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Fire Protection Systems for Rail Transportation of Class A Explosives: Interim Report

Richard W. Bukowski

Center for Fire Research
National Engineering Laboratory
National Bureau of Standards
U.S. Department of Commerce
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U.S. DEPARTMENT OF COMMERCE, Philip M. Klutznick, ***Secretary***

Jordan J. Baruch, ***Assistant Secretary for Productivity, Technology, and Innovation***

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

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Richard W. Bukowski

Abstract

As a result of several accidents involving fire induced detonation of military explosives during rail shipment, a research project, funded by the Federal Railroad Administration (FRA), was initiated at the Center for Fire Research (CFR) at the National Bureau of Standards (NBS). This project was initiated to evaluate various methods of protection of Class A explosives from fire, and to identify one or more cost-effective approaches which could be explored in greater detail in later studies.

Active systems (detection, notification, and extinguishment) and passive systems (thermal insulating barriers) were evaluated regarding cost, feasibility and level of protection provided for the major hazard scenarios involved in rail shipment of explosives. The passive, thermal barrier approach was selected as the most reliable and less costly of the options studied while providing an acceptable level of protection.

Small-scale and full-scale tests were conducted to obtain performance data on one specific thermal barrier material. Based on this data, a computer model was developed which can predict temperatures of the boxcar floor, top surface temperature of a thermal barrier, and casing/explosive interface temperature of a wood-pallet mounted bomb for a range of fire sizes. The model predictions compare favorably with measured results from a limited number of experiments. Further experimental data are needed to refine the model and establish an acceptable confidence level in the predicted values. The proposed work necessary to provide this refinement and verification is described.

Key words: Bombs (ordnance); boxcars; computer models; fire detection systems; fire suppression; full-scale fire tests; heat transfer; railroad accidents; small-scale fire tests; thermal protection.

1. INTRODUCTION

Accidents involving rail transport of hazardous materials are receiving increasing public attention. While most of these accidents involve private sector shipments of industrial chemicals, the Federal Government, primarily the Department of Defense (DOD), ships significant quantities of explosives by rail. Although there have been only eight rail accidents since 1973 involving military shipments of munitions (with no fatalities) both DOD and the Federal Railroad Administration (FRA), which regulates the railroad industry, recognize the need to ship hazardous cargoes safely.

In response to this need, in 1979 the FRA initiated a contract with the Center for Fire Research (CFR) at the National Bureau of Standards (NBS) to do a preliminary study of possible methods of protecting shipments of military explosives from fires occurring during rail transport. Since DOD also has an ongoing project in this area titled "Safe Transport of Munitions (STROM)", every attempt was made to coordinate the two projects to minimize unnecessary duplication of effort.

2. BACKGROUND

In 1973 two separate railroad accidents occurred in the western U.S. involving trains carrying military shipments of bombs. Although neither accident resulted in fatalities, both resulted in extensive damage to railroad equipment and one resulted in considerable civilian property damage and several injuries. Due to the extent of damage, and the likelihood that under slightly different circumstances injuries and deaths could have been extensive, these two accidents were investigated in greater depth than most incidents. The National Transportation Safety Board (NTSB) investigation report of the Benson accident resulted in several safety related rules changes which impacted on the problem. And in addition, the information from both of these detailed investigations were beneficial in developing the necessary research plan for this study.

The first incident occurred on April 28, 1973, in a railroad yard at Roseville, California [1][1]. On the day of the accident, the yard contained 21 boxcars loaded with 250 lb (114 kg) bombs, 10 car loads of LPG gas, and two propane tank cars. A fire occurred from some undetermined cause which exposed these cars and resulted in the complete or partial detonation of 18 of the 21 bomb cars. The ensuing fire and explosions resulted in 63 injuries and required evacuation of 4700 persons from the area. Shrapnel and debris was spread over a one mile area with one house set afire almost one mile from the center of the explosions; windows were broken in downtown Roseville - three miles away, as well as in Rocklin almost ten miles away. The town of Antelope

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

(less than one mile from the explosions) was almost totally destroyed, with several buildings including the fire station leveled and burned. The estimated direct cost to the U.S. Government as a result of the accident was on the order of $5 million.

The second accident occurred on May 24, 1973 (36 days later) in the area of Benson, Arizona [2]. In this accident, a 106 car freight train carrying 12 boxcars loaded with 500 lb (228 kg) bombs was proceeding at approximately 45 miles per hour (73 kmph) when an explosion occurred in one of the cars. As the train was brought to a stop, a second and third explosion occurred resulting in a crater 115 feet (35 m) long by 93 feet (28 m) wide by 25 feet (8 m) deep. The explosions scorched the desert for about 1/4 mile (400 m) in all directions, destroying 460 feet (140 m) of track and road bed. All but approximately 500 of the 2,600 bombs either exploded or were destroyed. Unexploded bombs were thrown as far as one mile (1.6 km) from the main crater area and windows were broken in a home 5 miles (8 km) from the accident site. Fortunately, there were only two minor injuries of train crew members which occurred when they jumped from the moving caboose.

Availability of information from investigation of the Roseville accident has been somewhat limited due to litigation which was finally completed in mid 1980. However, a litigation report released in June 1980 [3] indicated that the most probable causes were either: 1) a misapplied brake shoe on one explosives car which initiated a subcar fire as the train entered the rail yard, or 2) a yard fire of unknown origin occurring just after the train entered the rail yard.

Investigations indicated that the probable cause of the Benson accident was overheated or sparking brakes on one of the bomb cars which resulted in ignition of the underside of the wood boxcar floor. The subfloor fire subsequently penetrated the floor and caused the initial explosion.

Attempts were made to replicate the scenario through full-scale testing conducted at the Naval Weapons Center, China Lake, California in conjunction with the U.S. Government defense of law suits extending from the two accidents. These tests revealed that a fire of moderate size, burning under a wood floored boxcar, can penetrate the floor and expose the bombs in as little as six to ten minutes. Additional tests demonstrated that cast iron brake shoes can, under conditions of jamming or heavily applied braking, produce sufficient sparks or can overheat wheels to the point of ignition of the underside of the car.

As a result of the Benson accident, several rule changes were promulgated by the FRA in an attempt to reduce the likelihood of this type of incident [4]. These rule changes required that only the lower sparking type of composition brake shoes be used on boxcars carrying Class A explosives and that the cars be equipped with either a continuous steel subfloor or metal spark shields located over each of the truck assemblies. Also, explosive cars were required to use only roller type bearings. These employ a sealed lubricant system that does not cause excess lubricating oil to be sprayed on the underside of the car during transit which is typical with the older "friction" type bearings. Finally, the new rules required increased pre-and post-loading inspection and increased surveillance during transport.

In addition to these rule changes, the National Transportation Safety Board recommended that the FRA and DOD conduct studies of other methods of protecting Class A explosives from fire while being transported by rail.

Shortly after the study began at NBS, it was determined that the DOD was conducting a concurrent study of rail transport of Class A explosives. Contact was made with the DOD project manager and meetings were arranged to coordinate the studies to minimize unnecessary duplication of effort. From that time on, NBS project personnel have attended the regular DOD project meetings in order to enhance coordination between the two programs. Furthermore, since the DOD project was well established, the scope and plan of the NBS project was adjusted to complement similar research areas in the DOD project and to focus on research areas not generally pursued under the DOD project.

3. SCOPE

The scope of the project at CFR was essentially to evaluate current methods of fire protection technology and to determine which would best apply to the hazards of rail transport of Class A explosives.

One of the subtasks included in the DOD project (conducted by the Naval Weapons Center, China Lake, California) involved the development of an "on board" detection and suppression system. However, because a large portion of the testing in this subtask was being conducted as part of the U.S. defense in the law suits extending from the Benson and Roseville accidents, it focused exclusively on wood floored railcars.

Discussions with DOD personnel revealed that since the 1973 accidents, the character of the boxcar fleet has changed. Wood floored boxcars are becoming obsolete and are being replaced by all steel cars. DOD records indicate that by 1979, 85 percent of all Class A explosive shipments were being made in all steel cars [5]. And, it is expected that this percentage will be continually increasing as the wood floored cars reach their end of service life and are replaced by steel cars. Based on this information it was determined that NBS could provide a significant contribution by focusing its study on the all steel boxcar.

4. HAZARD SCENARIOS

The first step was to identify the major hazard scenarios involved in the transportation of munitions. Once these scenarios had been defined, various intervention strategies could be evaluated in order to determine which will best prevent fire penetration of the railcars, and subsequent detonation of the bombs. A study of railroad and DOD accident reports resulted in the identification of three principal fire hazard scenarios. These included derailments, brake fires, and rail yard fires.

4.1 Derailments

By far, the largest single accident type involving rail shipment is derailment. However, since munitions are unfused during shipment, their sensitivity to detonation from impact is relatively low. Thus, the derailment of munition cars would not ordinarily result directly in explosion unless the derailment led to a fire or explosion of some other hazardous train cargo.

