ASET-B: Comparison of Model Predictions with Full-scale Test Data

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ABSTRACT: Predictions of upper layer temperature and elevation made using the computer fire model ASET-B were compared to data from two full-scale test series. Although measurements of the upper layer temperature varied with elevation within the layer, ASET-B predictions agreed reasonably well with average smoke layer temperatures or temperatures measured at intermediate elevations within the smoke layer. ASET-B tended to underpredict layer temperatures measured at the top of the layer. ASET-B predictions were within 20% of measurements of the smoke layer elevation.

KEY WORDS: computer modeling, evaluation of computer fire models.

BACKGROUND

THE PROPER USE of computer fire models requires an understanding of their applicability and limitations, since all computer models are, at least to a certain extent, empirically based. Equations or constants used within computer models are frequently based on curve fits to data from experiments. Typically, the experiments used to develop the correlations were conducted under a limited set of conditions, e.g., compartment sizes, heat release rates or fire growth rates. If the computer model is used for an application that falls outside of the bounds of the experiments used to develop the correlations, uncertainty may be introduced. Additionally, inaccuracies can be introduced in the numerical methods used to solve

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integral or differential equations, or more simply in math errors that were created during coding of the program.

To facilitate a greater understanding of the limitations of computer fire models by model users, the Society of Fire Protection Engineers has formed a computer fire model evaluation task group. The task group follows the evaluation methodology contained in ASTM E-1355, *Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models* [1]. The ASTM methodology addresses four areas of evaluation: (1) model definition and evaluation scenarios, (2) verification of theoretical basis and assumptions used in the model, (3) verification of the mathematical and numerical robustness of the model, and (4) quantification of the uncertainty and accuracy of the model predictions.

A subset of the evaluation effort identified in ASTM E-1355 is an analysis of the predictive capability of the model. ASTM E-1355 identifies three methods that can be used to analyze the predictive capability of a model: blind calculations, specified calculations, and open calculations. For blind calculations, the modeler is provided with a basic description of the fire scenario to be modeled. This allows for an evaluation of both the predictive capability of the model and the ease of translating scenario characteristics into model inputs. When conducting specified calculations, the modeler is presented with a complete description of model inputs. For open calculations, the modeler is given a complete description of the scenario, and is allowed to select the most appropriate model inputs. For each of these three methods, comparisons of model predictions with standard tests, full-scale tests conducted specifically for the evaluation or previously published full-scale test data, can be used.

This paper describes an evaluation of the predictive capability of ASET-B [2]. "Open calculations" are used for comparisons with test data from previously conducted full-scale fire tests.

TEST DESCRIPTIONS

For this evaluation, two sets of previously published full-scale test data were used. The first set of data came from a set of smoke filling experiments conducted in a $5.62 \times 5.62 \times 6.15$ m enclosure by Hägglund et al. [3] (In this paper, this room is referred to as "$6 \times 6 \times 6$ m enclosure.") The second set of data came from tests conducted by the National Institute of Standards and Technology in a Nike missile silo barracks building with horizontal dimensions of 18.9 m $\times$ 9.1 m with a ceiling height of 2.35 m. The test data for the Nike barracks building was provided by employees of the National Institute of Standards and Technology and was not published at the time this paper was written.

$6 \times 6 \times 6$ Meter Enclosure

With the exception of a 0.35 m wide by 0.25 m high opening located on a wall at floor level, the room where the fire tests were conducted was closed. The walls and ceiling were constructed of concrete. The fire sources for these experiments were kerosene in square pans that measured 0.25, 0.50 or 0.75 m on a side. Fifteen different experiments were conducted with the pan in either the center of the room, centered on one of the walls, or in a corner. For the fires in the center of the room, the fire source was elevated 0.2, 3.0 or 4.5 m above the floor. For the fires located along a wall or in the corner, the pan elevation was 0.2 m above the floor level in all of the tests.

During the experiments, mass loss was measured using a load cell, and recordings of the elevation of the smoke layer were made based on video tape data, visual observations and smoke density measurements. Smoke density measurements were made using smoke density meters at elevations of 1, 3, 4 and 5 m above floor level. When using smoke density meters, the smoke layer was determined to have reached the elevation of a smoke meter when the measured optical density began to rise from zero. Smoke layer temperatures were recorded using five arrays of bare wire thermocouples located in the center and in each corner of the room with thermocouples spaced at 0.50, 1.00, 1.50, 2.00, 2.50, 3.00, 3.50, 4.00, 4.50, 5.00, 5.50 and 6.05 m above floor level.

A listing of the test conditions can be found in Table 1.

Table 1. Experimental conditions for the $6 \times 6 \times 6$ m enclosure.

Test No.	Pan Size (m)	Pan Location	Pan Elevation (m)
1	0.50×0.50	Center	0.20
2	0.50×0.50	Center	0.20
3	0.50×0.50	Center	0.20
4	0.25×0.25	Center	0.20
5	0.25×0.25	Center	0.20
6	0.25×0.25	Center	0.20
7	0.75×0.75	Center	0.20
8	0.50×0.50	Wall	0.20
9	0.50×0.50	Corner	0.20
10	0.50×0.50	Center	3.0
11	0.50×0.50	Center	4.5
12	0.50×0.50	Wall	0.20
13	0.75×0.75	Wall	0.20
14	0.50×0.50	Corner	0.20
15	0.75×0.75	Corner	0.20

The heat of combustion for kerosene was reported as 30 MJ/kg, which was determined using oxygen consumption calorimetry.

Tests #2, 3, 5, 6, 7, 9, 12, 13 and 15 were selected for comparison with model predictions. The temperature data from the thermocouples located 5.50, 4.00 and 1.00 m above the floor was used for comparisons with ASET-B predictions.

Barracks Building

The barracks building was a closed, but not sealed, rectangular room. The compartment was constructed of concrete block walls and a 12 mm thick gypsum board ceiling. The area of the ceiling directly above the fire was covered with 12 mm thick calcium silicate boards.

The fire source was a gaseous propane diffusion flame. The burner was an open top cylinder, 0.6 m in diameter and 0.1 m in height, placed directly on the floor. The burner assembly was filled with pea gravel and covered with expanded metal. Heat release rates were calculated based on fuel flow rates. Experiments were run at heat release rates of 28, 56, 112, 168, 224, 280, 336, 392, 448 and 504 kW. More than one replicate test was conducted at each heat release rate; the results from tests with the same heat release rates were grouped and analyzed together.

Thermocouple arrays were placed at radial distances of 1.5, 3.0, 4.6 and 6.1 m from the center of the burner. Each of the arrays contained thermocouples located at ceiling level and 25, 76, 150, 300, 610, 910 and 1200 mm below ceiling level. Additionally, the thermocouple arrays located 1.5 and 6.1 m from the burner centerline also had an additional thermocouple located 1500 mm below the ceiling.

Data on the layer elevation as a function of time was not available. Therefore, the elevation of the smoke layer was estimated using Cooper's "*N%* rule" [4]. The "*N%* rule" first requires calculation of a reference upper layer temperature change based on the maximum temperature change among the thermocouples located at the highest elevation. This can be stated as follows:

$$\Delta T_{\text{ref}}(t) = \max[T(z_{\text{top}}, t)] - T_{\text{amb}}(z_{\text{top}})$$

where, $\Delta T_{\text{ref}}\ (t)$ is the reference upper layer temperature at time t(°C); $T(z_{\text{top}},t)$ is the temperature at the top most thermocouple at time t(°C); z_{top} is the top most thermocouple; $T_{\text{amb}}(z_{\text{top}})$ is the ambient temperature at the top most thermocouple at $t = 0$(°C).

When using the "*N%* rule", z_{top} was taken as the thermocouples located 25 mm below the ceiling.

The "*N*% rule" then states that the interface can be determined to pass elevation $z_i(t)$ at the time t when z_i first satisfies

$$T(z_i, t) - T_{\mathrm{amb}}(z_i) = \frac{N \Delta T_{\mathrm{ref}}(t)}{100}$$

where, $T(z_i,t)$ is the temperature of thermocouple at elevation z_i at time t(°C); $T_{\mathrm{amb}}(z_i)$ is the ambient temperature of thermocouple at elevation z_i at time $t = 0$(°C).

Cooper suggests using a value of $N = 10$.

The "*N*% rule" was implemented as an IF statement in a spreadsheet that contained thermocouple data as a function of time. Determinations as to whether the smoke layer interface height had descended to a given thermocouple elevation were made by visually checking spreadsheets to determine when the columns containing the IF statements changed from "FALSE" to "TRUE."

In interpreting the temperature data in the Barracks building tests where the fires had lower heat release rates, whether or not the layer was found to be at a given elevation would typically change from "TRUE" to "FALSE" repeatedly. This can be seen in the data in Table 2, which is taken from thermocouples located 76 mm below the ceiling in the 28 kW tests (when the *N*% rule indicated that the smoke layer was present at this elevation, the smoke layer temperature was displayed).

In cases where the determination of whether the smoke layer was present at a thermocouple elevation using the *N*% rule switched from "TRUE" to "FALSE" repeatedly, the layer was determined to be present at the thermocouple elevation when "TRUE" statement was first calculated after several sequential "FALSE" statements. In the example cited in Table 2, the layer would have been determined to reach 76 mm below the ceiling at 7.2 s.

MODELING APPROACH

ASET-B requires the following input:

- Title of run
- Heat loss fraction
- Height of base of fire
- Room ceiling height
- Floor area
- Maximum run time

The input data was developed as follows (note that SI values were converted to English since ASET-B requires English values).

Table 2. Sample of data using the N% rule for a thermocouple located 76 mm below the ceiling in tests in the barracks building with heat release rates of 28 kW.

