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Post-Flashover Fires in Simulated Shipboard Compartments: Phase II-Cooling of Fire Compartment Boundaries

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13. ABSTRACT *(Maximum 200 words)*

A series of fire tests was conducted in simulated shipboard compartments to evaluate the effectiveness of various compartment cooling techniques in preventing the spread of fire both horizontally and vertically. The compartments were steel cubes, 2.4 x 2.4 x 2.4 m (8 x 8 x 8 ft), arranged such that the fire compartment was in the center with two cubes on either side and one compartment was directly overhead. All compartments were instrumented with thermocouples and heat flux transducers. The fire threat was a 2 gpm JP-5 fuel spray fire to simulate instant flashover of the fire compartment. Both manual and installed water spray nozzles were evaluated for cooling efficiency.

An application rate of 2.04 lpm (0.05 gpm/ft^2) was found to be the minimum required to cool both horizontal and vertical compartment boundaries to 100°C (212°F). Although cooling of horizontal boundaries was not affected by application technique, cooling of vertical boundaries was highly dependent on technique. Maximum cooling of vertical boundaries was achieved by applying water tangentially to the boundary surface in sheets or large droplets with nozzles that produce a fan shaped water spray pattern. Maximum cooling was achieved when the nozzle was oriented to provide complete coverage of the bulkhead by the water spray pattern, and the water droplets remained on the heated surface for a sufficient time to absorb the heat. Full cone nozzles spraying perpendicular to the heated surface provided some cooling for medium size droplets at higher application rates, while fine atomizing nozzles did very little to reduce the bulkhead surface temperature.

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POST-FLASHOVER FIRES IN SIMULATED SHIPBOARD COMPARTMENTS: PHASE II — COOLING OF FIRE COMPARTMENT BOUNDARIES

1.0 BACKGROUND

The Internal Ship Conflagration Control (ISCC) program was initiated to address issues raised by the missile-induced fire on the USS STARK. The overall objectives of the program are to develop guidance to the Fleet on the control of horizontal and vertical fire spread and to develop concepts and criteria for new ship design. The program includes small scale fire tests in a simulated shipboard compartment and large scale tests in full scale compartments aboard the Navy's fire test ship, the ex-USS SHADWELL, in Mobile, AL.

As part of the ISCC program, an analysis was conducted to characterize the conditions occurring during post-flashover compartment fires in a simulated shipboard compartment [1]. In this test series, the thermal conditions occuring in the fire compartment were quantified, and the likelihood and estimates of fire spread rates were determined. In the present study, optimum water cooling quantities (flow rates) for containing post-flashover compartment fires were determined, and manual cooling techniques were developed for preventing vertical and horizontal fire spread.

2.0 INTRODUCTION

According to the current shipboard firefighting procedures, the first crewman to arrive on the scene must decide whether to attack the fire or begin containment procedures. If the fire is still small, then an attack on the fire would be appropriate. If, however, the fire is large, as in the case of a missile-induced fire or a fire fed by a pressurized fuel source, then initial actions should be taken towards isolation and containment of the fire. After the fire has been contained and additional personnel become available, firefighting and containment can then proceed together.

Containment procedures require that boundaries be established around the periphery of the fire including both above and below the fire compartment. It is very important that these boundaries be established as quickly as possible. An analysis conducted in the post-flashover characterization test series [1] showed that fire may spread both horizontally and vertically within five minutes of flashover. Since fire tends to spread faster vertically than horizontally, emphasis should also be placed on establishing the boundary above the fire compartment. Typical procedures employed to establish these boundaries include cooling of bulkheads and decks, cooling of ordnance, and wetting of combustibles to prevent ignition.

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Chapter 555, Section V, of the Naval Ships Technical Manual on fire fighting [2] suggests that when cooling bulkheads or extinguishing interior fires, short water bursts are preferred over flowing water continuously. The practice of using continual water flow produces large amounts of steam, reduces visibility, and creates potential flooding and stability problems. If this excess water is not removed from the ship by either cutting holes in decks and bulkheads or by the use of portable dewatering equipment, the ship may develop a list. In many cases, depending on the sea state, a severe list can be more threatening to the ship than the fire itself.

This water efficiency test series served as an initial investigation into optimum water cooling quantities (flow rates) and techniques for preventing vertical and horizontal fire spread. These initial quantities and techniques will be further refined in full scale fire tests on the Navy's Fire Research and Test Ship, the ex-SHADWELL.

3.0 OBJECTIVES

The objectives of this test series were to develop techniques and procedures so that water may be used efficiently to cool bulkheads and decks to establish fire boundaries in order to prevent vertical and horizontal fire spread, while minimizing the hazards of flooding.

4.0 APPROACH

These cooling tests were conducted in the intermediate scale shipboard compartment mock-up developed for the post-flashover characterization test series [1]. The tests were conducted at the Naval Research Laboratory's (NRL) Chesapeake Bay Detachment (CBD) fire test facility. The mock-up was designed to withstand multiple high intensity fires while still approximating the thermal characteristics (i.e., heat transfer characteristics) of a typical shipboard compartment. Application rates and techniques were evaluated against the "design fire" used in the post-flashover characterization test series. The "design fire" was developed to approximate the thermal insult resulting from a nearly instantaneous, post-flashover compartment fire. Such a fire might result from a missile strike in which the warhead fails to detonate, but burning missile propellant is strewn about the compartment. Air temperatures of over 1000°C (1832°F) were measured in the fire compartment during the design fire as shown in Fig. 1. Bulkhead and deck surface temperatures were observed to approach 800°C (1472°F) as shown in Figs. 2a and 2b. By using the design fire as the test fire in this evaluation, the application rates and boundary cooling techniques were evaluated against worst case bulkhead/deck thermal conditions.

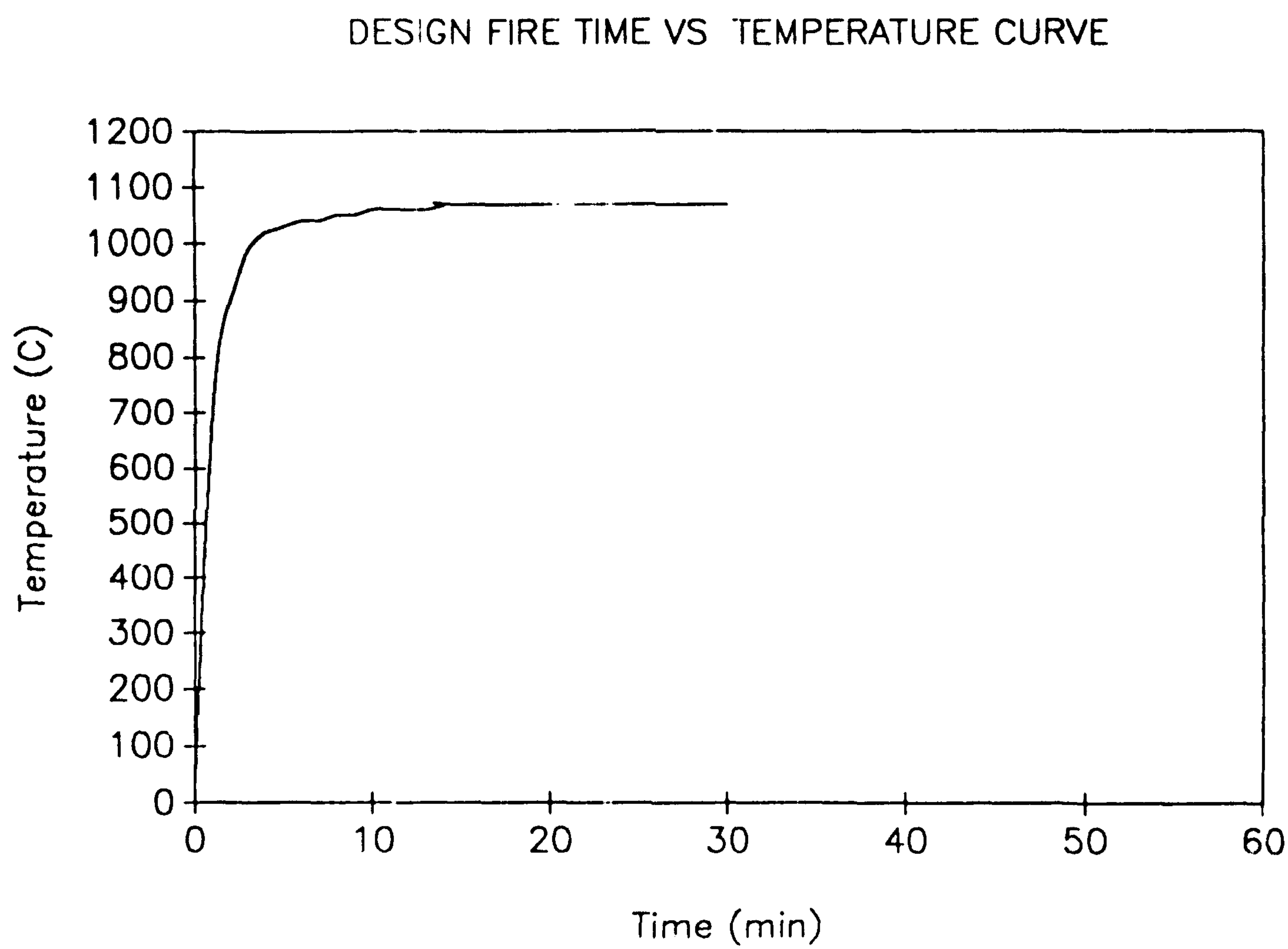


Fig. 1 - Fire compartment air temperatures (design fire)