Another difficulty encountered in derailment is that the resultant damage to the boxcars carrying the munitions is unpredictable. The cars may remain upright or may be thrown into any conceivable orientation. In addition, the cars could be torn open and the load spilled. This makes the derailment situation complex, and a difficult one to handle due primarily to its unpredictable nature. This complexity suggests that the best approach is to try to prevent the derailment in the first place.

One of the subtasks in the DOD project involved the study and prevention of derailments. The primary causes of derailments identified by the DOD study were 1) bad track, and 2) instability of the car when rounding curves, a result of improper train make-up (short/long or heavy/light car combinations). Since the causes and solutions to the derailment problem do not directly involve fire hazards it was felt that this problem was not reasonably within the scope of the NBS study and was not addressed.

4.2 Boxcar Fires

As exemplified by the Roseville and Benson accidents, there are two primary scenarios for boxcar fires. The first, similar to the Benson accident, involves sparking brake shoes or overheated wheels or bearings igniting the underside of a wood floored car. Fire subsequently burns through the floor and exposes the load. The second is the rail yard fire (Roseville) where a boxcar is exposed to an external fire while the car is stationary in a yard awaiting a train make-up. These two fire related scenarios involve different effects as a function of whether the boxcar is a wood floored or a steel floored car.

4.2.1 Brake Fires

Sparking brake shoes or overheated brakes or wheels are significantly more hazardous with wood floored cars than with steel floored cars. This is because of the combustibility of the flooring material itself and the fact that the underside of the wood floor typically becomes coated with lubricating oil sprayed from the friction type wheel bearings common on older wood floor cars. Once the underside of the flooring is soaked, the hot sparks associated with a heavy application of brakes, or an overheated wheel or bearing resulting from a stuck brake, can ignite the underside of the wood floor. Steel cars typically employ roller bearings which do not produce this oil spray.

As was discussed earlier, rule changes promulgated following the Benson accident required the use of lower sparking types of brake shoes and spark shields to protect the underside of wood floored cars from this exposure. A review of accident records since the promulgation of these rules indicates that no further subfloor fires have occurred in cars so equipped [5].

In the case of steel floored cars the noncombustible nature of the flooring minimizes the hazard from sparking brakes or overheated wheels. For example, data taken by the Southern Railroad shows that the typical radiant flux from a locked brake with cast iron brake shoes is as high as 7 to 10 BTU per square foot second (24 to 34 kw/m^2) (with heavy sparking), and from a composition brake shoe is only 2 BTU per square foot-second (7 kw/m^2) (no-sparking) for a maximum period of 10 minutes before the brake burns out [1]. In the case of steel floored cars this level of radiant flux would be insufficient to cause a fire problem in the load. Thus, the lack of fires subsequent to the rule change in wood floored cars, and the apparent lack of hazard potential due to locked brakes and brakes sparking in steel floored cars, coupled with the current 85 percent steel car shipping rate all indicate that this scenario is no longer a significant problem.

4.2.2 Yard Fires

Railroad and DOD munition transport data indicate that as much as 90 percent of the total transit time of a munitions laden car is spent stationary in rail yards awaiting train make-up [5]. Also, yard fires are relatively common, particularly in certain yards. For example, it was reported that the Roseville, California yard averaged one fire every three days for seven years prior to the accident [1].

Most major U.S. cities contain rail yards, often near high density population areas. Since trains carrying explosives are not specially routed to avoid these yards (such routing would be impractical), the consequence of an accident like Roseville occurring in one of these yards could be catastrophic. The possibility of a large population exposure, coupled with an apparent high incidence of yard fires and long standing time in the yards, make the yard fire the primary scenario of interest.

5. FIRE PROTECTION SYSTEMS

Having identified the exterior exposure fire in the rail yards as the most frequent scenario, the focus was directed at identifying various alternative fire protection systems which would be effective intervention strategies for this scenario, and assessing their feasibility in terms of implementation. Fire protection systems can be divided into two general categories: active systems (including automatic detection, notification, and extinguishment) and passive systems (structural elements which will resist the fire exposure and prevent the development of a hazardous condition in the load for a given period of time).

5.1 Active Systems

An active fire protection system designed for use in a railcar would consist of a number of hardware components. Automatic fire detectors would be required on the interior and/or exterior of the car to provide early detection of an impending hazardous condition. These detectors would need to be connected to a control/notification system by which the train crew, or in the case of a car in a rail yard the yard master, would be notified that a fire condition existed and the system had activated. Also, an "on-board" extinguishing system, actuated by the detection system, would be necessary to prevent fire spread to the interior of the car.

A study was conducted in 1977 by the Naval Civil Engineering Laboratory at Port Hueneme, California in which a heat-actuated alarm system for railroad boxcars carrying explosives was developed [6]. The system consisted of bimetal snap-disk type heat detectors located on the underside of the car above each of the truck assemblies, connected to a control and radio transmitter unit which transmitted an alarm signal to a receiver unit located in the caboose.

Tests conducted as part of this study indicated that the design was feasible in that it would not activate from a heavy application of brakes but would detect an overheated wheel, and could transmit signals reliably to the caboose in the case of long trains or trains running through tunnels. Problems of shock and vibration associated with rail transport could be overcome by proper shock mounting and design of system components. However, a major problem with this approach was that dirt and grime accumulation on the underside of boxcars would necessitate a regular maintenance program of cleaning the sensors.

As part of the DOD project, the Naval Weapons Center at China Lake, California built upon the Port Hueneme system. Smoke detectors were added in the interior of the car to provide a "second line of defense" should the subcar heat detection system fail to operate due to this grime accumulation. Their tests indicated that (for wood floored cars) a subfloor fire created sufficient smoke inside the car to actuate interior smoke detectors before the floor was breached by the fire. In tests run with both ionization and photoelectric type smoke detectors in the car, their test data showed a stronger signal from the photoelectric type due to the character of the smoke produced.

Furthermore, advancements in electronics during the time period between the Port Hueneme tests and the Naval Weapons Center tests resulted in the availability of an improved transmitter unit capable of identifying the specific car and the specific sensor activated.

The Naval Weapons Center work also included the development a prototype suppression system. This system consisted of a 300 gallon (1135 ℓ) pressure tank using several nitrogen cylinders as a pressurizing source. When activated by the detection system, the tank was pressurized and, after pressure stabilization, water was provided to a series of fog nozzles located around the interior of the car and connected to the pressure tank with high pressure flexible hose. In order to maximize the amount of operating time, the system was designed to apply water for 30 seconds and then shut off for 30 seconds and repeat. This would result in an approximate 1-1/2 hour water supply with 200 gallons (757 ℓ) of water in the tank.

Several tests conducted on this system indicated that a significant amount of interior wetting on the floor and walls was achieved. However, a major problem as yet unresolved is that the fire could develop in the open stud space between the exterior metal wall and the interior plywood sheathing. In this location, the fire would be shielded from the water fog and could spread up through the stud space and involve the combustible insulation on the interior of the roof. Currently, it is unknown whether the cooling effect of the water fog would prevent the achievement of critical temperatures and explosions in the load if this roof insulation became involved.

While this active system appears to provide an improvement in fire protection, there are a number of disadvantages, including cost and complexity. Naval Weapons Center estimates for the cost of such a complete active system are over $6,000 per car [1]. This cost is somewhat variable as a function of the number of cars per train since only one receiving system is necessary for each train. Not included in these cost figures would be the cost of installing a receiver system in each yard master's tower in every rail yard through which these trains pass. This would obviously be necessary because of the 90 percent of transit time spent in yards and the frequency of yard fires. The system would also need coordination among the car identification codes so that, if more than one train is in the yard at a given time, the specific car could be identified quickly.

The complexity problem is even more difficult to overcome. This active system involves a large number of individual components, both electrical and mechanical, which must all function reliably. In addition, the system must be portable in nature and capable of rapid and reliable installation and removal by untrained personnel. There are any number of things that can go wrong with such a system including loss of primary power (batteries), improper installation, component failure, and even the failure to properly activate the system, such as a switch or valve being left closed when installed. Also, the portable nature of the system could result in difficulties in securing the equipment adequately within the car. For example, in the case of a derailment, it is possible that the impact would tear loose the heavy suppression equipment and damage both the load and the protection system.

All of these factors have a detrimental effect on the feasibility of such an active system.

5.2 Passive Systems

In contrast to the active systems approach which serves the multiple-purposes of detection, notification, and extinguishment or control; passive fire protection measures serve a single purpose - containment. That is, passive fire protection measures involve structural elements which are designed to withstand the effects of a given fire exposure for a period of time.

The primary advantage of passive systems is simplicity. If properly designed and installed, a passive fire protection system will function until its design limits (fire severity and time) are exceeded. In addition, passive systems require little or no maintenance and have an almost unlimited useful life unless physically damaged.