Time(s)	Layer Temperature (°C)
0.0	20.8125
1.9	FALSE
3.7	FALSE
5.5	FALSE
7.2	20.95
9.0	20.8625
10.7	20.825
12.5	FALSE
14.3	FALSE
16.1	FALSE
17.8	FALSE
19.6	FALSE
21.4	FALSE
23.2	FALSE
24.9	FALSE
26.7	21
28.4	21.025
30.2	21.2
32.0	21.175
33.8	21.025
35.5	FALSE
37.3	21.1
39.1	FALSE
40.8	FALSE
42.6	21.0625

6 × 6 × 6 Meter Enclosure

The input variables related to dimensions were input based on the physical dimensions of the compartment. For the 6 × 6 × 6 m enclosure, these variables were as follows:

- Height of base of fire = 0.655 ft (0.2 m)
- Room ceiling height = 20.2 ft (6.15 m)
- Floor area = 338.6 ft^2 (31.5 m^2)
- Maximum run time – set to the length of the test.

The heat release rate was determined by multiplying the measured mass burning rate by the reported net heat of combustion of kerosene. For the scenarios where the fire was located in the center of the room (Test #2, 3, 5, 6 and 7), the peak burning rate during the scenario was used as a steady

Table 3. Heat release rates input into ASET-B for the 6 × 6 × 6 m enclosure.

Test No.	Steady Heat Release Rate (kW)	Ramped Heat Release Rate (kW)								
		0 s	15 s	30 s	45 s	60 s	75 s	90 s	105 s	120 s
2	195									
3	204									
5	33									
6	36									
7	414									
9	900	0	120	300	504	744	780	816	876	900
12	408	0	54	114	204	312	354	408		
13	870	0	408	780	870					
15	1920	0	708	1296	1776	1800	1920			

state heat release rate input into ASET-B. This tended to overstate the heat release rate during the first 30–60 s, as the measured mass loss rate ramped up during this time. Because the tests where the fire was located along a wall or in a corner (Tests #9, 12, 13 and 15) typically took longer to reach steady state, the calculated heat release rate during the growth stage was input at 15-s intervals until a maximum rate was achieved, and the maximum heat release rate was used as input for the remainder of the test duration. The heat loss fraction was varied; for each test ASET was run using values of 0.6, 0.7, 0.8 and 0.9.

For tests where the fire was located along a wall, the burning rates determined for the experiments and the floor area were multiplied by a factor of two prior to input into ASET-B to account for the reduced entrainment into the fire plume. Similarly, for fires in a corner, the burning rates and floor areas were multiplied by a factor of four prior to input into ASET-B. The heat release rates input into ASET-B are shown in Table 3.

Barracks Building

For the Barracks building data, the variables were input as follows:

- Height of base of fire = 0.3275 ft (0.1 m)
- Room ceiling height = 7.7 ft (2.35 m)
- Floor area = 1844.6 ft^2 (171 m^2)
- Maximum run time – set to the length of the test.

The heat release rate was input in accordance with the test specifications (28, 56, 112, 168, 224, 280, 336, 392, 448 or 504 kW). Again, the heat loss fraction was varied; for each test, ASET was run using values of 0.6, 0.7, 0.8 and 0.9.

COMPARISON OF MODEL PREDICTIONS WITH DATA

All modeling results were output to text files. Model predictions of the smoke layer elevation and temperature as a function of time were then compared to the data from the $6 \times 6 \times 6$ m enclosure and the barracks building by plotting them on graphs with ASET-B predictions. In each case, predictions for smoke layer temperatures or smoke layer elevations for heat loss fractions (X_l) of 0.6, 0.7, 0.8 and 0.9 are plotted on a single graph along with the applicable test data. It should be noted that the heat loss fraction is expressed as X_l on the graphs, and λ_c in the ASET-B documentation. Graphs showing comparisons of measured and predicted smoke layer temperatures are presented in Figures 1–19, and comparisons of measured and predicted smoke layer elevations are presented in Figures 20–38.

In comparing predicted and measured smoke layer temperatures, smoke layer temperatures were sampled from the data at discrete time intervals (e.g., every 60 or 100 s.) In all of the tests, the smoke layer was not a homogeneous temperature, as is assumed by ASET-B. The nonhomogeneity of the smoke layer temperature increased with increasing heat release rates. For the purposes of the evaluation of the predictive capability of ASET-B, the average or intermediate thermocouple temperatures were used for comparison with ASET-B predictions. In the comparisons with the barracks building data, high, low and the average of the high and low thermocouple temperature readings were plotted at 100-s intervals with

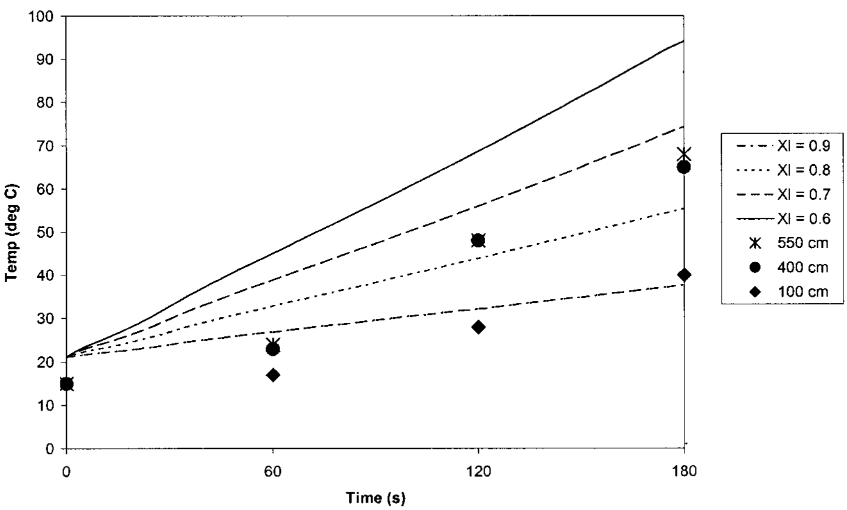

Figure 1. Comparison of predicted and observed smoke layer temperatures – $6 \times 6 \times 6$ m enclosure test #2.

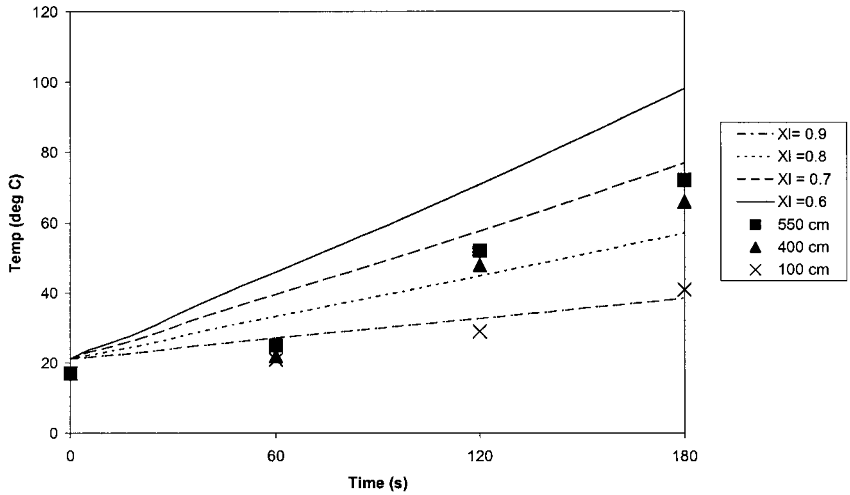

Figure 2. *Comparison of predicted and observed smoke layer temperatures – 6 × 6 × 6 m enclosure test #3.*

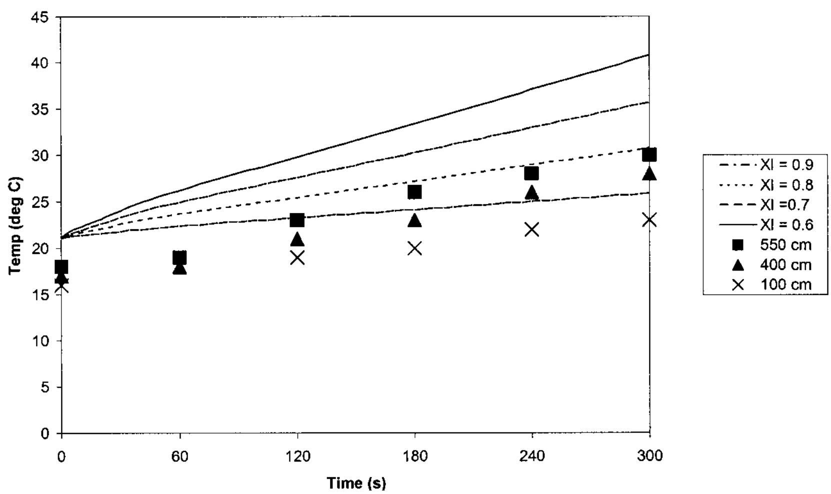

Figure 3. *Comparison of predicted and observed smoke layer temperatures – 6 × 6 × 6 m enclosure test #5.*

ASET-B predictions. The 6 × 6 × 6 m enclosure temperature data is plotted at 60-s time intervals for thermocouple elevations of 1.00, 4.00 and 5.50 m.