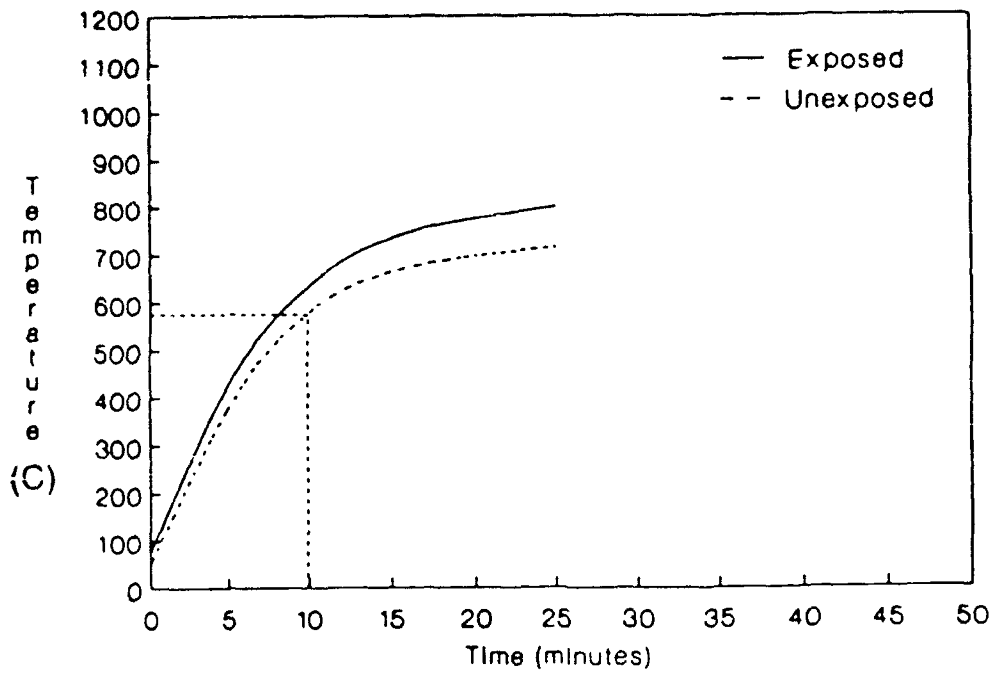


Fig. 2a - Upper compartment average deck temperatures

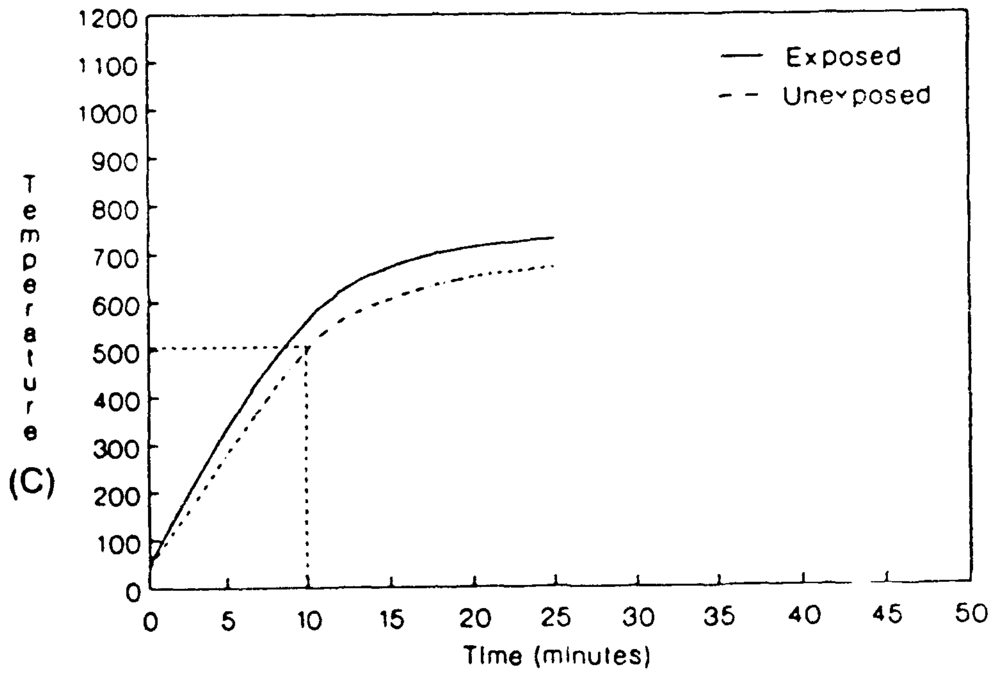


Fig. 2b - Adjacent compartment average bulkhead temperatures

The systematic approach incorporated in the development of optimum water cooling techniques was as follows:

* A series of preliminary tests designed to answer specific questions pertaining to boundary cooling were conducted to serve as a baseline in the latter test series.

* The minimum application rate for cooling the ideal case (flat, level, horizontal decks) was determined.

* Incorporating the above application rate, the spray configurations required to produce maximum cooling of vertical bulkheads with minimum water flow were developed.

* Using the above knowledge, the techniques for cooling decks and bulkheads using standard Navy hardware were then determined.

5.0 GENERAL TEST DESCRIPTION

5.1 Mock-Up

The full size mock-up constructed at CBD for the post-flashover characterization test series [1] was used in this evaluation. The mock-up consisted of four 2.4 x 2.4 x 2.4 m (8 x 8 x 8 ft) cubical enclosures, three cubes long and two cubes high in the center as shown in Figs. 3 and 4. The mock-up was constructed of 0.95 cm (3/8 in.) thick steel plates. Stiffeners having "T" shape cross sections were welded vertically to the center of each wall in all compartments. The outside lower compartments each contained two 66 x 167.6 cm (26 x 66 in.) openings, one to the outside air and one to the center compartment. The upper compartment contained one door opening to the outside air and one (0.61 m (2 ft) diameter) hatch opening in the overhead. The center compartment contained four doors, one to each of the adjacent compartments and two to the outside air.

5.2 Fuel System

The fueling system and nozzle assembly are shown in Figs. 5 and 6. This system was used to achieve post-flashover fire conditions in the fire compartment as quickly as possible. The fueling control station was located 6.1 m (20 ft) behind the fire compartment. Quick operating quarter-turn valves were installed for manual shutdown of the system. A nitrogen system was installed to pressurize the fuel storage tank and to flush out the fuel system after each test. The fueling station was manned at all times during testing.

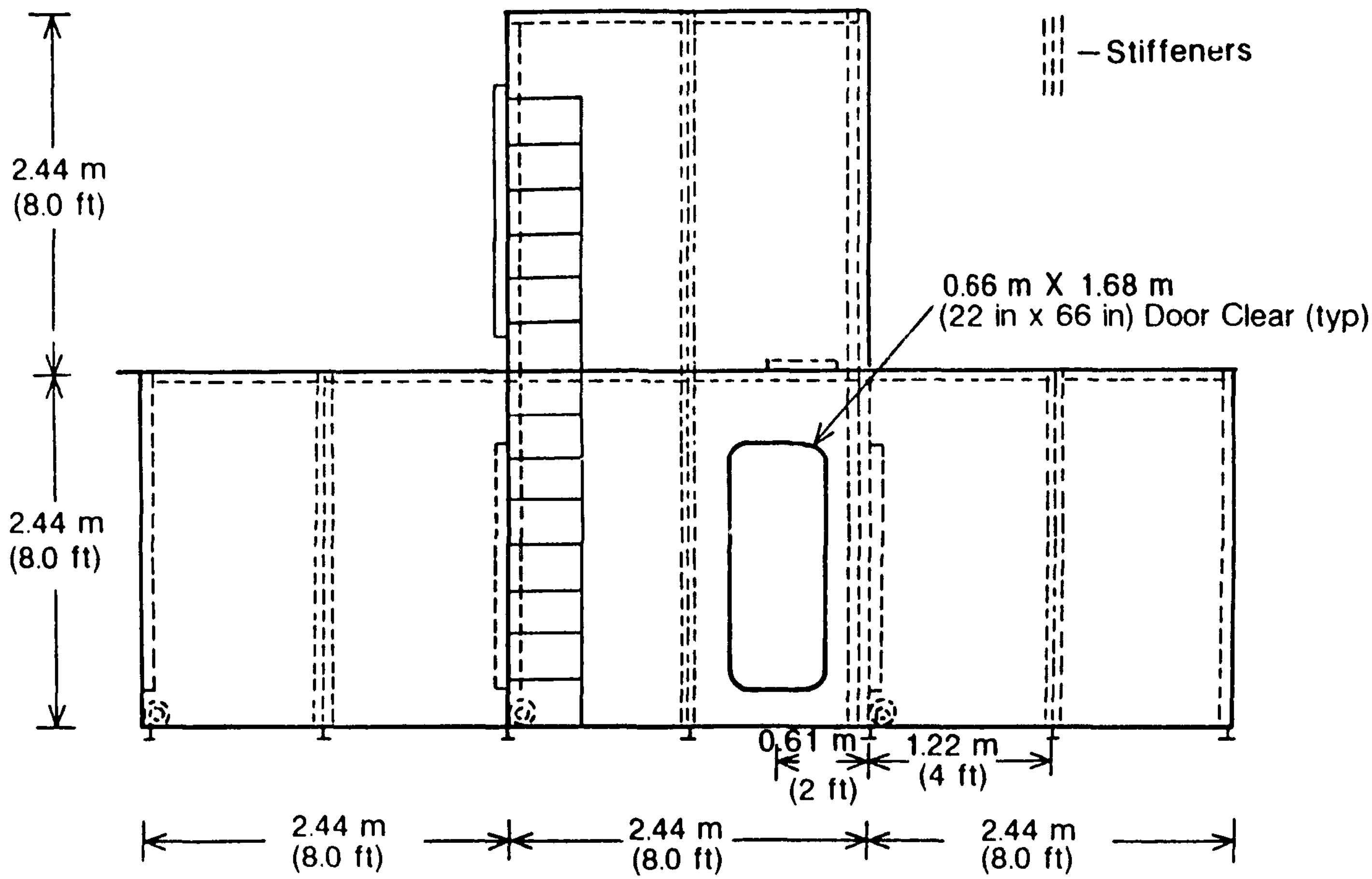


Fig. 3 - Ship compartment mock-up (elevation view)