For the specific case of fire protection of explosives in rail transport, and particularly in the case of the all-steel car, the passive protection approach is an appealing alternative to the more complex active systems. The steel car flooring is noncombustible and will maintain its structural strength when exposed to temperatures exceeding 1000°C. Therefore, the more immediate problem in a fire situation is not structural collapse, but rather that the steel floor is a good conductor of heat. When the floor temperature reaches approximately 400°C, the wooden pallets on which the explosives rest will begin to burn. Once this combustion takes place, the explosives will be heated to their critical temperature quickly and detonation will occur. In addition, even if the ignition temperature of the wood is not reached, heat transfer through the steel by radiation and convection can eventually heat the bombs to their critical temperature anyway. Therefore, the problem associated with exposure fires becomes one of simply maintaining an interior floor temperature at a low enough level so as to both prevent ignition of the wood pallet and overheating of the load.

Since the passive approach appeared to be feasible, less costly, and potentially more reliable than the active approach, and since considerable work on the active system had already been done as part of the DOD project, it was decided that the major effort of this project should be concentrated in the area of the passive protection. Therefore, an experimental program was developed to evaluate the feasibility, and estimate the performance of a passive protection system for the yard fire scenario.

6. EXPERIMENTAL PROGRAM

Three groups of experiments were conducted as a part of the program. They included simulations of (1) reduced scale tests of a wood pallet-mounted bomb in a steel floored car, (2) reduced scale tests of a wood pallet-mounted bomb in a wood floored car, and (3) full-scale tests of a wood pallet-mounted bomb in a steel floored car with and without an insulating, thermal barrier above the floor. Since the DOD project included full-scale tests with wood floored cars, it was decided that it would not be necessary to reproduce these tests. The purpose of these tests was to obtain the necessary data to evaluate the feasibility and performance of a passive thermal barrier in preventing the attainment of critical load temperatures when the railcar is exposed to an external fire and to develop a first approximation computer model to estimate the temperature rise in a typical explosive load as a function of fire size and characteristics of a thermal barrier.

6.1 Reduced-Scale Steel Floor Test

Considerable experience has been attained at NBS and other fire research organizations in recent years in reduced-scale physical testing in order to reduce the cost of collecting performance information by full-scale replication testing. Reduced-scale tests permit the researcher to gather approximate, qualitative information concerning the performance of a structure or configuration so that the number of full-scale tests necessary to fully define the situation can be minimized.

The initial experiments were conducted in a 1/3 scale configuration. For these experiments, the boxcar floor was represented by a 2 foot (61 cm) square, 10 gauge flat steel plate. The bomb was represented by a 12 inch (30 cm) long, 2 inch (5 cm) diameter steel pipe threaded at both ends and fitted with steel end caps. The pipe was rested on two 1-inch (2.5 cm) high pine strips representing the wood pallet. The pipe was filled with sand to represent the explosive (as is normally done in thermal testing of inert munitions) and thermocouples were mounted on the inside and outside of the pipe as well as on the upper surface of the steel floor-plate directly above the fire.

The test assembly was suspended 12 inches (30 cm) above a burner formed of 3/16 inch (0.5 cm) inside diameter stainless steel tubing. This burner was fed from a methane tank through a calibrated flow meter and pressure regulator. Figure 1 shows the test assembly and burner.

The tests were conducted in a laboratory fume hood, which caused a small air flow across the assembly. Air flow measurements with a hot wire anemometer indicated a peak flow of 50 feet per minute (0.25 m/sec). It was felt that this air flow had a minimal affect on the temperatures achieved.

Four tests were run (tests #5-8) at constant heat release rates ranging from 1.8 to 11 kilowatts for the 30-minute test period. During each test, three temperature points were recorded at 30 second intervals by an automatic data acquisition system. The system had an overall accuracy (including conversion to temperature) of plus or minus 3°C.

6.2 Reduced-Scale Wood Floor Test

Discussion of the results of full-scale wood floor car tests conducted at China Lake with Naval Weapons Center personnel revealed several interesting phenomena. Shortly after ignition, dense smoke was observed in the interior of the car, coming from the seams between the wooden floor boards. This smoke production appeared to increase continually until, between 6 and 10 minutes after ignition, small flames broke through at these seams. It was then observed that these flames spread along the seams, eventually reaching the floor/wall junction. Smoke issuing from the seams near the wall appeared to be drawn into the wall "stud space" which acted as a chimney. When the flames at the floor board seams reached the floor/wall junction, the gases contained in the smoke in the stud space were ignited, resulting in flame spread up through the stud space and out the top, impinging on the insulation on the underside of the roof. Since this insulation is combustible, fire involvement of the entire car interior was observed shortly afterward. Examination of the damage after the test indicated that the floor had burned through above the fire and that the plywood sheathing on the interior side of the wall had burned completely through between the two wall studs. The metal exterior car wall showed a clearly defined burn pattern at the affected stud space.

It was desirable to be able to reproduce the above described phenomenon to obtain a relative comparison of the performance of the wood and steel floored cars in the 1/3 scale test arrangement. Two floor/wall sections were constructed of 3 foot (0.9 m) long tongue and grooved oak flooring bolted at both ends to steel angles representing the side rails of the car. Wall studs were formed of 3/4 by 1-1/2 inch (1.9 by 3.8 cm) pine strips with a light gage steel plate forming the exterior wall and 1/4 inch (0.6 cm) plywood forming the interior wall surface. The bottom edge of the plywood interior wall surface was 1/2 inch (1.3 cm) above the floor as is typical in wood floored boxcars.

The 2 inch (3 cm) steel pipe and 3/4 by 1 inch (1.9 by 2.5 cm) wood strips upon which the pipe rested were the same as used in the 1/3 scale steel floor test. The same gas burner was used, and the spacing between the gas burner and the underside of the floor was maintained at 12 inches (30 cm). The rate of heat release used for both of the wood floor tests was 11 kilowatts. Figure 2 shows the reduced scale wood floor test assembly.

In the first wood floor test (test #9) the simulated bomb and burner were located in the center of the floor. For the second wood floor test (test #10) the bomb was located approximately 4 inches (10 cm) from the floor/wall junction. In test #9 the entire burner flame was contained under the floor and in test #10 (due to the proximity to the wall) a portion of the flame curled over the edge and up the outside wall.

The phenomenon observed in the full-scale wood floor tests conducted by Naval Weapons Center was also observed in the reduced scale tests conducted at NBS. That is, dense smoke issued from the floor seams, flame penetration at the seams was observed in about 8 minutes, and (test #10) one of the wall stud spaces became involved shortly after flame appeared through the floor (see figure 3).

6.3 Full-Scale Steel Floor Tests

Eight experiments were conducted in the full-scale steel floor tests, five without an insulating barrier and three with a barrier. Two 64 by 40 inch (163 by 102 cm) test specimens of nailable steel boxcar flooring were obtained from a manufacturer. These floor sections were rested on concrete blocks 3 feet (1 m) above the test burner. No attempt was made to simulate walls or the enclosed volume of a railcar. The burner used for the full-scale tests was a 12 inch (0.3 m) square diffusion type burner connected to bottled methane through calibrated flow meters and pressure regulators. A MK-82 500 pound (227 Kg) practice bomb was obtained from the U.S. Ammunition Plant at Rock Island, IL. The bomb was mounted on two 4 by 4 inch (10 by 10 cm) wood blocks and was filled with sand and instrumented in the same manner as in the 1/3 scale test. Heat release rates ranging from 16.5 to 500 kilowatts were used for the full-scale uninsulated test and heat release rates of 66, 99, and 500 kilowatts were used for the insulated tests. Figure 4 shows the full-scale steel floor test assembly.

One instrumentation change was made for the insulated tests. Since the temperature differential between the outside and inside surface of the bomb was negligible during all of the uninsulated tests, and since it was necessary to know the upper surface temperature of the insulating barrier, the thermocouple which had been located on the exterior of the bomb was moved to the upper surface of the insulator. It should also be noted that, in the full-scale test, all tests except for the 500 kilowatt heat release rates were run for 30 minutes. In the case of the 500 kilowatt heat release rate, two full methane tanks were sufficient only for about 17 minutes. Therefore, the total test time for the 500 kilowatt experiments was 15 minutes.

7. HAZARD CRITERION

In order to evaluate the success or failure of the protection scheme, some indicator of a hazardous condition must be established; in this case a thermal initiation temperature for the explosive. Reference [7] discusses, both through theoretical calculations and experimental results, the chemical reactions which occur for various explosives when heated under known conditions of confinement. Table 1 of this paper gives experimental values for temperatures at which runaway reactions occurred in five common explosive materials. These temperatures range from 189°C (462°K) for PETN to 288°C (561°K) for TNT. On this basis, it was decided to use a value of 180°C (453°K) as the critical temperature beyond which an explosion may result.

8. DISCUSSION OF RESULTS

8.1 Reduced-Scale Steel Floor Tests

The purpose of the reduced-scale steel floor tests was to obtain a qualitative, preliminary estimate of the range of temperatures which would likely be encountered under full-scale conditions as a function of fire size, so that the number of more-expensive full-scale tests could be minimized. It was also hoped that a scaling relationship could be developed which would allow a direct comparison of small to full-scale results.