In the comparison graphs of predicted and observed smoke layer elevations in the barracks buildings, the ASET-B predictions appear as a step function. This is because given the size of the space in comparison to the heat release rates of the fires, the smoke layer descended slowly. Since

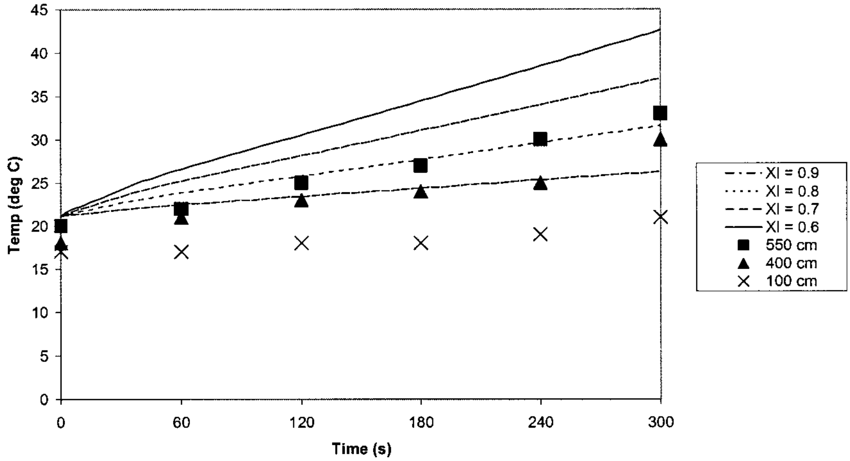

Figure 4. *Comparison of predicted and observed smoke layer temperatures – 6 × 6 × 6 m enclosure test #6.*

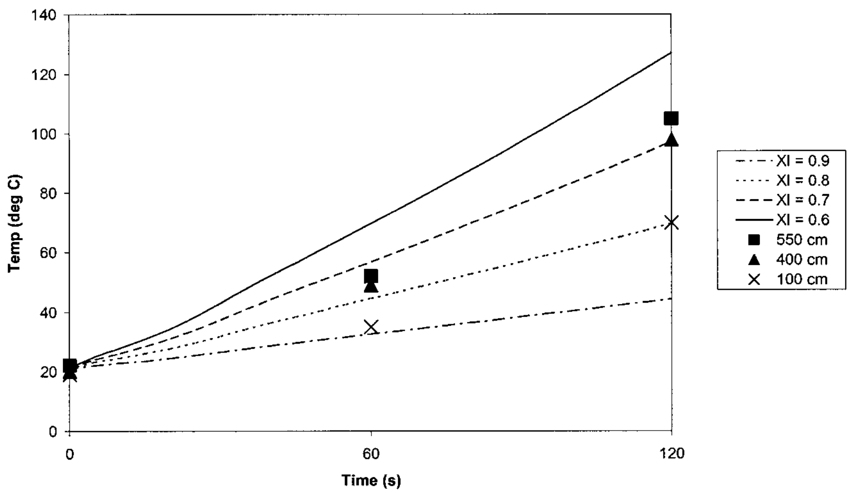

Figure 5. *Comparison of predicted and observed smoke layer temperatures – 6 × 6 × 6 m enclosure test #7.*

ASET-B only provides output to the nearest tenth of a meter, several sequential time steps typically had the same predicted smoke layer elevation. Because the fires in the 6 × 6 × 6 m enclosure were larger with respect to the enclosure size and the smoke layer descended more rapidly, this did not occur with the ASET-B predictions for these scenarios.

ASET-B failed to converge for predictions of fire effects in the 6 × 6 × 6 m enclosure Test #15 when heat loss fractions of 0.6 and 0.7 were input.

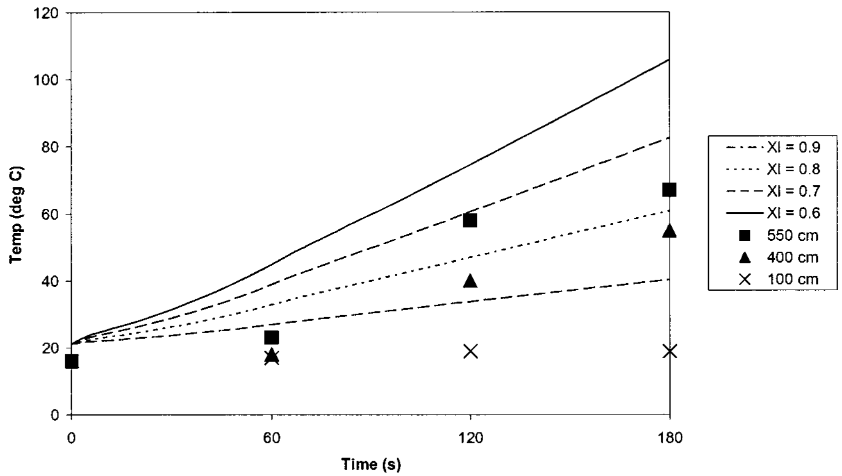

Figure 6. *Comparison of predicted and observed smoke layer temperatures – 6 × 6 × 6 m enclosure test #9.*

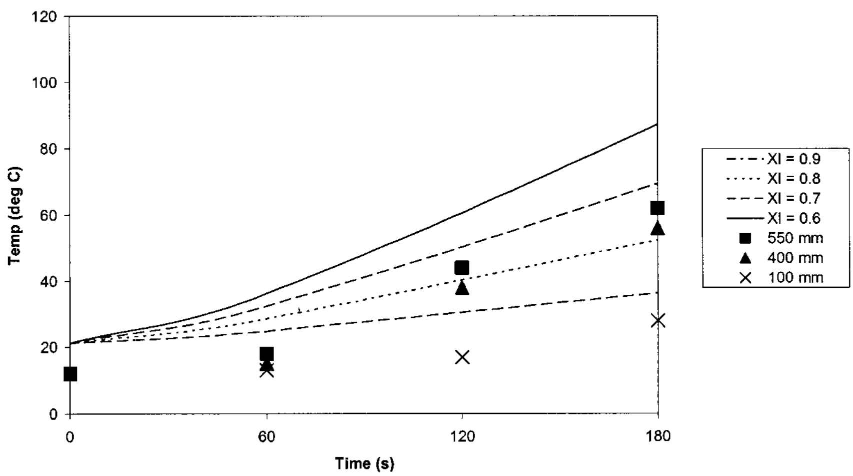

Figure 7. *Comparison of predicted and observed smoke layer temperatures – 6 × 6 × 6 m enclosure test #12.*

DISCUSSION

Smoke Layer Temperature

The documentation for ASET-B [2] notes that lower heat loss fraction values correspond to high aspect ratio spaces with smooth ceilings and fires

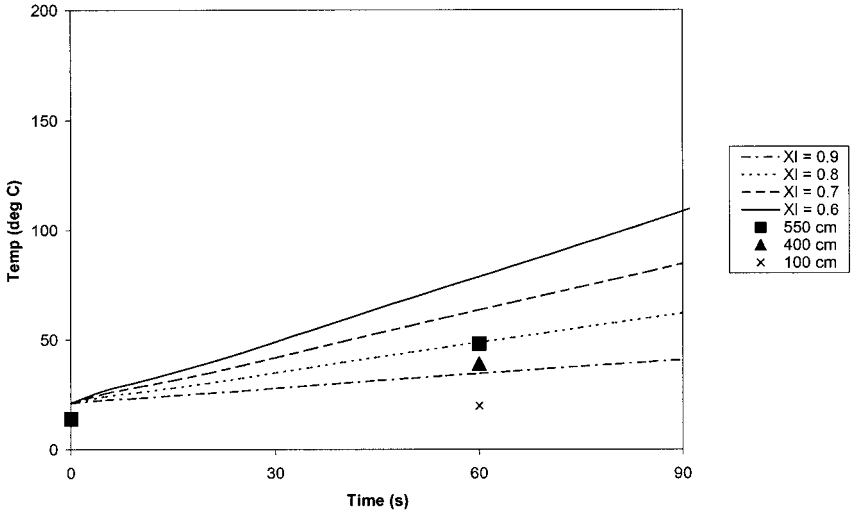

Figure 8. *Comparison of predicted and observed smoke layer temperatures – 6 × 6 × 6 m enclosure test #13.*

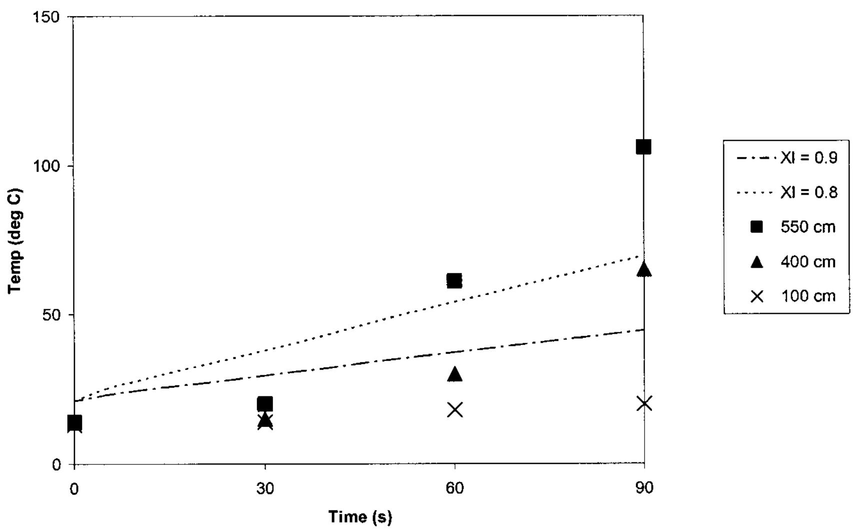

Figure 9. *Comparison of predicted and observed smoke layer temperatures – 6 × 6 × 6 m enclosure test #15.*

located remotely from the walls, and that intermediate to higher values should be used in rooms with low aspect ratios, rooms with irregular surfaces, or rooms where the fire is within one ceiling height of a wall. Using this guidance, lower heat loss fraction values would apply to all of the fire tests

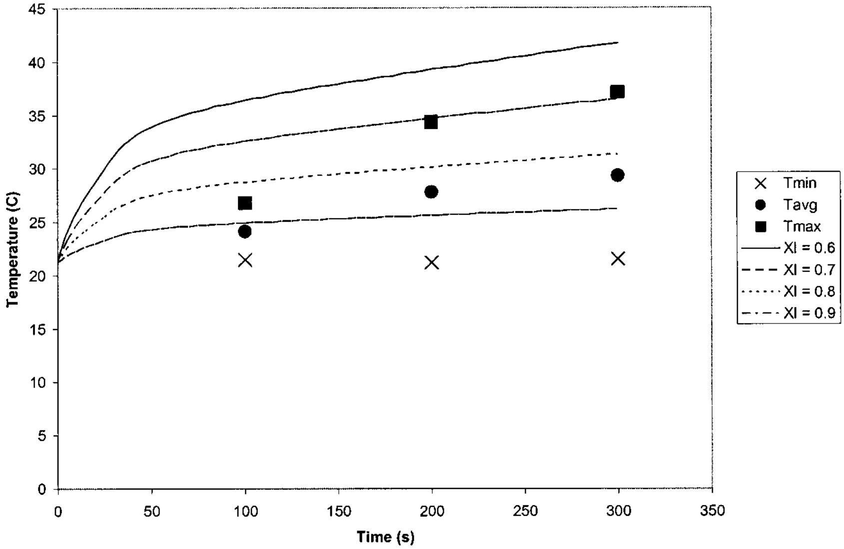

Figure 10. *Comparison of predicted and observed smoke layer temperatures – barracks building with heat release rate = 28 kW.*

