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Test Results and Predictions for the Response of Near-Ceiling Sprinkler Links in a Full-Scale Compartment Fire

Leonard Y. Cooper and David W. Stroup

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

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U.S. Fire Administration
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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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TEST RESULTS AND PREDICTIONS FOR THE RESPONSE OF NEAR-CEILING SPRINKLER LINKS IN A FULL-SCALE COMPARTMENT FIRE

By

Leonard Y. Cooper and David W. Stroup

Abstract

This paper presents and analyzes a portion of the data acquired during a test program which involved full-scale, sprinklered, compartment fires. The work here focuses attention specifically on key features of the typical sprinkler link deployment/response problem. It is found that the elevated temperature, upper smoke layer which develops inevitably in compartment fires can have a major impact on the thermal response of sprinkler links. It is shown that traditionally accepted methods of predicting sprinkler link response which do not account for this upper layer can be totally inadequate. Link response predictions used here involve a new method of calculation which does take account of the smoke layer environment. Favorable comparisons between predictions and experiment are obtained and experiments for further validation of this method are recommended. Finally, it is found that sprinkler link-to-ceiling spacing can have a significant effect on the thermal response of links and it is recommended that a method which accounts for this effect be developed and validated.

Key words: Automatic sprinklers, ceiling jets, compartment fires, fire-generated flows, fusing, heat transfer, link-to-ceiling spacing, link-to-fire spacing, smoke layer, sprinkler links, thermal response, unconfined ceilings, validation.

1. BACKGROUND

A series of full-scale, sprinklered, compartment fire tests were carried out [1]. One purpose of the test series was to study the response of sprinkler links and resulting sprinkler actuation during realistic compartment fire scenarios. This report presents and analyzes a portion of the data acquired during the test program. It focuses attention specifically on key features of the typical sprinkler link deployment/response problem which are of such critical importance to fire safe design.

For any fire which develops in a given compartment configuration, the response of a sprinkler link is a function of 1) location and design of the link, and 2) time from fire initiation. Here, the location of the link is defined by the distance between the fire plume-ceiling impingement point (the point on the ceiling directly above the effective center of the fire) and the point on the ceiling directly above the effective center of the link, and by the distance of the link from the ceiling. The design of the link is characterized by the RTI (response time index). The RTI of a particular link is a measure of its rate-of-temperature change when immersed in a relatively uniform-velocity, uniform-temperature stream [1,2].

The effects of the link location parameters were of particular interest here. Also of key interest was the effect on link response of a changing, high temperature, upper-layer fire-generated environment which typically develops prior to link actuation in compartment fire scenarios. These effects, some of which are ignored in currently accepted sprinkler deployment technology [3-7], are studied here within the context of a growing fire in an office module-type scenario.

2. THE NEAR-CEILING FIRE-GENERATED ENVIRONMENT AND RESPONSE OF SPRINKLER LINKS - EXPERIMENT MOTIVATION

2.1 The Fire-Driven Ceiling Jet

As a fire grows, it releases energy and other products of combustion, both gaseous and solid. Because of their elevated temperature, the products of combustion, typically referred to as smoke, are driven upwards by buoyancy forces. These products generate a turbulent plume of upward moving, elevated temperature gases. All along the axis of the plume, relatively quiescent ambient air is entrained into and mixed with the plume gases as they continue their ascent to the ceiling. As a result of the entrainment, the total upward mass flux in the plume continuously increases and the average temperature in the plume continuously decreases with increasing height. When the upward movement of the plume gases is blocked by the compartment ceiling, they spread radially outward forming a relatively thin, high-temperature, high-velocity turbulent ceiling jet. Unlike the location of the unwanted fire and its plume which is not known a priori, the near-ceiling region is one zone in a compartment of fire origin where one is insured of a relatively intense fire environment. For this reason the near-ceiling region, i.e., the location of the ceiling jet, is a prime zone for the deployment of sprinklers and their heat sensitive actuating links. Effective and reliable selection and deployment of sprinkler links must be based on an understanding of the flow conditions in this zone, local to the link, which provide the driving mechanism for its response and actuation.

2.2 The Distribution of Velocity and Temperature Within the Ceiling Jet

As the gases of the ceiling jet flow radially outward under the ceiling surface from the region of fire plume-ceiling impingement, they entrain and mix with relatively cool gases from below. With increasing radius, this leads to a continuous increase in thickness and decrease in the peak temperature and velocity of the ceiling jet gases.

At any given radial position, the velocity and temperature of the ceiling jet varies significantly throughout its thickness. The velocity is always zero at the ceiling surface. Below the ceiling the velocity rises rapidly to its peak value. The velocity then decreases continuously with further increases in distance from the ceiling, until, at the local thickness of the ceiling jet, it approaches the negligible velocity of the lower, near-quiescent environment. Velocity distributions in ceiling jets have been measured [e.g., 8,9] and a general equation which predicts the velocity and correlates well these data has been developed [10]. The equation predicts the ceiling jet velocity distribution as a function of fire energy release rate, fire-to-ceiling spacing, distance from the fire plume-ceiling impingement point, and distance below the ceiling.

The situation for the temperature distribution thoughout the thickness of the ceiling jet is somewhat different than that of the velocity. Immediately adjacent to the ceiling itself, the temperature of the ceiling jet is identical to that of the ceiling surface. However, at any given radius, this surface temperature is itself changing rapidly from its initial, cool, ambient temperature state. Below the ceiling surface the temperature typically rises rapidly to its peak value and then, with increasing distance from the ceiling, the temperature continously decreases. Further below the ceiling and near the edge of the ceiling jet, its temperature approaches the temperature of the lower quiescent environment. Significant progress has been made in the development of means to predict the radial- and time-dependent temperature of ceiling surfaces [11-13]. Also, temperature distributions of ceiling surfaces [14-16] and throughout ceiling jets [e.g., 15-19] have been measured in ,a variety of test configurations. However, as compared to the ceiling jet velocity distribution, a complete methodology for predicting the time- and space-dependent temperature distribution in the ceiling jet has not yet been assembled. Such a methodology could be used to enhance significantly the effectiveness and reliability of sprinkler link design and deployment.

2.3 Effect of the Upper Hot Gas Layer

Existing accepted design methods for predicting sprinkler link response are based on characteristics of fire plume-driven ceiling jets flowing beneath what are referred to as unconfined ceilings, i.e., ceilings without any confining walls. The unconfined ceiling configuration is associated with an idealized fire scenario. In actuality, real compartment fires involve structural walls that capture and contain fire-generated plume and ceiling jet gases. Throughout the early stages of a fire, these gases fill the space with an upper layer of smoke which grows continuously in thickness and in temperature. In many real fires it is typical for the growing smoke layer to engulf the ceiling jet rapidly, i.,e., in time intervals which are comparable to the expected time of sprinkler actuation. Also, prior to sprinkler actuation the fire plume gases which drive the ceiling jet would have to travel a large part of their total fire-to-ceiling ascent through the elevated temperature upper smoke layer. As a result of all this, the characteristics of real fire plumes in the region of ceiling impingement and the characteristics of resulting plume-driven ceiling jets can differ significantly from those of idealized, unconfined ceiling, "design" fire scenarios. These upper layer effects have been modeled analytically [11,20,21] and they have been observed experimentally [16,18,22]. Depending on the fire growth history and on the dimensions of the compartment, the effect of the upper layer and the ceiling structure can lead to link temperatures which are higher, and possibly even lower than corresponding link temperatures that would be measured in a comparable unconfined ceiling fire scenario.

3. THE EXPERIMENTS

3.1 General Remarks

The purpose of this paper is to discuss those aspects of the experiments which bring into play and measure some of the above-mentioned effects of real compartment fires and corresponding sprinkler link response. Only those features of the experiments which were essential to this objective will be included here. For a comprehensive description of the overall test program the reader is referred to [1].

3.2 The Experimental Setup

One test scenario is considered. It involves a wastepaper-basket fire initiation of an office-module compartment fire. The office furniture includes a desk, chair and bookcase, all heavily loaded with a paper/book-type fuel load. Referring to Figure 1, the combustibles are assembled and the fire is initiated in the inside corner of a 2.44 m x 3.66 m room of 2.44 m height. There is an open doorway to the room, 0.76 m wide x 2.03 m high, and this is located in the far 2.44 m wall. Smoke flowing out of the doorway is collected in a large hood/ventilated duct flow-through system equipped with oxygen-depletion-measurement capabilities. Data from this lead to an estimate of the time-dependent total energy release rate of the fire. The realistic, but relatively modest size of the test space, the general magnitude of the energy release rate of the fire and the size of the doorway are such as to lead to an

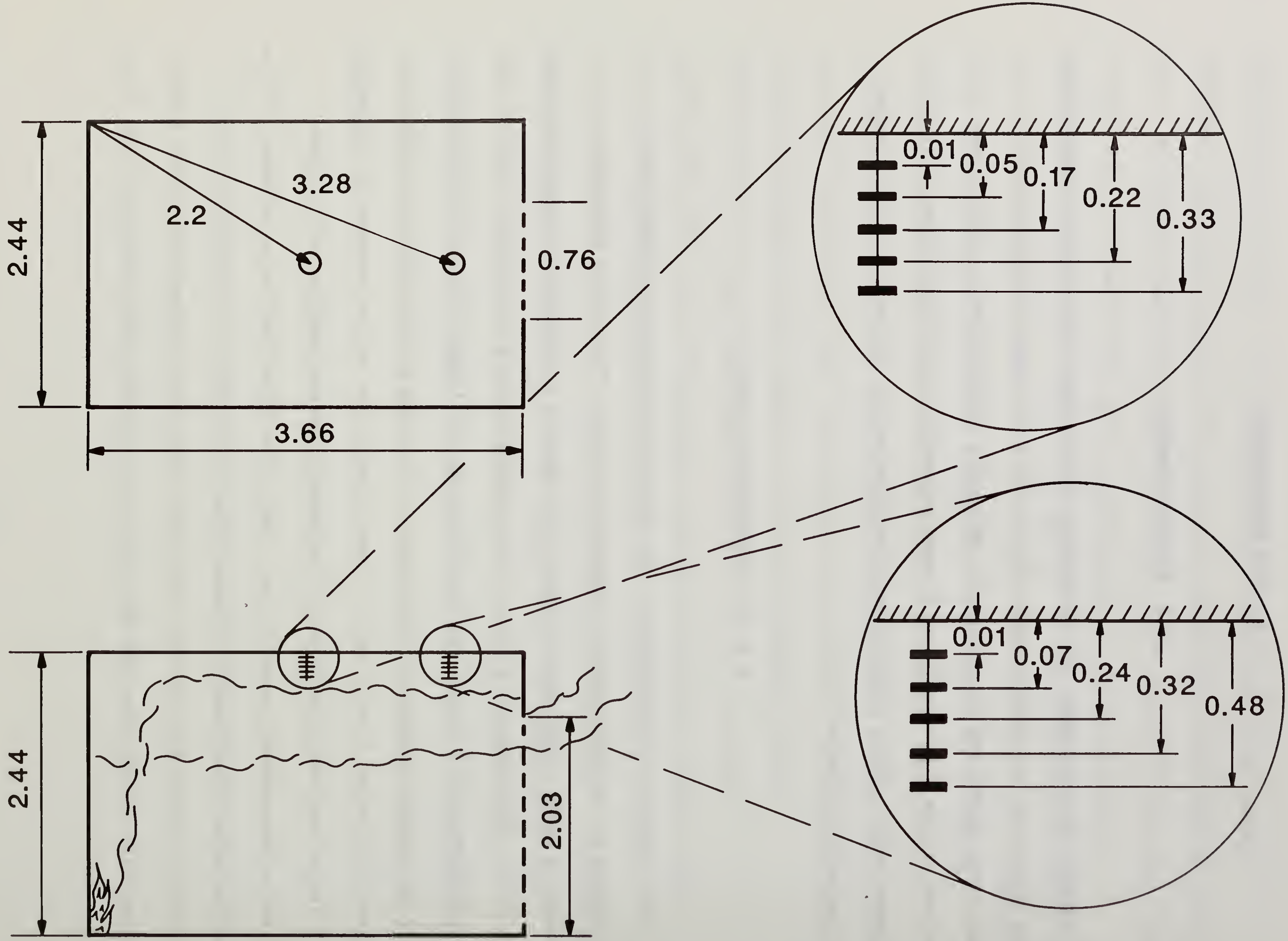

Figure 1. Sketch of Test Enclosure

upper layer in the burn room which would achieve very rapidly (compared to the response of sprinkler links) a deep, and relatively constant thickness.