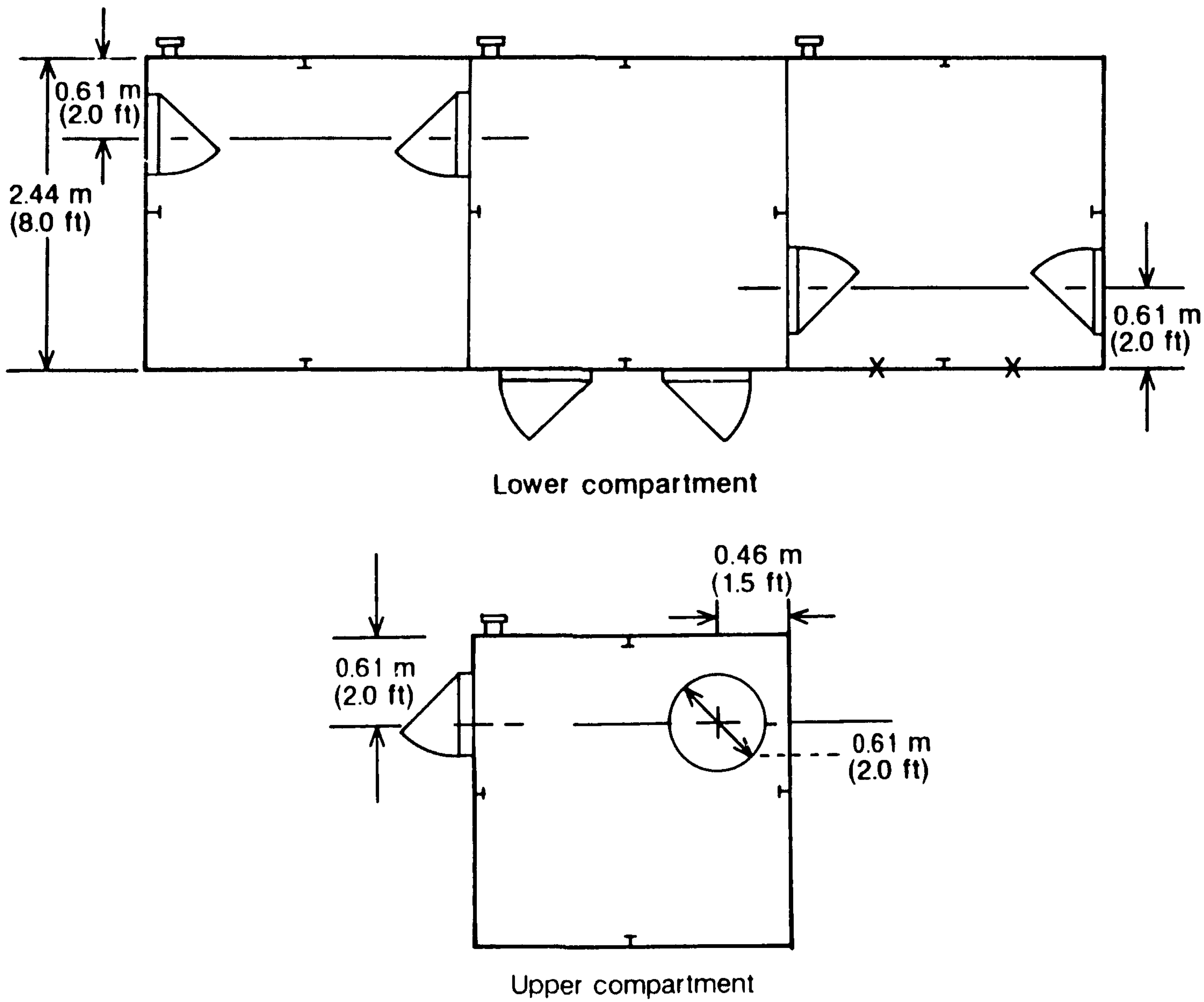


Fig. 4 - Ship compartment mock-up (plan view)

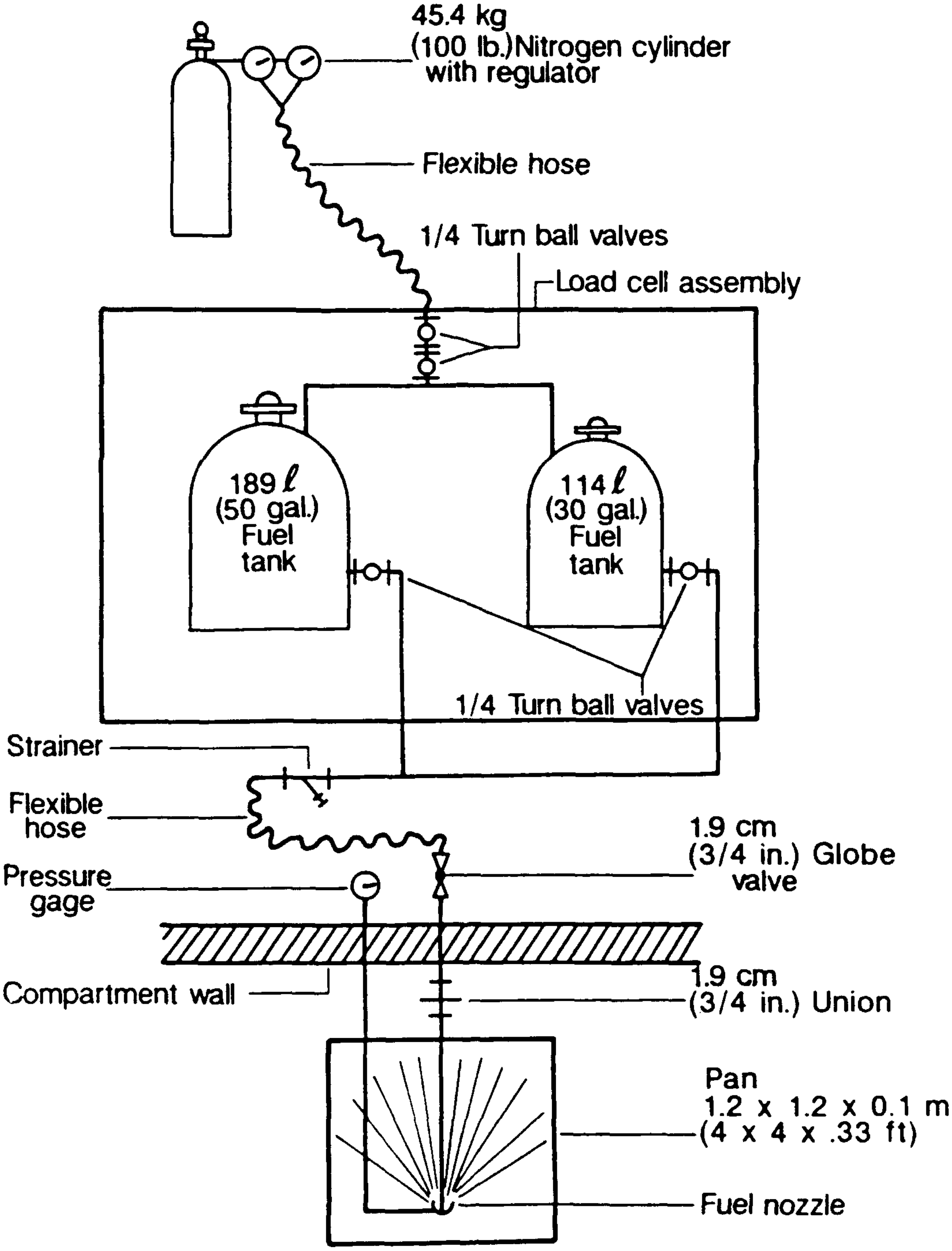
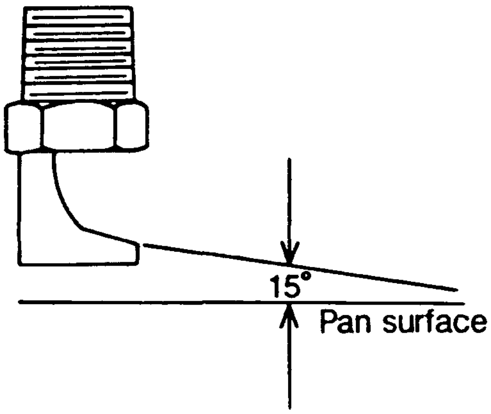
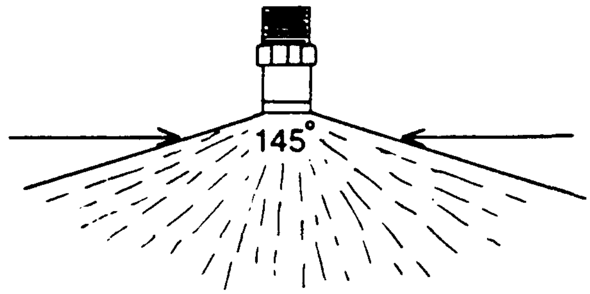


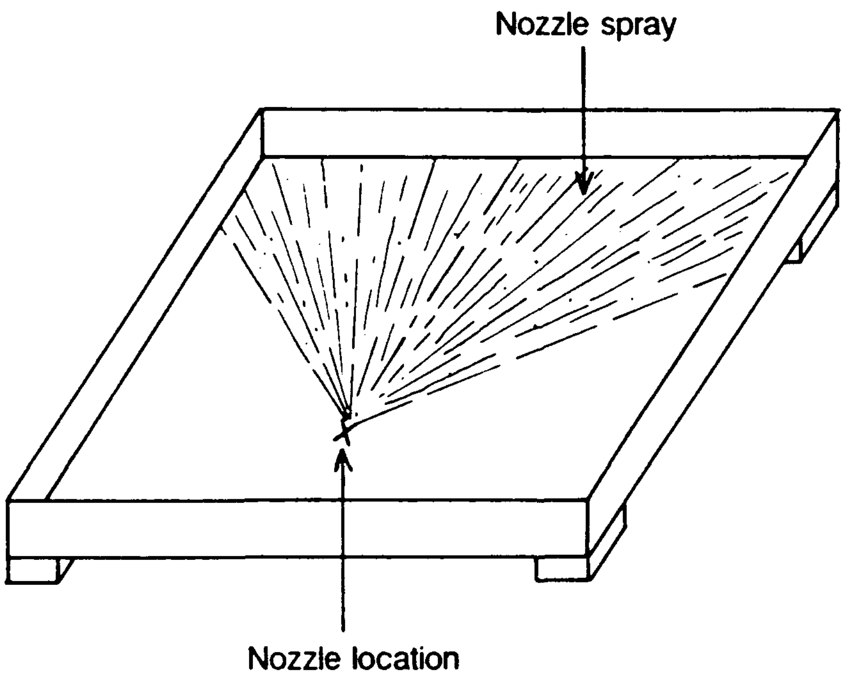
Fig. 5 - Fueling system



Bete FF125145 nozzle
side elevation



Bete FF125145 nozzle
front elevation



Fuel pan - schematic

Fig. 6 - Nozzle assembly

5.3 Instrumentation

The same instrumentation scheme installed for the post-flashover characterization test series was incorporated in this evaluation (Figs. 7 and 8).