By applying a scaling relationship equal to the dimensional scale factor squared (an approximation usually used when radiation predominates as in this case), the reduced-scale tests indicated that heat release rates below $\sim$ 15 kw posed little hazard and that steady-state floor temperatures increased the most rapidly between 15 kw and 70 kw (see figure 5). On this basis, test values for heat release rate of 16.5, 33, 66, 99, and 500 kw were selected for the full-scale tests.

When the full-scale data had been obtained and the results compared to the reduced-scale using the same scaling relationship, satisfactory agreement was not found. The temperatures in the full-scale tests were lower than would be expected from the reduced-scale data. The most probable reason for this is that the area and mass of the 2-foot square floor plate was too small, resulting in much less conduction loss to the edges than in the full-scale. In addition, differences in flame height and the complex geometrical nature of the nailable steel flooring as compared to a flat plate were also probable factors in the lack of correlation.

8.2 Reduced-Scale Wood Floor Tests

The two reduced-scale wood floor tests were conducted to attempt to reproduce the fire spread phenomena observed in the Naval Weapons Center full-scale wood floor tests and to demonstrate the differences in fire performance between rail cars with wood floors and with steel floors.

Figures 6 and 7 show the floor and simulated bomb temperatures for 1/3 scale tests at 11 kw for steel and wood floors respectively. With a steel floor, the floor temperature increases rapidly, reaching a high steady-state value in about 6 minutes. With a wood floor, however, the upper surface temperature increased at a slow, almost linear rate until flame penetration occurred at about 15 minutes. At this point the temperature increased rapidly to a value nearly double that of the steel floor steady-state value.

The simulated bomb temperatures for the two flooring types were also quite different. With the steel floor the bomb temperature increased steadily, reaching 160°C at 30 minutes. In the wood floored car the bomb temperature remained almost at ambient until flame penetration of the floor assembly; then rapidly rose rising to the critical temperature (180°C) [7] in less than 3 minutes.

The results of these wood floor tests demonstrate that wood is a good thermal insulator in a fire; but that its combustibility leads to early failure, particularly at the floor board seams where the fire penetrates first. This leads to the observation that a floor made of a thermally insulating noncombustible material which prevents fire penetration might be effective in delaying achievement of a hazardous temperature long enough for the fire to be discovered or extinguished.

8.3 Full-Scale Steel Floor Tests

As was discussed in section 4.2, when a steel floored railcar is exposed to a subcar fire, it is principally the heat transferred through the floor that raises the temperature to a critical value. If a thermal barrier is placed over the floor to inhibit temperature rise of the top surface, this critical temperature could be either prevented or delayed for a long enough time to allow discovery and extinguishment of the fire.

Figure 8 illustrates a comparison of predicted (by the model discussed in section 9) and measured floor temperatures at 30 minutes as a function of fire size (filled-in symbols indicate measured values). For the 500 kw fire the bare steel floor reached a temperature of 625°C (circle). Placing a 1 inch (25 mm) thick sheet of calcium silicate board over the steel floor resulted in an increase in the steel temperature to 725°C (square), but the top surface of the insulating board was much cooler, measuring only 94°C at 17 minutes (end of the test). The extrapolated temperature at 30 minutes is 137°C (open triangle).

Calcium silicate board was selected because it has excellent insulating properties. The material comes in 4' x 8' (1.2 x 2.5 m) sheets and appears similar to gypsum wallboard without a paper cover. It is available in various thicknesses from 1/2" (1.2 cm) to 2" (5 cm). In addition, at 900 psi, its compressive strength should be sufficient to withstand railcar loading and unloading operations. It may be necessary however to provide metal cladding to protect the surfaces from impact damage. The same process used to produce metal clad gypsum board might be used in this case.

9. DEVELOPMENT OF COMPUTER MODEL

Since the cost of full-scale tests to evaluate various thermal barrier materials of different thicknesses would be prohibitively high, a computer model of a steel floor railcar exposed to a subfloor fire was developed to estimate the necessary parameters. The model calculations can be run with or without a thermal barrier of any desired thermal conductivity or thickness, and will compute steel floor temperature, thermal barrier top surface temperature (if included), and bomb temperature vs time for any fire size (heat release rate).

9.1 Model Assumptions

The model employs a one-dimensional (lumped) thermal network analysis, which is the simplest and most conservative approach. The bare steel flooring was treated as a mass of metal at uniform temperature, losing heat from the bottom by radiation and from the top by radiation and convection (assumed values: heat capacity (C_P) = 0.46 J/g-s; mass (m) = 173.8 Kg; heat transfer coefficient (h_c) = 0.0016 J/s-cm^2-°C). No attempt was made to model the increase in ambient temperature within the enclosed volume of the boxcar.

A fire burning below a finite horizontal surface will transfer part of its energy to the surface and part will flow around the surface edges, and be lost to the atmosphere. The fraction absorbed by the surface will also change with time as a function of the difference between the flame temperature and the surface temperature, the emissivities of the flame and surface, convective flow patterns under the surface, and others. Without direct flux measurements under the surface, estimates of the fraction of heat absorbed by the surface must be made in order to calculate the temperature rise in the system. Since sufficient data was not available to estimate the changes in this fraction with time, only a single-point estimate could be made at steady-state conditions.

The unprotected floor temperature data obtained in the full-scale experimental portion of the study were used to estimate the fraction of heat released by the fire which was transferred to the floor at steady-state. Table 1 shows these estimates for the five fire sizes tested along with the measured and predicted floor temperatures at the end of the test using these estimates. It is expected that the fraction of heat transferred to the floor would decrease with increasing fire size (due to increasing steel floor temperatures) as was observed. The value (0.60) for the 33 kw fire appears low, being bracketed by values of 0.79 and 0.75, but the reason for the low value is not apparent. For consistency (and to remain conservative) a fraction of 0.75 was used in the model for the 33 kw case even though this results in a predicted temperature 30° C higher than measured.

Table 1

Heat Release Rate from Fire (kw)	Estimated Heat Transfer Rate to Flooring (kw)	Fraction	Temperatures Measured (°C)	Temperatures Predicted
16.5	13.0	0.79	127	126*
33.0	19.7	0.60	166	167*
66.0	50.0	0.75	290	292*
99.0	75.0	0.75	360	359*
500.0	276.0	0.55	625	628**

* Temperature at 30 minutes
** Temperature at 15 minutes

For the insulated case, the same fractions of heat transferred to the steel floor were used. This is conservative since the higher steel temperatures which occur with the thermal barrier in place would result in an overall smaller fraction of transferred heat.

For the insulated case, a one dimensional thermal network analysis was again used. It was assumed that there is heat loss from the bottom of the steel by radiation, conduction from the steel to the thermal barrier, and loss by convection and radiation from the top of the barrier layer. The properties of the calcium silicate board were taken from the manufacturer's data.

In both the uninsulated and insulated cases, the bomb was treated as a 300 lb (136 kg) steel cylinder 11.2 in (28.4 cm) diameter by 61 in (154.9 cm) long. Heat is gained in the bomb by convection and radiation from the bottom and lost by radiation from the top.

9.2 Model Predictions

Figure 9 shows a comparison between predicted and measured temperatures for the 500 kw fire without a thermal barrier. The predicted steel temperatures are slightly lower initially, then higher, and then converge as steady-state values are reached. These differences are most likely due to the single-point estimate of the fraction of heat transferred to the steel. Likewise the predicted bomb temperature is somewhat low initially, becoming slightly higher than measured at the end of the test.

Figure 10 shows the comparison between predicted and measured temperatures for the 500 kw fire with the 1 inch (2.5 cm) thick calcium silicate board. As was discussed previously, the predicted steel temperature is significantly higher than measured. The predicted thermal barrier temperature is much closer to measured (but still slightly conservative at later times) and the predicted bomb temperature is within $\sim$ 2°C of measured values. If the predictions are extended for longer times for this 500 kw case, at 2 hours the predicted bomb temperature is approximately 84°C and in 10 hours it still remains below 100°C.

It would be useful to determine the time to reach steady-state temperatures on the top surface of the thermal barrier. Figure 11 shows predicted top surface temperature as a function of heat release rate at 30, 60, and 120 minutes. From this it can be seen that 60 minutes is adequate time to reach steady-state for all but the lowest fire sizes, and here it would appear to be a satisfactory approximation. Thus, if steady-state conditions were desired in a full-scale test, it would have to be run for at least 1 hour.

9.3 Model Limitations

As discussed above, this first approximation model provides conservative results. While it shows that a thermal barrier approach is feasible, more data are needed to allow the replacement of several estimated parameters with measured values. Also, the model must be tested against more than one barrier material and thickness before acceptable confidence in the predictions can be obtained, providing a more generalized tool. However, the model is useful, not only because it shows the feasibility of the approach, but also because it provides an indication of the range of temperatures encountered and the time necessary for the system components to reach steady-state (limiting) values.