Toward the center of the burn room is a "tree" of 20 mil diameter chromel-alumel, bare-wire thermocouples located at the ceiling and between the ceiling and floor at 0.152 m (6.0 in) intervals. These are used to obtain the temperature in the burn room, away from the combustion zone and plume, as a function of time and elevation.

There is one active sprinkler and quick response link with RTI of 46 $(ms)^{1/2}$. It is deployed in the center of the room, approximately 2.20 m from the room corner and from the fire plume-ceiling impingement point. The link is approximately 0.10 m (4. in) below the ceiling surface. Also near the center of the room is a near-ceiling, vertical "tree" of five simulated sprinkler link disks each having an RTI of 46 $(ms)^{1/2}$. The disks are 0.0095 m (0.375 in) in diameter and 0.00079 m (0.03125 in) thick and they are aligned with their axes parallel to the ceiling and in a near-optimum-streamline orientation in relation to a radial velocity ceiling jet. The ceiling-to-simulated-link separation distances were indicated in Figure 1. There is a second, near-ceiling tree of simulated links located near the middle of the doorway. It is identical to the first tree except for the ceiling-disk separation distances whose values are also identified in Figure 1. All simulated links are instrumented with thermocouples so that their temperature-time response could be monitored during the tests. Since the simulated links have the same RTI as the active link, their temperature response during a test would provide a direct indication of the effect of link-to-ceiling spacing (i.e., the effect of the anticipated spatial distribution of ceiling jet velocity and temperature) on the response of an active link.

4. ANALYSIS AND DISCUSSION OF THE EXPERIMENTAL RESULTS

4.1 Temperatures in the Burn Room and Thickness of the Ceiling Layer

Plots of temperature as a function of distance from the ceiling as measured by the floor-to-ceiling thermocouple tree are presented in Figure 2 for different times following initiation of the fire, but prior to the activation of the sprinkler which occured at approximately 175 s subsequent to ignition. These temperature distributions are normalized by the temperature measured at the uppermost, gas-submerged thermocouple (0.152 m below the ceiling) and the normalized results are replotted in Figure 3. It can be noted from these latter plots that 1) an upper, elevated-temperature gas layer grows rapidly to a relatively uniform thickness; 2) there is an interface that separates these upper layer gases from a relatively low-temperature and spatially-uniform lower layer; and 3) the interface is at a near-constant elevation of 0.99 m below the ceiling (1.45 m above the floor), corresponding to an elevation of 0.58 m below the top of the doorway.

Based on the above observations, the above-interface temperature measurements for each time of the Figure 2 and 3 plots were averaged spatially. The result, the average upper-layer temperature as a function of time, is plotted in Figure 4 and used below in the analysis of link response. Also included in Figure 4 are the actual temperature-time measurements of the individual

