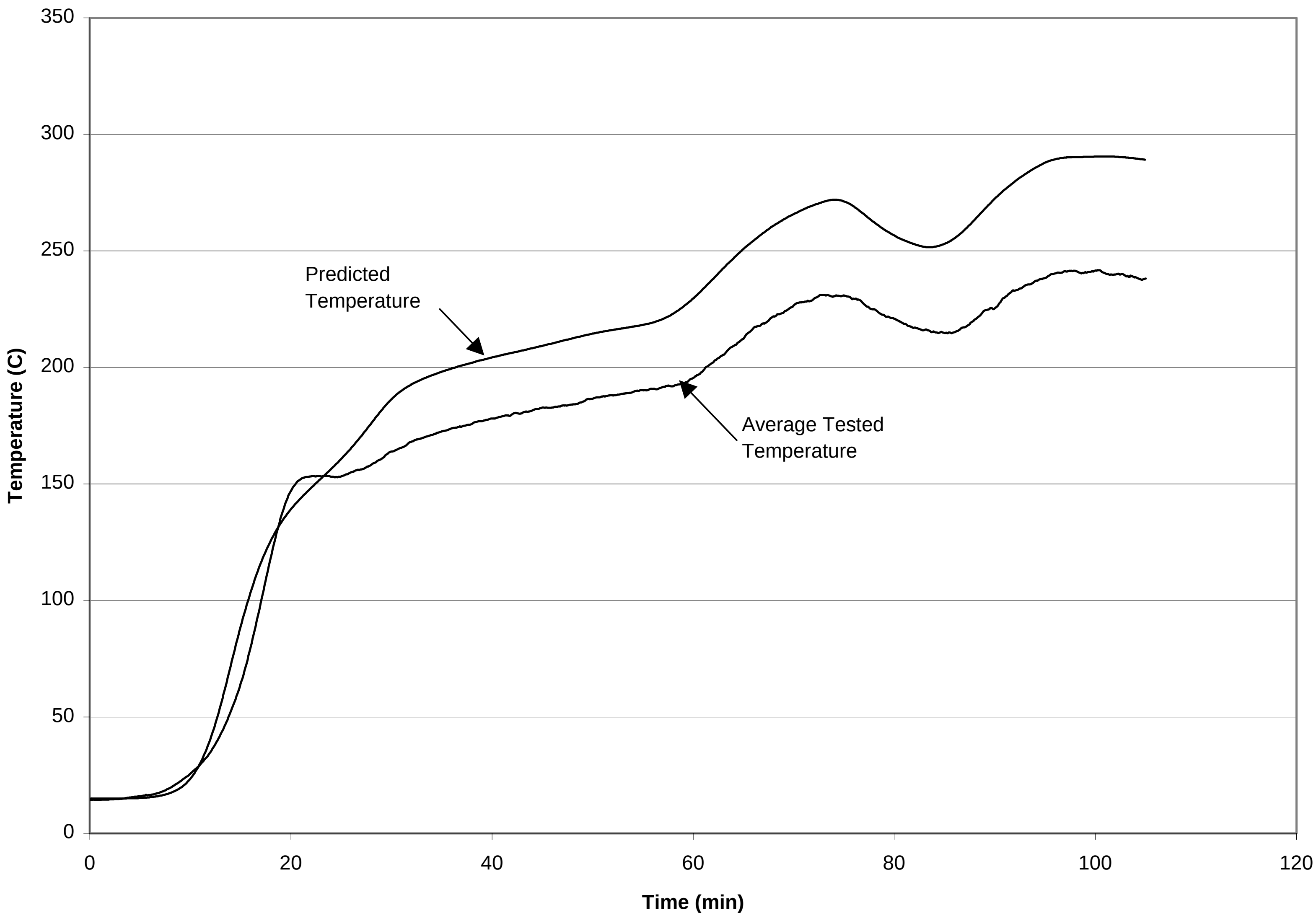

Figure 20. Mineral fiber bulkhead predicted and tested 50 percent of baseline thickness unexposed surface temperatures.

The optimized insulation thicknesses shown in table 19 indicate the predicted times to exceed the temperature limits were within approximately 5 percent of the division classification time. Application of the calculation method using the predicted 67 mm (2.625 inches) insulation thickness as the baseline yielded a 50 percent of baseline insulation thickness of 34 mm (1.3 inches) and a 75 percent of baseline insulation thickness of 50 mm (2.0 inches). These insulation thicknesses developed using the calculation method were greater than the predicted insulation thicknesses, indicating that the calculation method remained conservative given the newly reduced, optimized baseline insulation thickness.

5.4.2 Mineral Fiber Marine Board Deck Tests

The mineral fiber marine board insulation material evaluated had a USCG Certificate of Approval for use as a deck insulation material at a baseline thickness of 51 mm (2 inches). Application of the calculation method for insulation thickness provided an insulation thickness of 38 mm (1.5 inches), corresponding to 75 percent of the baseline thickness, and an insulation thickness of 25 mm (1 inch), corresponding to 50 percent of the baseline thickness. The model was “calibrated” for the baseline test results and then re-configured to predict the time to exceed the temperature limits for the reduced sample thicknesses (insulation thicknesses only adjusted accordingly). Table 20 provides the initial model results for the three tested configurations. For the modeling of the mineral fiber marine board deck insulation, the initial ambient temperature was taken as 19 °C (66 °F) and the average unexposed face temperature limit was 159 °C (318 °F).

Table 20. Predicted mineral fiber marine board deck test results.

Tested Insulation Thickness mm (in)	Tested Time to Exceed Temperature Limits (min)	Predicted Time to Exceed Temperature Limits (min)
51 (2)[1]	99.5	102
38 (1.5)	60.2	59.8
25 (1)	42.0	35.7

[1] USCG approved baseline thickness

In the fire test, the average unexposed surface temperatures of the baseline thickness test samples exceeded the temperature limits at 99.5 minutes. The HEATING 7 model predicted the insulation material would exceed the temperature limit at 102 minutes. Figure 21 provides a plot of the average unexposed surface temperature from the fire test and as predicted by the heat transfer model. The insulation thickness was then adjusted down from the baseline thickness of 51 mm (2 inches) to 38 mm (1.5 inches), corresponding to 75 percent of the baseline insulation thickness, and the model re-run. The model predicted a time to exceed the temperature limits of 59.8 minutes. The predicted 75 percent of baseline thickness time to exceed the temperature limits was nominally the same as the test results (60.2 minutes) indicating a good simulation of the actual tested assemblies. Adjustment of the insulation thickness to 25 mm (1 inch), corresponding to 50 percent of the baseline thickness, yielded a predicted time to exceed the temperature limits of 35.7 minutes. The model underpredicted the time to exceed the temperature limits for the tested 50 percent of baseline thickness sample (42.0 minutes) by approximately 6 minutes. Figures 22 and 23 provide plots of the predicted unexposed surface temperatures compared to the unexposed surface temperatures generated during the tests for the 75 percent and 50 percent of baseline insulation thickness samples, respectively. Further refinement of the insulation thicknesses was conducted to determine the “optimized” insulation thicknesses for these tests.

The insulation thickness was iteratively changed in the model in 3 mm (1/8 inch) increments until insulation thicknesses corresponding to the times to exceed the 15, 30, and 60 minutes temperature limits were obtained. These thicknesses represented the “optimum” insulation thickness. Table 21 provides the numerical modeling results. Included in table 21 is the calculated 50 percent and 75 percent insulation thickness based on the new, optimized baseline insulation thickness using the calculation method.

Table 21. Optimized mineral fiber marine board deck insulation material.

Tested Insulation Thickness mm (in)	Optimized Time to Exceed Temperature Limits (min)	Optimized Insulation Thickness mm (in)	Calculation Method Insulation Thickness mm (in)
51 (2)[1]	59.8	38 (1.5)	N/A
38 (1.5)	30.4	22 (0.875)	29 (1.125)
25 (1)	14.2	10 (0.375)	19 (0.75)