5.3.1 Air Thermocouples

Thermocouple trees installed in all compartments provided air temperature measurements. All thermocouples used in the test series were Type K. Inconel-sheathed thermocouples were installed in the fire compartment, while high temperature glass braided thermocouples were installed in the adjacent compartments.

5.3.2 Wall Thermocouples

Matrices of thermocouples installed on both exposed and unexposed surfaces of the bulkheads and decks bounding the fire compartment provided information on the energy conducted through the steel plates and the quantities of heat being removed from the plate during the cooling process. Inconel-sheathed thermocouples were used to measure surface temperature. These thermocouples were fastened to the boundaries by drilling a small hole and peening the end of the thermocouple to the surface.

5.3.3 Heat Flux Transducers

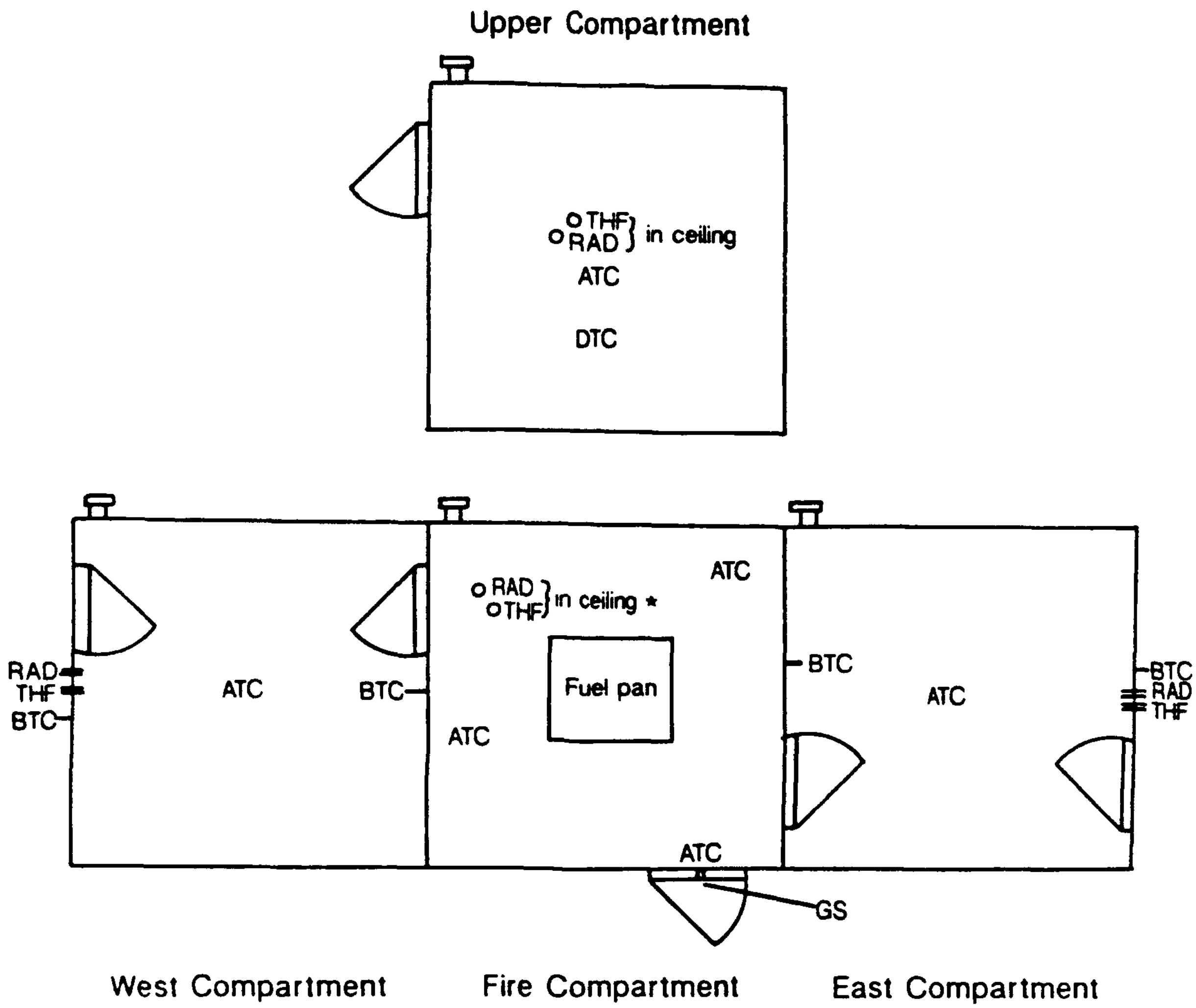
Radiation and total heat flux data collected from each compartment served as an indicator of the energy being removed from the boundaries during the cooling process. High range (330 kW/m^2 (30 BTU/ft^2 s)) transducers were installed in the ceiling of the fire compartment and medium range (110 kW/m^2 (10 BTU/ft^2 s)) transducers were installed in each of the adjacent compartments.

5.3.4 Load Cells

Load cell assemblies installed under the fuel storage tank provided mass loss rates from which fuel flow was calculated.

5.3.5 Computer

An IBM compatible computer, a data acquisition system produced by Metrabyte Corporation consisting of one DAS-8 and seven EXP-16 interface cards were used to scan the above instruments in ten second intervals. A commercial software package (Lab Tech Notebook) was used to drive the entire system. The data were stored on floppy disks (ASCII format) to be analyzed and manipulated at a later date.



ATC - Air Thermocouples (Type K)
DTC - Deck Thermocouples (Type K)
BTC - Bulkhead Thermocouples (Type K)
GS - Gas Sampling (O_2,CO, CO_2)
RAD - Radiometers 110 kW/m^2 (10 BTU/ft^2 sec) Range
THF - Total Heat Flux Transducers
110 kW/m^2 (10 BTU/ft^2 sec) Range
*330 kW/m^2 (30 BTU/ft^2 sec) Range

Fig. 7 - Instrumentation layout (plan view)

Instrumentation Detail

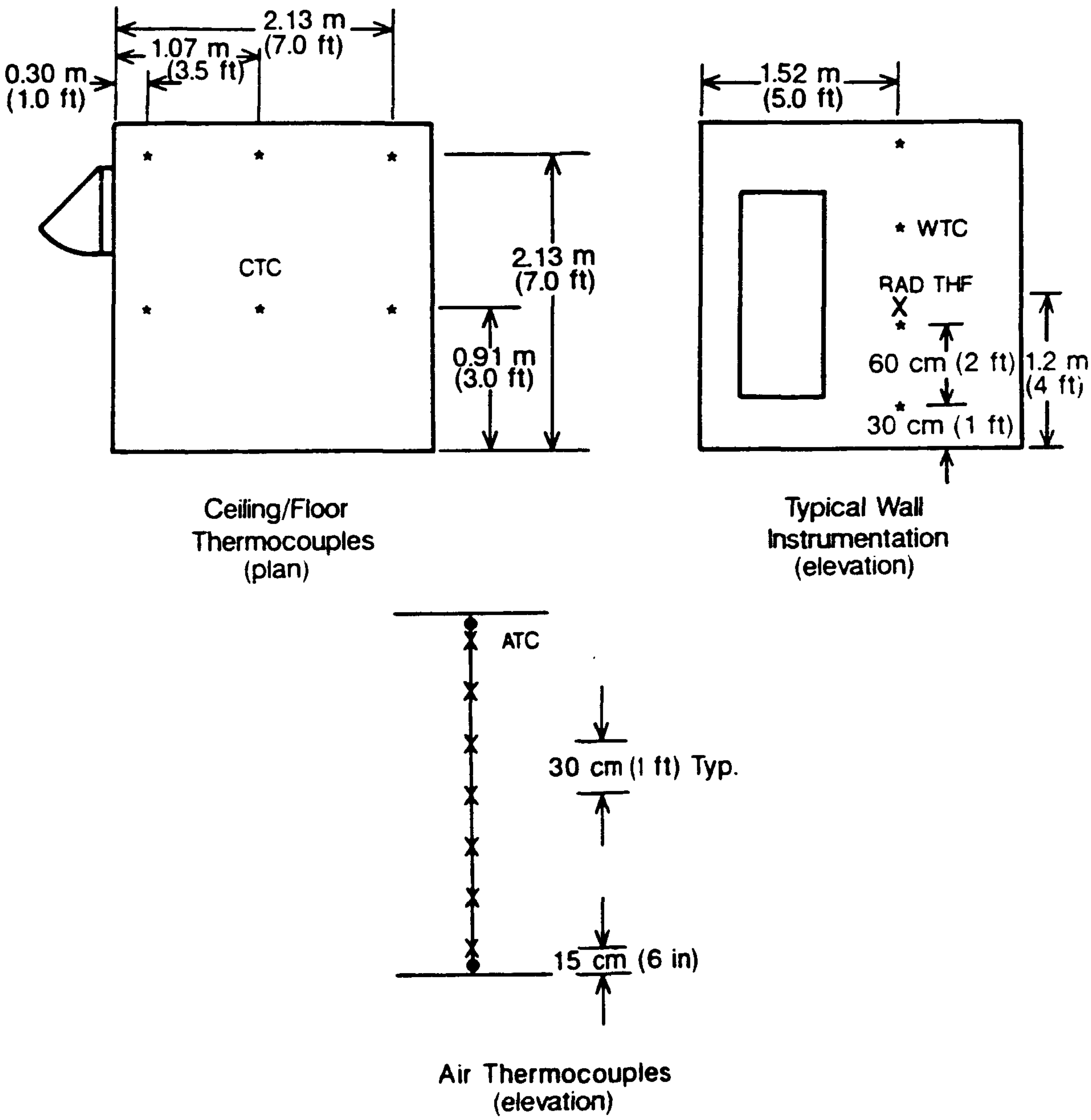


Fig. 8 - Instrumentation detail

5.3.6 Video and 35 mm Still Cameras

Visual recordings, both still and motion, were made of each test. These records serve as a means of estimating the level and volume of steam produced by the water application and were archived to serve as a visual record.