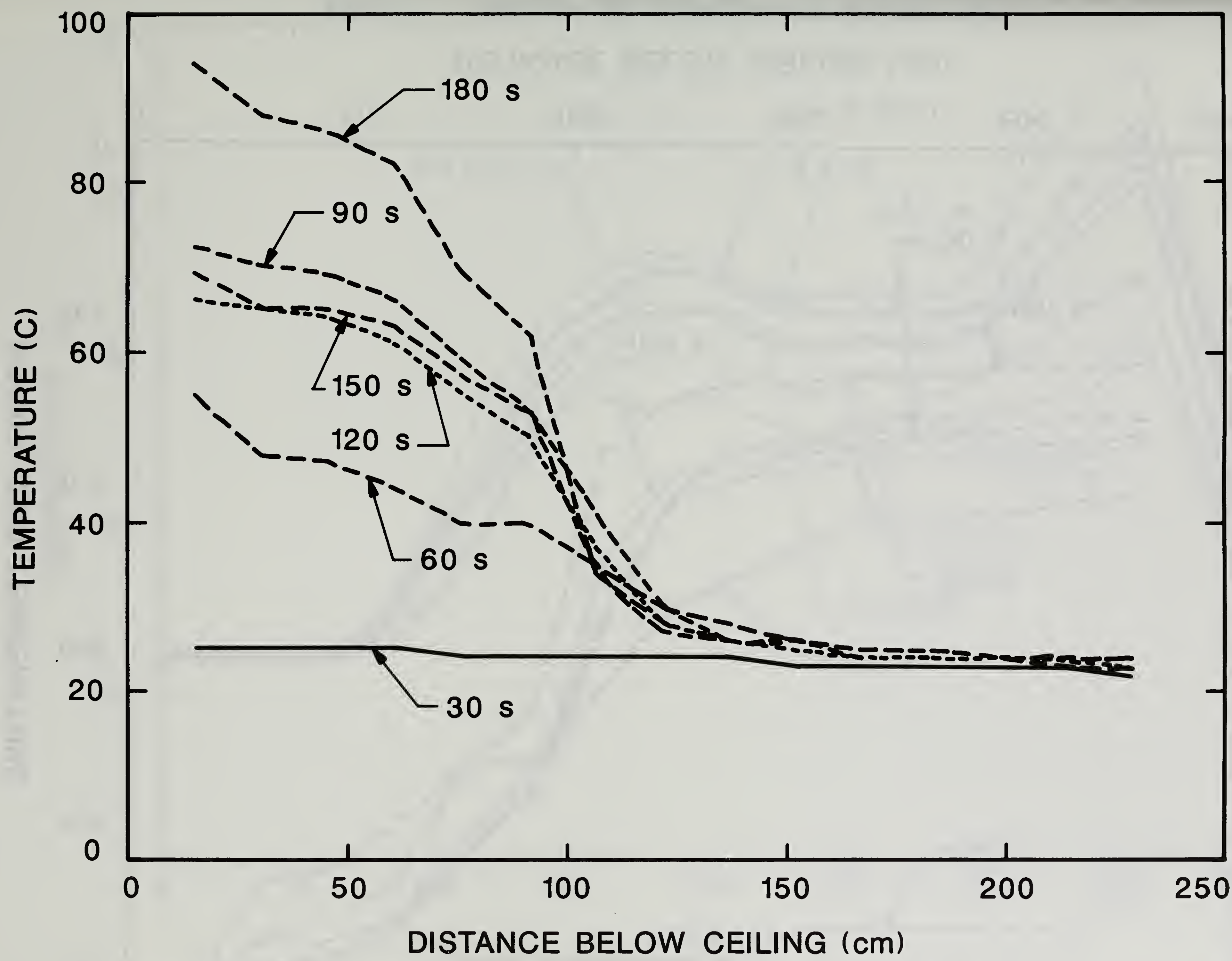

Figure 2. Measured gas temperatures at specified times

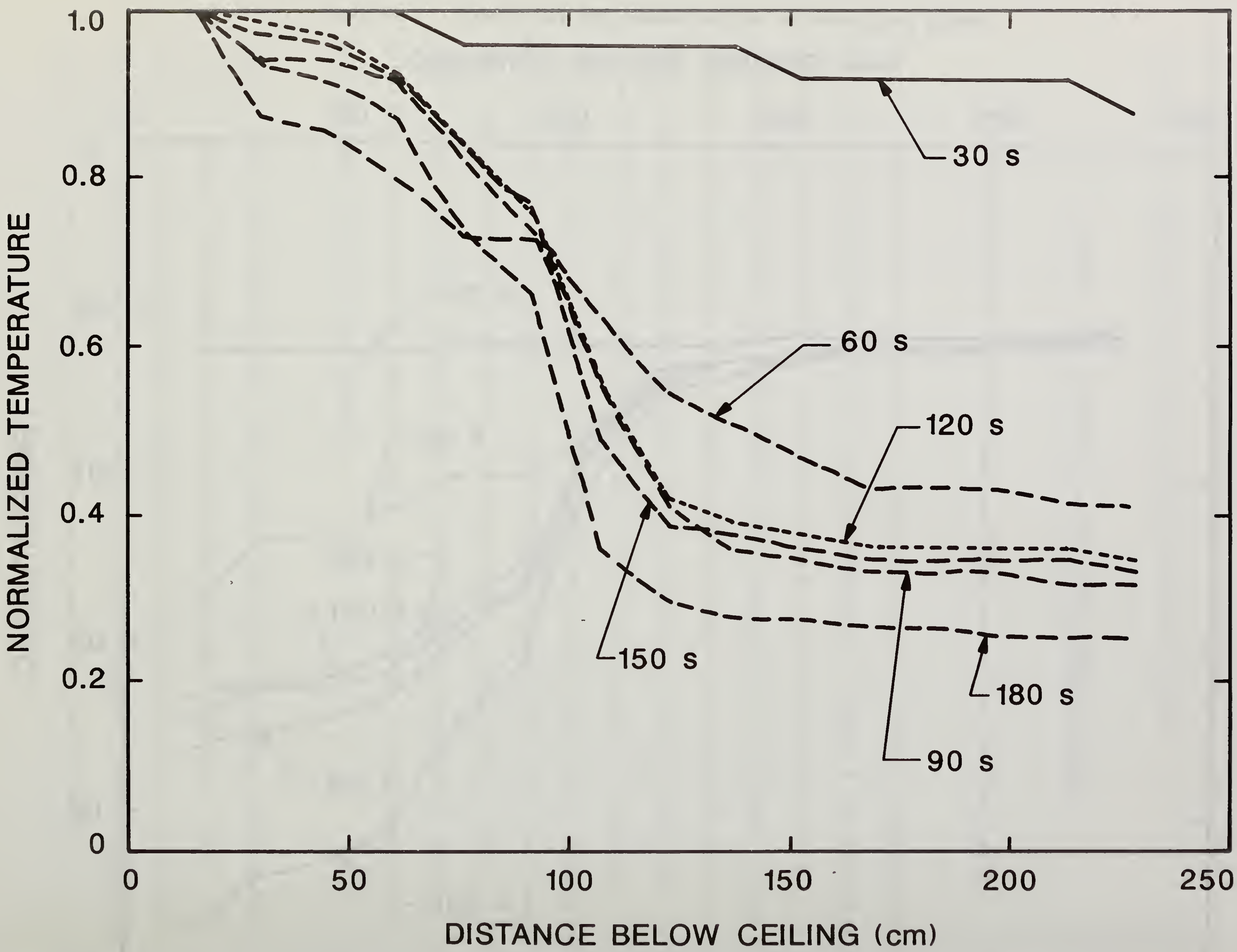

Figure 3. Normalized gas temperatures at specified times

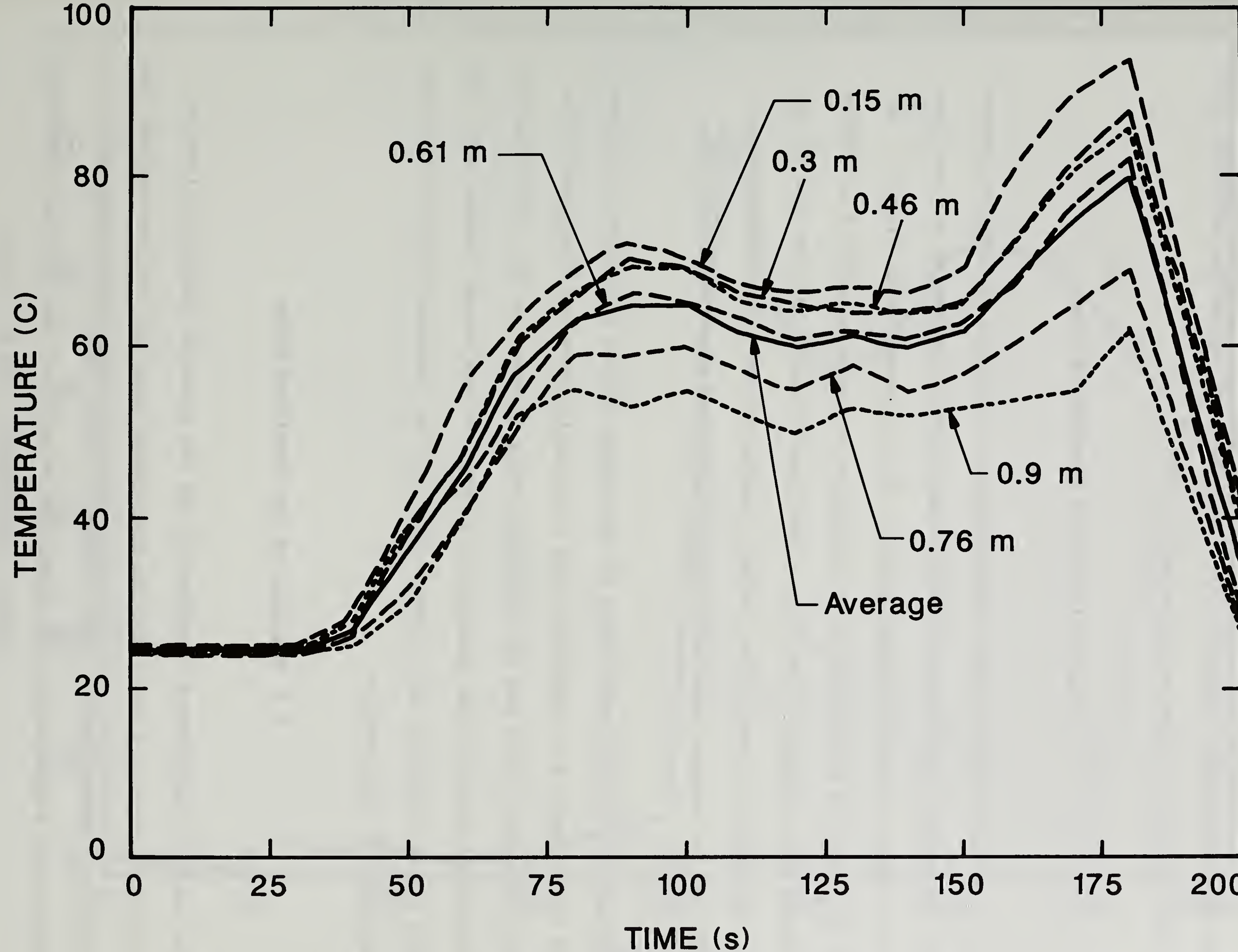

Figure 4. Measured gas temperatures in the upper layer at different distances below the ceiling and the average (solid curve) upper layer gas temperature

upper-layer-submerged thermocouples. Activation of the active sprinkler head is seen clearly to occur at approximately 175 s.

4.2 Heat Release as a Function of Time

The total heat release of the combustibles as a function of time was deduced from the oxygen depletion calorimetry measurements acquired in the hood/duct of the smoke collection/exhaust system. This is presented in Figure 5. As can be seen, the activation of the sprinkler at approximately 175 s reduces abruptly the strength of the fire. The Figure 5 result will be used in the next paragraph to predict the thermal response of the simulated sprinkler links and to compare these predictions to measured time-temperature data.

Although the general peak levels of the energy release rate curve of Figure 5 and their timing are consistent with the visually observed fire growth, the very low early levels and the indicated sharp increase at 100 - 125 s are not. Predicted sprinkler link response to a Figure 5-type energy release rate, but with a more realistic early growth rate, will be presented below in the last paragraph of this section.

4.3 Response of the Simulated Links

The measured temperature responses of the two trees of simulated links are plotted in Figures 6 and 7 for the room-center tree and the near-doorway tree locations, respectively. Also included in these figures are plots of theoretical estimates for the normalized velocity of the elevated-temperature

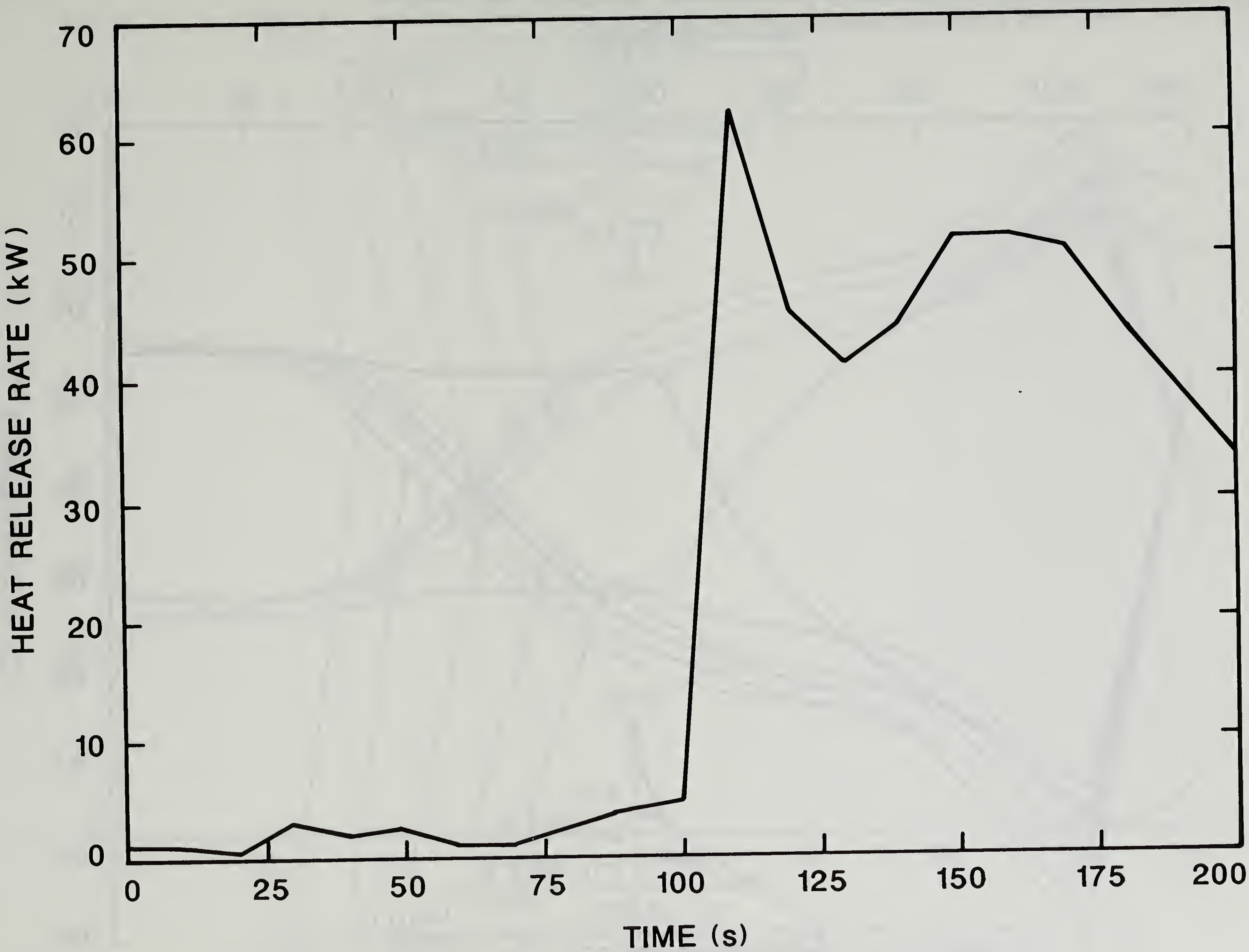

Figure 5. Heat Release Rate

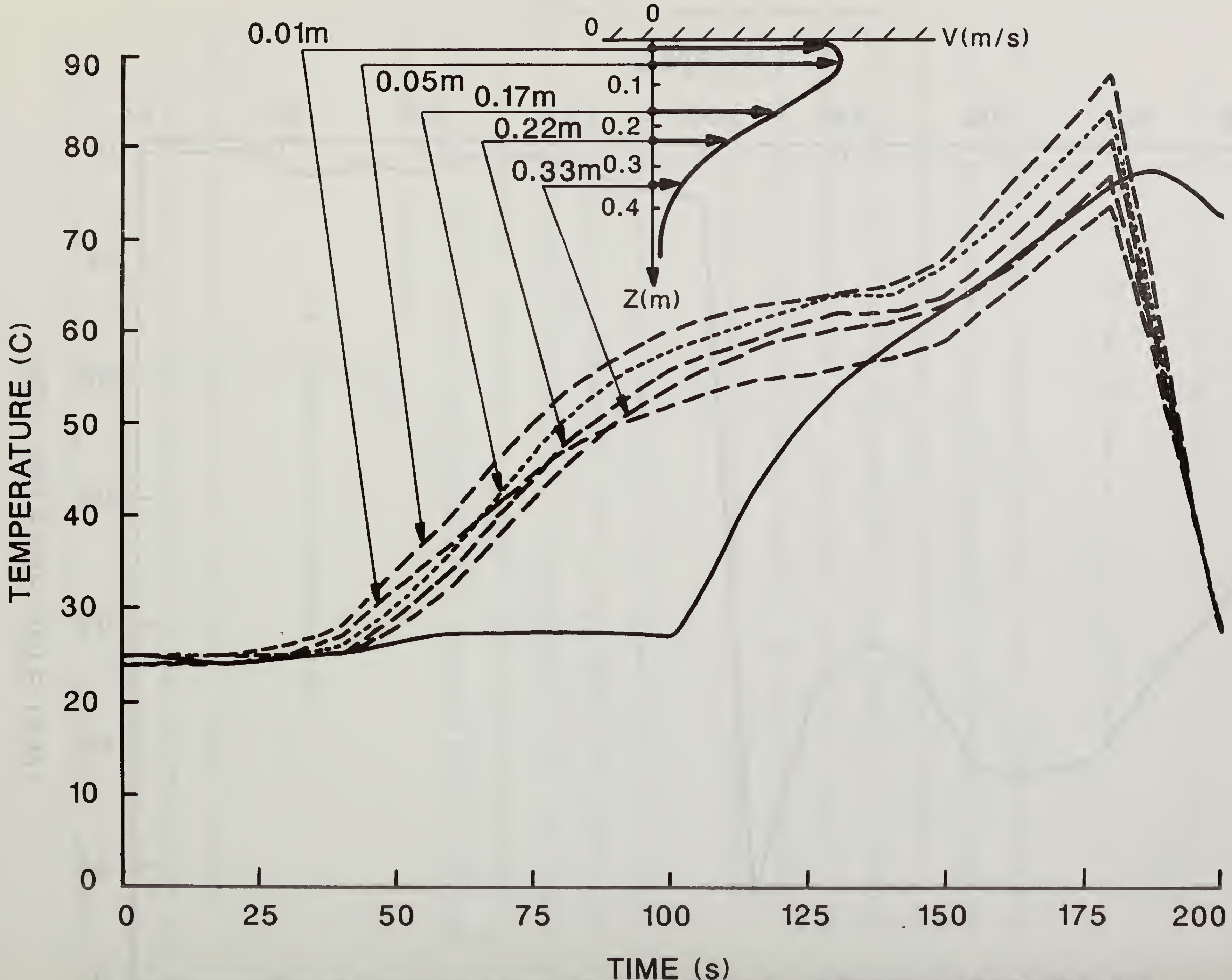

Figure 6. Measured dummy link temperatures at different distances below the ceiling, the calculated temperature of a near-ceiling link (solid curve), and a plot of the predicted, normalized ceiling jet velocity profile (insert): Center of the Room