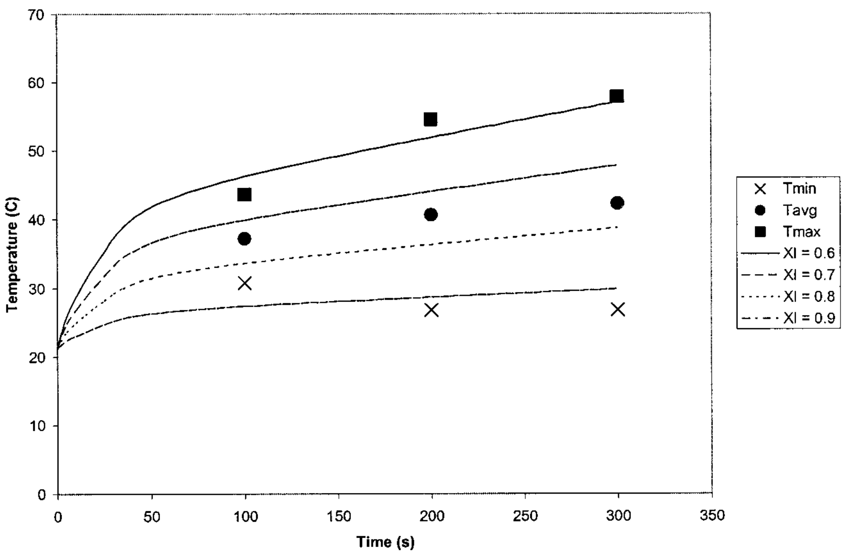

Figure 11. *Comparison of predicted and observed smoke layer temperatures – barracks building with heat release rate = 56 kW.*

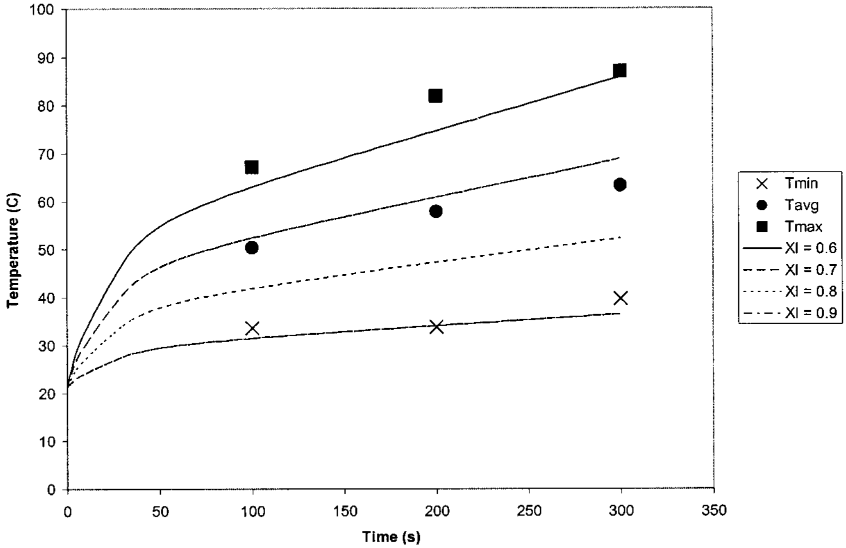

Figure 12. *Comparison of predicted and observed smoke layer temperatures – barracks building with heat release rate = 112 kW.*

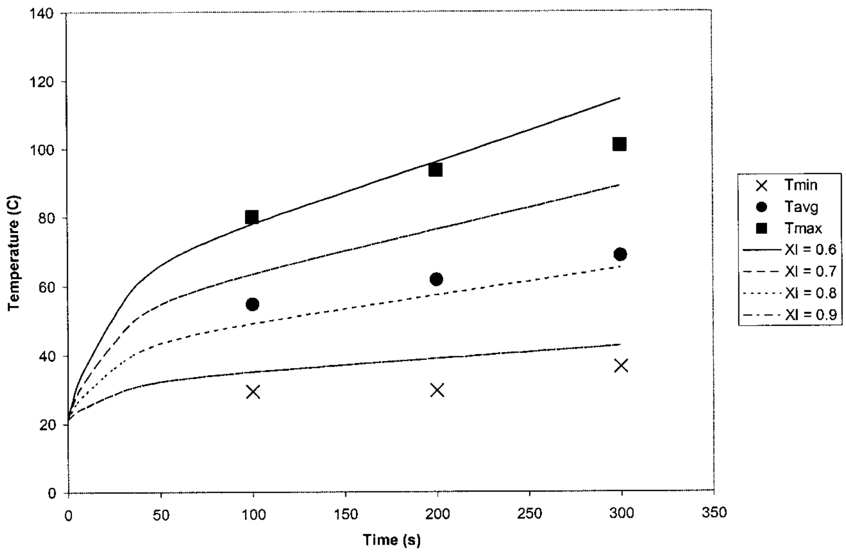

Figure 13. *Comparison of predicted and observed smoke layer temperatures – barracks building with heat release rate = 168 kW.*

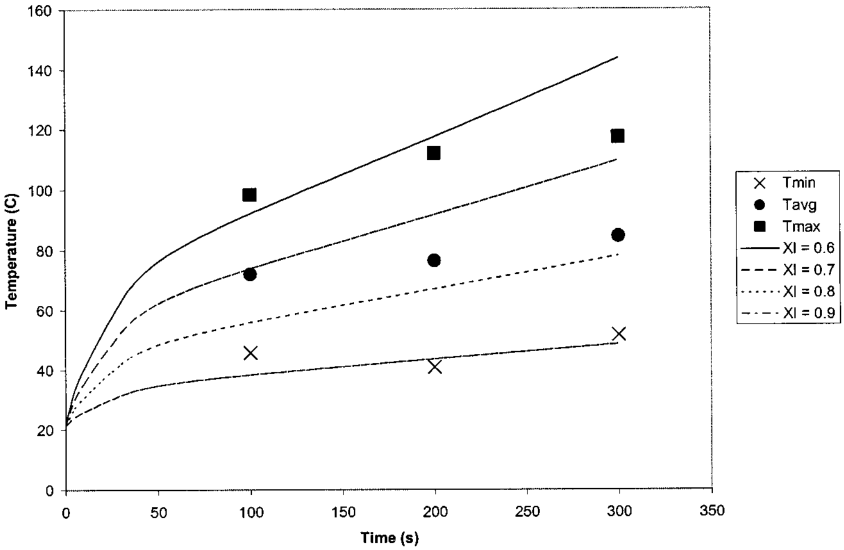

Figure 14. *Comparison of predicted and observed smoke layer temperatures – barracks building with heat release rate = 224 kW.*

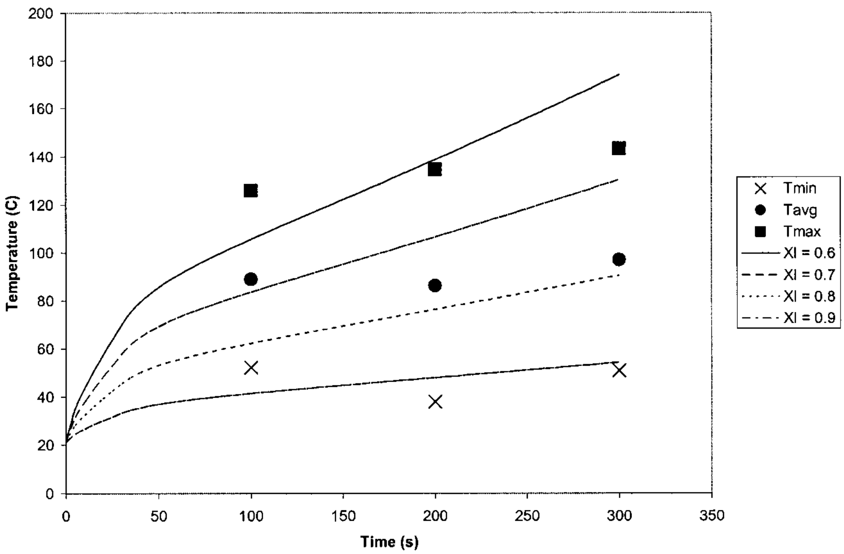

Figure 15. *Comparison of predicted and observed smoke layer temperatures – barracks building with heat release rate = 280 kW.*

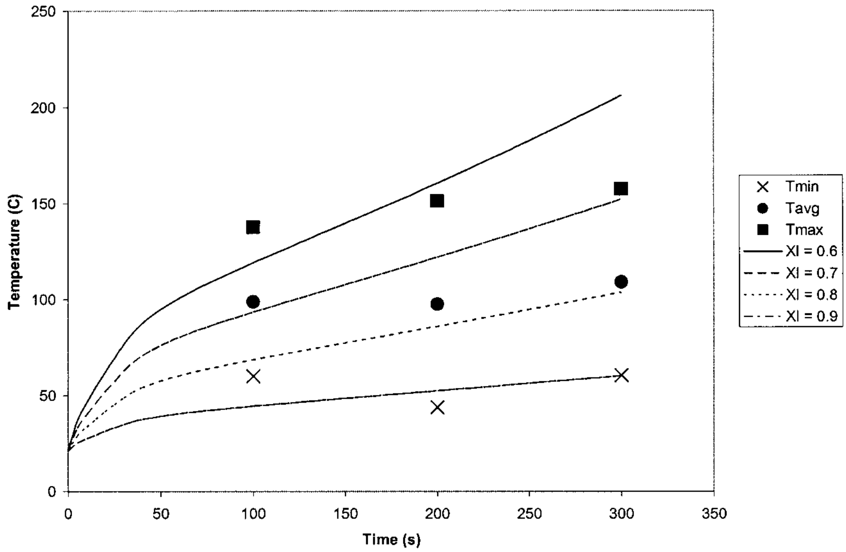

Figure 16. *Comparison of predicted and observed smoke layer temperatures – barracks building with heat release rate = 336 kW.*