6.0 PROCEDURES

6.1 General Procedures

Upon completion of the pre-test checks of instrumentation, fueling system, and safety equipment, the area was cleared for the start of the test. Once all crewmembers were in position, the data acquisition system, video cameras, and stopwatches were all started marking the beginning of the test. These systems were activated one minute before ignition to collect background data and to record the ignition information. Thirty seconds after activation of the above systems, a small torch was lit and placed in the fuel pan in the fire compartment. At one minute into the test, the fuel system was charged and the fuel flow rate was adjusted to the desired amount (7.5 lpm (2 gpm)). The cooling or water application system was not activated until eleven minutes into the test. At the eleven minute mark, steady state conditions were approached; i.e., the fire compartment temperatures reached 1000°C (1832°F) and bulkhead temperatures, exposed (fire side) and unexposed surface temperatures, reached 600°C (1112°F) and 500°C (932°F) respectively. The cooling system was then activated for the desired amount of time (usually three minutes). Once the required information was collected, the fuel and cooling systems were shutdown and the test was terminated.

6.2 Preliminary Tests

A series of tests were conducted to: aid in the refinement of test procedures, check instrumentation, and to answer specific questions about water application, steam production, and fire spread prevention. These tests included the following:

6.2.1 Variable Flow Test

The objective of this test series was to determine the minimum application rate for effective cooling of both vertical and horizontal boundaries.

Theoretically, the quantity of water required to cool a compartment boundary is relatively low in comparison to flow rates of vari-nozzles, all purpose nozzles, and applicators. These theoretical quantities of water are based on the conversion of water to steam independent of how the water is applied, the type of surface or the surface orientation. Estimates developed by NIST [3] show that an aluminum deck above a fire compartment having 50 kw/m^2 (4.5 BTU/ft^2 sec) of heat being conducted through it can be cooled to below 100°C (212°F) with an application rate of 1.34 lpm/m^2 (0.033 gpm/ft^2). This assumes the water is applied in an infinitely thin layer evenly across the deck and at such a rate that all the water is turned into steam. This corresponds to an application efficiency of 100%. MPR [4] suggests that a higher application rate of 2.44 lpm/m^2 (0.06 gpm/ft^2) is a better approximation. Using a safety factor of 0.66 to produce an application rate of 4.07 lpm (0.1 gpm/ft^2), this means that a "typical" fire fighter using a standard Navy 360 lpm (95 gpm) vari-nozzle could effectively cool a 93 m^2 (1000 ft^2) boundary.

The unknown in the above theoretical calculations is the efficiency with which the water is applied to the surface (application efficiency). The assumption of 100% efficiency made by both NBS and MPR may be realized or nearly realized when cooling a flat, unobstructed, horizontal deck. The justification for this assumption is that for any application rate greater than the theoretical value, a layer of water will develop covering the entire deck independent of application technique. Application efficiency does not come into play until attempting to cool a vertical bulkhead, or a deck which is no longer level due to ship listing or rough seas.

Application rates from 0.4 lpm/m^2 (0.01 gpm/ft^2) to 4.0 lpm/m^2 (0.1 gpm/ft^2) were evaluated in this test series to determine the critical application rates required to effectively cool both horizontal and vertical boundaries. Application rates were determined by dividing the flow rate of the nozzle by the heated surface area. Water was applied to the heated surface using the fixed system shown in Fig. 9. The system consisted of one spray nozzle (Model TF14FC manufactured by Bete Fog Nozzle, Inc.) which produced a solid cone water spray pattern. The TF14FC has a K factor of 1.4 as defined in the following equation,

$$flow\,(gpm) = K\sqrt{pressure\,(psi)}$$

The nozzle was installed 1.2 m (4 ft) from the heated surface to provide complete coverage by the water spray.

The system was activated eleven minutes into the test as described above. The system was initially set for an application rate of 0.4 lpm/m^2 (0.01 gpm/ft^2). After the first minute of cooling, the application rate was increased by 0.4 lpm/m^2 (0.01 gpm/ft^2) each minute thereafter until an application rate of 4.0 lpm/m^2 (0.1 gpm/ft^2) was reached and the test was terminated.

6.2.2 Total Periphery Cooling Test

The objective of this test series was to determine whether fire compartment temperatures could be reduced to any extent by aggressively cooling all sides of the compartment. Five standard Navy 360 lpm (95 gpm) vari-nozzles were used to cool the boundaries in this evaluation. A portable hydrant was used to supply water for the five hand lines used in this test. The portable hydrant was connected to a domestic hydrant via 6.3 cm (2.5 in.) fire hose. The design fire was allowed to burn for 15 minutes with agressive cooling occuring the last 5 minutes.

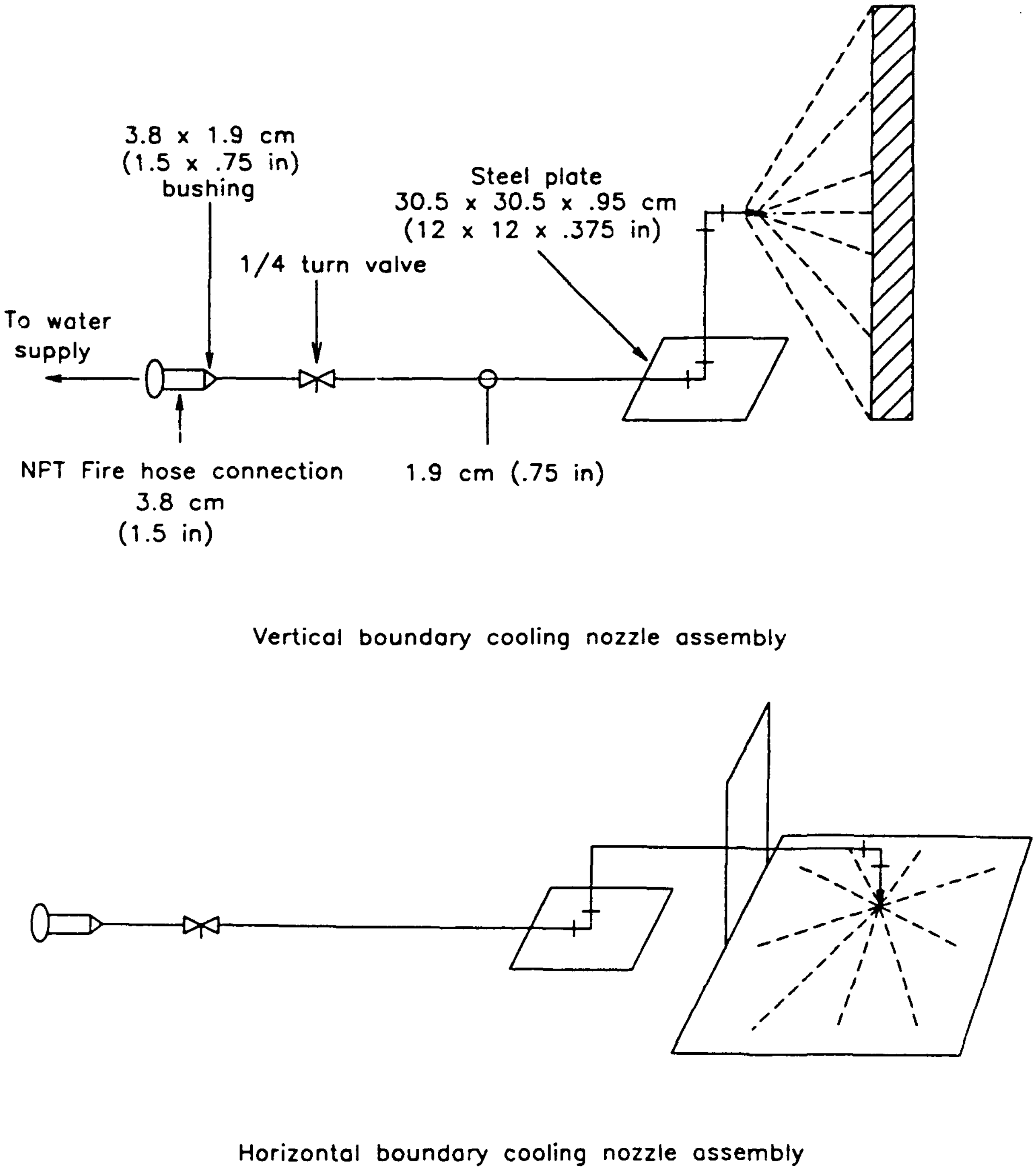


Fig. 9 - Boundary cooling nozzle assembly

6.2.3 Water Curtain Test

The objective of this test series was to determine if low flow water curtains could block heat radiating from hot bulkheads as suggested in Reference 5.

The nozzle assembly developed for the variable flow test series was used in this evaluation. A nozzle that produced a uniform wall of water was selected for this analysis (Bete Model TF8XW, K = 0.5). The nozzle was positioned to produce a water curtain 0.92 m (3.0 ft) in front of the heated bulkhead. A radiometer was positioned behind the nozzle assembly 1.2 m (4.0 ft) from the bulkhead. Water from the nozzle did not come into contact with the heated surface. The procedures were the same as above; i.e., the nozzle was charged eleven minutes into the test and allowed to flow for 5 minutes. The nozzle was flowing 11.4 lpm (3.0 gpm) at a pressure of 0.35 MPa (50 psi).

6.3 Horizontal Boundary Cooling Tests

The objective of this test series was to determine how water should be applied to a flat, horizontal deck to achieve maximum cooling with minimum application rates.

The nozzle assembly developed for the variable flow tests was used in this evaluation. Nozzles having various water spray patterns were purchased from Bete Fog Nozzle, Inc. The following nozzles and corresponding spray patterns were used in this evaluation:

Nozzle	K factor	Spray Pattern
FF93145	0.24	Flat fan-shaped
FF125145	0.39	Flat fan-shaped
TF10FC	0.65	Full cone, medium drop size
TF8XW	0.41	Flat 360° wall
TF14FC	1.25	Full cone, large drop size
P120	0.38	Full cone fine atomization

The flow characteristics of the nozzles were selected based on the critical application rate of 2.04 lpm/m^2 (0.05 gpm/ft^2) over a bulkhead/deck surface area of 6 m^2 (64 ft^2). These nozzles were selected to produce this application rate at or below the domestic water main pressure of 0.35-0.41 MPa (50-60 psi). In most cases, the flows were low enough to ensure that the water main and the nozzle pressures were relatively equal. Only during the tests with higher application rates were the nozzle pressures different. The nozzles were evaluated over a range of flow rates and nozzle orientations to achieve maximum cooling with minimum water. The nozzle was always oriented in such a way to assure total coverage of the heated surface by the nozzle's water spray pattern. A baseline comparison of two vari-nozzles (Akron Brass Co. 360 lpm (95 gpm) Model No. 3019 and Akron Brass Co. 114 lpm (30 gpm) Model No. 4508) was also conducted.