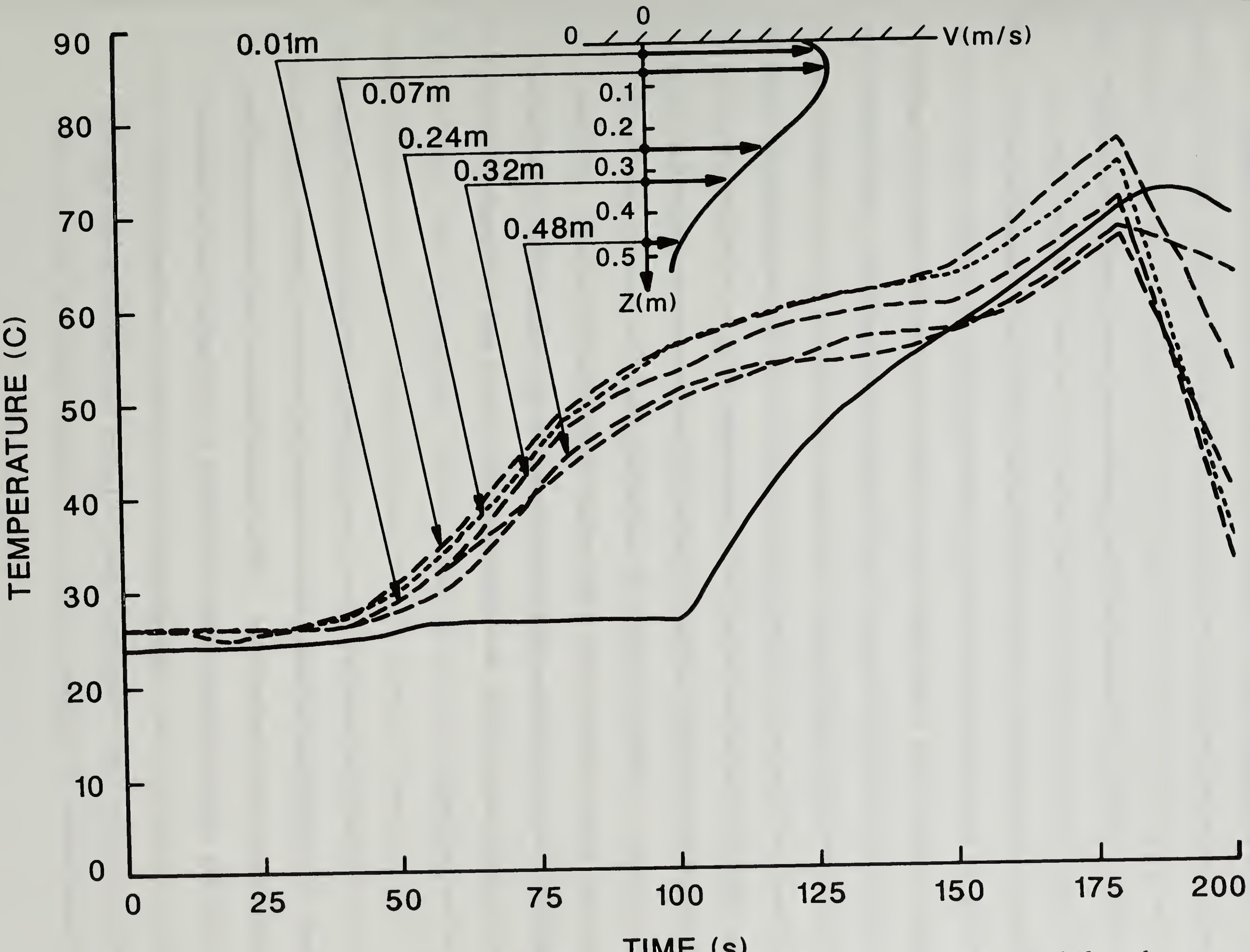

Figure 7. Measured dummy link temperatures at different distances below the ceiling, the calculated temperature of a near-ceiling link (solid curve), and a plot of the predicted, normalized ceiling jet velocity profile (insert): Near the Doorway

smoke as it flows past each link of the two simulated link trees. These velocity estimates were obtained from Eq. (1) of [10].

The thermal response of sprinkler links are determined by and depend on the local "free-field" gas temperature and velocity. As seen from the plots of predicted smoke velocity, a significant variation in link response as a function of ceiling elevation is to be expected and was measured. For example, for the link tree at the center of the room, near the deployed active sprinkler, it is seen in Figure 6 that at the time of sprinkler actuation the coolest of the links was the one 0.01 m below and closest to the ceiling. At this time that link was 14°C less than the hottest of the center-of-the-room links which reached approximately 64°C above ambient (i.e., 88°C) and was located 0.05 m below the ceiling. Similarly, for the near-doorway tree, it is seen in Figure 7 that at the time of sprinkler actuation the coolest of the links was, again, the one 0.01 m below and closest to the ceiling. At this time that link was 10°C less than the hottest of the near-doorway links which reached approximately 53°C above ambient (i.e., 77°C) and was located 0.07 m below the ceiling.

It is particularly noteworthy that all existing accepted and recently proposed methods of estimating sprinkler link response [3,5-7] are based on estimates of peak velocity and temperature. These depend only on radial distance from the fire and not on distance from the ceiling. Provided a link is located within a relatively wide range of elevations, below the ceiling, but not too close or too far, the relatively broad velocity distributions and measured link temperatures of Figures 6 and 7 are consistant with the fact that the traditional approach is a reasonable one. However, for more reliable and versatile design, especially for links very close to ceilings, it is evident that predictions of the response of a link must be determined as a function of the vertically-varying, local, free-field gas environment.

The accepted approach to sprinkler link deployment design is based on calculation procedures of link response which are strictly valid only for links deployed below unconfined ceilings, i.e., where there is no growth of an upper smoke layer. To the extent that they generate reliable results in such configurations they can also provide reasonable engineering estimates of link response relatively early in time for confined ceilings. However, for most of the time interval between fire initiation and sprinkler actuation, ceiling jets and sprinkler links are typically submerged in a hot upper smoke layer. For this reason, such calculation procedures do not have general applicability. This is illustrated graphically in the dashed plots of Figures 8 and 9 which are the result of an unconfined ceiling calculation for the link temperature response in the present experiment for the center-room and near-door deployed links, respectively. The calculation used the DETACT-QS computer program [6], the previously described room geometry characteristics, the energy release rate history of Figure 5, and a 46 $(ms)^{1/2}$ RTI. The predicted link thermal responses are far lower than would be required to predict the observed, 175 s sprinkler actuation. It is clear that a design procedure which uses predictions of unconfined ceiling link response is not adequate in the present type of typical fire scenario.

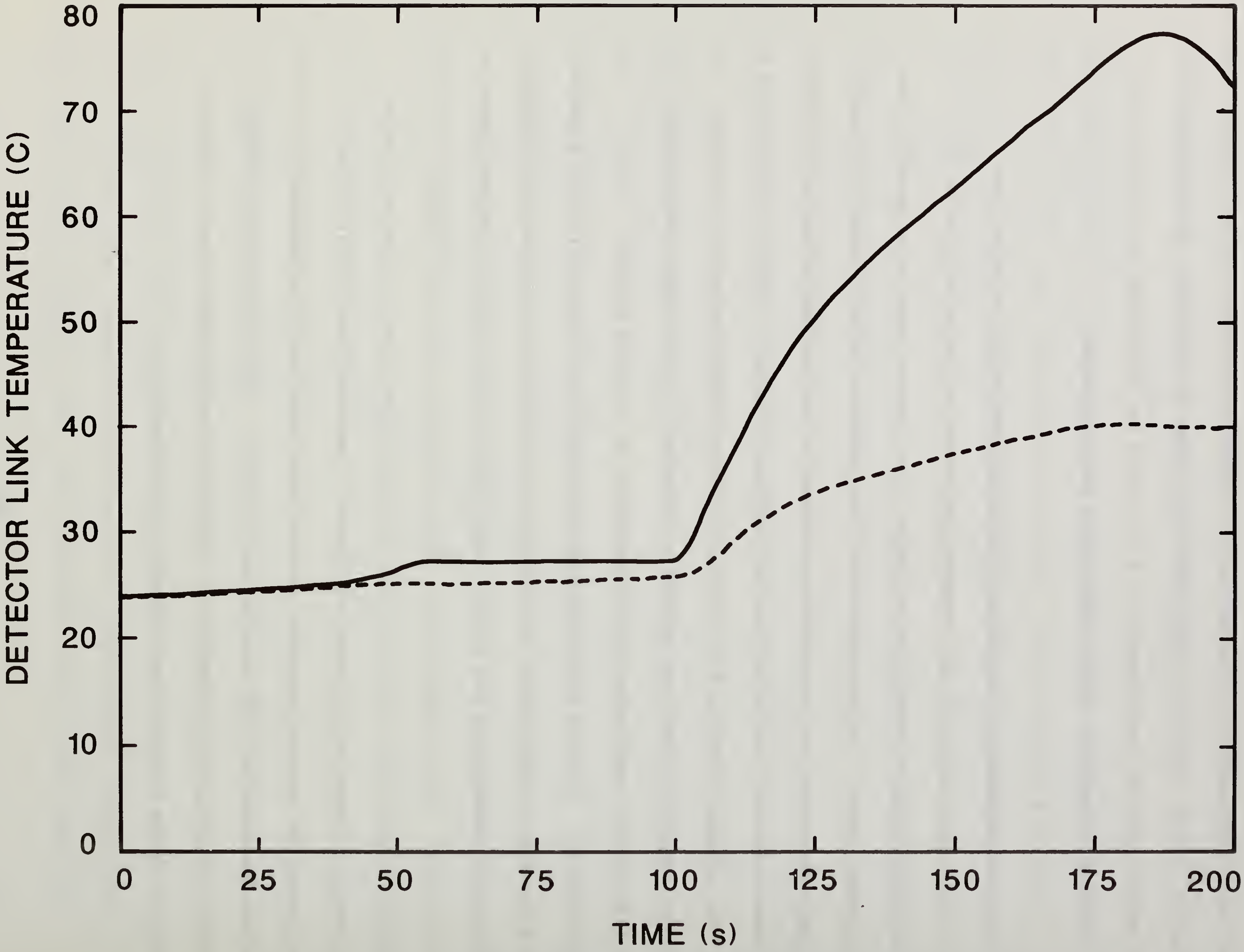

Figure 8. Calculated link temperature with (solid curve) and without (dotted curve) upper layer: Center of the Room