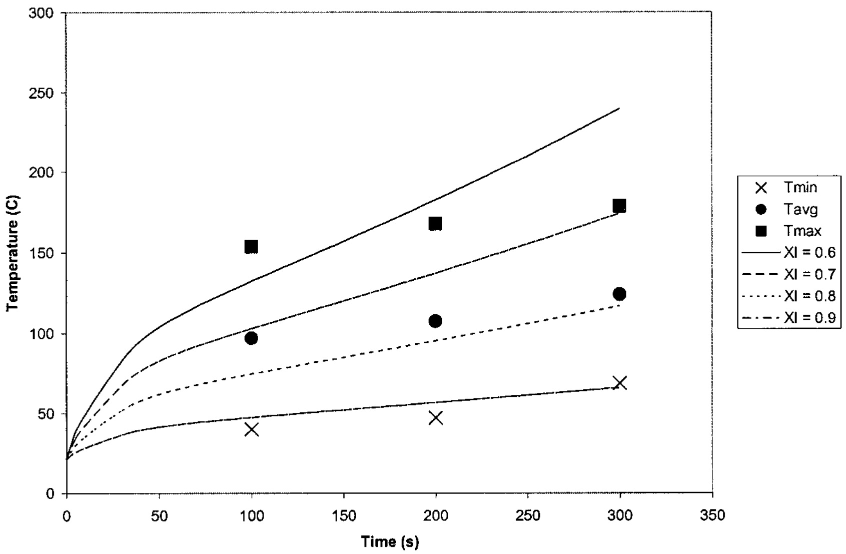

Figure 17. *Comparison of predicted and observed smoke layer temperatures – barracks building with heat release rate = 392 kW.*

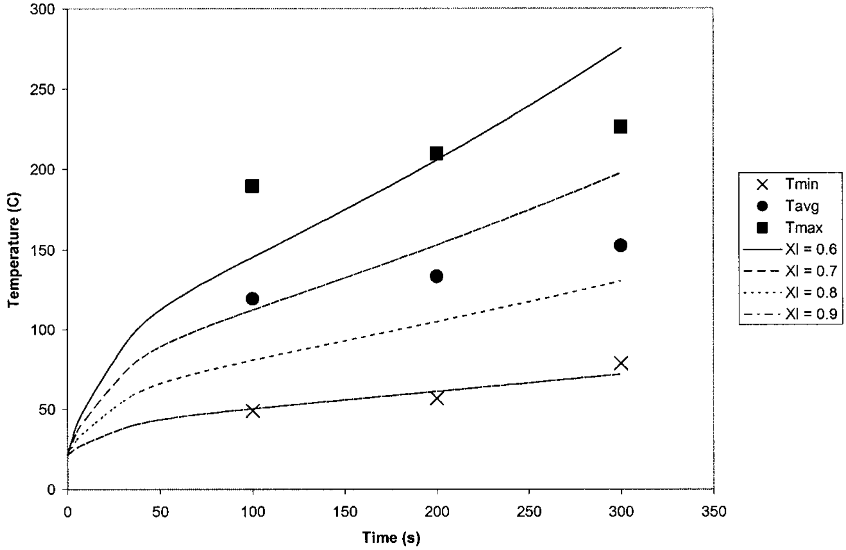

Figure 18. *Comparison of predicted and observed smoke layer temperatures – barracks building with heat release rate = 448 kW.*

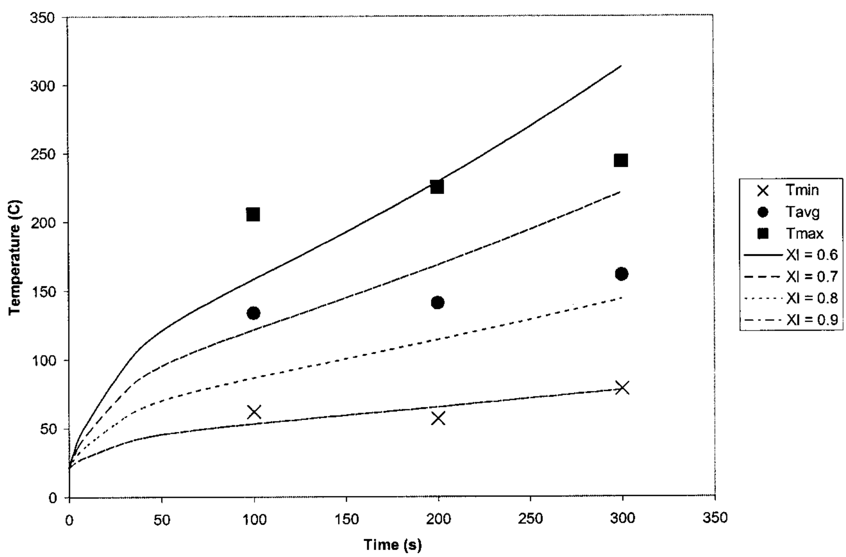

Figure 19. *Comparison of predicted and observed smoke layer temperatures – barracks building with heat release rate = 504 kW.*

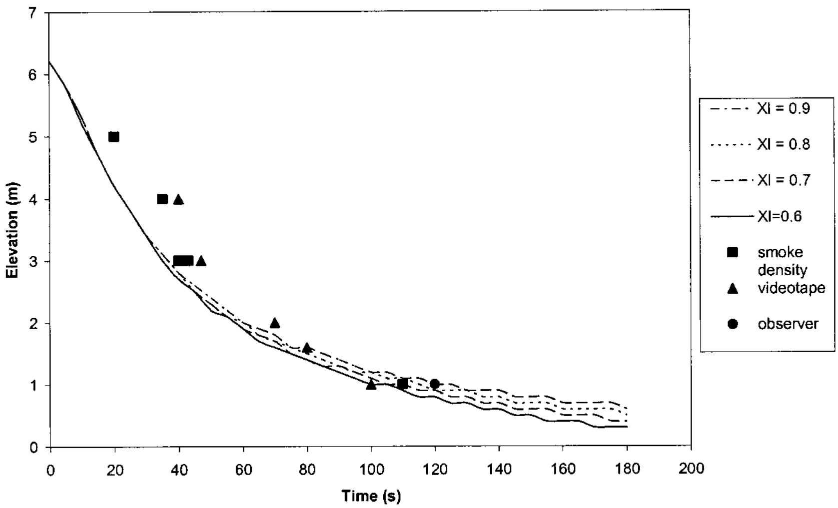

Figure 20. *Comparison of predicted and observed smoke layer elevations – 6 × 6 × 6 m enclosure test #2.*

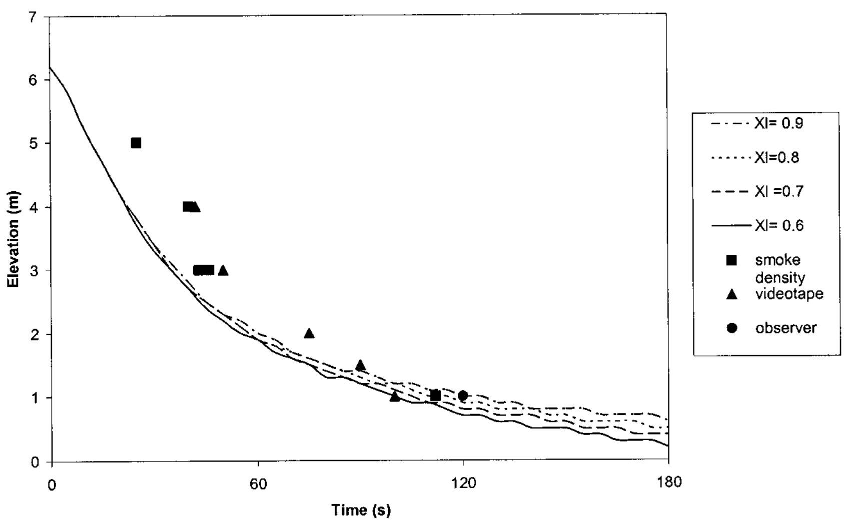

Figure 21. *Comparison of predicted and observed smoke layer elevations – 6 × 6 × 6 m enclosure test #3.*

in the Barracks building and the fires in the 6 × 6 × 6 m enclosure that were positioned in the center (Tests # 2, 3, 5, 6 and 7). Intermediate to higher heat loss fractions would be applicable to the tests in the 6 × 6 × 6 m enclosure where the fire was placed close to a wall or corner (Tests #9, 12, 13 and 15.)