6.4 Vertical Boundary Cooling Tests

The objective of this test was to determine how water should be applied to a vertical boundary to achieve maximum cooling with minimum application rates. The nozzles, nozzle assembly, and procedures developed for the horizontal test series were incorporated in this evaluation. The nozzles were evaluated in the following orientations:

* Center Sideways - The nozzle was installed on the left side, one half way up the wall spraying across (to the right) of the horizontal centerline as shown in Fig. 10(a).

* Deck-Up - The nozzle was installed in the middle of the bulkhead at the deck level spraying up the vertical centerline as shown in Fig. 10(b).

* Ceiling-Down - The nozzle was installed in the middle of the bulkhead at the ceiling level spraying down the vertical centerline as shown in Fig. 10(c).

The nozzles that produced conical water spray patterns were installed 1.2 m (4 ft) from the center of the boundary, spraying perpendicular to the heated surface as shown in Fig. 10(d).

6.5 Manual Cooling Techniques

The objective of the manual cooling test series was to determine how to cool bulkheads and decks using standard Navy 360 lpm (95 gpm) and 114 lpm (30 gpm) vari-nozzles. The analysis combined continuous water flow, pulses of water, variations in water spray patterns, and sweeping maneuvers to determine an optimum cooling technique. Other lower flow nozzles were also evaluated in this test series.

The procedures for the manual cooling tests were similar to those used previously. Upon completion of the pre-test checks of instrumentation, fueling system, and safety equipment, the area was cleared for the start of the test. Once all crewmembers were at their stations and the fire fighters were dressed and in position, the data acquisition system, video cameras, and stopwatches were all started marking the beginning of the test. These systems were activated one minute before ignition to collect background data and to record information pertaining to the ignition sequence. Thirty seconds later, a small torch was lit and placed in the fuel pan in the fire compartment. At one minute into the test, the fuel system was charged, and the fuel flow rate was adjusted to the desired amount (7.5 lpm (2 gpm)). Manual cooling techniques were initiated eleven minutes into the test as in the previous tests. The fire fighters, dressed in turnout gear, began cooling of the fire compartment bulkhead through the adjacent compartment east of the fire compartment. During the majority of the tests, the fire fighters executed their cooling techniques from the base of the door leading into the east adjacent compartment. Once the required information was collected, the fuel system was shutdown and the test was terminated.

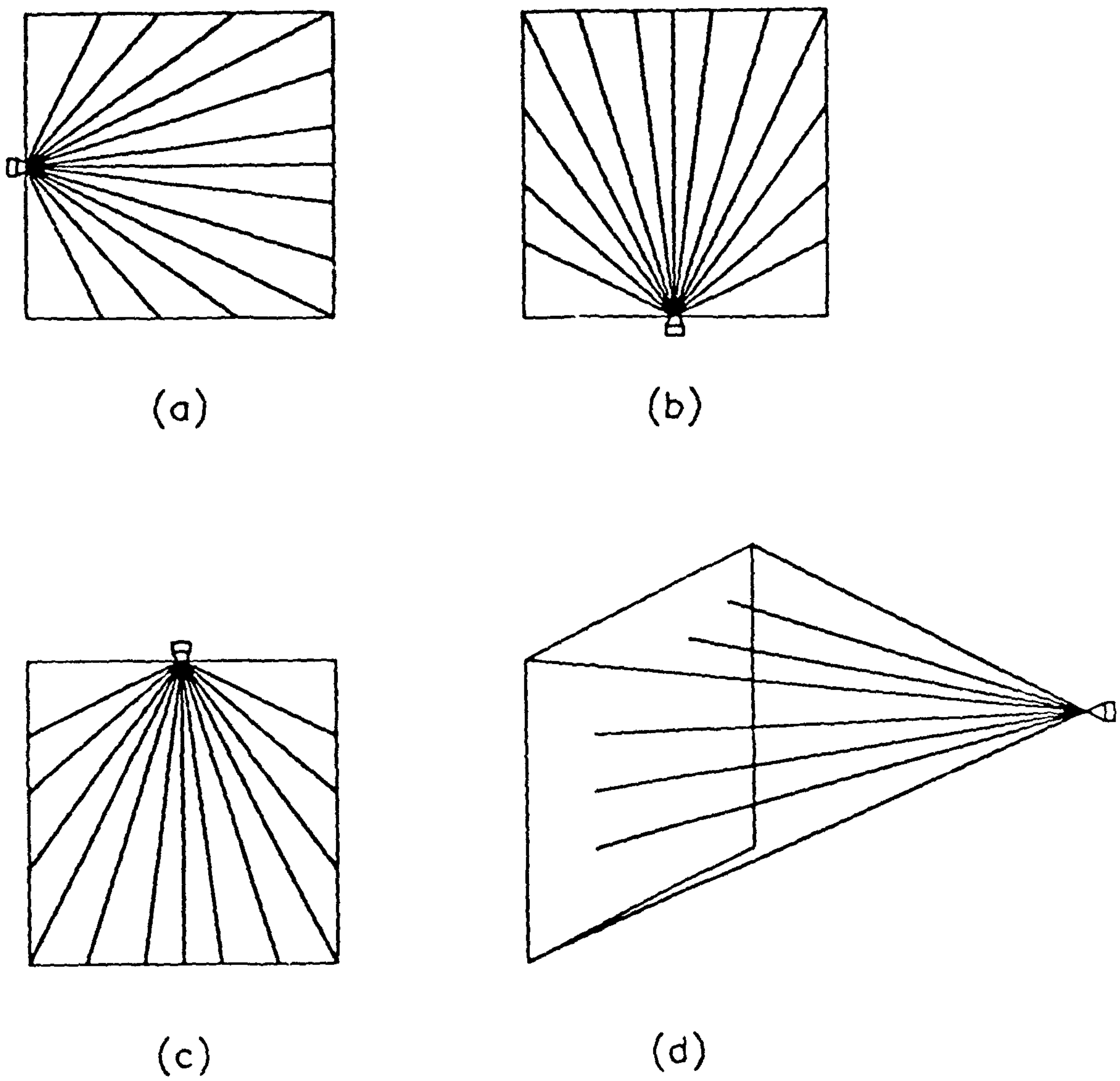


Fig. 10 - Water spray nozzle orientations for vertical boundary cooling tests:
(a) center sideways, (b) deck up, (c) ceiling down, and
(d) perpendicular to heated surface (conical spray pattern)

7.0 RESULTS AND DISCUSSION

7.1 Preliminary Tests

7.1.1 Variable Flow Test

The results from the variable flow tests conducted on the horizontal deck above the fire compartment are shown in Figs. 11a and 11b. As shown in Fig. 11a, 2.04 lpm/m^2 (0.05 gpm/ft^2) was determined to be adequate to lower the unexposed horizontal surface temperatures of the upper deck to 100°C (212°F). As predicted, application rates above 2.04 lpm/m^2 (0.05 gpm/ft^2) resulted in a layer of residual water developing on the deck providing effective cooling independent of water application technique. As the depth of the water layer increased, the exposed surface temperature of the deck was observed to decrease.

The results of the vertical bulkhead variable flow tests are also shown in Fig. 11b. As shown in this figure, vertical boundary cooling is strongly dependent on application technique. Although the technique used in this test series never cooled the bulkhead below 150°C (302°F), the relation between application rate and bulkhead surface temperature can still be determined. The cooling gained through increased application rate becomes minimal for application rates above 2.04 lpm/m^2 (0.05 gpm/ft^2). This application rate was also the rate determined in horizontal deck variable flow test.

7.1.2 Total Periphery Cooling Test

The temperatures recorded in the fire compartment, while cooling all four boundaries, are shown in Fig. 12. As shown in Fig. 12, aggressively cooling of all boundaries had no effect on fire compartment temperature. The volume of flame produced by the design fire is adequate to fill the entire compartment producing extremely high temperatures independent of losses through enclosure boundaries. Less severe fires may have produced different results.

7.1.3 Water Curtain Test

The radiant heat measured during the water curtain test is shown in Fig. 13. As shown in this figure, the radiant exposure 1.2 m (4.0 ft) from the bulkhead was reduced from 17.0 kW/m^2 (1.6 BTU/ft^2 sec) to 3 kW/m^2 (0.28 BTU/ft^2 sec) during this test. Although it was determined that low flow water curtains substantially reduce radiant heat exposures, it is doubtful that this technique could be applied to shipboard fire situations due to obstructions and overall clutter in most compartments. This 75% reduction in radiant heat flux exposure may warrant further investigation for protection of exposures during manual fire fighting procedures.