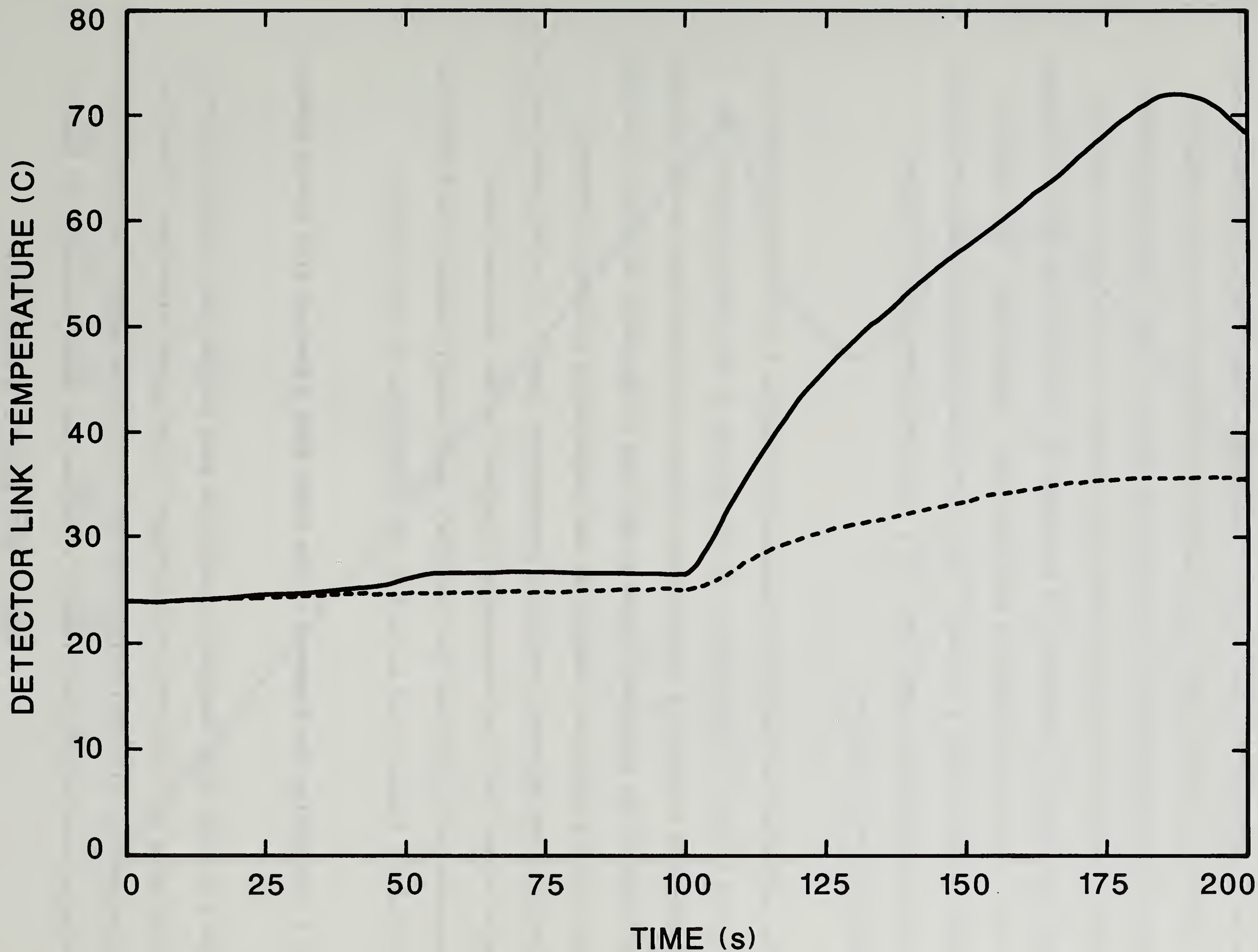

Figure 9. Calculated link temperature with (solid curve) and without (dotted curve) upper layer: Near the Doorway

As mentioned in an earlier section, calculation procedures which take account of the effect of the upper layer on link reponse (but not yet the link-to-ceiling distance) have been developed [11,20,21]. These have been advanced further and applied in the present fire scenario. The result of applying these calculation procedures are presented in the solid line plots of Figures 8 and 9 for a center-room and near-door link, respectively. The Figure 8 result predicts that a 46 $(ms)^{1/2}$ RTI, 74°C fuse-temperature link would fuse at approximately the same time, 175 s, that the experimental link and sprinkler were actuated.

The calculated two-layer link responses of Figures 8 and 9 are replotted in Figures 6 and 7, respectively. As can be seen in the latter figures, the comparisons between the experimental data and the predictions are quite good at times of the experiment close to the time of sprinkler actuation. However, there is a significant qualitative and quantitative difference between predicted and measured results at intermediate times. It is believed that the major reason for this discrepency is related to the above-mentioned inaccuracies in the data for the fire's early energy release rate history as plotted in Figure 5 and as used in the predictions of link response.

4.4 Predicting the Response of the Links With a Revised Fire Growth History

The two-layer link response calculations were carried out a second and third time using two different revised-Figure 5 fire growth histories. These two fire growths, plotted in Figures 10 and 11, involve early-time fire energy release rates which grow linearly with time and which intercept the Figure 5

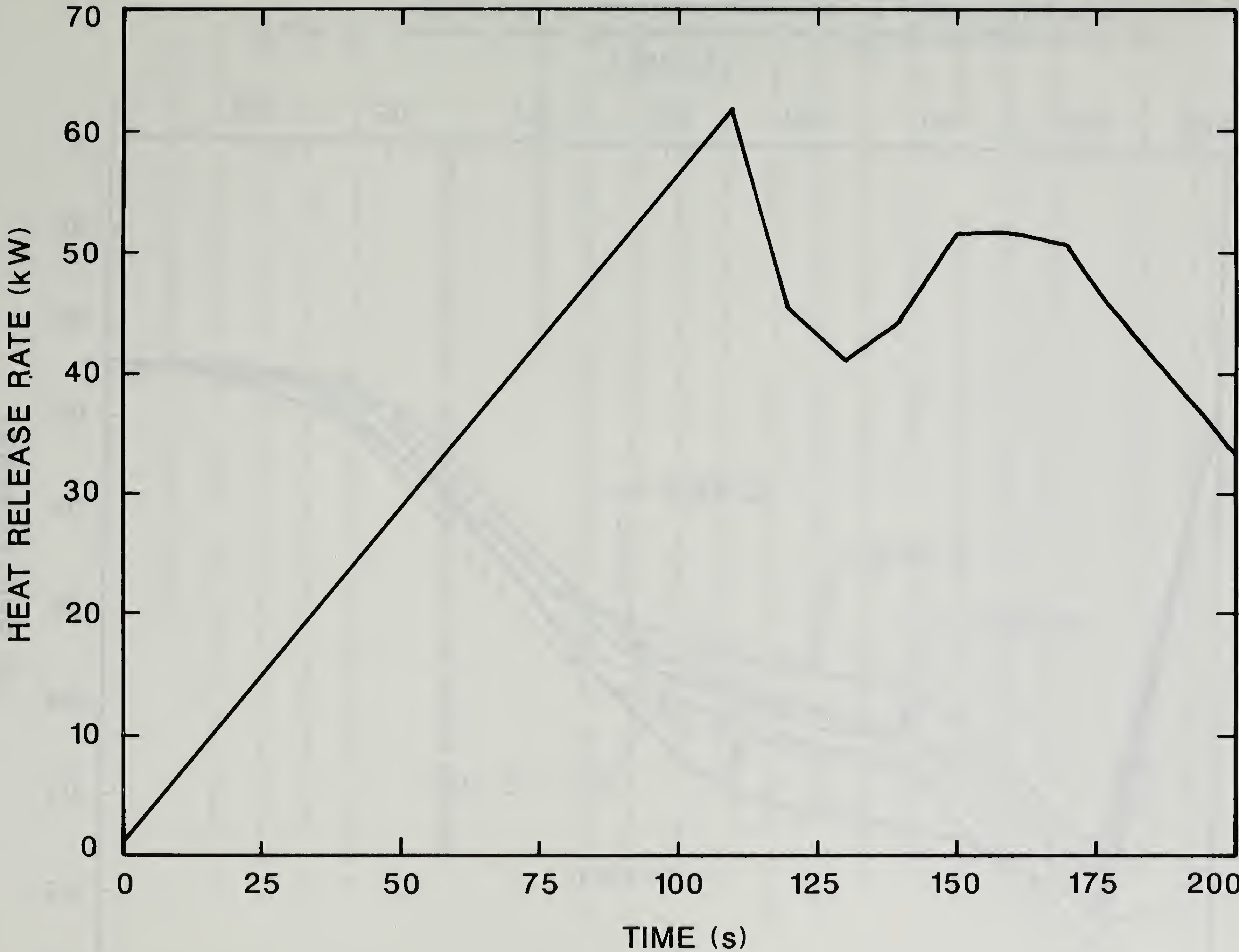

Figure 10. Heat Release Rate (Revision 1)

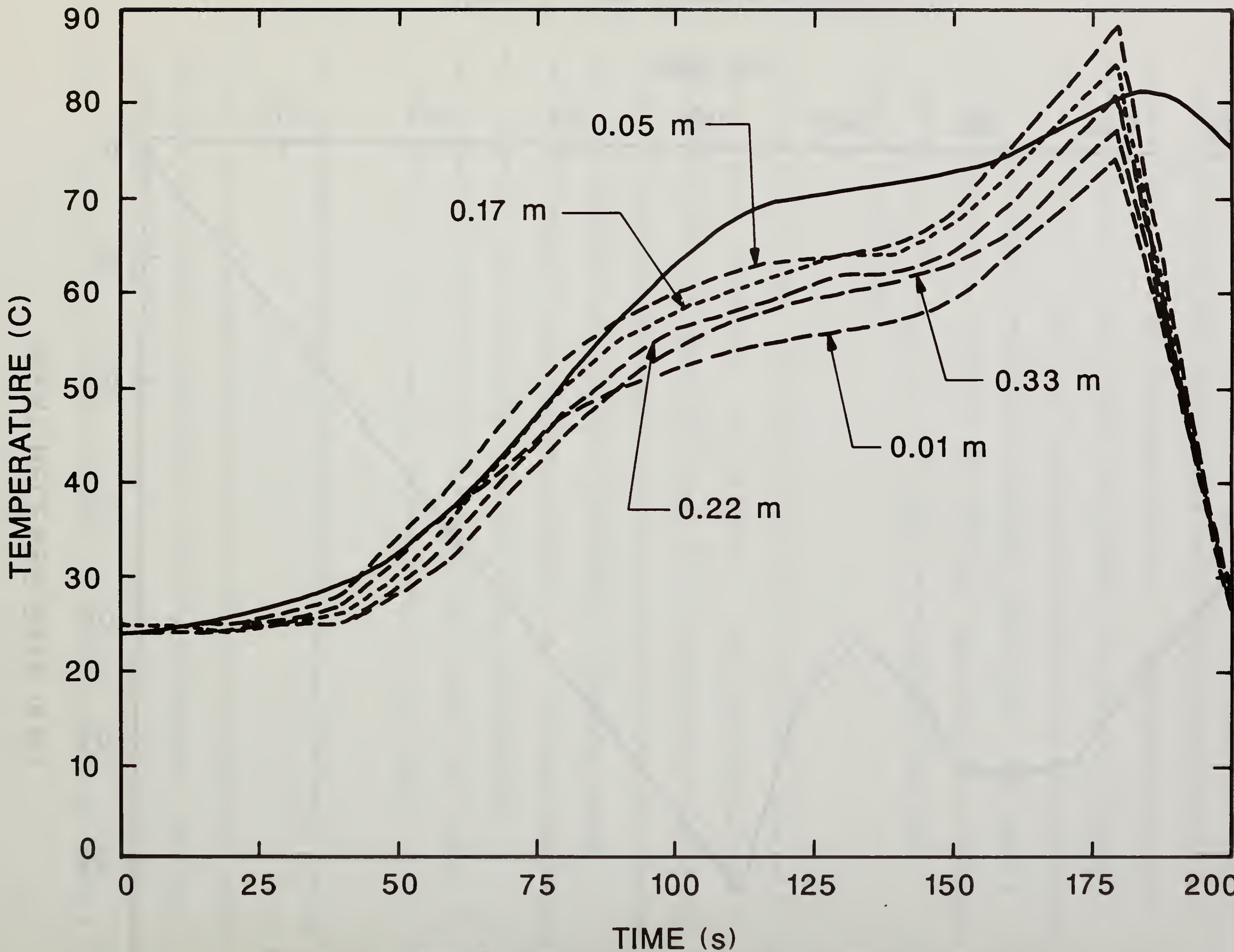

Figure 11. Measured dummy link temperatures at different distances below the ceiling and the calculated temperature of a near-ceiling link using the Figure 10 Heat Release Rate (solid curve): Center of the Room

growth rates at each of two different times close to its 100 - 125 s peak. It is believed that these revised fire growth histories represent experimentally the observed fire growth more accurately than the fire growth of Figure 5.