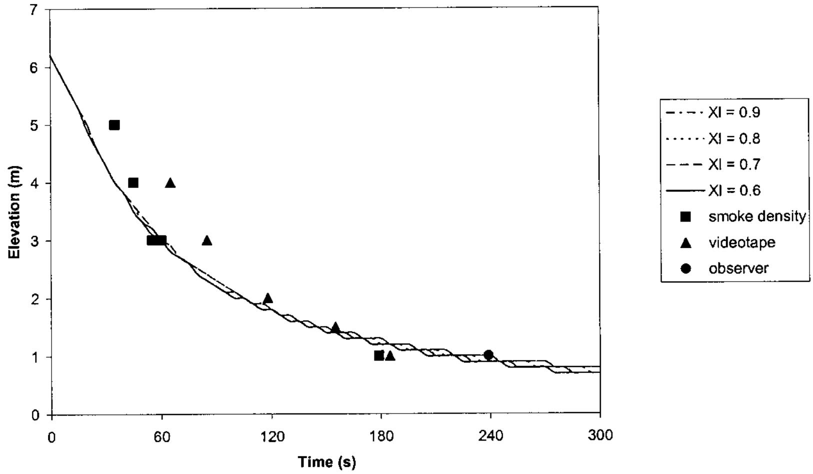

Figure 22. *Comparison of predicted and observed smoke layer elevations – 6 × 6 × 6 m enclosure test #5.*

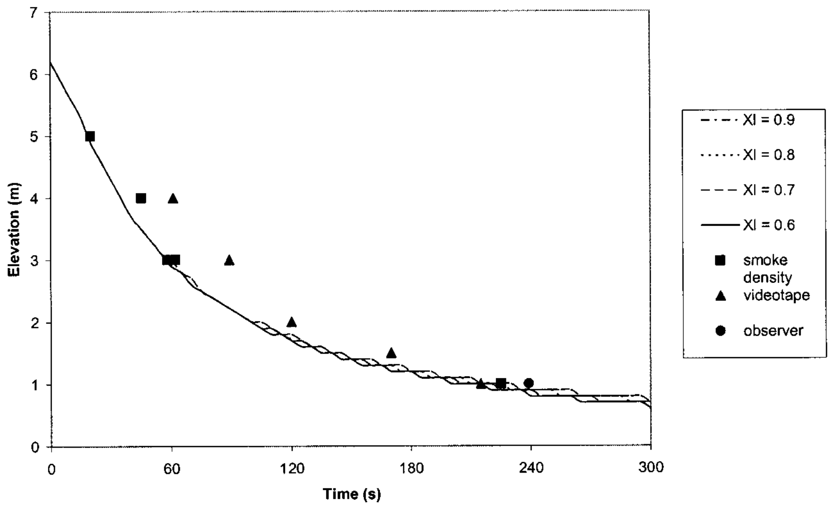

Figure 23. *Comparison of predicted and observed smoke layer elevations – 6 × 6 × 6 m enclosure test #6.*

However, ASET-B better predicted average or intermediate smoke layer temperatures in all scenarios when values of the heat loss fraction in the range of 0.7–0.8 were used.

In many of the tests in the 6 × 6 × 6 m enclosure, ASET-B overpredicted the smoke layer temperature in the initial portions of the tests. ASET-B assumes an ambient temperature of 21°C, and the initial temperature of the

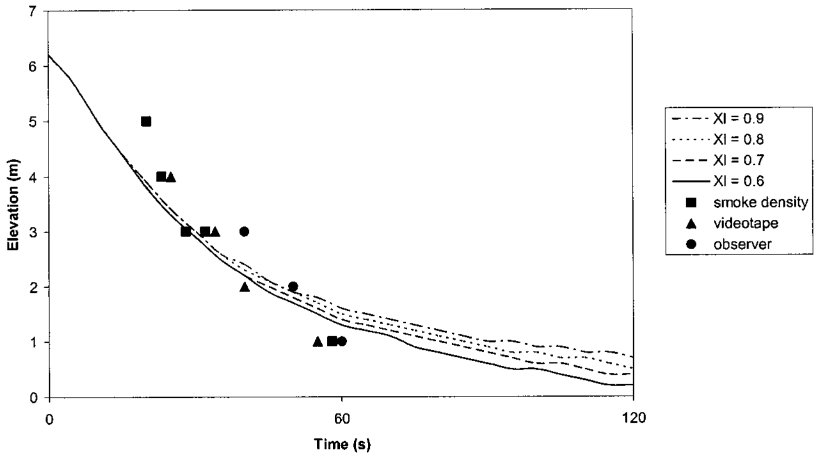

Figure 24. *Comparison of predicted and observed smoke layer elevations – 6 × 6 × 6 m enclosure test #7.*

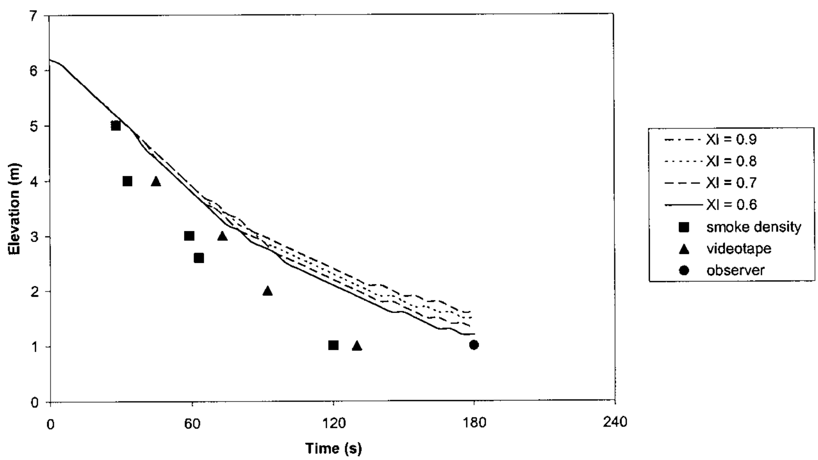

Figure 25. *Comparison of predicted and observed smoke layer elevations – 6 × 6 × 6 m enclosure test #9.*

test enclosure in many of these tests was several degrees below 21°C. In these cases, this was taken into consideration when interpreting the comparison of ASET-B predictions with the test data.

In general, depending on the heat loss fraction selected, ASET-B provides good predictions of average or intermediate smoke layer temperatures when heat loss fractions in the range of 0.7–0.8 were used. However, even when considering ambient temperatures below 21°C, ASET-B tended to underpredict temperatures that were measured at the top of the upper layer.

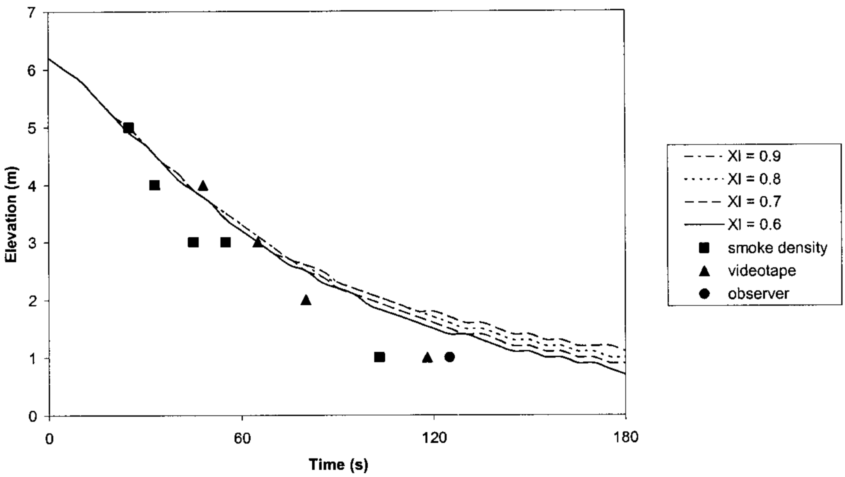

Figure 26. *Comparison of predicted and observed smoke layer elevations – 6 × 6 × 6 m enclosure test #12.*

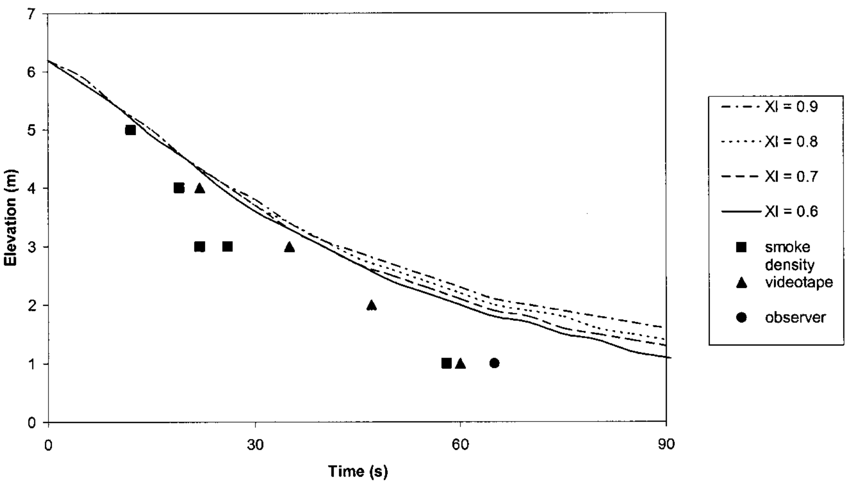

Figure 27. *Comparison of predicted and observed smoke layer elevations – 6 × 6 × 6 m enclosure test #13.*

Smoke Layer Elevation

The ASET-B predictions of the smoke layer elevation did not vary significantly with the selection of heat loss fraction. This is to be expected, since according to Charles' Law, gas volume varies proportionately with changes in temperature referenced to 0 K.

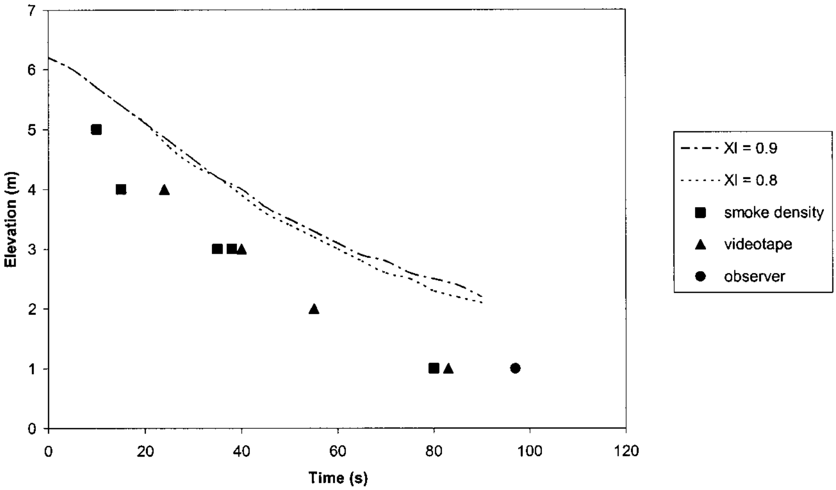

Figure 28. Comparison of predicted and observed smoke layer elevations – 6 × 6 × 6 m enclosure test #15.