10. CONCLUSIONS

The results of the experiments conducted indicate that, for the case of a steel-floored boxcar exposed to a subcar fire, a thermal barrier such as 1 inch thick calcium silicate board will be effective in preventing overheating and subsequent detonation of an explosive load for more than 1 hour at subcar fire rates of heat release up to 1000 kilowatts. This passive thermal barrier approach has a number of advantages over an active system including simplicity, greater reliability, and lower cost. In addition, since explosive laden boxcars are almost always weight limited in the amount of load shipped, every pound of material added for fire protection results in one less pound of load which can be shipped. The weight of a complete 1 inch layer of calcium silicate board in a 50 foot (15.2 m) boxcar is under 1,800 pounds (818 kg), exclusive of any metal cladding or decking used to mechanically protect the insulator. While a total weight of the detection/suppression system designed by Naval Weapons Center is not available, the weight of 300 gallons (1136 ℓ) of water alone would be 2400 pounds (1091 kg), which is more than the weight of the insulating barrier. Thus, the weight penalty for the passive approach would be less than for the active approach.

The primary disadvantages of the passive system are that 1) it does nothing about extinguishing or controlling the fire, and 2) it does not incorporate a notification system. This is not felt to be a significant detriment in light of the primary hazard scenario of the yard fire. It is difficult to think of a situation where a large yard fire could occur without fairly rapid discovery. If a maximum expected severity for a yard fire can be estimated and the amount of insulation provided is designed accordingly, sufficient time should be available for both discovery and extinguishment of the fire prior to the approach of critical conditions within the car. By design, the thermal barrier can maintain temperatures below selected critical values for any time period desired.

11. RECOMMENDED FURTHER WORK

The feasibility of a thermal barrier approach to the protection of a heat sensitive load from an exposure fire has been demonstrated. There is, however, insufficient data to build a mathematical model which would allow accurate prediction of the performance of other insulating materials or different thicknesses of the insulating material tested with any degree of confidence. Also, the model currently assumes the load consists of MK-82 bombs. However, this type of protection could also be applied to any thermally sensitive load in any type of container or configuration with additional modifications to the model. Such modifications should be made, so that the model can handle other explosive loads such as shells or bulk explosives.

It is proposed that additional tests be carried out in full-scale using different thicknesses of calcium silicate board and various thicknesses of other types of insulators as well as to increase the numbers and types of measurements taken (for example flux measurements under the car) which would allow the development of a mathematical model capable of accurate prediction of the performance of these insulating materials for bombs and other thermally sensitive load configurations. The tests would provide the data necessary to improve the accuracy of the existing model and its verification. Ideally the proposed model would allow the designer to select any critical load temperature and configuration (horizontal cylinder, vertical cylinder, metal drum, etc.) and compute the time to reach hazardous conditions as a function of fire size and characteristics of the insulating barrier.

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Figure 1. Photograph of reduced-scale steel floor test assembly and burner

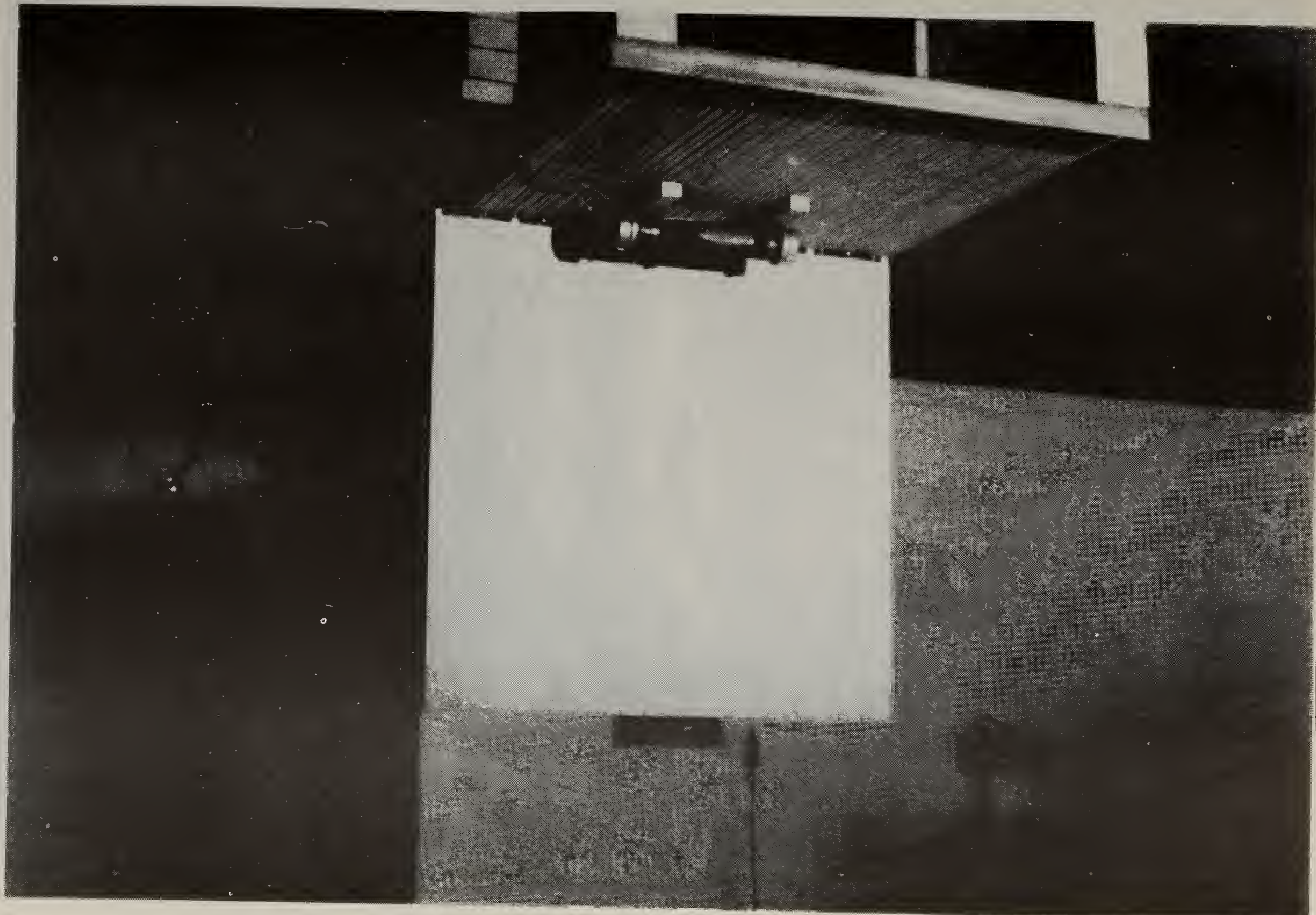

Figure 2. Photograph of reduced-scale wood floor test assembly and burner

Figure 3. Photograph showing boxcar wall involvement several minutes after flame penetration of floor