The results of the analysis of link response to the Figure 10 fire growth rate are plotted in Figures 12 - 15 in a manner which is analogous to the plots of Figures 6 - 9. Results of a similar analysis, but using the Figure 11 fire growth rate, are presented in Figures 16 - 19. As can be seen from these figures, there is a significant improvement in the comparison between the measured and newly predicted results for link response. For example, as can be seen in Figure 16 (to be compared to the previous results of Figure 6), for a link deployed at the center of the room both the qualitative and quantitative aspects of the predicted link response is remarkably close to measured values. These favorable results provide very encouraging support for the overall link response prediction methodology which has, heretofore, never been evaluated experimentally.

5. SUMMARY OF CONCLUSIONS AND RECOMENDATIONS FOR FURTHER RESEARCH

This report presented and analyzed a portion of the data acquired during a test program which involved full-scale, sprinklered, compartment fires. The work here focused attention specifically on key features of the typical sprinkler link deployment/response problem. The following is a summary of conclusions and recommendations for futher research:

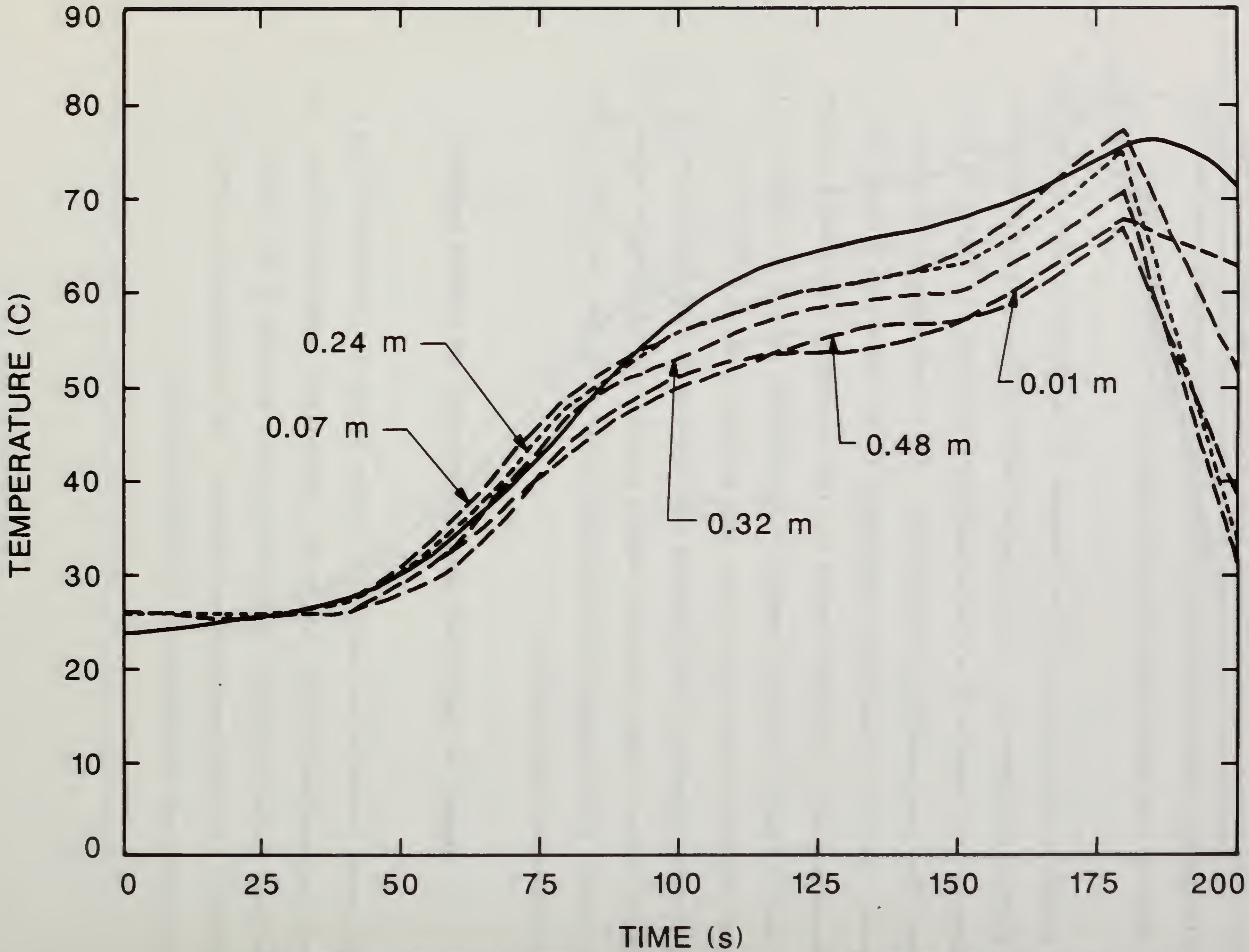

Figure 12. Measured dummy link temperatures at different distances below the ceiling and the calculated temperature of a near-ceiling link using the Figure 10 Heat Release Rate (solid curve): Near the Doorway

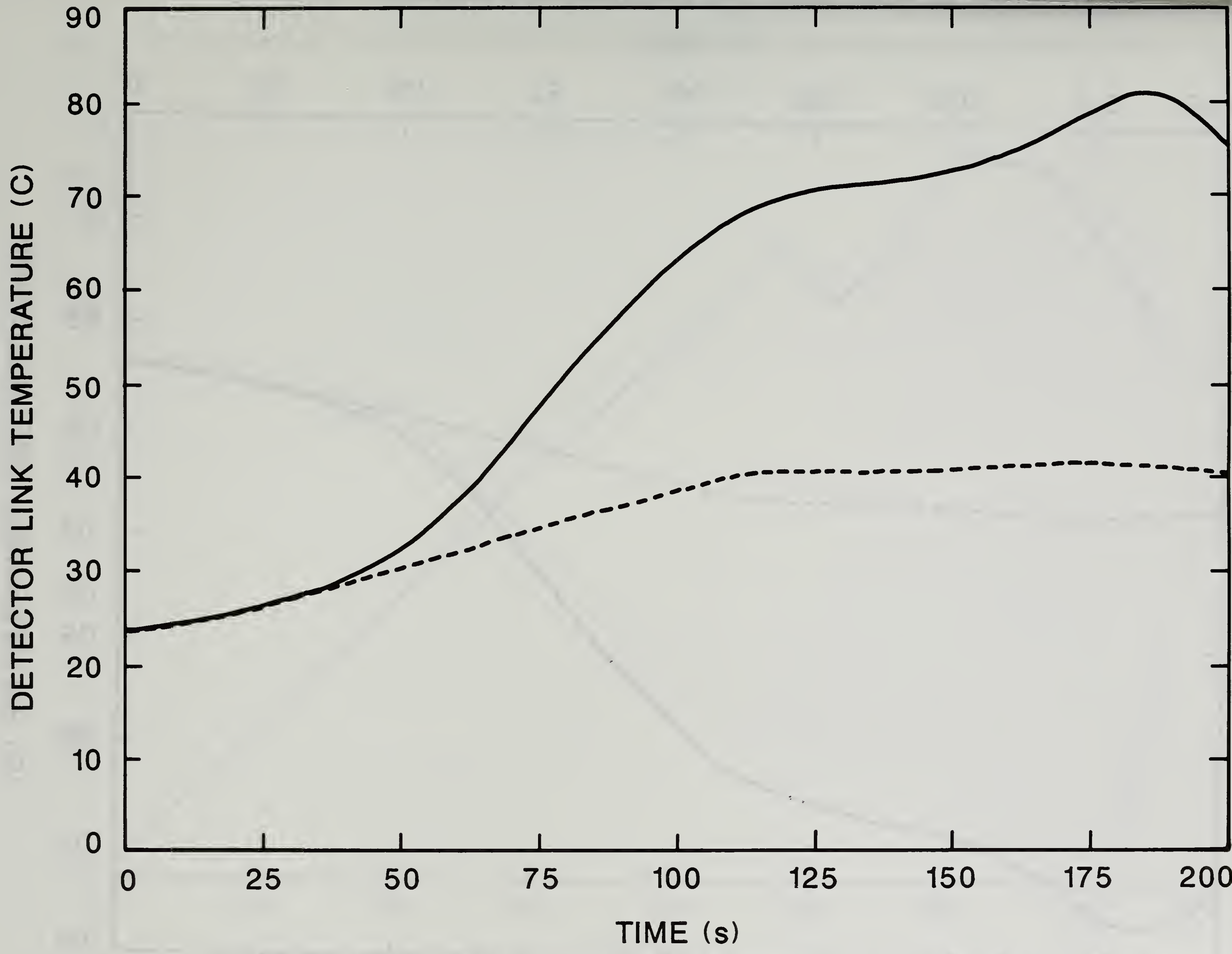

Figure 13. Calculated link temperature with (solid curve) and without (dotted curve) upper layer using the Figure 10 Heat Release Rate: Center of the Room

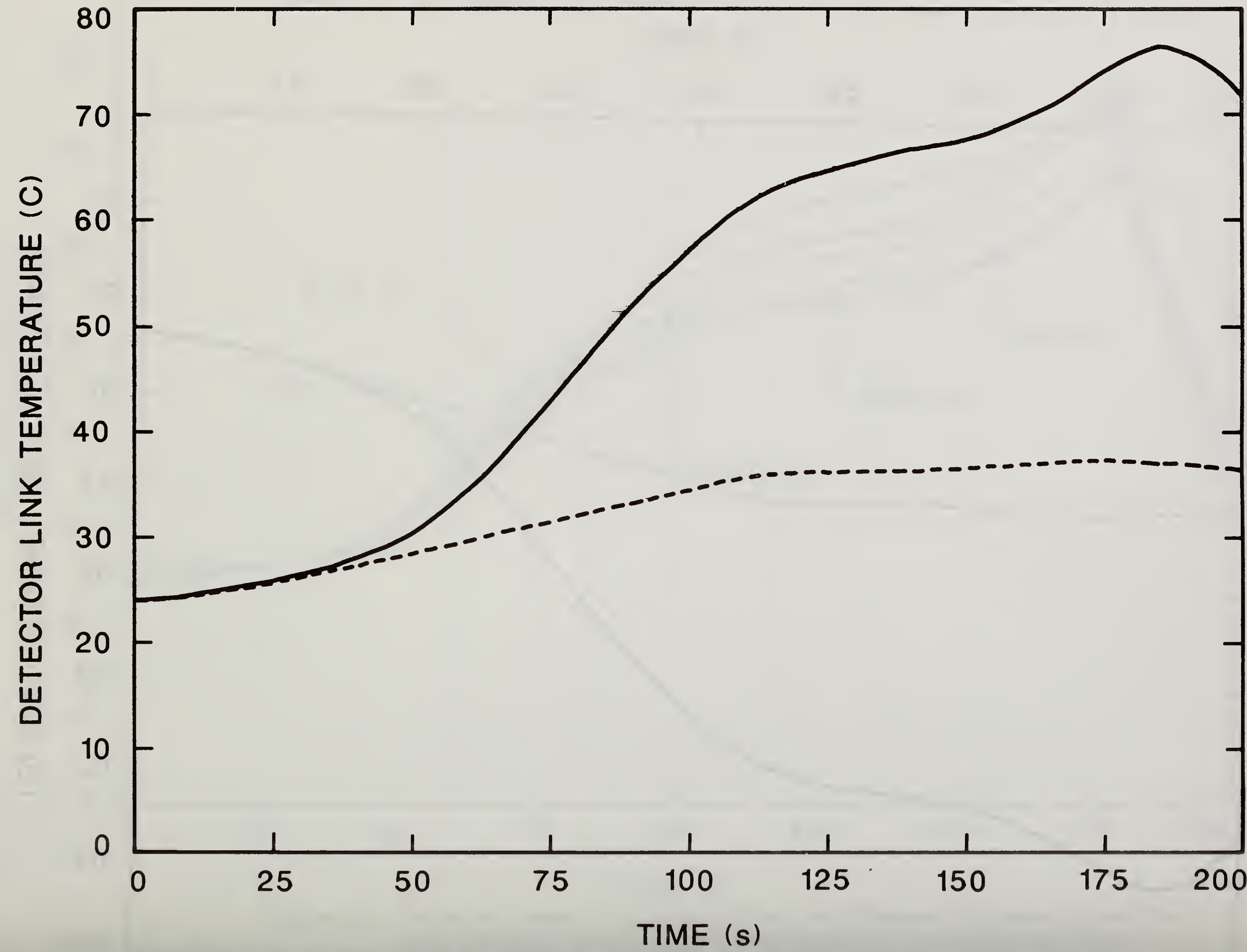

Figure 14. Calculated link temperature with (solid curve) and without (dotted curve) upper layer using the Figure 10 Heat Release Rate: Near the Doorway