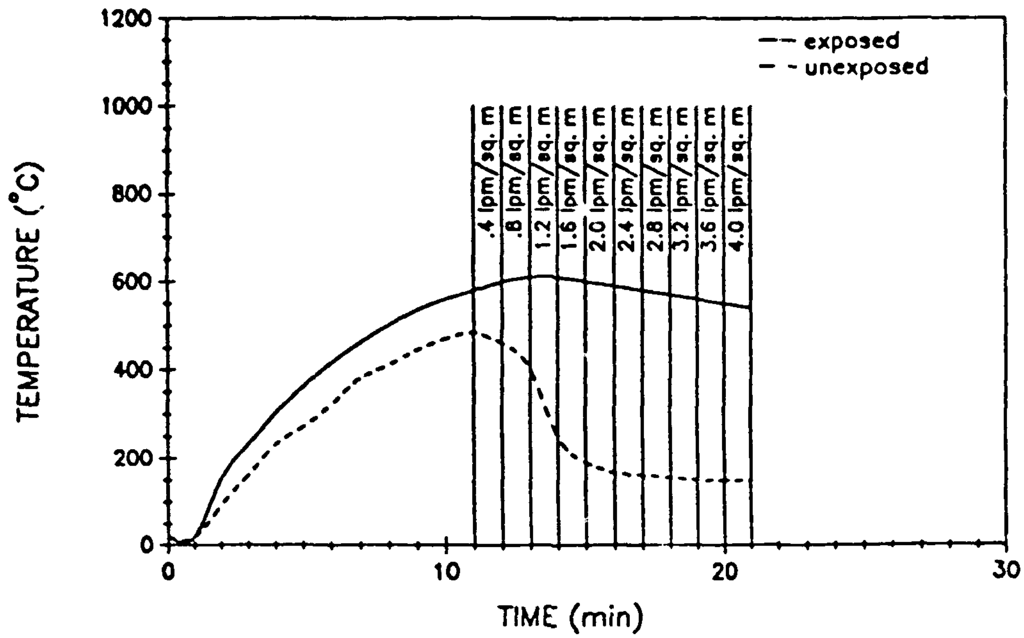


Fig. 11a - Variable flow test–horizontal deck average surface temperatures

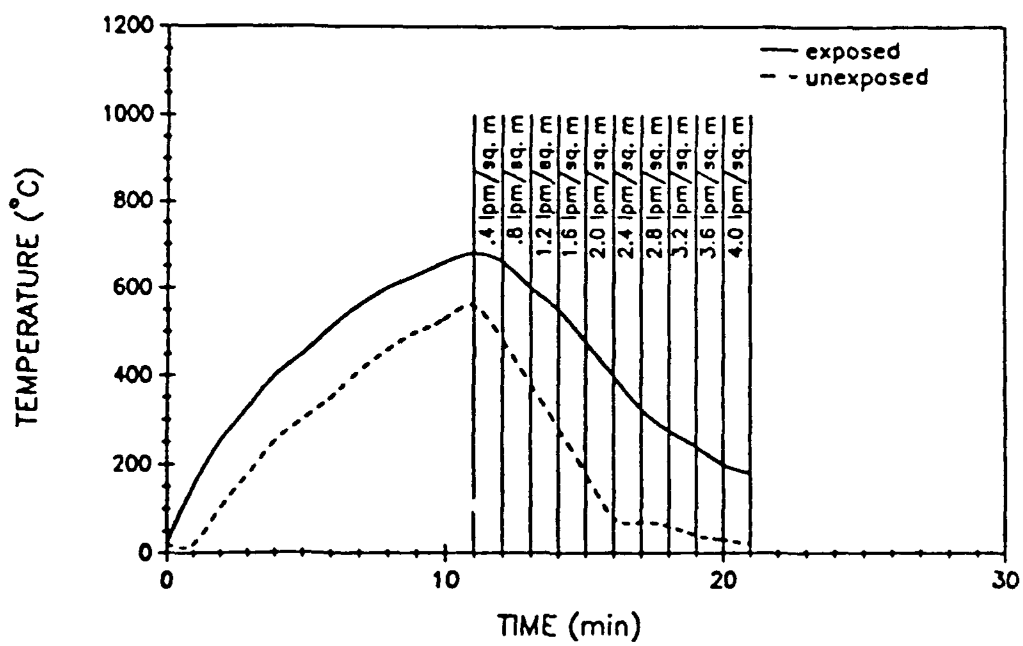


Fig. 11b - Variable flow test–vertical bulkhead average surface temperatures

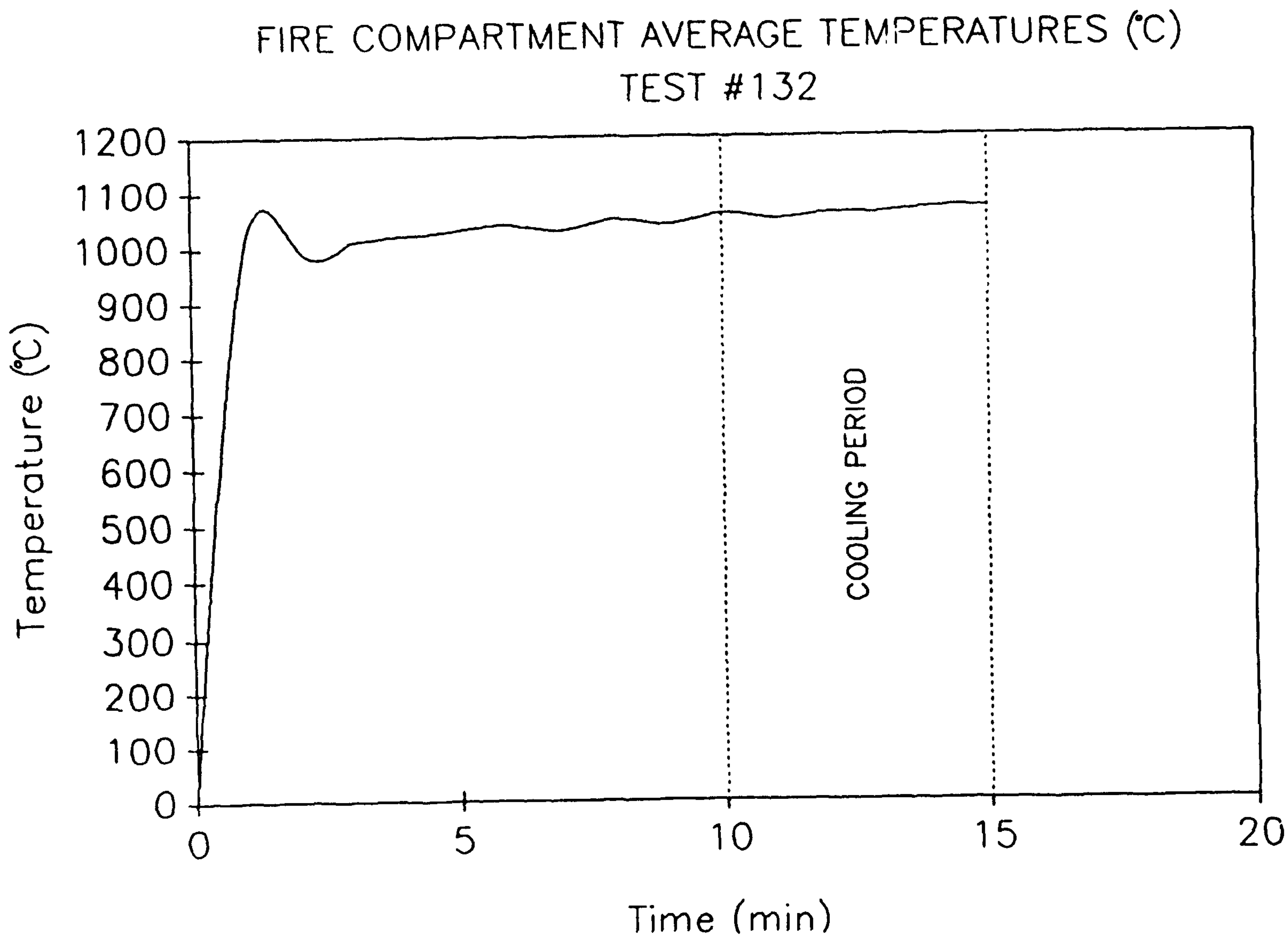


Fig. 12 - Fire compartment air temperatures during aggressive cooling of all boundaries

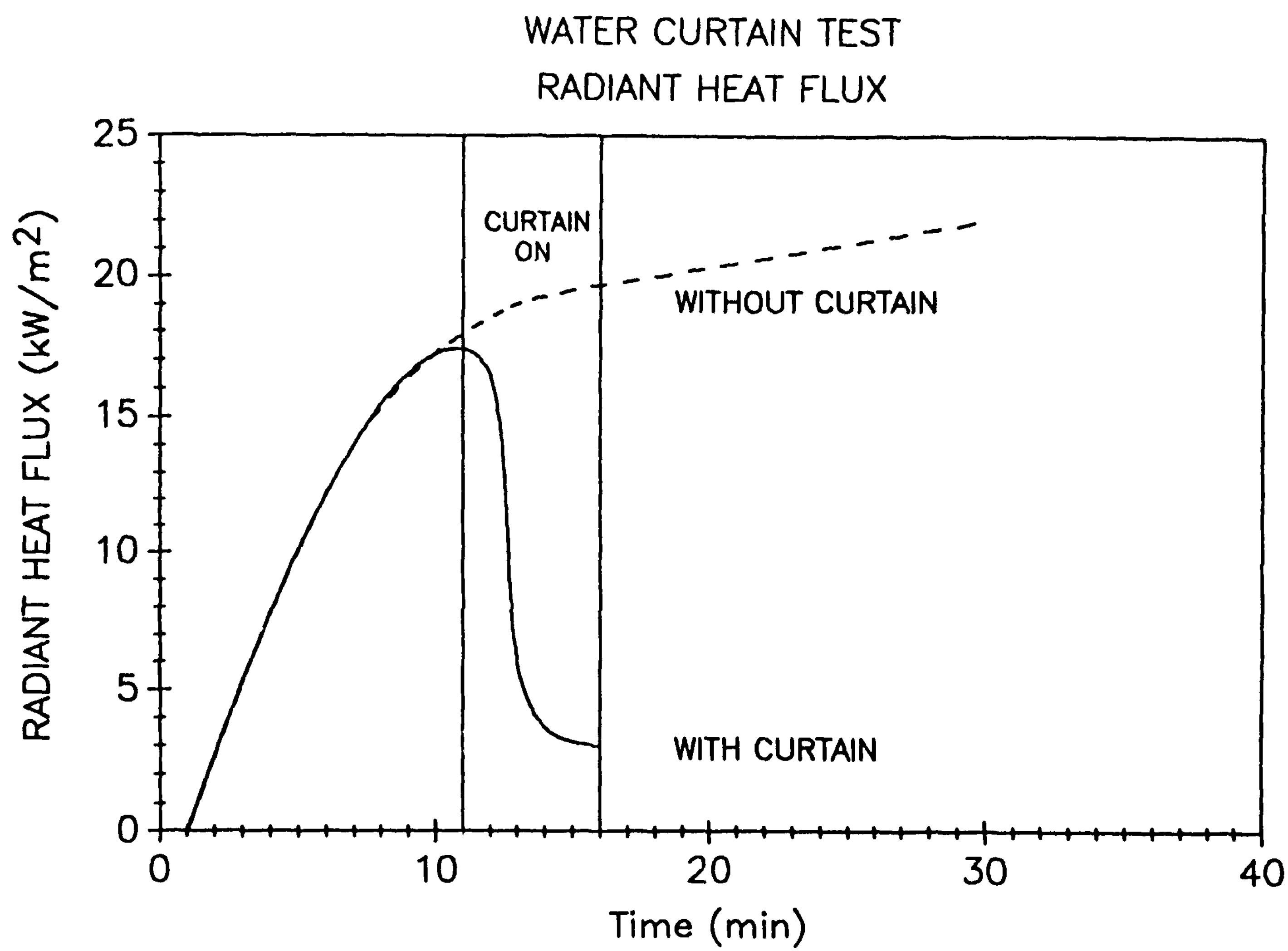


Fig. 13 - Water curtain test - radiant heat flux

7.2 Horizontal Boundary Cooling Tests

The results of the horizontal boundary cooling tests are listed in Table 1. Surface temperature measurements for these tests can be found in Appendix A. The results of this test series are similar to those recorded during the variable flow tests. Application rates greater than or equal to 2.04 lpm/m^2 (0.05 gpm/ft^2) provide roughly the same amount of cooling independent of the type and orientation of the nozzle. The ability to cool a heated surface dropped off dramatically for application rates less than the critical value as shown in the variable flow tests and in Test 131. All tests conducted with application rates greater than or equal to 2.04 lpm/m^2 (0.05 gpm/ft^2) reduced the unexposed surface temperature of the deck to 100°C (212°F) or below. Application rates above the critical value provided only a minimum difference in results as shown by Test 126. In Test 126, with the application rate nearly nineteen times the critical value, the unexposed surface temperature was only 25°C (45°F) less than the average temperature produced using the critical application rate. These higher application rates produced a layer of water on the deck resulting in uniform cooling independent of the system or technique used to apply the water. As a result of the residual water buildup for application rates greater than the critical value, the application technique analysis became unnecessary. Application rates below 2.04 lpm/m^2 (0.05 gpm/ft^2) were found to have only a minimum effect on compartment and deck surface temperatures.