[1] USCG Approved Baseline Thickness

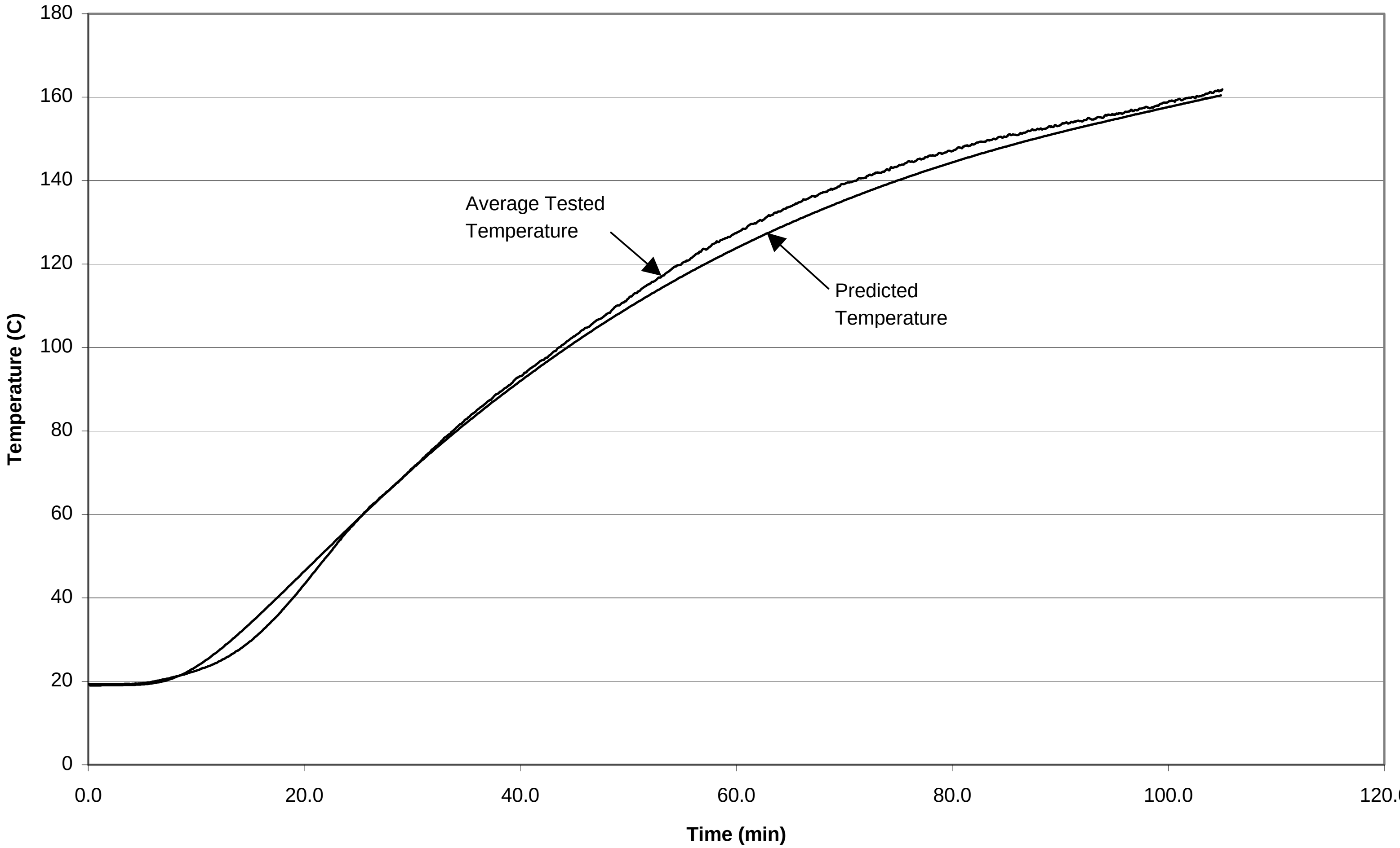

Figure 21. Mineral fiber deck predicted and tested baseline thickness unexposed surface temperatures (calibration run).

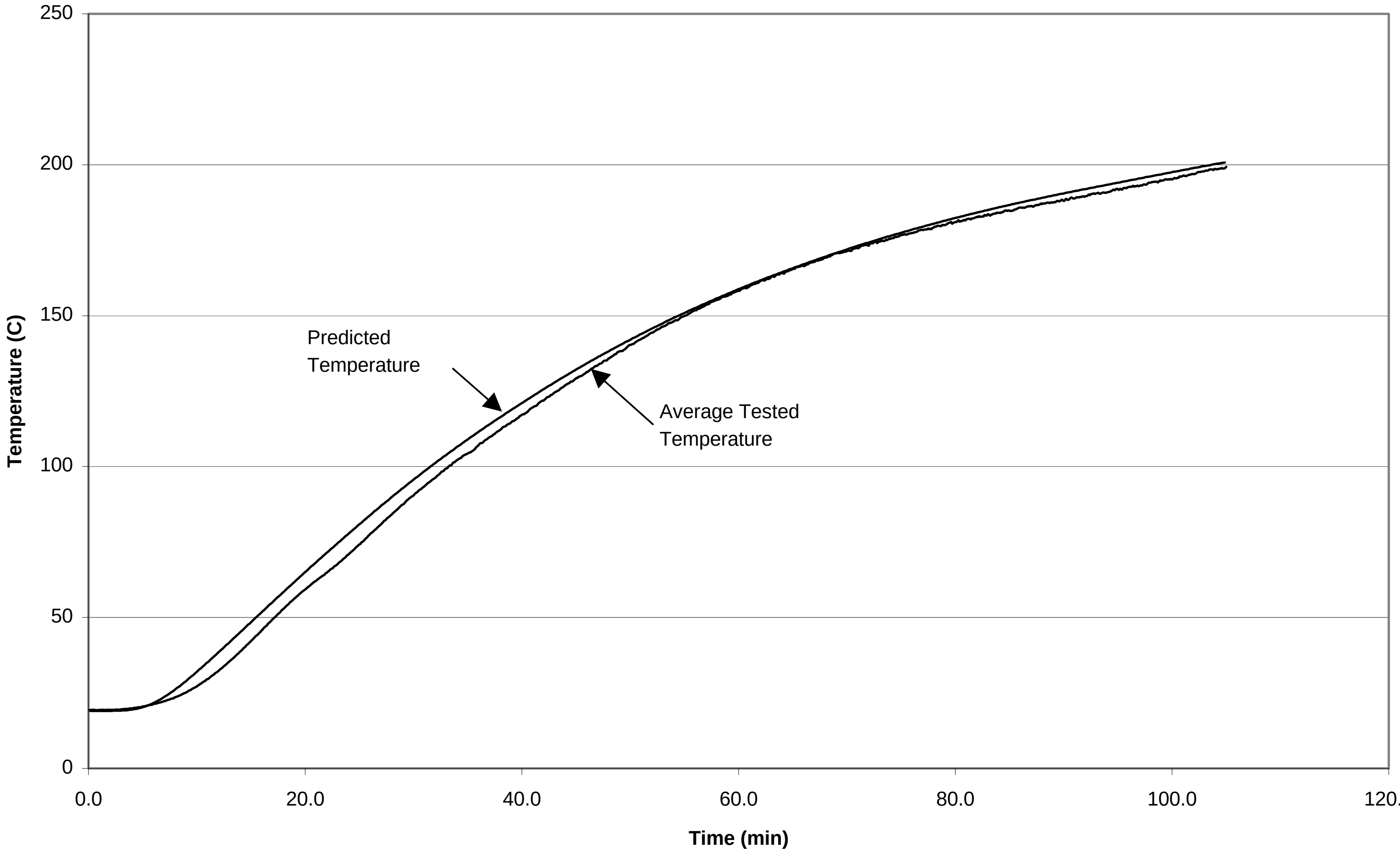

Figure 22. Mineral fiber deck predicted and tested 75 percent of baseline thickness unexposed surface temperatures.

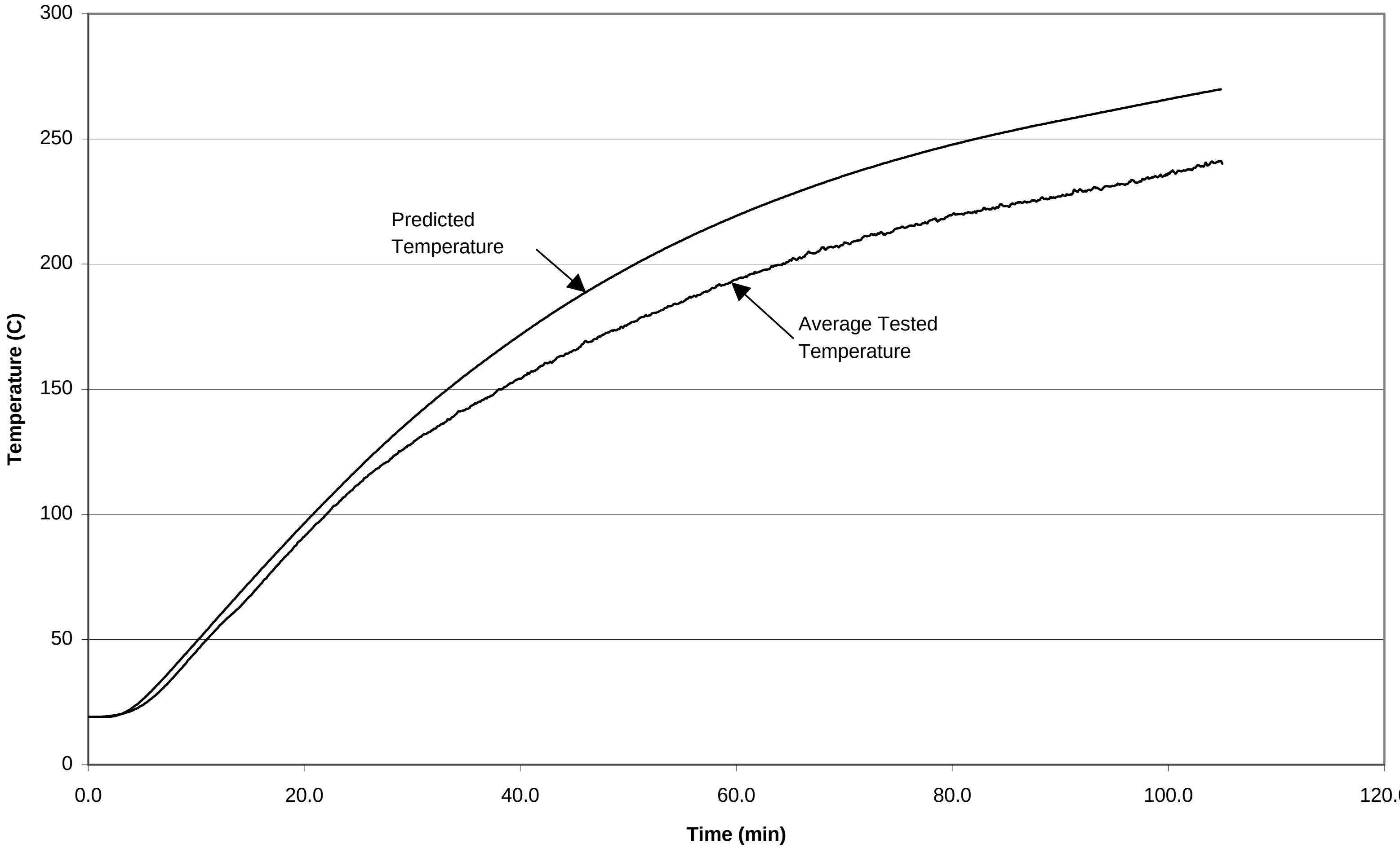

Figure 23. Mineral fiber deck predicted and tested 50 percent of baseline thickness unexposed surface temperatures.

The optimized insulation thicknesses shown in table 21 indicate the predicted times to exceed the temperature limits were within approximately 5 percent of the division classification time. Application of the calculation method using the predicted baseline insulation thickness of 38 mm (1.5 inches) yielded a 50 percent of the baseline insulation thickness of 19 mm (0.75 inch) and a 75 percent of the baseline insulation thickness of 9 mm (1.125 inches). These insulation thicknesses developed using the calculation method were greater than the predicted insulation thicknesses, indicating that the calculation method remained conservative given the newly reduced, optimized baseline insulation thickness.