Figure 4. Photograph of full-scale steel floor test assembly and burner

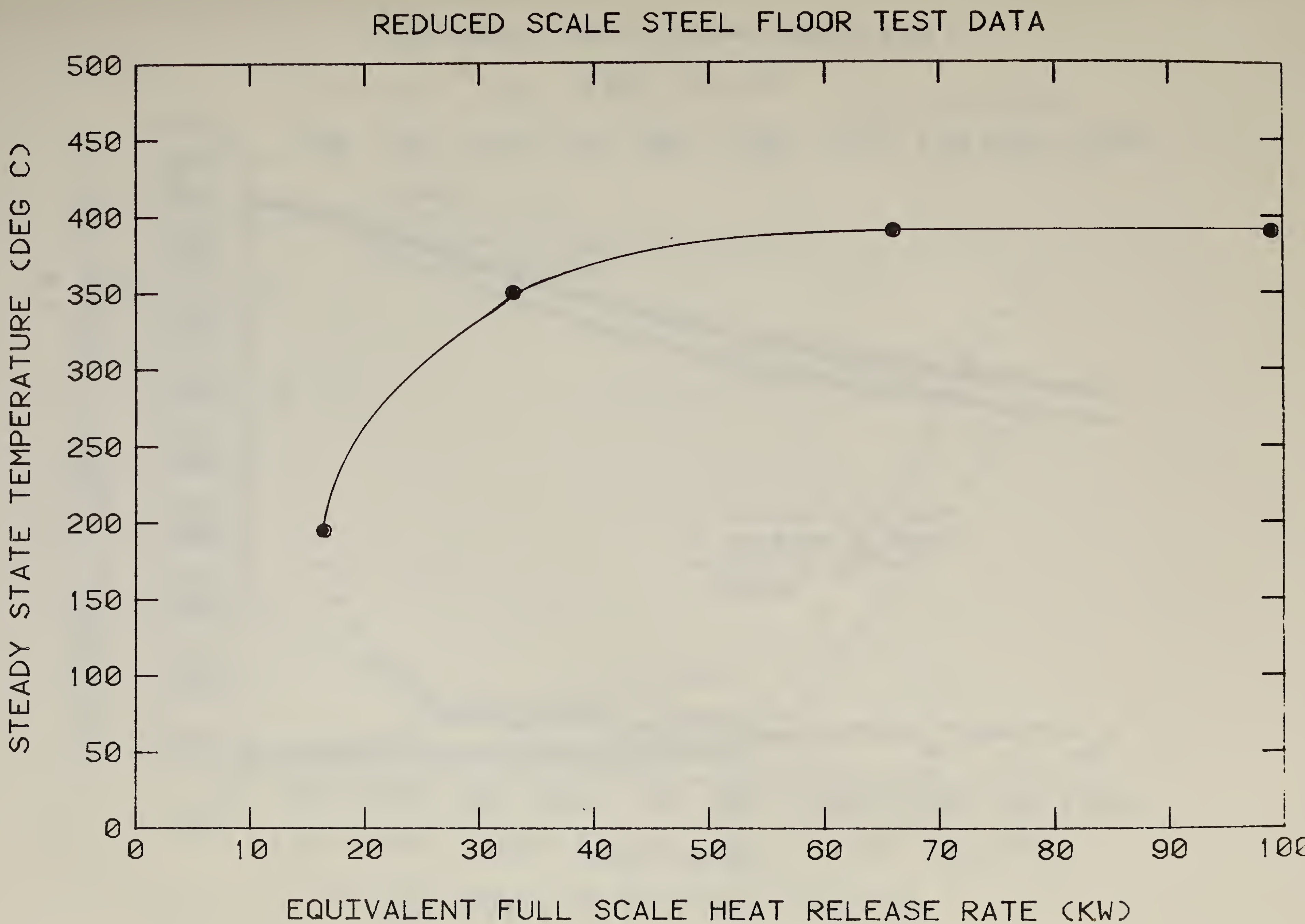

Figure 5. Summary of data from reduced-scale steel floor tests

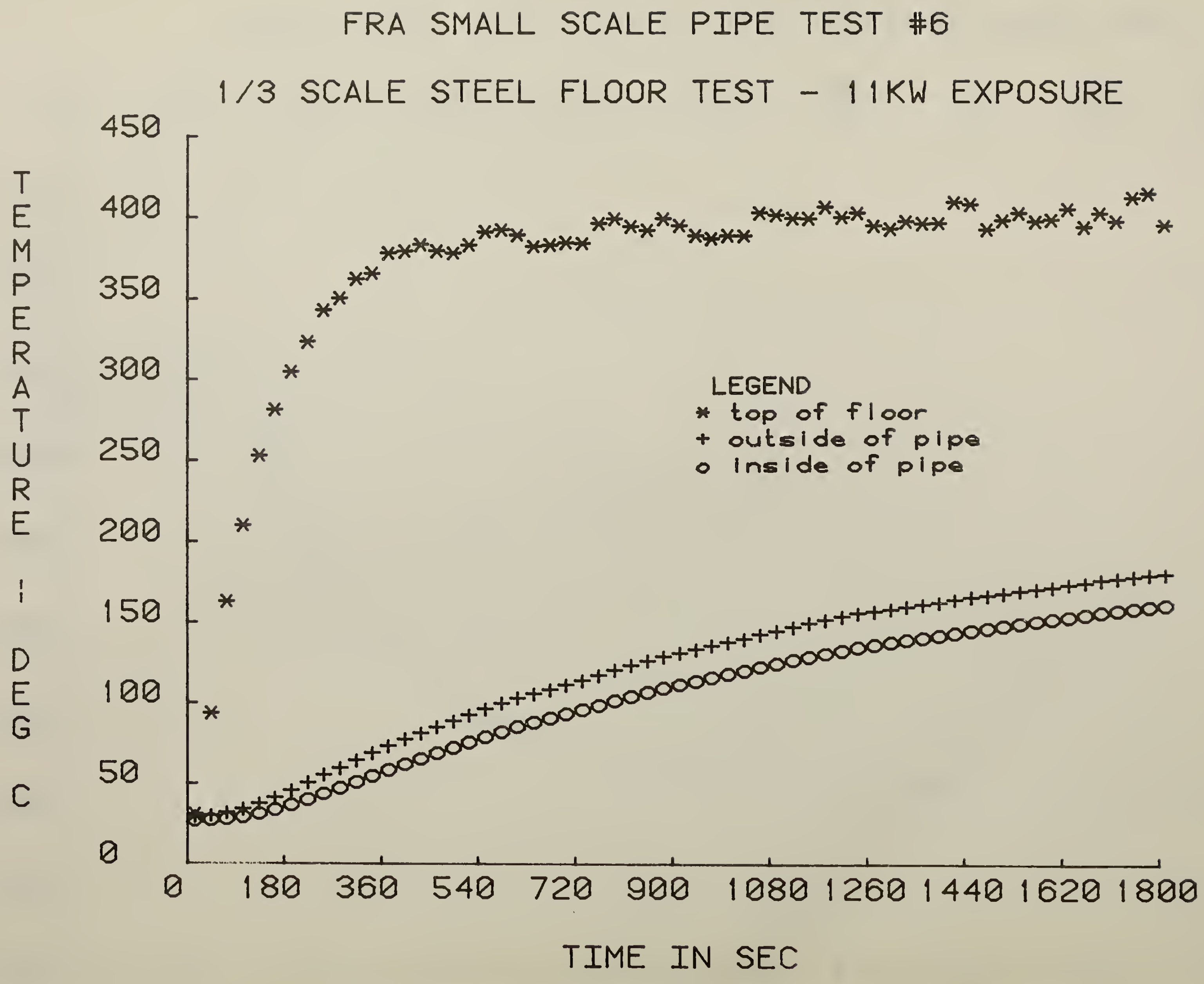

Figure 6. Test results for reduced-scale steel floor test no. 6

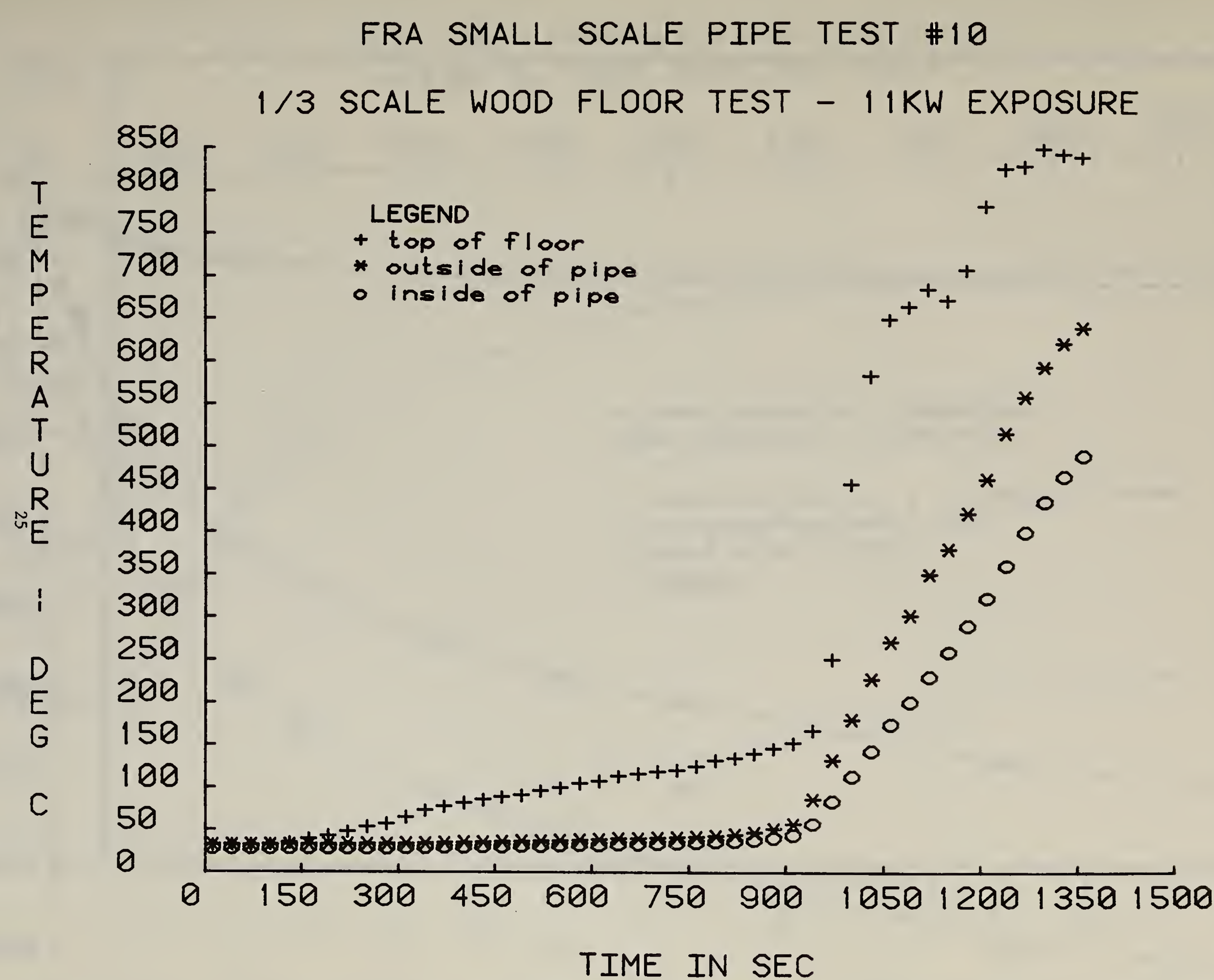