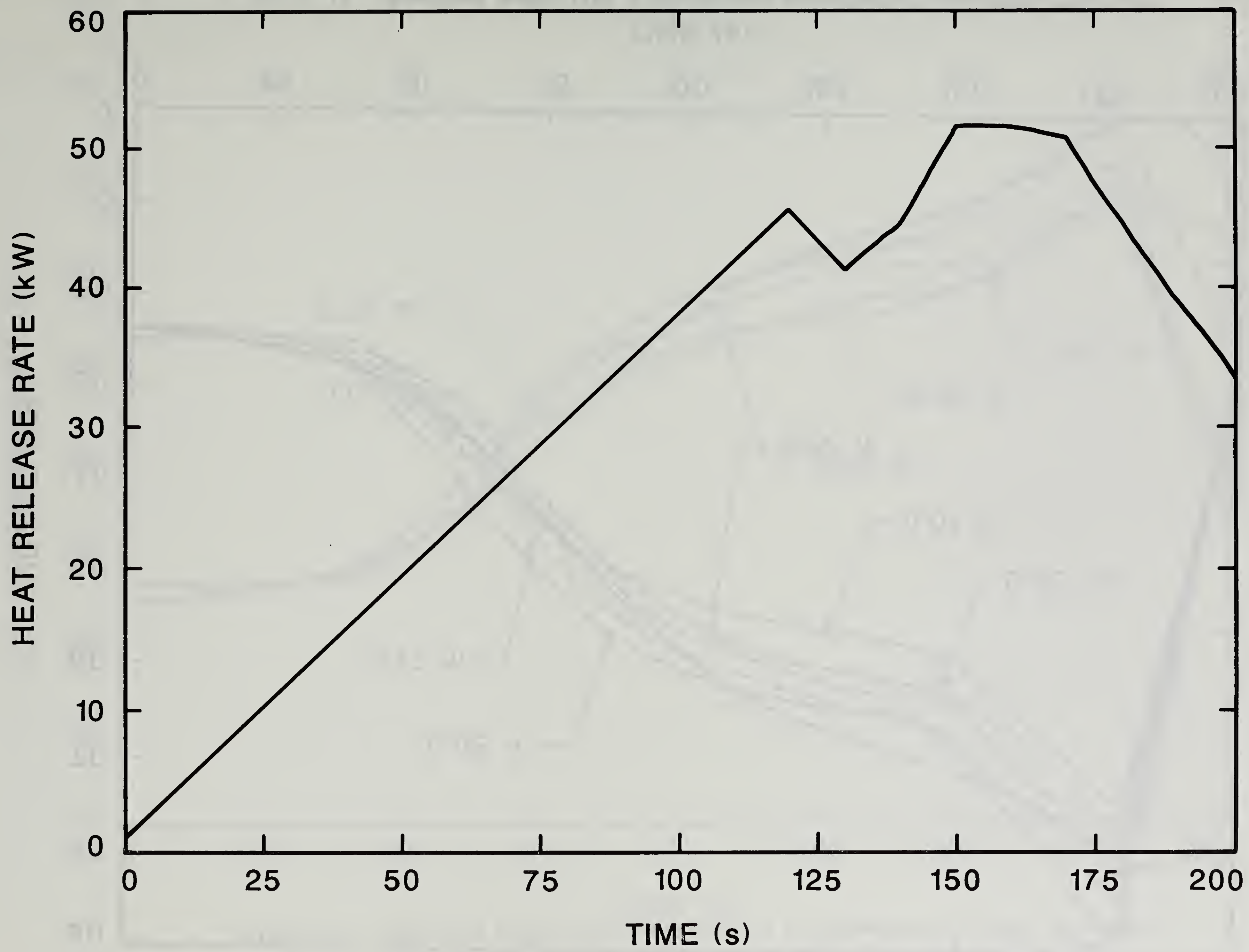

Figure 15. Heat Release Rate (Revision 2)

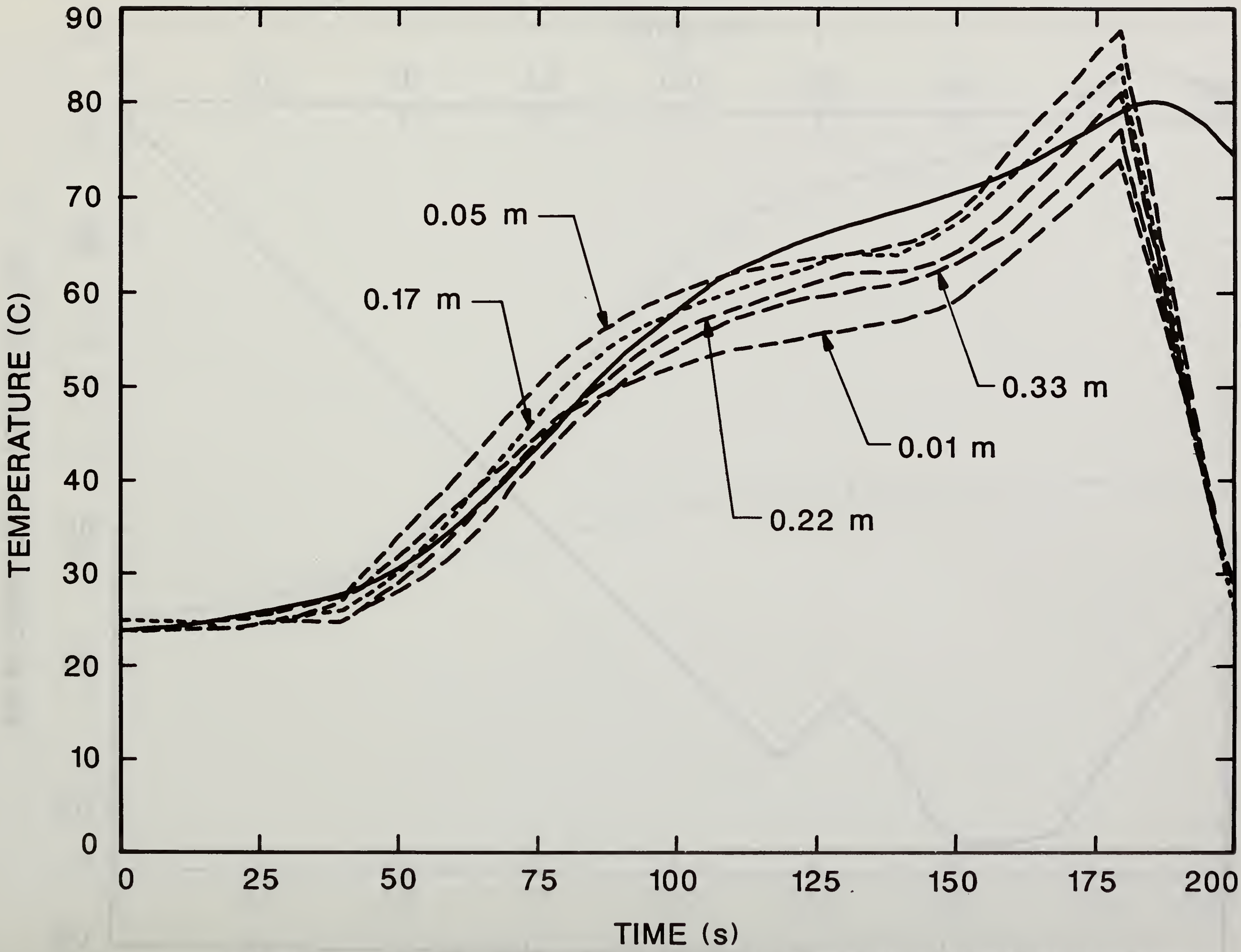

Figure 16. Measured dummy link temperatures at different distances below the ceiling and the calculated temperature of a near-ceiling link using the Figure 15 Heat Release Rate (solid curve): Center of the

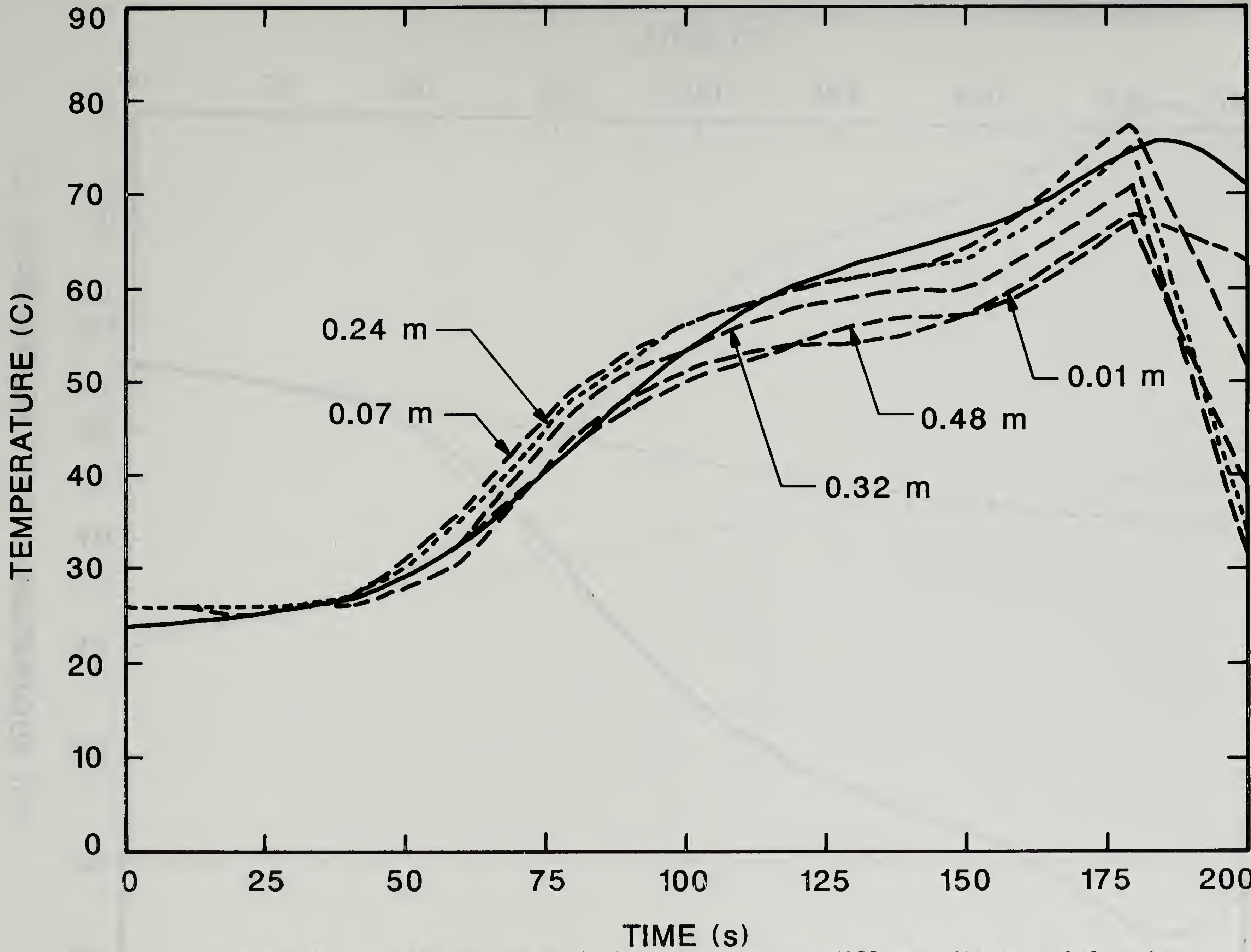

Figure 17. Measured dummy link temperatures at different distances below the ceiling and the calculated temperature of a near-ceiling link using the Figure 15 Heat Release Rate (solid curve): Near the Doorway