5.4.3 Ceramic Fiber Blanket Bulkhead Tests

The ceramic fiber blanket insulation material evaluated had a USCG Certificate of Approval for use as a bulkhead insulation material at a thickness of 38 mm (1.5 inches) to achieve a minimum 30 minutes of fire resistance. This thickness was used as the 75 percent of baseline thickness (i.e., 75 percent of the typical “baseline” approved insulation thickness). Application of the calculation method for insulation thickness was utilized to provide an increased thickness (baseline insulation thickness) of 51 mm (2 inches) and a 50 percent of baseline insulation thickness of 25 mm (1 inch). The model was “calibrated” for the 75 percent baseline test results and then re-configured to predict the time to exceed the temperature limits for the “baseline” (60 minutes of fire resistance) and 50 percent of baseline insulation thicknesses (insulation thicknesses only adjusted accordingly). Table 22 provides the initial model results for the three tested configurations. For the modeling of the ceramic fiber blanket bulkhead insulation, the initial ambient temperature was taken as 12 °C (54 °F) and the average unexposed face temperature limit was 152 °C (306 °F).

Table 22. Ceramic fiber insulation bulkhead results.

Tested Insulation Thickness mm (in)	Tested Time to Exceed Temperature Limits (min)	Predicted Time to Exceed Temperature Limits (min)
51 (2)	51.8	54.8
38 (1.5[1])	34.1	33.8
25 (1)	19.9	19.0

[1] USCG Approved Baseline Thickness

In the fire test, the average unexposed surface temperatures of the 75 percent of baseline thickness test samples exceeded the temperature limits at 34.1 minutes. The “calibrated” baseline thickness HEATING 7 model predicted the insulation material would exceed the temperature limit at 33.8 minutes. Figure 24 provides a plot of the average unexposed surface temperatures from the fire test and as predicted by the heat transfer model for the 75 percent of baseline insulation thickness. The insulation thickness was then adjusted from the 75 percent of baseline thickness of 38 mm (1.5 inches) up to 51 mm (2 inches), corresponding to the baseline thickness, sample and the model re-run. The model predicted a time to exceed the temperature limits of 54.8 minutes compared to 51.8 minutes measured in the test. Adjustment of the insulation thickness down to 25 mm (1 inch), corresponding to the 50 percent of the baseline thickness, yielded a predicted time to exceed the temperature limits of 19.0 minutes. The predicted baseline and 50 percent of baseline times to exceed the temperature limits were nominally the same, indicating an adequate simulation of the actual tested assemblies. Figures 25 and 26 provide plots of the average unexposed surface temperatures compared to the predicted temperatures for the baseline and 50 percent of baseline thickness insulation samples, respectively. Further refinement of the insulation thicknesses was conducted to determine the “optimized” insulation thicknesses for this insulation material.

The insulation thickness was iteratively changed in the model in 3 mm (1/8 inch) increments until the insulation thicknesses corresponding to the times to exceed the 15, 30, and 60 minutes temperature limits were obtained. These thicknesses represented the “optimum” insulation thicknesses. Table 23 provides the numerical modeling results. Included in table 23 is the calculated “baseline,” 50 percent, and 75 percent of the baseline insulation thickness (based on the new, predicted baseline insulation thickness of 54 mm (2.125 inches).

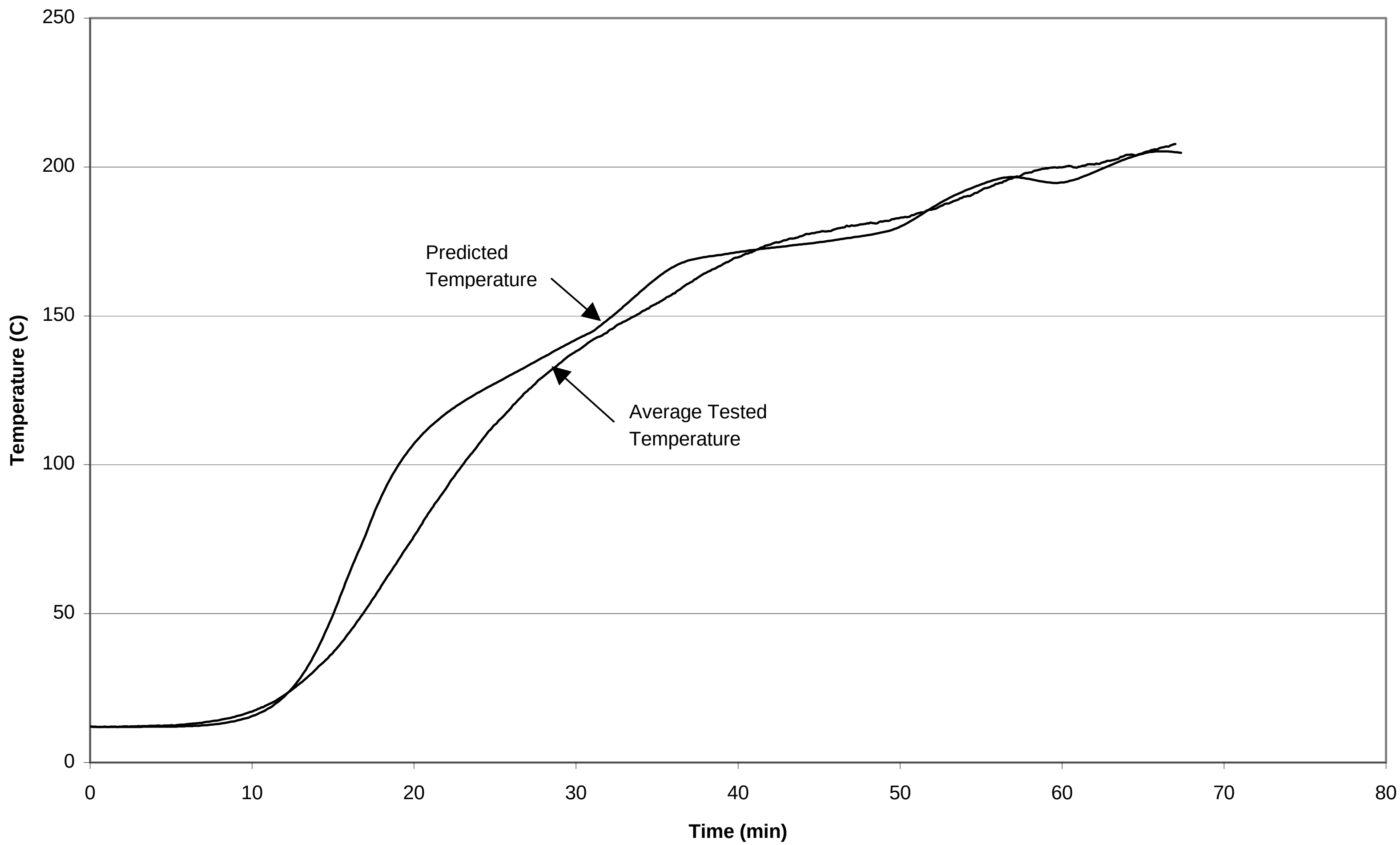

Figure 24. Ceramic fiber bulkhead predicted and tested 75 percent of baseline thickness unexposed surface temperatures (calibration run).

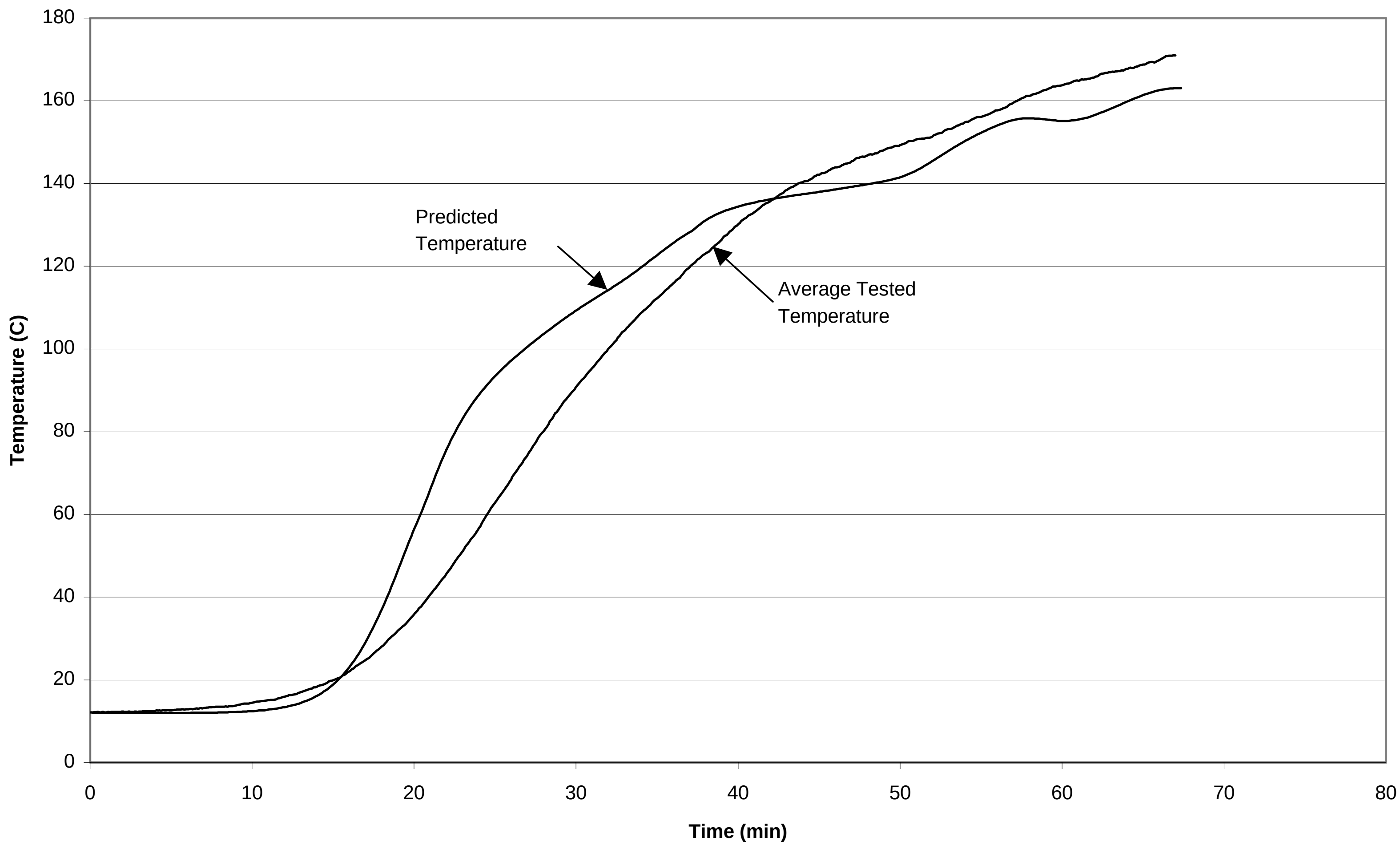

Figure 25. Ceramic fiber bulkhead predicted and tested baseline thickness unexposed surface temperatures.