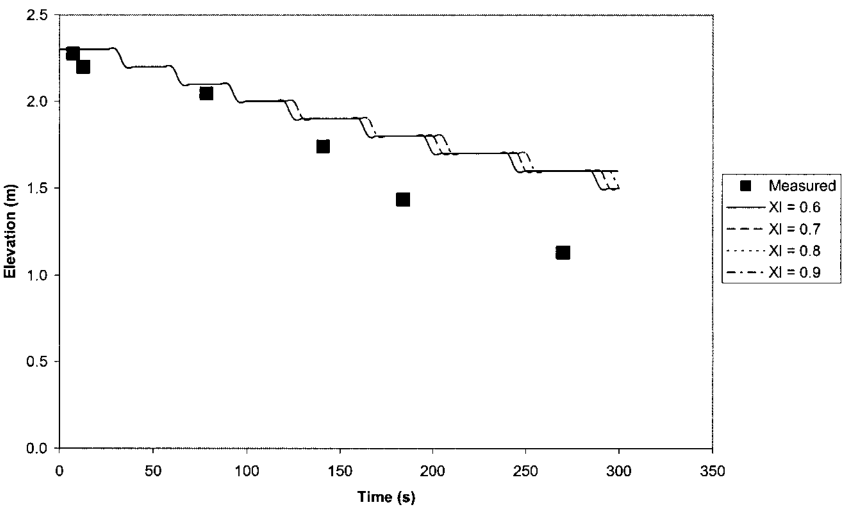

Figure 29. Comparison of predicted and observed smoke layer elevations – barracks building with heat release rate = 28 kW.

In the tests in the 6 × 6 × 6 m enclosure, ASET-B predicted smoke layer elevations to within one meter (or within approximately 20% of the floor to ceiling height). In the tests in the barracks building, ASET-B generally predicted that the smoke layer was at a higher elevation than was measured using the *N%* rule. These differences were within approximately one meter,

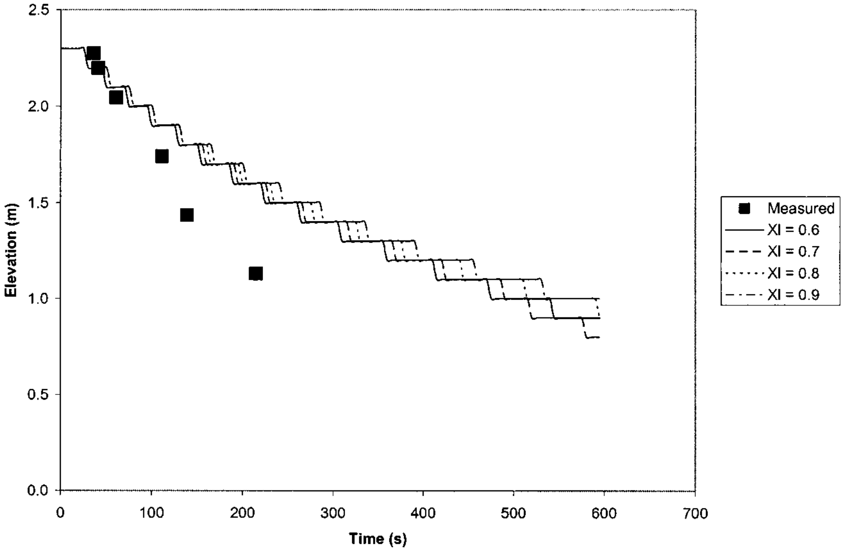

Figure 30. *Comparison of predicted and observed smoke layer elevations – barracks building with heat release rate = 56 kW.*

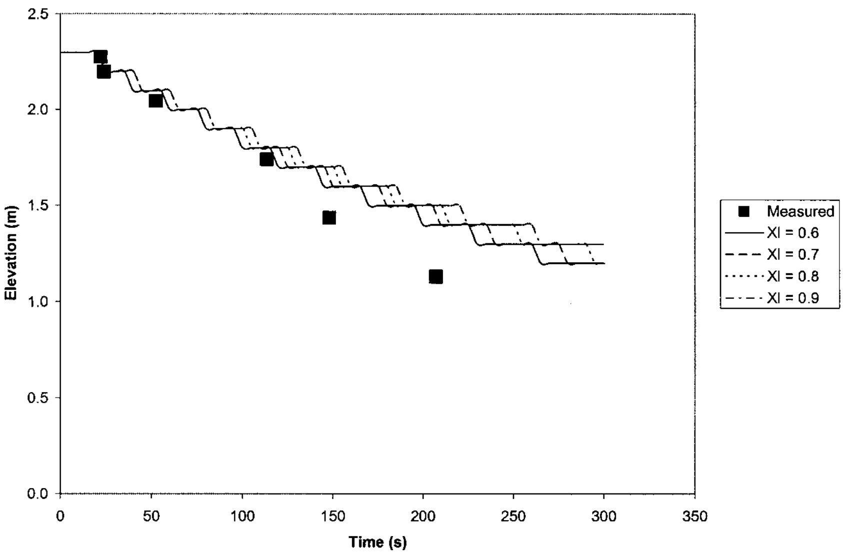

Figure 31. *Comparison of predicted and observed smoke layer elevations – barracks building with heat release rate = 112 kW.*

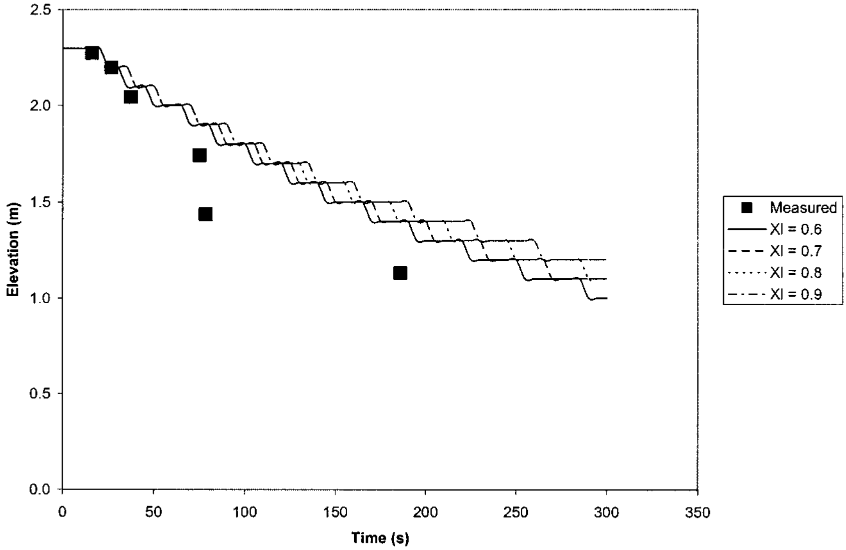

Figure 32. *Comparison of predicted and observed smoke layer elevations – barracks building with heat release rate = 168 kW.*

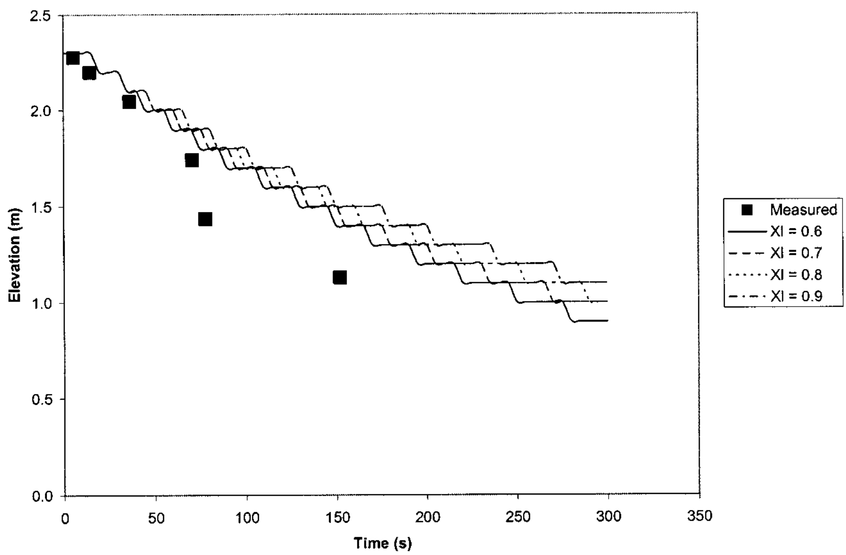

Figure 33. *Comparison of predicted and observed smoke layer elevations – barracks building with heat release rate = 224 kW.*

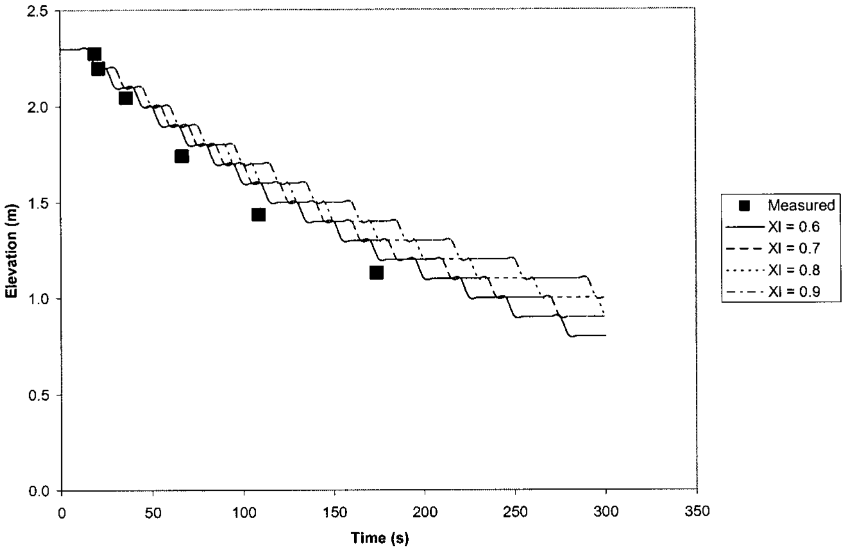

Figure 34. *Comparison of predicted and observed smoke layer elevations – barracks building with heat release rate = 280 kW.*