Figure 7. Test results for reduced-scale wood floor test no. 10

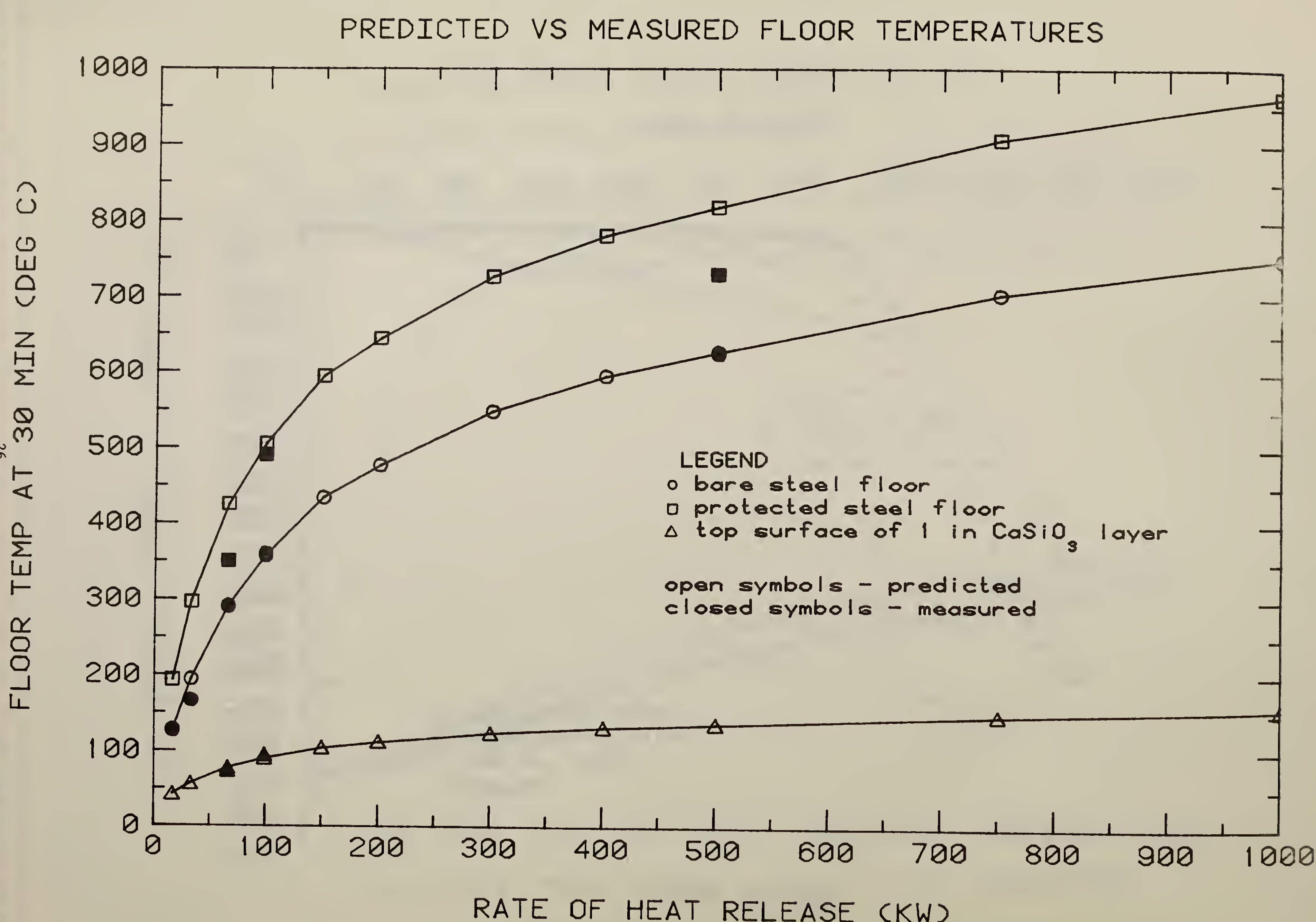

Figure 8. Predicted vs measured temperatures at 30 minutes - full-scale tests

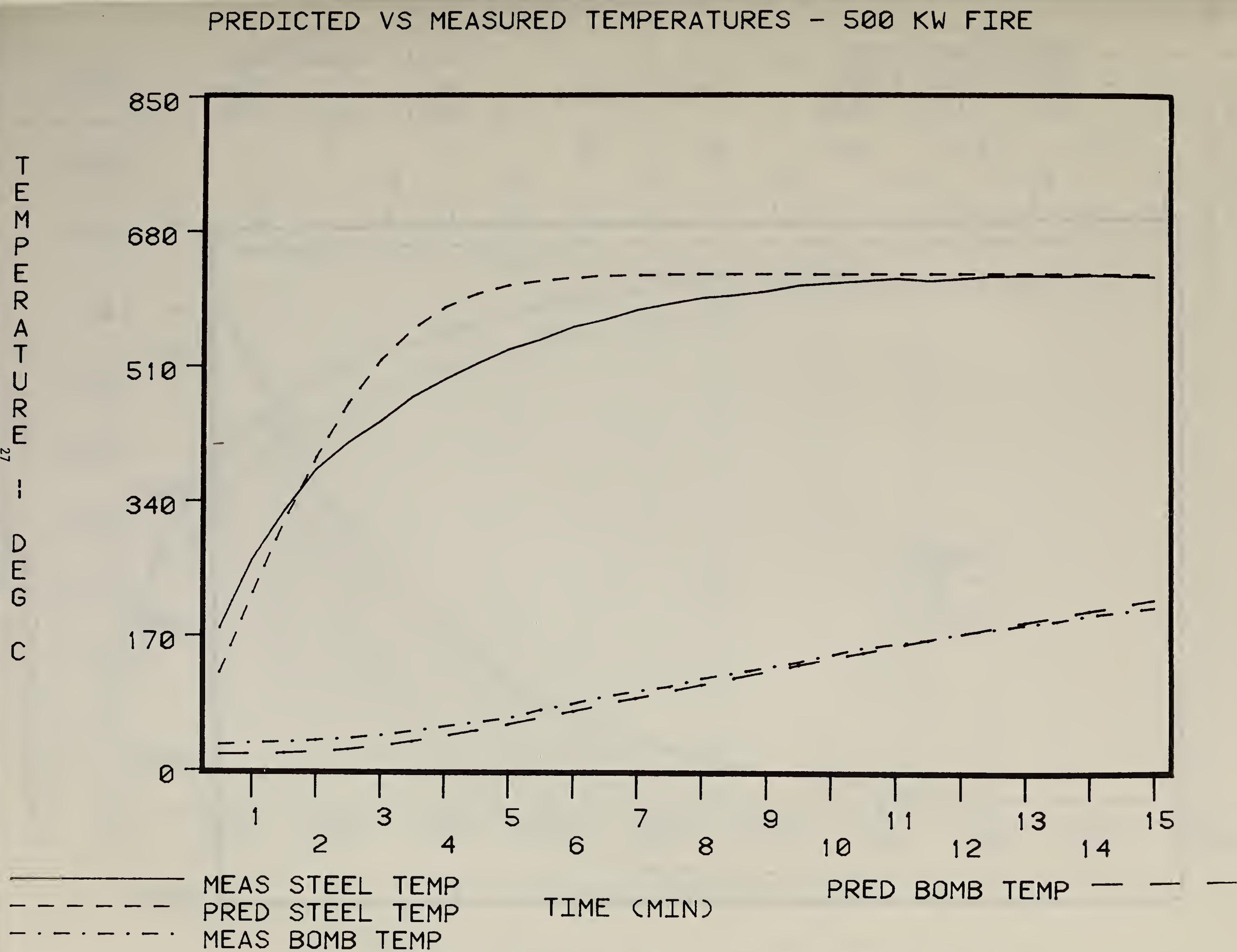

Figure 9. Predicted vs measured temperatures - 500 KW fire without insulating barrier