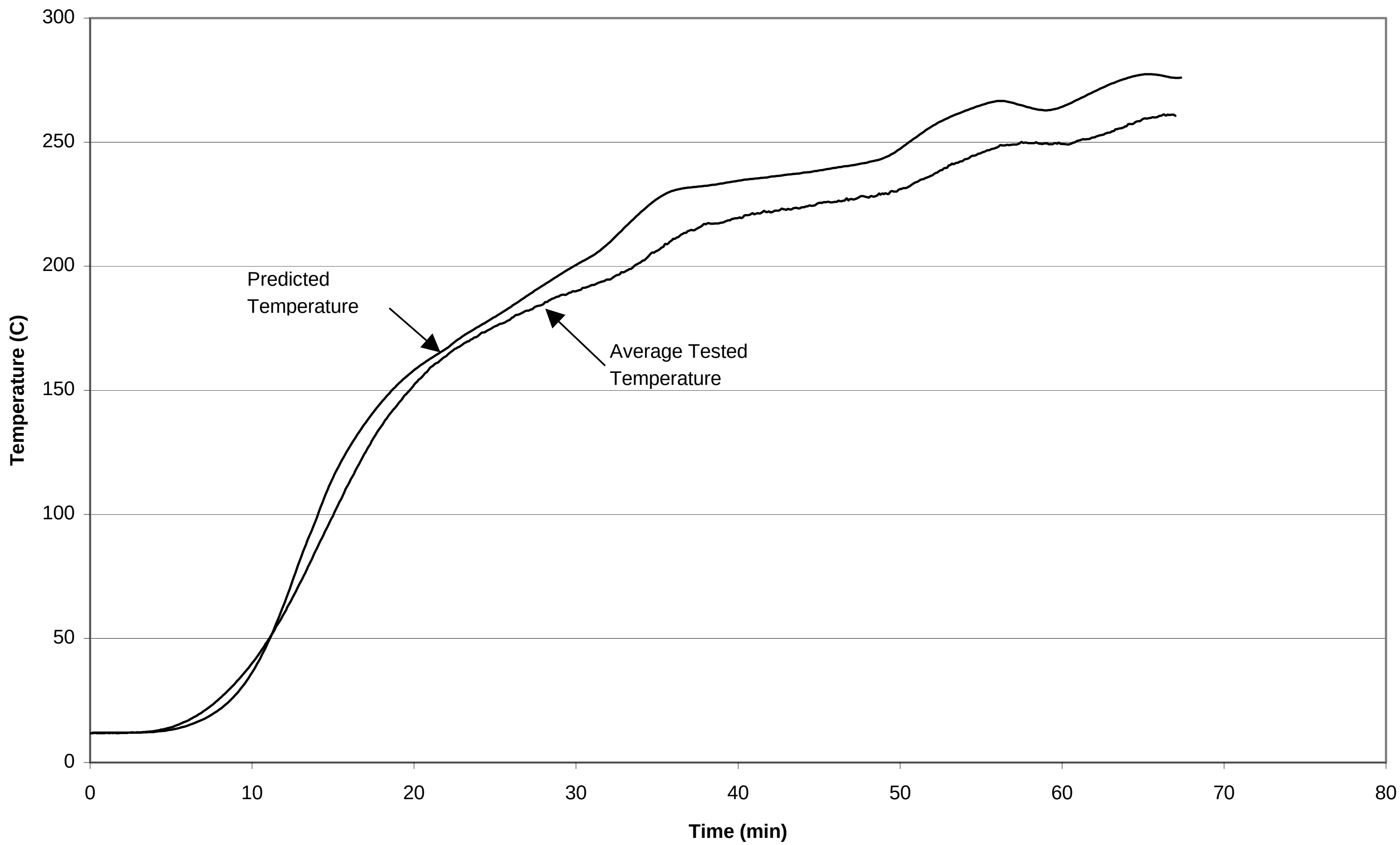

Figure 26. Ceramic fiber bulkhead predicted and 50 percent of baseline thickness unexposed surface temperatures.

Table 23. Optimized ceramic fiber bulkhead insulation material.

Tested Insulation Thickness mm (in)	Optimized Time to Exceed Temperature Limits (min)	Optimized Insulation Thickness mm (in)	Calculation Method Insulation Thickness mm (in)
51 (2)	69.5	54 (2.125)	N/A
38 (1.5)[1]	33.8	38 (1.5)	41 (1.6)
25 (1)	16.7	22 (0.875)	27 (1.1)

[1] USCG Approved Baseline Thickness

The optimized insulation thicknesses shown in table 23 indicate the predicted times to exceed the temperature limits were within approximately 15 percent of the division classification time. Application of the calculation method using the optimized "baseline" insulation thickness (i.e., A-60) yielded a 50 percent of the baseline insulation thickness of 27 mm (1.1 inches) and a 75 percent of the baseline insulation thickness of 41 mm (1.6 inches). The insulation thicknesses developed using the calculation method are greater than the predicted insulation thicknesses, indicating that the calculation method remains conservative given the newly reduced, optimized baseline insulation thickness.

5.4.4 Ceramic Fiber Deck Tests

The ceramic fiber insulation material evaluated had a USCG Certificate of Approval for use as a deck insulation material at a baseline thickness of 38 mm (1.5 inches). Application of the calculation method for insulation thickness provided an insulation thickness corresponding to 75 percent of the baseline thickness of 25 mm (1 inch) and an insulation thickness of 19 mm (0.75 inch), corresponding to 50 percent of the baseline thickness. The model was "calibrated" for the baseline test results and then re-configured to predict the time to exceed the temperature limits for the reduced sample thicknesses (insulation thicknesses only adjusted accordingly). Table 24 provides the initial model results for the three tested configurations. For the modeling of the ceramic fiber deck insulation, the initial ambient temperature was taken as 16 °C (61 °F) and the average unexposed face temperature limit was 156 °C (313 °F).

Table 24. Ceramic fiber insulation deck results.

Tested Insulation Thickness mm (in)	Tested Time to Exceed Temperature Limits (min)	Predicted Time to Exceed Temperature Limits (min)
51 (2)[1]	64.7	66.2
38 (1.5)	50.7	39.5
25 (1)	45.8	29.3

[1] USCG approved baseline thickness

In the fire test, the average unexposed surface temperatures of the baseline thickness test samples exceeded the temperature limits at 64.7 minutes. The "calibrated" baseline HEATING 7 model predicted the insulation material would exceed the temperature limit at 66.2 minutes. Figure 27 provides a plot of the average unexposed temperatures for the baseline thickness compared to the predicted temperatures. The insulation thickness was then adjusted down from the baseline thickness of 51 mm (2 inches) to 38 mm (1.5 inches), corresponding to 75 percent of the baseline thickness sample, and 25 mm (1 inch), corresponding to 50 percent of the baseline thickness, and the model re-run. Due to the close times to exceed the temperature limits for the 50 percent and 75 percent thickness samples in the actual tests (average times of 50.7 and 45.8 minutes, respectively), the model severely underpredicted the times to exceed the temperature limits for both insulation thicknesses. Figures 28 and 29 provide plots of the average unexposed surface temperatures measured during the test compared to the predicted temperatures for the 75 percent and 50 percent of baseline thickness test samples, respectively. Numerous changes to the heat transfer model inputs were made in an attempt to improve the predicted times to exceed the temperature limits, however, the changes had negligible effect on the model output. Closer review of the test data did not indicate a substantial reason for the close grouping of the test developed times to exceed the temperature limits.

Recognizing the severe underprediction of the "calibrated" base heat transfer model, further refinement of the insulation thicknesses was determined not to be practical.