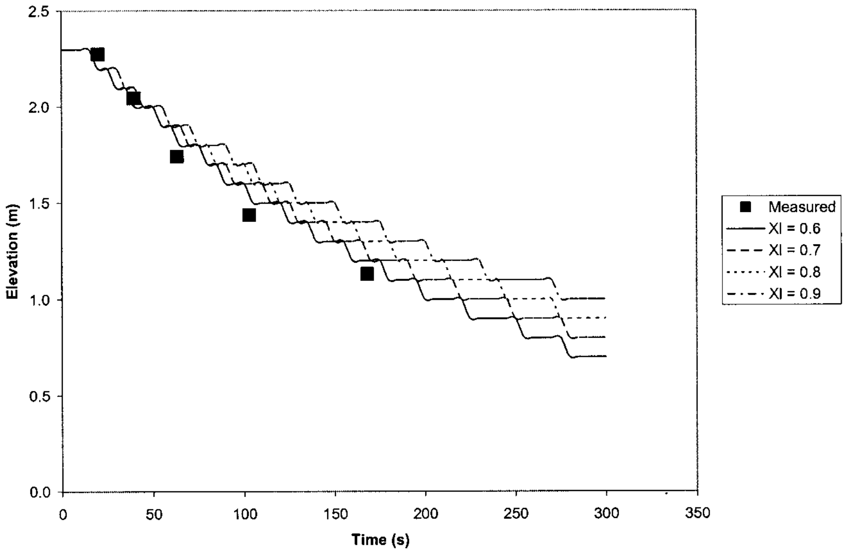

Figure 35. *Comparison of predicted and observed smoke layer elevations – barracks building with heat release rate = 336 kW.*

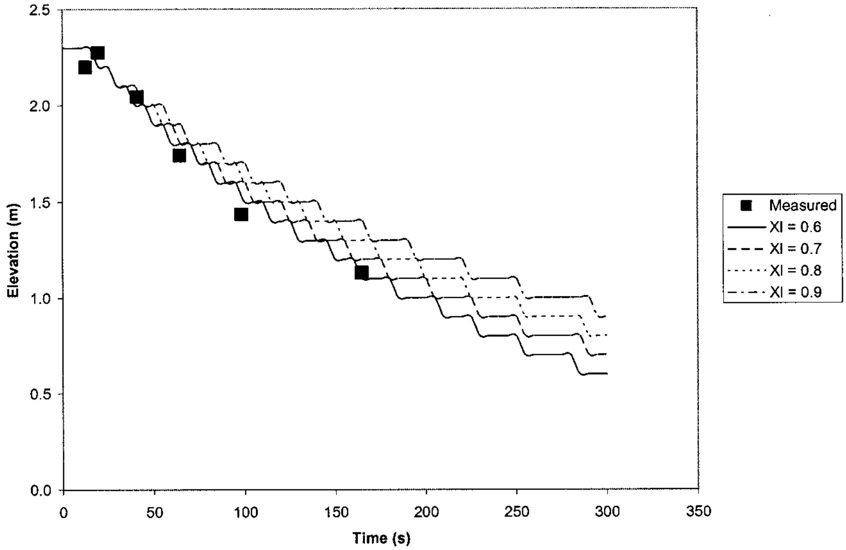

Figure 36. *Comparison of predicted and observed smoke layer elevations – barracks building with heat release rate = 392 kW.*

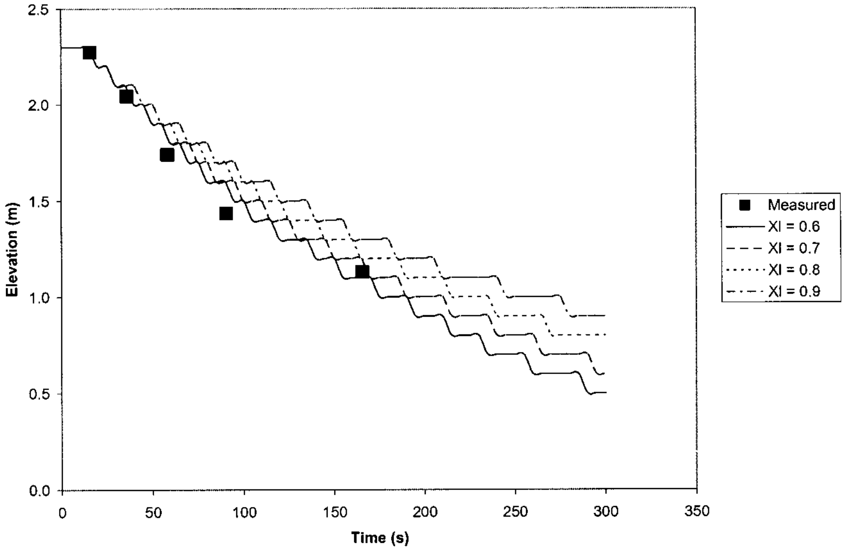

Figure 37. *Comparison of predicted and observed smoke layer elevations – barracks building with heat release rate = 448 kW.*

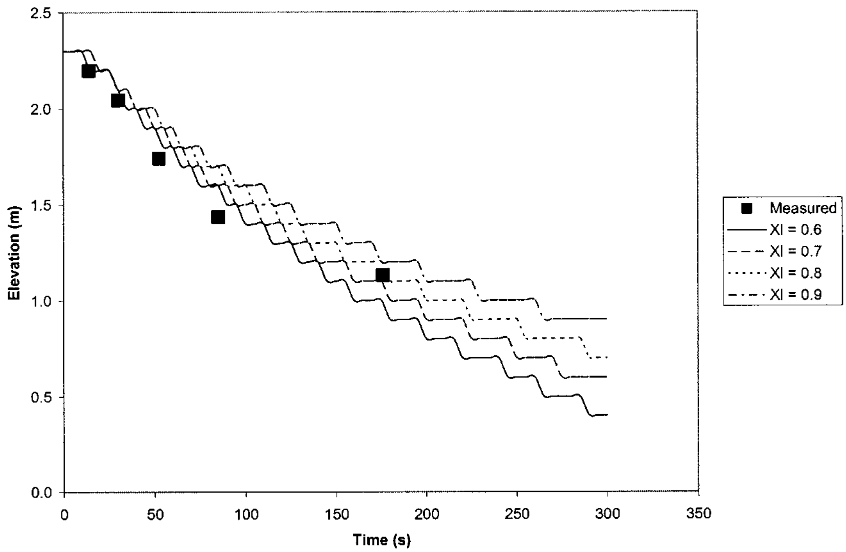

Figure 38. *Comparison of predicted and observed smoke layer elevations – barracks building with heat release rate = 504 kW.*

which represented approximately 40% of the floor to ceiling height of the test enclosure. However, ASET-B predictions better corresponded to the data as the heat release rate increased.

One possible reason that the ASET-B predictions did not better agree with the data from the Barracks building tests with lower heat release rates could be due to uncertainty with the *N%* rule at lower heat release rates. ASET-B temperature predictions agreed well with data in the 6 × 6 × 6 m enclosure, even at lower heat release rates. The smoke layer data in the 6 × 6 × 6 m enclosure was gathered by direct observation, by visual interpretation of video data, and by smoke density meter. Given the method that temperature data was reported for the tests conducted in the 6 × 6 × 6 m enclosure (crude graphs), it was not possible to test this hypothesis in the test series with low heat release rates.

CONCLUSIONS

For experiments in enclosures that measured 5.62 × 5.62 × 6.15 m and 18.9 × 9.1 m with a ceiling height of 2.35 m and with heat release rates ranging from 28 to 504 kW, ASET-B provided reasonably accurate predictions of average smoke layer temperatures or temperatures measured at intermediate elevations within the smoke layer when a heat loss fraction in the range of 0.7–0.8 was used as input. However, ASET-B frequently underpredicted temperatures measured at the top of the smoke layer regardless of the heat loss fraction used.

In these scenarios, ASET-B predictions of the smoke layer elevation were typically accurate to within 1 m or 20% of the floor to ceiling height.

As with any empirically-based analysis, caution should be exercised when applying these conclusions in scenarios that differ from those that were used to generate the test data, e.g., with higher or lower heat releases, with differing room geometry, or with differing aspect ratios.

ACKNOWLEDGMENTS

This analysis was prepared as part of an evaluation of ASET-B by the Society of Fire Protection Engineers. Shirelle Johnson, a University of Maryland student intern, performed most of the ASET-B modeling that was used for comparisons with the test data, and prepared the initial spreadsheets that were used for interpreting the comparisons. The National Institute of Standards and Technology provided financial assistance under grant #60NANB0D0098. Members of the SFPE Task Group on Computer Model Evaluation provided suggestions on how to approach the comparison effort.

NOMENCLATURE

$\Delta T_{ref}(t)$	reference upper layer temperature at time t (°C)
$T(z_{top},t)$	temperature at top most thermocouple at time t (°C)
z_{top}	the top most thermocouple in a thermocouple array
$T_{amb}(z_{top})$	ambient temperature at top most thermocouple at $t=0$ (°C)
$T(z_i,t)$	temperature of thermocouple at elevation z_i at time t (°C)
$T_{amb}(z_i)$	ambient temperature of thermocouple at elevation z_i at time $t=0$ (°C)
X_l	heat loss fraction (–)
T_{min}	minimum temperature measured in upper layer (°C)
T_{avg}	average of minimum and maximum temperatures measured in upper layer (°C)
T_{max}	maximum temperature measured in upper layer (°C)

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