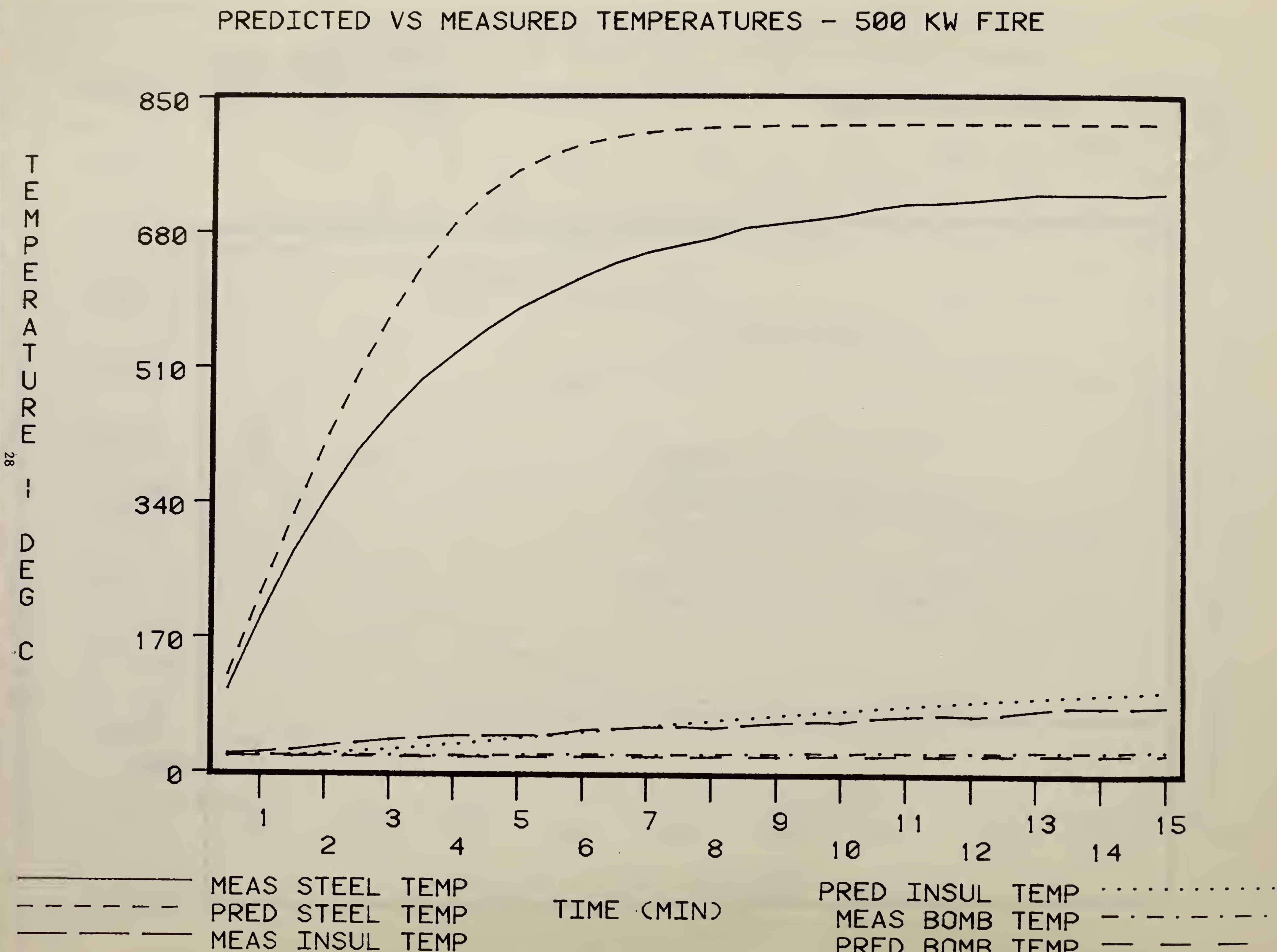

Figure 10. Predicted vs measured temperatures - 500 KW fire with 1 inch calcium silicate board as a thermal barrier

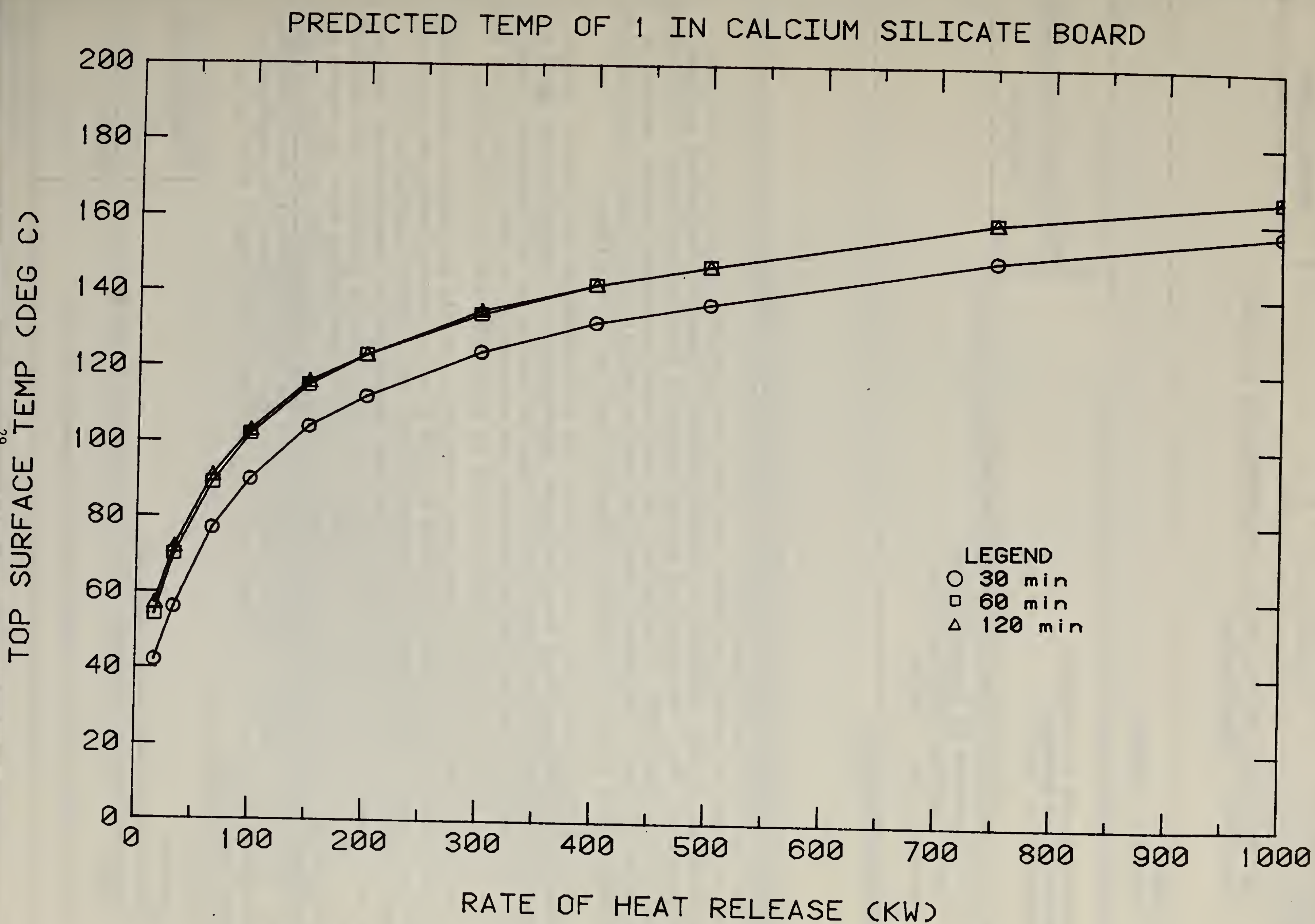

Figure 11. Predicted top surface temperature of 1 inch calcium silicate board at 30, 60, and 120 minutes as a function of fire size

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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)*

As a result of several accidents involving fire induced detonation of military explosives during rail shipment, a research project, funded by the Federal Railroad Administration (FRA), was initiated at the Center for Fire Research (CFR) at the National Bureau of Standards (NBS). This project was initiated to evaluate various methods of protection of Class A explosives from fire, and to identify one or more cost-effective approaches which could be explored in greater detail in later studies.

Active systems (detection, notification, and extinguishment) and passive systems (thermal insulating barriers) were evaluated regarding cost, feasibility and level of protection provided for the major hazard scenarios involved in rail shipment of explosives. The passive, thermal barrier approach was selected as the most reliable and less costly of the options studied while providing an acceptable level of protection.

Small-scale and full-scale tests were conducted to obtain performance data on one specific thermal barrier material. Based on this data, a computer model was developed which can predict temperatures of the boxcar floor, top surface temperature of a thermal barrier, and casing/explosive interface temperature of a wood-pallet mounted bomb for a range of fire sizes. The model predictions compare favorably with measured results from a limited number of experiments. Further experimental data are needed to refine the model and establish an acceptable confidence level in the predicted values. The proposed work necessary to provide this refinement and verification is described.

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

Bombs (ordnance); boxcars; computer models; fire detection systems; fire suppression; full-scale fire tests; heat transfer; railroad accidents; small-scale fire tests; thermal protection.

13. AVAILABILITY

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