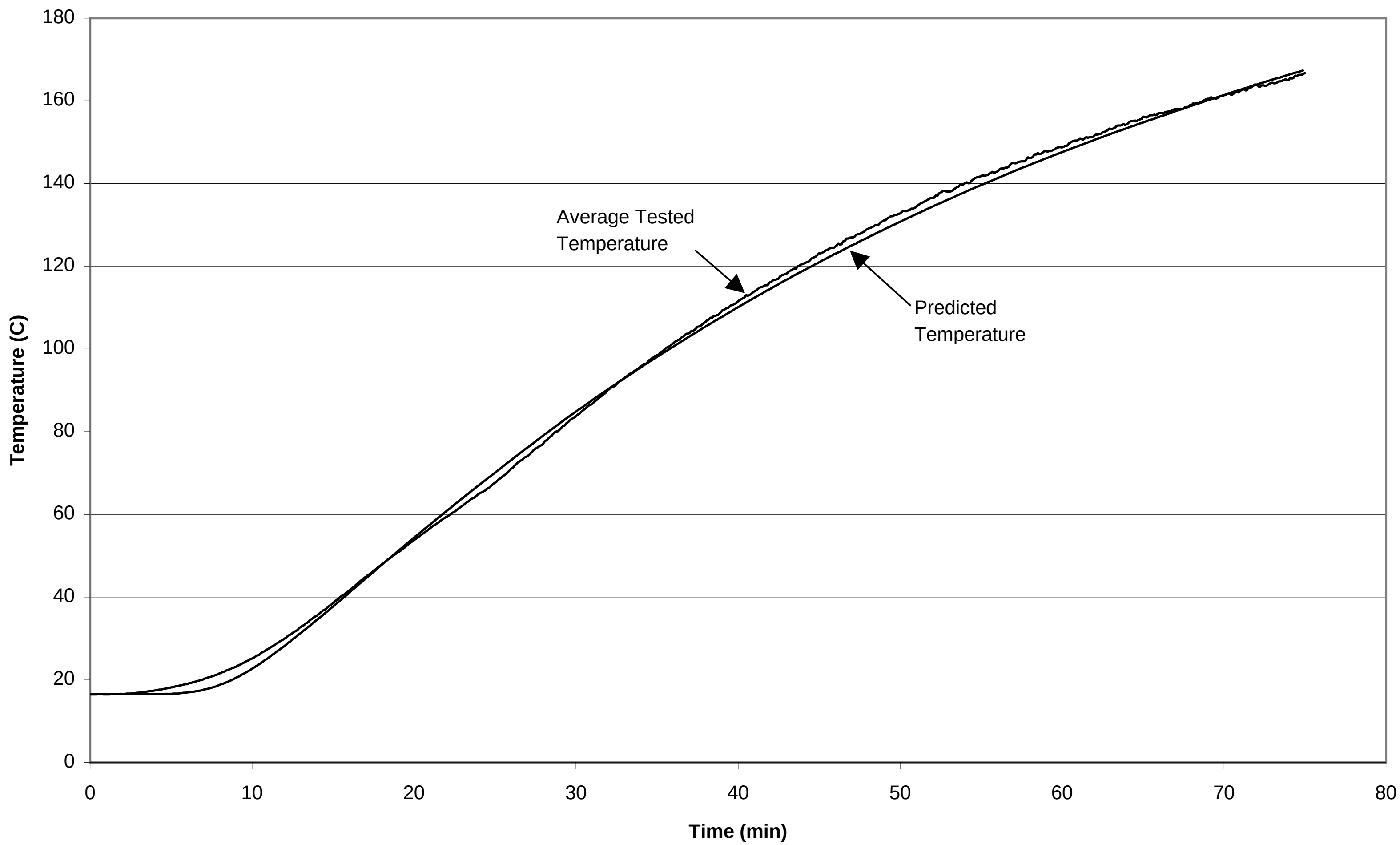

Figure 27. Ceramic fiber deck predicted and tested baseline thickness unexposed surface temperatures (calibration run).

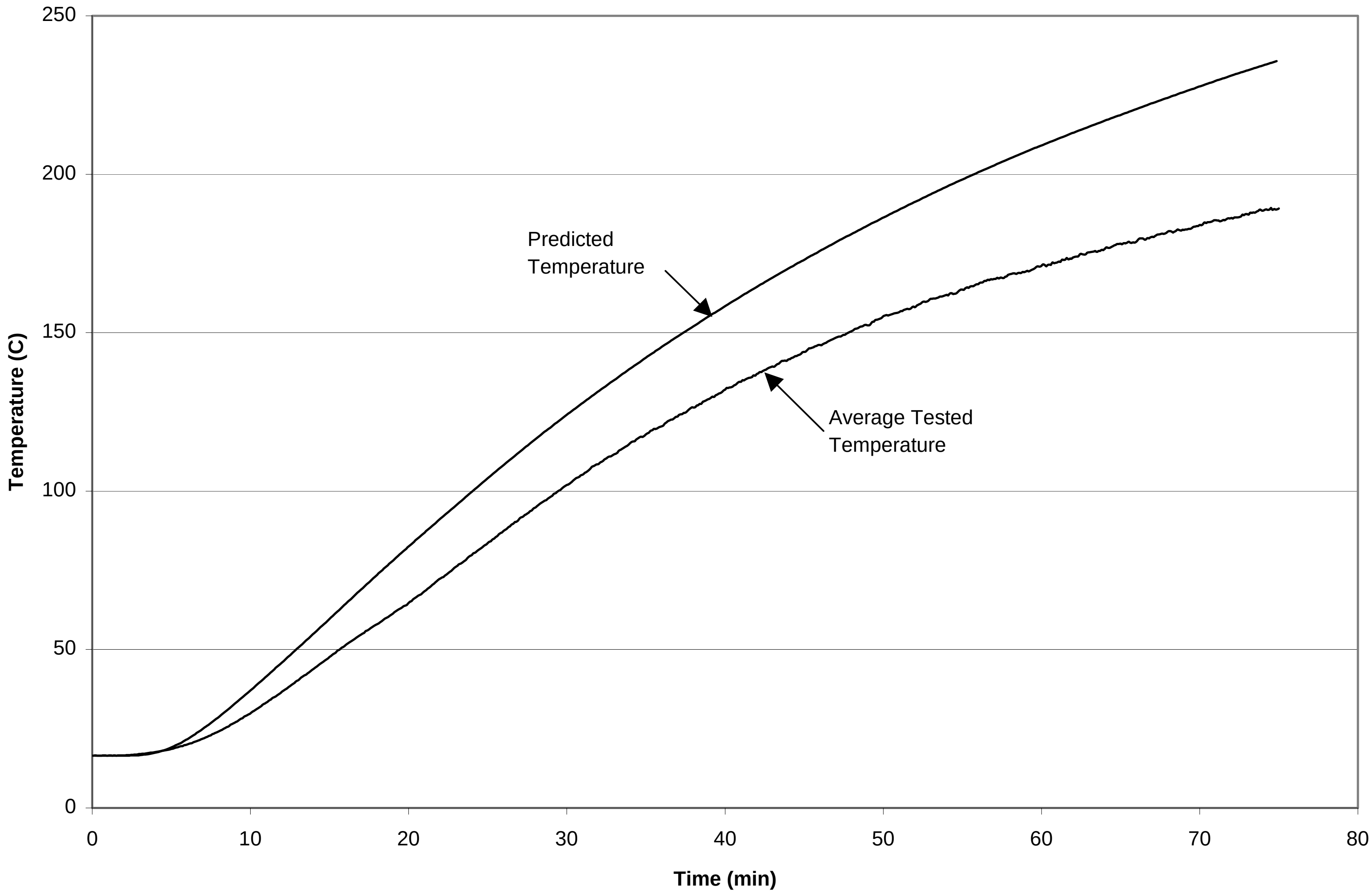

Figure 28. Ceramic fiber deck predicted and tested 75 percent of baseline thickness unexposed surface temperatures.

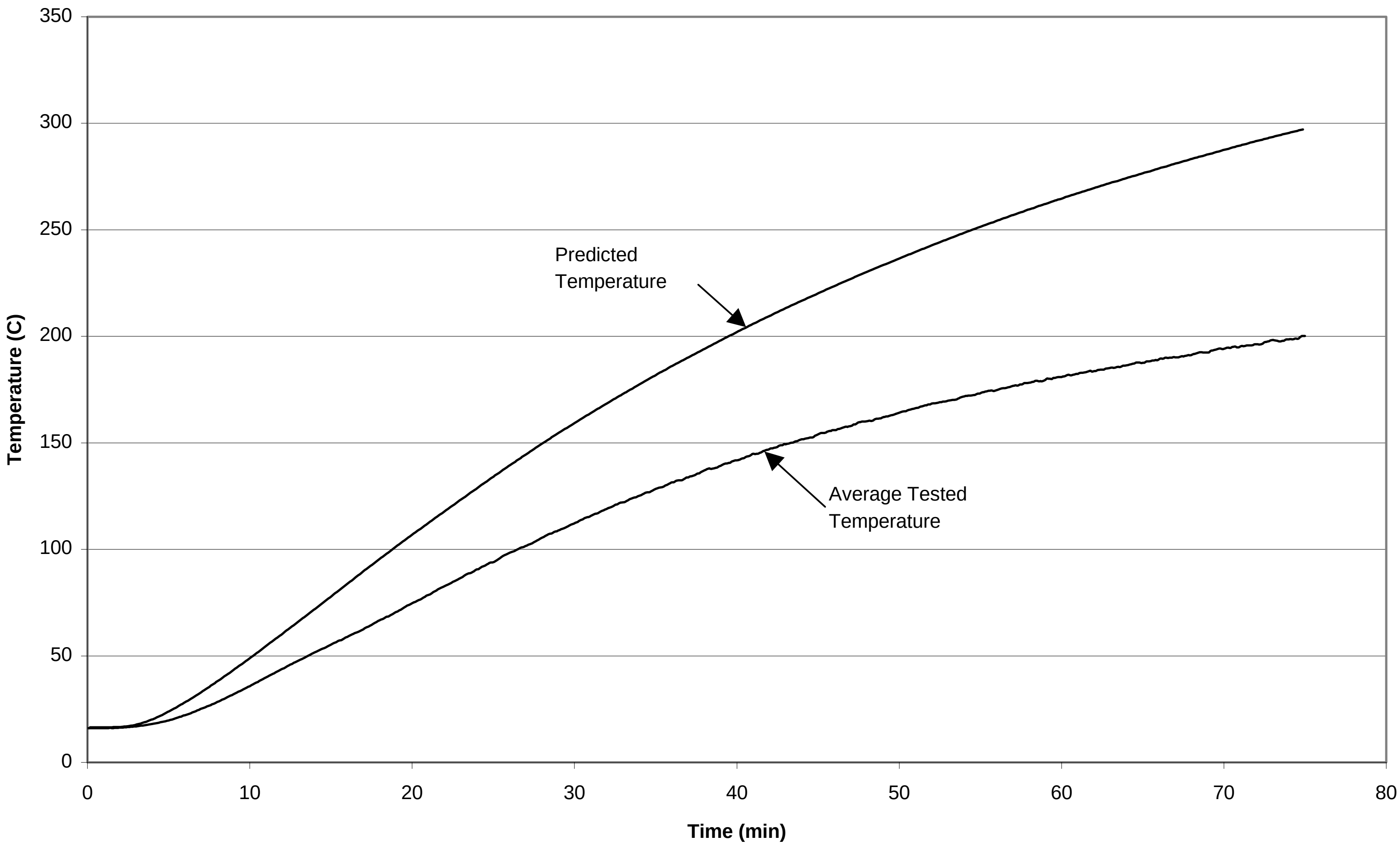

Figure 29. Ceramic fiber deck predicted and tested 50 percent of baseline thickness unexposed surface temperatures.

5.4.5 Foil-faced Mineral Fiber Marine Board Bulkhead Tests

The foil-faced mineral fiber marine board insulation material evaluated did not have a specific USCG Certificate of Approval. However, the mineral fiber marine board base material was identical to the unfaced mineral fiber marine board insulation and which had a USCG approved bulkhead thickness of 76 mm (3 inches). This was, therefore, used as the baseline insulation thickness for this test. Application of the calculation method for insulation thickness provided an insulation thickness of 57 mm (2.25 inches) corresponding to 75 percent of the baseline thickness and an insulation thickness of 38 mm (1.5 inches) corresponding to 50 percent of the baseline thickness. The model was "calibrated" for the baseline test results and then re-configured to predict the time to exceed the temperature limits for the reduced sample thicknesses (insulation thicknesses only adjusted accordingly). Table 25 provides the initial model results for the three tested configurations. For the modeling of the foil-faced mineral fiber marine board bulkhead insulation, the initial ambient temperature was taken as 14 °C (59 °F) and the average unexposed face temperature limit was 154 °C (309 °F).