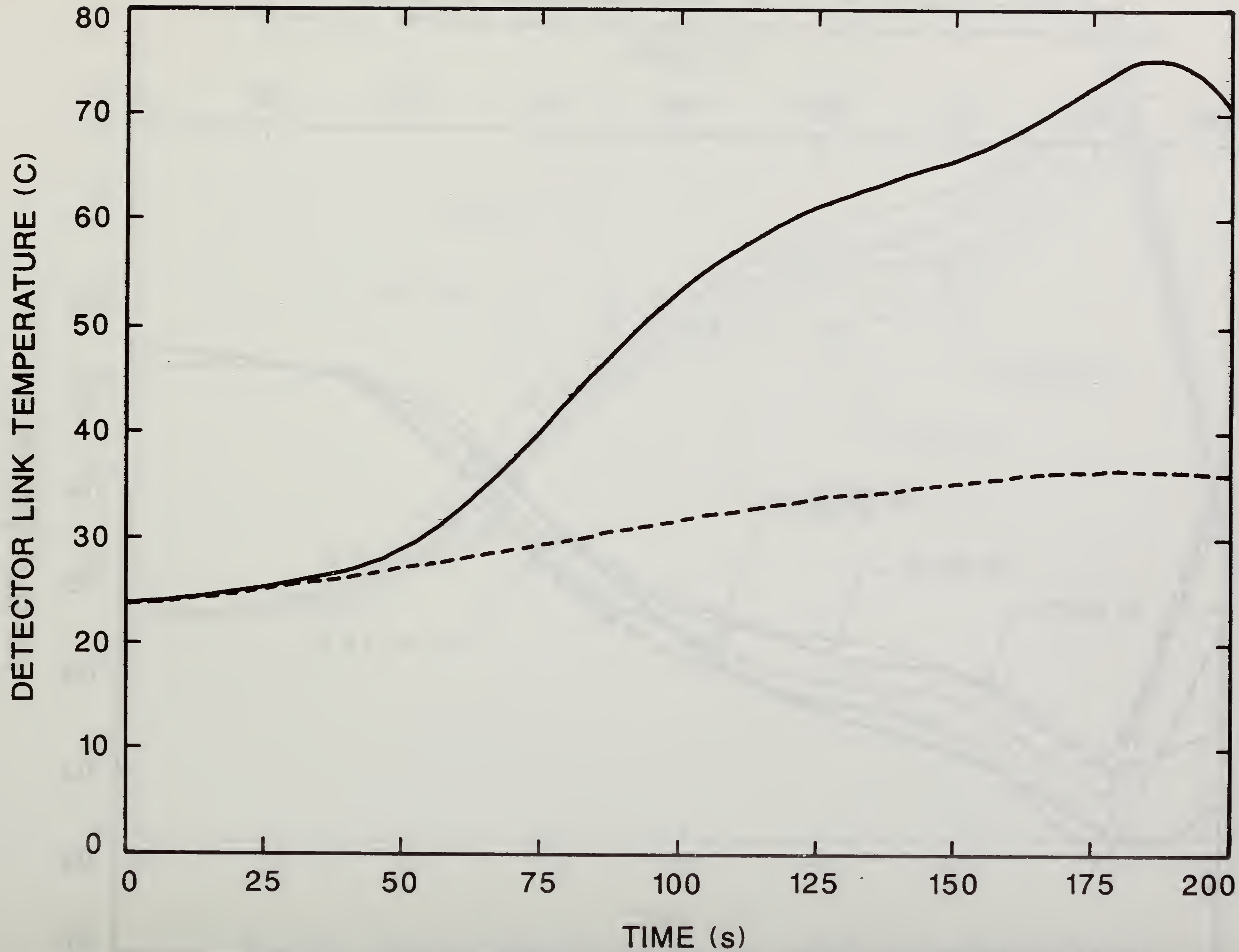

Figure 18. Calculated link temperature with (solid curve) and without (dotted curve) upper layer using the Figure 15 Heat Release Rate: Center of the Room.

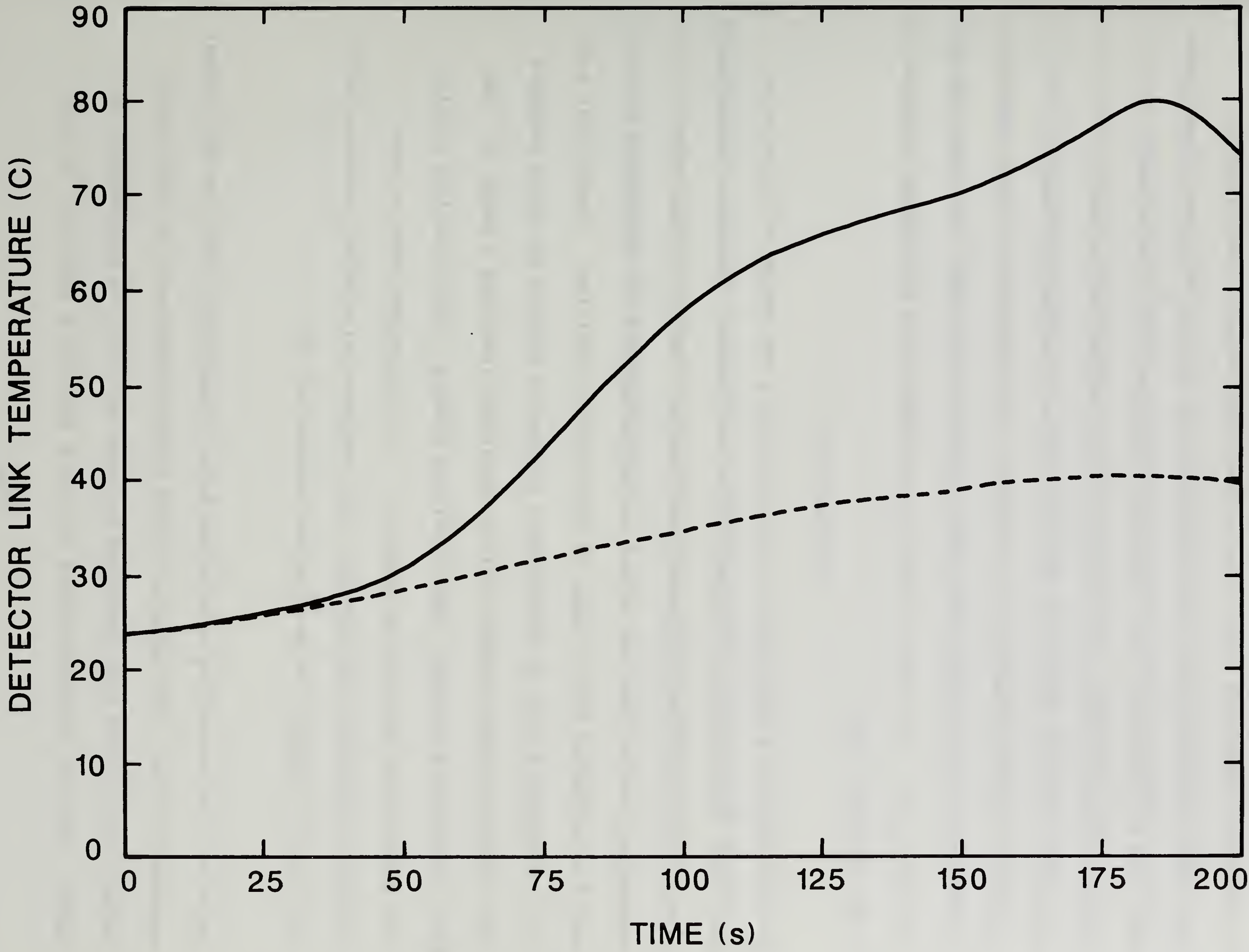

Figure 19. Calculated link temperature with (solid curve) and without (dotted curve) upper layer using the Figure 15 Heat Release Rate: Near the Doorway.

The elevated temperature, upper smoke layer which develops inevitably in compartment fires can have a major impact on the thermal response of sprinkler links. As was the case in the experiment discussed here, traditionally accepted methods of predicting sprinkler link response can be totally inadequate. This is because of the fact that such methods are based on idealized, unconfined ceiling fire scenarios, and they do not account for the effects of the smoke layer on the flow dynamics of the upper fire plume and on the ceiling jet, the latter of which engulfs and drives the thermal response of the sprinkler link.

The link response predictions of this work used a new method of calculation which does take account of the smoke layer environment. Favorable comparisons between predictions and experiment were obtained. While this was very encouraging, before this new method can be recommended for general use it should be validated over a range of experimental conditions. Toward this end it is recommended that an experimental program be carried out which measures link responses under confined ceiling conditions involving a range of: link RTI, link-to-fire spacing, link-to-ceiling spacing, fire-to-ceiling spacing, fire growth rate, and ceiling material. It is noteworthy that no such validation exists for the sprinkler link response calculation procedure which was used, for example, to develop the Standard of [5].

Sprinkler link-to-ceiling spacing can have a significant effect on the thermal response of links. For example, in the present experiment, at the time of fusing of the active link (designed to occur at 74°C) the temperatures of nearby, like-RTI, simulated links at 0.01 m and 0.05 m below the ceiling varied by approximately 14°C, with the link closer to the ceiling being the cooler of the two. This can be of critical importance, especially in the reliable use of certain modern sprinkler-link systems which are often deployed very close to, and even embedded into ceiling surfaces. Although a method is at hand to include the effect of link-to-ceiling spacing in link response predictions, such a method does not yet exist. It is recommended that such a method be developed and validated with the data base which will be generated by the above-recommended test program.

6. ACKNOWLEDGMENTS

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Leonard Y. Cooper and David W. Stroup

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

This paper presents and analyzes a portion of the data acquired during a test program which involved full-scale, sprinklered, compartment fires. The work here focuses attention specifically on key features of the typical sprinkler link deployment/response problem. It is found that the elevated temperature, upper smoke layer which develops inevitably in compartment fires can have a major impact on the thermal response of sprinkler links. It is shown that traditionally accepted methods of predicting sprinkler link response which do not account for this upper layer can be totally inadequate. Link response predictions used here involve a new method of calculation which does take account of the smoke layer environment. Favorable comparisons between predictions and experiment are obtained and experiments for further validation of this method are recommended. Finally, it is found that sprinkler link-to-ceiling spacing can have a significant effect on the thermal response of links and it is recommended that a method which accounts for this effect be developed and validated.

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

automatic sprinklers; ceiling jets; compartment fires; fire-generated flows; fusing; heat transfer; link-to-ceiling spacing; link-to-fire spacing; smoke layer; sprinkler links; thermal response; unconfined ceilings; validation

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