Table 25. Foil-faced mineral fiber insulation bulkhead results.

Tested Insulation Thickness mm (in)	Tested Time to Exceed Temperature Limits (min)	Predicted Time to Exceed Temperature Limits (min)
76 (3)[1]	52.4	51.2
57 (2.25)	32.7	36.3
38 (1.5)	21.8	21.8

[1] USCG Approved Baseline Thickness

In the fire test, the average unexposed surface temperatures of the test samples exceeded the temperature limits at 52.4 minutes. The premature failure of the baseline test samples was discussed in Section 4.2.3. The "calibrated" baseline HEATING 7 model predicted the insulation material would exceed the temperature limit at 51.2 minutes. Figure 30 provides the average unexposed surface temperatures for both baseline thickness test samples compared to the predicted temperatures. The insulation thickness was then adjusted from the baseline thickness of 76 mm (3 inches) to 57 mm (2.25 inches), corresponding to 75 percent of the baseline thickness, and 38 mm (1.5 inches), corresponding to 50 percent of the baseline thickness, and the model re-run. The model predicted a time to exceed the temperatures limits at 36.3 minutes for the 75 percent of the baseline thickness test samples and 21.8 minutes for the 50 percent of baseline thickness samples. The model slightly over-predicted the time to exceed the temperature limits for the 75 percent of the baseline thickness test samples by approximately 4.5 minutes, but accurately predicted the time to exceed the temperature limits for the 50 percent of baseline thickness test sample. Figures 31 and 32 provide the average unexposed surface temperatures for the 75 percent and 50 percent of baseline thickness test samples, respectively, compared to the corresponding predicted temperatures from the model. Further refinement of the insulation thicknesses was then conducted to determine the "optimized" thickness for this insulation material.

The insulation thickness was iteratively changed in the model in 3 mm (1/8 inch) increments until insulation thicknesses corresponding to the times to exceed the 15, 30, and 60 minutes temperature limits were obtained. These thicknesses represented the new "optimum" insulation thickness. The "baseline" insulation thickness was optimized (i.e., increased) to account for the premature failure of the test samples. Table 26 provides the optimized insulation thicknesses as well as the numerical modeling time to exceed the temperature limit results. Included in table 26 is the calculated 50 percent and 75 percent of baseline insulation thickness based on the new, predicted baseline insulation thickness using the calculation method.

Table 26. Optimized foil-faced mineral fiber bulkhead insulation material.

Tested Insulation Thickness mm (in)	Optimized Time to Exceed Temperature Limits (min)	Optimized Insulation Thickness mm (in)	Calculation Method Insulation Thickness mm (in)
76 (3)[1]	60.0	83 (3.25)	N/A
57 (2.25)	30.7	51 (2)	62 (2.4)
38 (1.5)	15.8	29 (1.125)	42 (1.7)

[1] USCG approved baseline thickness

The optimized insulation thicknesses shown in table 26 indicate the predicted times to exceed the temperature limits were within approximately 5 percent of the division classification time. Application of the calculation method using the predicted baseline insulation thickness yielded a 50 percent of baseline insulation thickness of 42 mm (1.7 inches) and a 75 percent of

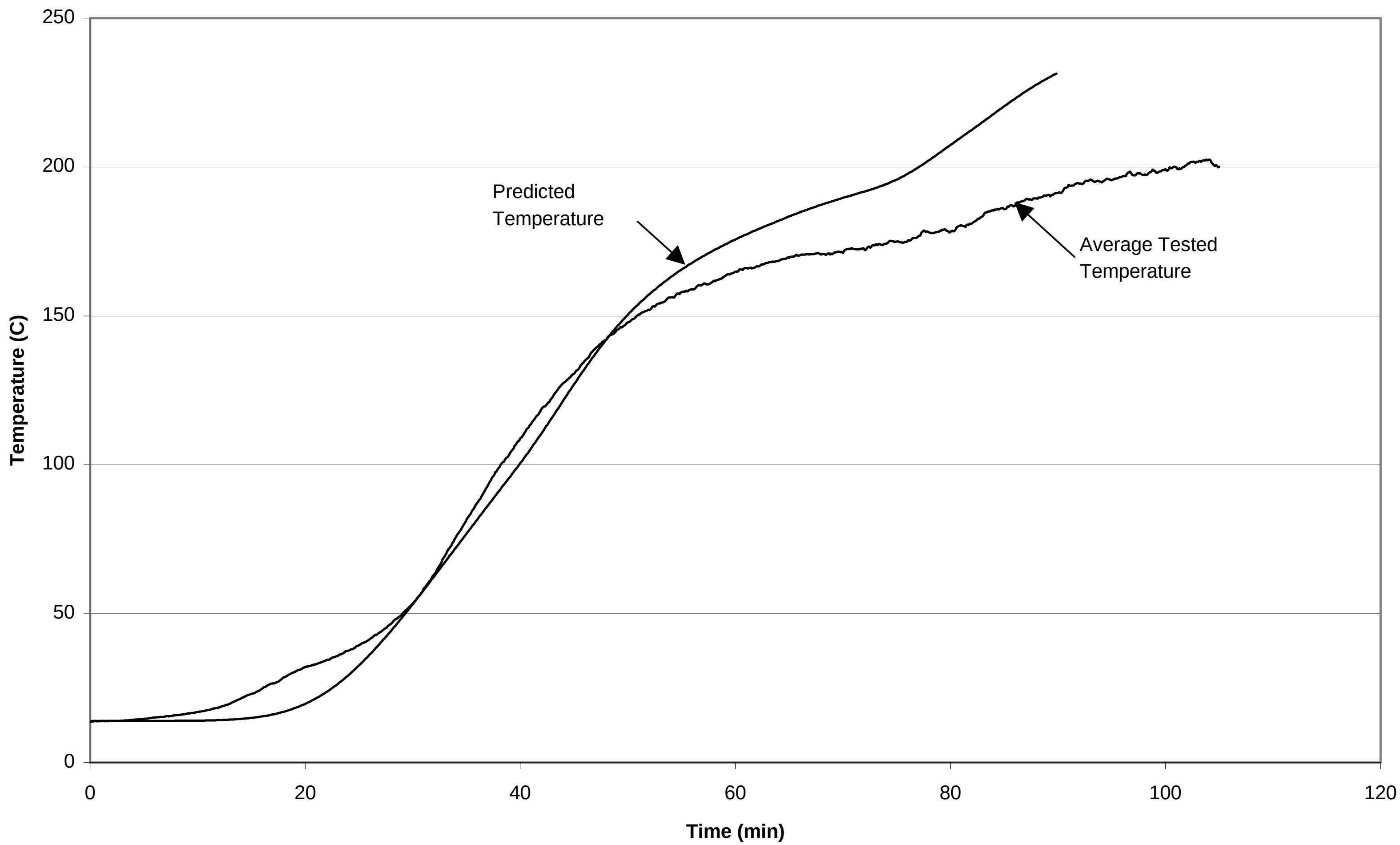

Figure 30. Foil-faced mineral fiber bulkhead predicted and tested baseline thickness unexposed surface temperatures (calibration run).

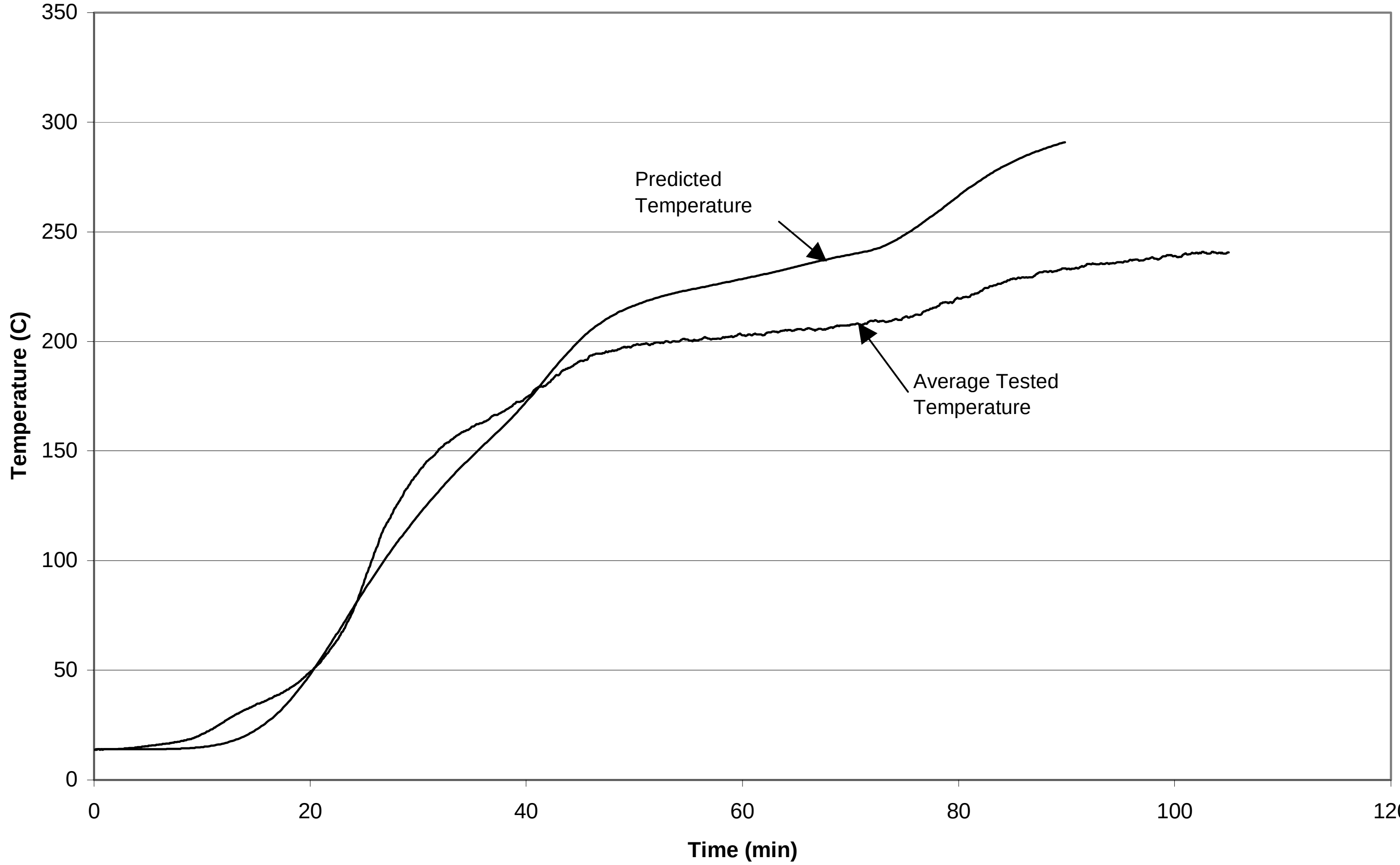

Figure 31. Foil-faced mineral fiber bulkhead predicted and tested 75 percent of baseline thickness unexposed surface temperatures.

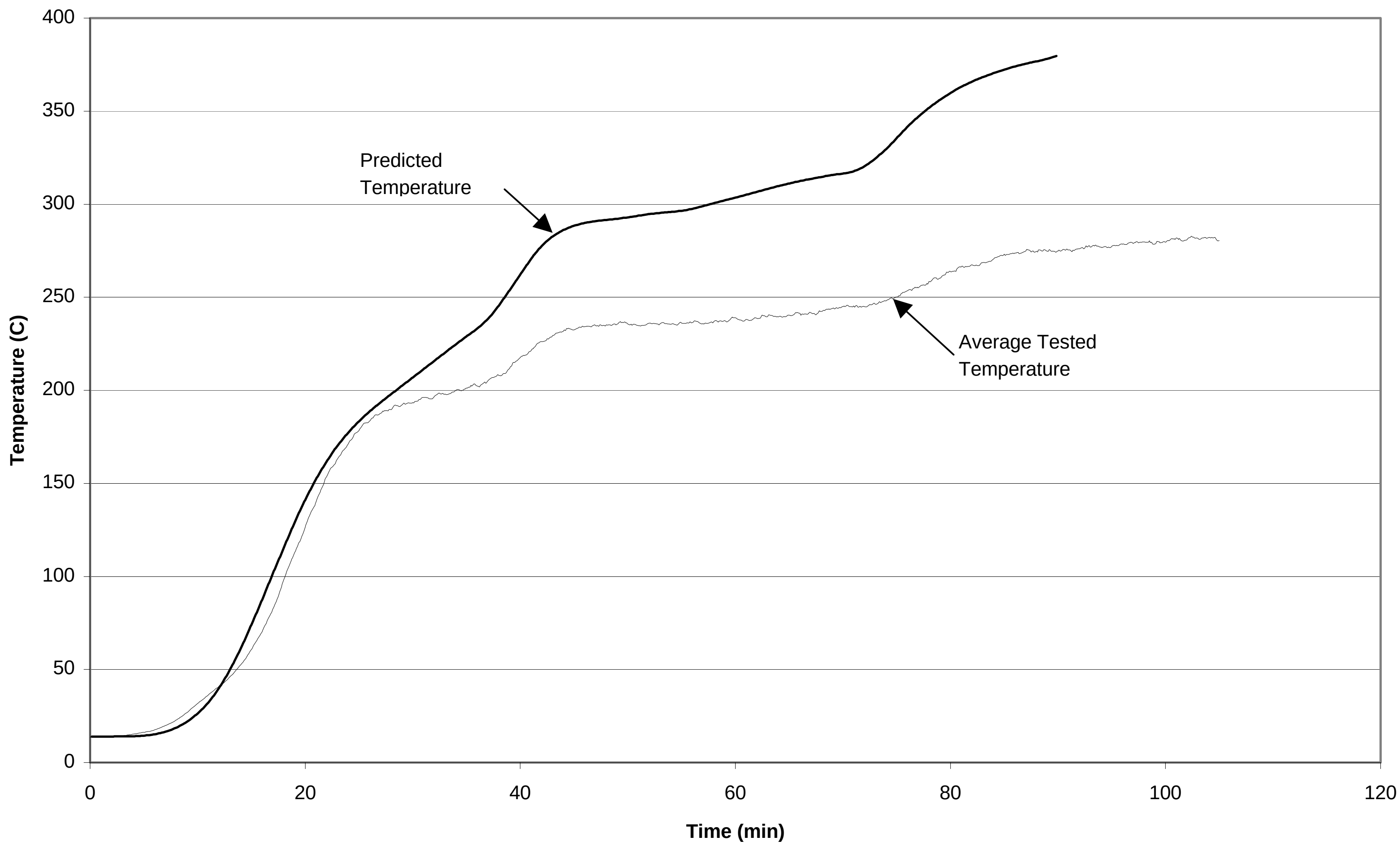

Figure 32. Foil-faced mineral fiber bulkhead predicted and tested 50 percent of baseline thickness unexposed surface temperatures.

baseline insulation thickness of 62 mm (2.4 inches). These insulation thicknesses developed using the calculation method were greater than the predicted insulation thicknesses, indicating that the calculation method remained conservative given the newly reduced predicted baseline insulation thickness.

5.5 Numerical Modeling Conclusions

The heat transfer model HEATING 7 was utilized to model the generated test results and "optimize" the insulation thickness for the mineral fiber marine board and ceramic fiber bulkhead and deck tests, and the foil-faced mineral fiber bulkhead test. The spray-applied fiber insulation was not modeled due to the water evaporation issues encountered in the tests. The foil-faced mineral fiber deck insulation was not modeled due to the similar performance compared to the unfaced mineral fiber deck insulation (i.e., the exposed foil-face burned away at the start of the test). The tested insulation thicknesses were optimized to remove some of the conservatism inherent in the USCG approved baseline thicknesses based on the full-scale testing conducted by the manufacturers for qualification of the insulation. Application of the calculation method to the "optimized" baseline insulation material resulted in 50 percent and 75 percent of baseline insulation thicknesses slightly greater than predicted by the heat transfer model, indicating the calculation method still applied and the modeling effort was conservative.

Evaluation of the optimized test results from the numerical modeling effort are contained in table 27. Table 27 contains the optimized insulation thickness for each of the four samples evaluated, the corresponding $x/\sqrt{t}$ calculated based on the optimized insulation thickness, and the calculated insulation thickness using the Fourier number. The baseline thickness $x/\sqrt{t}$ value was utilized to predict the corresponding thickness for the 75 percent and 50 percent of the baseline thickness samples, assuming that the $x/\sqrt{t}$ value was constant for each insulation material thickness. For the 75 percent of the baseline thickness samples, the value developed using the Fourier number was subsequently increased 5 percent corresponding to the difference between the heat transfer ratio value of 70 percent and the 75 percent value used in the USCG calculation method.

Table 27. $x/\sqrt{t}$ calculated values for optimized insulation thicknesses.

Insulation Material	Insulation Configuration (insulation thickness)	Optimized Insulation Thickness mm (in)	Optimized $x/\sqrt{t}$	Calculated $x/\sqrt{t}$ thickness mm (in)
Mineral Fiber	Bulkhead (B.T.)	67 (2.6)	8.42	N/A
Mineral Fiber	Bulkhead (75 percent)	45 (1.8)	8.22	48 (1.9)
Mineral Fiber	Bulkhead (50 percent)	29 (1.1)	7.27	33 (1.3)
Foil-faced mineral fiber	Bulkhead (B.T.)	83 (3.3)	10.72	N/A
Foil-faced mineral fiber	Bulkhead (75 percent)	51 (2.0)	9.2	61 (2.4)
Foil-faced mineral fiber	Bulkhead (50 percent)	29 (1.1)	7.29	42 (1.7)
Ceramic fiber	Bulkhead (100 percent)	54 (2.1)	6.48	N/A
Ceramic fiber	Bulkhead (B.T.)	38 (1.5)	6.54	37 (1.5)
Ceramic fiber	Bulkhead (50 percent)	22 (0.9)	5.38	25 (1.0)
Mineral fiber	Deck (B.T.)	38 (1.5)	4.91	N/A
Mineral fiber	Deck (75 percent)	22 (0.9)	3.99	28 (1.1)
Mineral fiber	Deck (50 percent)	10 (0.4)	2.65	19 (0.75)

Examination of the data in table 27 indicated that the optimized insulation thickness and the corresponding calculated $x/\sqrt{t}$ thickness values are similar in magnitude. The 75 percent of baseline mineral fiber bulkhead insulation thickness varied the most, 10 mm (0.4 inch); however, this difference in insulation thickness is arguably minor and would likely not have a detrimental effect on the outcome of a test. The optimized 50 percent of baseline thickness values are, however, noticably lower, similar to the observed results of the analysis of the tested data. The 75 percent and 50 percent of baseline insulation thicknesses were plotted against one another to graphically demonstrate the conservatism in the application of the calculation method. Figure 33 provides a plot of the calculated insulation thickness versus the optimized thickness.

In general, the results of using the Fourier number to calculate the required insulation thickness, (using the Fourier number for each “optimized” insulation thickness as the baseline), were similar to the results developed using the heat transfer model. This indicated that the USCG calculation method remains conservtive in predicting the appropriate insulation thickness for the required division classification time.

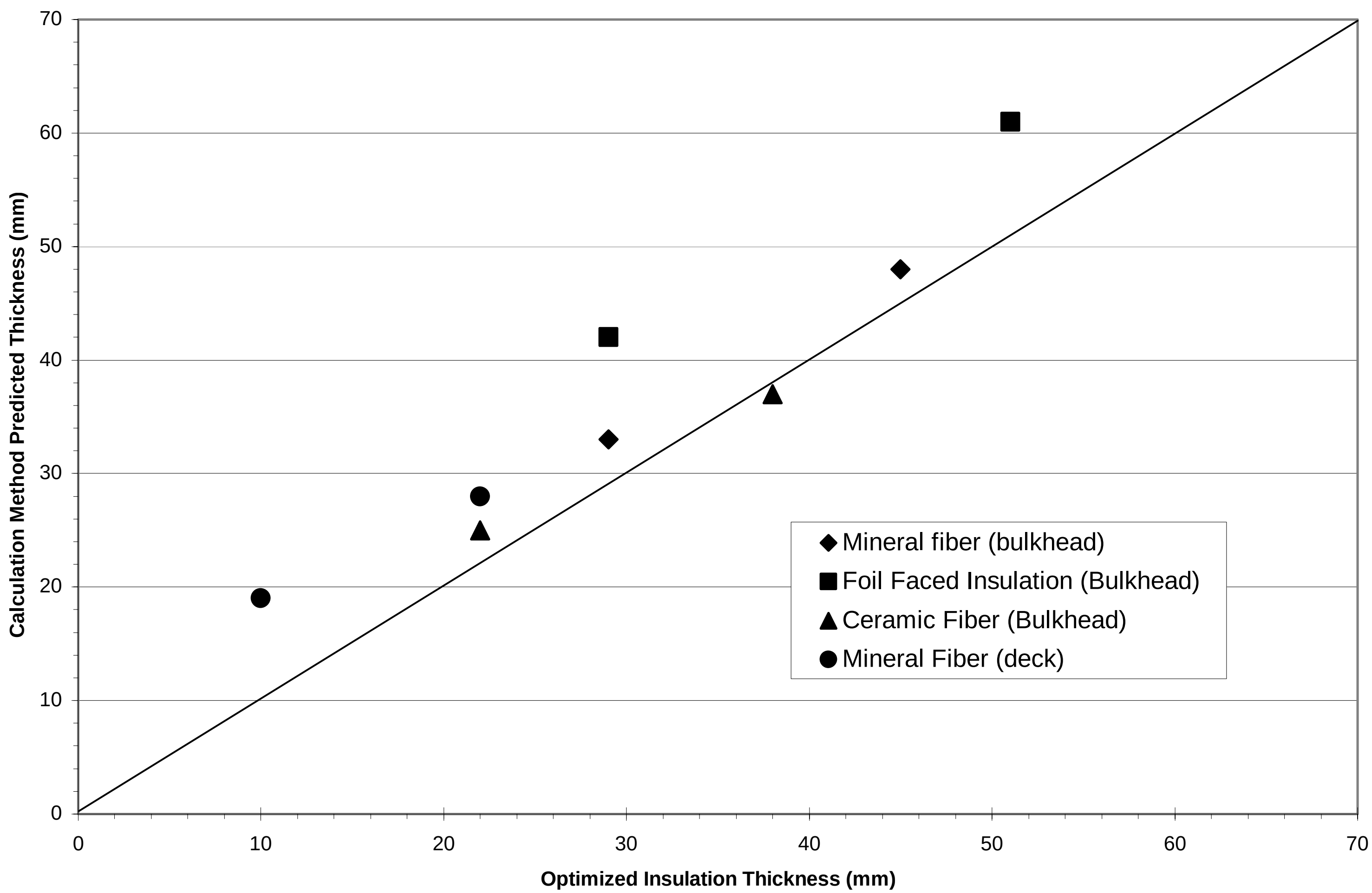

Figure 33. Calculation method predicted versus optimized insulation thicknesses.

6.0 CONCLUSIONS

A series of fire tests were conducted to develop data to support the current calculation method for insulation thicknesses used by the USCG to determine the appropriate thickness for structural insulation materials. Four insulation materials were evaluated in this test program and included:

- Mineral fiber marine board ;
- Ceramic fiber;
- Foil-faced mineral fiber; and
- Spray-applied fiber.

Duplicate samples of each insulation material were tested as bulkhead and deck insulation materials. Key conclusions developed from the fire tests include:

1. Application of the calculation method for determining bulkhead and deck insulation thicknesses yielded conservative results for the 50 percent and 75 percent of the baseline insulation thicknesses, given a USCG approved baseline thickness;

2. The 50 percent of the baseline bulkhead insulation materials averaged a time to exceed the temperature limits of 24 ± 6 minutes, and 44 ± 4 minutes for the deck insulation materials;

3. The 75 percent of the baseline bulkhead insulation materials averaged a time to exceed the temperature limits of 44 ± 4 minutes, and 56 ± 7 minutes for the deck insulation materials;

4. The foil-facing on the base mineral fiber bulkhead insulation material, when tested with the foil-facing on the unexposed face, resulted in premature failure of

the insulation material. The foil-facing prevented the heat from dissipating and reflected the heat back into the insulation material;

5. The foil-facing had a negligible effect on the performance of the insulation material when tested in the deck configuration as the foil-facing was directly exposed to the fire and melted away shortly after the start of the test;

6. In the case of the ceramic fiber blanket tested as a bulkhead insulation material, the manufacturer had a USCG Certificate of Approval for A-30 insulation on aluminum bulkheads. Application of the calculation method to determine the "baseline" insulation thickness (assuming approved thickness was 75 percent of the required 60 minutes "baseline") resulted in premature failure of the insulation material when tested on the unexposed side of the steel test bulkhead;

7. The spray-applied material contained bound water, which when released during the bulkhead fire test, resulted in many unexposed face thermocouples coming loose, giving erroneous temperature readings. A number of thermocouple readings were discarded prior to calculating the average unexposed surface averages due to poor adhesion of the thermocouples to the test samples as the test progressed;

8. The bound water in the spray-applied insulation material, when tested as a deck insulation material, had no effect on the test as the unexposed surface thermocouples were adhered to the backside of the steel plate; and

9. Normalization of the test results with the approved baseline insulation thickness using the basic heat transfer principle, which is the basis of the calculation method, indicated the calculation method remains conservative.

Upon completion of the data analysis of the fire test results, a numerical heat transfer modeling effort was undertaken to determine if some of the inherent conservatism from the approved baseline insulation thicknesses could be normalized to a sixty minute exposure since some of the A-60 materials withstood the test for over 90 minutes. The heat transfer model was setup with the appropriate thermal properties for each insulation material and calibrated for the baseline test results. The model was then utilized to predict the 75 percent and 50 percent of the baseline times to exceed the temperature limits. Further refinement of the insulation thicknesses was conducted to determine the "optimum" insulation thicknesses for each test scenario. The calculation method was applied to the "optimized" insulation thicknesses. It was shown that the calculation method provided conservative 50 percent and 75 percent of the baseline insulation thicknesses. Conclusions from the numerical modeling are:

1. Complete thermal data was not available for the insulation materials tested. Appropriate thermal conductivity and thermal heat capacities had to be numerically derived from the fire test data.

2. The numerical heat transfer model predicted the times to exceed the temperature limits for the insulation materials tested;

3. The numerical model severely underpredicted the times to exceed the temperature limits for the ceramic fiber deck insulations due to the close failure times of the 50 percent and 75 percent of baseline thickness samples (within 10 minutes for all four samples);

4. "Optimized" insulation thicknesses were calculated for the appropriate fire resistance times;

5. The calculation method was successfully applied to the "optimized" insulation thicknesses, using the optimized baseline thickness Fourier number as a constant. The calculation method for insulation thickness were greater than the "optimized" 50 percent and 75 percent of baseline insulation thicknesses, indicating that the calculation method remained conservative; and

6. The spray-applied materials were not modeled due to the bound water release issues encountered during the fire tests.

The data generated from the fire tests and the modeling effort provides the USCG with the information required to support the proposal to IMO and to change the existing policy regarding structural insulation materials. These data shows that the current calculation method adequately predicted a 50 percent and 75 percent of baseline insulation thickness, given an approved baseline insulation thickness.

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APPENDIX A - NUMERICAL MODELING INPUTS

Mineral Fiber Bulkhead Insulation Thermal Properties

Inputs for the numerical model utilized are as follows:

Density – 112 kg/m^3

Thermal Conductivity

Temperature (°C)	Thermal Conductivity (J/s-m-K)
24	0.035
93	0.042
149	0.050
204	0.061
260	0.071
302	0.15
699	0.15
1000	0.40

Thermal Heat Capacity

Temperature (°C)	Thermal Heat Capacity (J/kg-K)	Comments
20	700	
99	700	
100	2500	Moisture
110	2500	Moisture
111	700	
399	700	
400	7000	Dehydration
410	7000	Dehydration
411	700	
1000	800	

Mineral Fiber Deck Insulation Thermal Properties

Inputs for the numerical model utilized are as follows:

Density – 112 kg/m^3

Thermal Conductivity

Temperature (°C)	Thermal Conductivity (J/s-m-K)
24	0.035
93	0.042
149	0.050
204	0.061
260	0.071
302	0.0746
401	0.0874
501	0.099
600	0.1095
699	0.1188
802	0.1273
901	0.1342
1000	0.14

Thermal Heat Capacity

Temperature (°C)	Thermal Heat Capacity (J/kg-K)
20	500
1100	700

Ceramic Fiber Bulkhead Thermal Properties

Inputs for the numerical model utilized are as follows:

Density – 128 kg/m^3

Thermal Conductivity

Temperature (°C)	Thermal Conductivity (J/s-m-K)
10	0.015
250	0.3
540	0.1225
815	0.19
980	0.245

Thermal Heat Capacity

Temperature (°C)	Thermal Heat Capacity (J/kg-K)
10	375
1100	450

Ceramic Fiber Deck Thermal Properties

Inputs for the numerical model utilized are as follows:

Density – 96 kg/m^3

Thermal Conductivity

Temperature (°C)	Thermal Conductivity (J/s-m-K)
10	0.015
250	0.3
540	0.1225
815	0.19
980	0.245

Thermal Heat Capacity

Temperature (°C)	Thermal Heat Capacity (J/kg-K)
10	375
1100	450

Mineral Fiber Bulkhead Insulation Thermal Properties

Inputs for the numerical model utilized are as follows:

Density – 112 kg/m^3

Thermal Conductivity

Temperature (°C)	Thermal Conductivity (J/s-m-K)
24	0.035
93	0.042
149	0.050
204	0.061
260	0.071
302	0.15
699	0.15
1000	0.40

Thermal Heat Capacity

Temperature (°C)	Thermal Heat Capacity (J/kg-K)	Comments
20	700	
99	700	
100	2500	Moisture
110	2500	Moisture
111	700	
399	700	
400	7000	Dehydration
410	7000	Dehydration
411	700	
1000	800	

Note: Boundary conditions adjusted from unfaced mineral fiber board insulation to account for effect of foil-facing