7.3 Vertical Boundary Cooling Tests

The results from the vertical boundary cooling tests are listed in Table 2. Surface temperature measurements for these tests are found in Appendix A. A fan nozzle (FF 125145) demonstrated the highest application efficiency throughout this test series. The spray pattern produced by this nozzle is best described as a thin, flat sheet. This nozzle was evaluated at three orientations. Maximum cooling was achieved when the nozzle was oriented to provide complete bulkhead coverage and the water droplets remained on the hot surface for a sufficient time to absorb the required heat energy. A description of the orientations along with the corresponding results are listed below.

Center Sideways. With this nozzle and orientation, the critical application rate determined in the variable flow and horizontal boundary cooling tests produced similar results. During these tests, the unexposed surface temperatures were decreased to temperatures approaching 115°C (239°F) for all three tests. This nozzle and orientation produced the highest application efficiency for the systems evaluated in this test series (Tests 104, 112, and 117).

Deck Up. When the nozzle was moved to the deck, the application efficiency decreased. With the nozzle oriented in this fashion, the unexposed surface temperatures were measured to be 300°C (572°F) (Test 107). These results are dramatically higher than those recorded when the nozzle was mounted to the side. The decrease in cooling was the result of the water droplets falling down

Table 1. Horizontal Boundary Cooling Tests

Test #	Nozzle/ Orientation	K Factor	Nozzle Pressure MPa (psi)	Flow Rate lpm (gpm)	Application Rate lpm/m² (gpm/ft²)	Avg. Comp. Temp. Before °C (°F)	Avg. Comp. Temp. After °C (°F)	Avg. Deck Temp. Fire Comp. °C (°F)	Avg. Deck Temp. Adj. Comp. °C (°F)
124	FF125145 Side	0.39	0.41 (59)	11.4 (3.0)	2.04 (0.05)	240 (464)	100 (212)	325 (617)	105 (221)
125	TF14FC Cone Center	1.25	0.28 (41)	30.3 (8.0)	5.30 (0.13)	235 (455)	90 (194)	300 (572)	100 (212)
126	95 gpm Vari Hand Held	9.5	0.29 (42)	230.9 (61.0)	38.70 (0.95)	240 (464)	70 (158)	120 (248)	80 (176)
127	30 gpm Vari Hand Held	3.0	0.31 (45)	75.7 (20.0)	12.60 (0.31)	240 (464)	70 (158)	140 (284)	90 (194)
130	TF8XW Flat Pat. Center	0.41	0.37 (54)	11.5 (3.0)	2.04 (0.05)	230 (446)	125 (257)	315 (599)	105 (221)
131	TF8XW Flat Pat. Center	0.41	0.20 (29)	8.3 (2.2)	1.22 (0.03)	230 (446)	200 (392)	315 (599)	215 (419)

Table 2. Vertical Boundary Cooling Tests

Test #	Nozzle/ Orientation	K Factor	Nozzle Pressure MPa (psi)	Flow Rate lpm (gpm)	Application Rate lpm/m^2 (gpm/ft^2)	Avg. Comp. Temp. Before °C (°F)	Avg. Comp. Temp. After °C (°F)	Avg. Bulkhead Temp. Fire Comp. °C (°F)	Avg. Bulkhead Temp. Adj. Comp. °C (°F)
101	TF10FC Cone Center	0.65	0.14 (21)	11.4 (3.0)	2.04 (0.05)	250 (482)	175 (347)	625 (1157)	500 (932)
102	TF10FC Cone Center	0.65	0.20 (29)	13.5 (3.5)	2.04 (0.05)	250 (482)	125 (257)	450 (842)	310 (590)
103	95 gpm Vari Hand Held	9.5	0.28 (41)	230.9 (61.0)	38.70 (0.95)	220 (428)	50 (122)	100 (212)	50 (12)
104	FF125145 Fan Center-Sideways	0.39	0.38 (55)	11.0 (2.9)	2.04 (0.05)	220 (428)	120 (248)	425 (797)	105 (221)
105	P-120 Fine Atom. Center	0.38	0.37 (54)	11.0 (2.9)	2.04 (0.05)	200 (392)	110 (230)	550 (1022)	350 (662)
106	FF125145 Fan Ceiling-Down	0.39	0.38 (55)	11.0 (2.9)	2.04 (0.05)	210 (410)	150 (302)	510 (950)	380 (716)
107	FF125145 Fan Deck-Up	0.39	0.38 (55)	11.0 (2.9)	2.04 (0.05)	220 (428)	120 (248)	550 (1022)	300 (572)
108	TF8XW Flat Pat. Center	0.41	0.37 (54)	11.4 (3.0)	2.04 (0.05)	220 (428)	180 (356)	620 (1148)	500 (932)
110	2 P-120 Fine Atom. Center	0.38	0.34 (50)	20.1 (5.3)	3.26 (0.08)	220 (428)	100 (212)	475 (887)	300 (572)
111	FF93145 Fan Center-Sideways	0.24	0.39 (56)	6.8 (1.8)	1.22 (0.03)	220 (428)	175 (347)	475 (887)	300 (572)

Table 2. Vertical Boundary Cooling Tests (Continued)

Test #	Nozzle/ Orientation	K Factor	Nozzle Pressure MPa (psi)	Flow Rate lpm (gpm)	Application Rate lpm/m² (gpm/ft²)	Avg. Comp. Temp. Before °C (°F)	Avg. Comp. Temp. After °C (°F)	Avg. Bulkhead Temp. Fire Comp. °C (°F)	Avg. Bulkhead Temp. Adj. Comp. °C (°F)
112	FF125145 Fan Center-Sideways	0.39	0.41 (60)	11.7 (3.1)	2.04 (0.05)	220 (428)	150 (302)	500 (932)	120 (248)
113	TF14FC Cone Center	1.25	0.16 (23)	22.7 (6.0)	3.66 (0.09)	220 (428)	175 (347)	550 (1022)	200 (392)
114	TF8XW Flat Pat. Center	0.41	0.37 (54)	11.4 (3.0)	2.04 (0.05)	240 (464)	150 (302)	600 (1112)	375 (707)
115	30 gpm Vari Hand Held	3.0	0.17 (25)	56.8 (15.0)	9.37 (0.23)	230 (446)	50 (122)	450 (842)	100 (212)
117	FF125145 Fan Center-Sideways	0.39	0.38 (55)	11.0 (2.9)	2.04 (0.05)	220 (428)	140 (284)	325 (617)	120 (248)

the bulkhead, deflecting the pattern spraying upward. The net result was incomplete coverage of the heated surface by the water spray pattern.

Ceiling Down. With the nozzle mounted at the ceiling, the unexposed surface temperatures were measured to be 380°C (716°F) (Test 106). This configuration proved to have the lowest application efficiency of the three orientations. When the nozzle was mounted in the ceiling, the water droplets remained on the surface the shortest amount of time producing the least amount of cooling.

The nozzles that produced conical water spray patterns (TF10FC, TF14FC) provided inadequate cooling (Tests 101, 102, 113) for low application rates but improved substantially for higher application rates. Even at higher application rates, the conical water spray nozzles were unable to match the cooling produced by the fan nozzles. Even at double the critical application rate, 3.66 lpm/m^2 (0.09 gpm/ft^2) (Test 113), these nozzles were only able to reduce the unexposed bulkhead surface temperatures to 200°C (392°F).

The inefficient cooling produced by the fine atomizing nozzle P120 in Test 105 suggests that all the water droplets were not impacting the hot bulkhead surface, but instead, were being deflected by the thermal updraft of hot gases and steam. Even at twice the critical application rate (Test 110), the fine mist proved to be inadequate to cool the bulkhead (unexposed bulkhead temperatures of 300°C (572°F)). The surprisingly inefficient cooling produced by the fine droplets suggests that only the larger drops have sufficient mass and resulting momentum to penetrate the thermal updraft and strike the hot surface.

In summary, maximum application efficiency was obtained by applying water tangentially to the boundary surface in sheets or large droplets with nozzles that produce a fan shaped water spray pattern. Maximum cooling was achieved when the nozzle was oriented to provide complete coverage of the bulkhead by the water spray pattern, and the water droplets remained on the heated surface for a sufficient time to absorb the heat. Full cone nozzles spraying perpendicular to the heated surface provided some cooling for medium size droplets at higher application rates, while fine atomizing nozzles did very little to reduce the bulkhead surface temperature.

An interesting observation was made when comparing the bulkhead and deck surface temperatures of the lower application rates to the vari-nozzle baseline data. The lower application rates produced minimal amounts of visual steam and reduced only the unexposed surface temperature, while the higher application rates produced substantial amounts of steam and reduced the temperature across the plate, both exposed and unexposed surfaces (Fig. 14). The higher flows produced more steam as a result of additional energy being removed from the plate. This additional energy removal and increased steam production are only beneficial in slowing recovery (reheat) times which was a factor in developing manual cooling techniques using standard Navy hardware. Reducing the back side surface temperature had no effect on the fire compartment temperature when the fire is still burning as shown in the

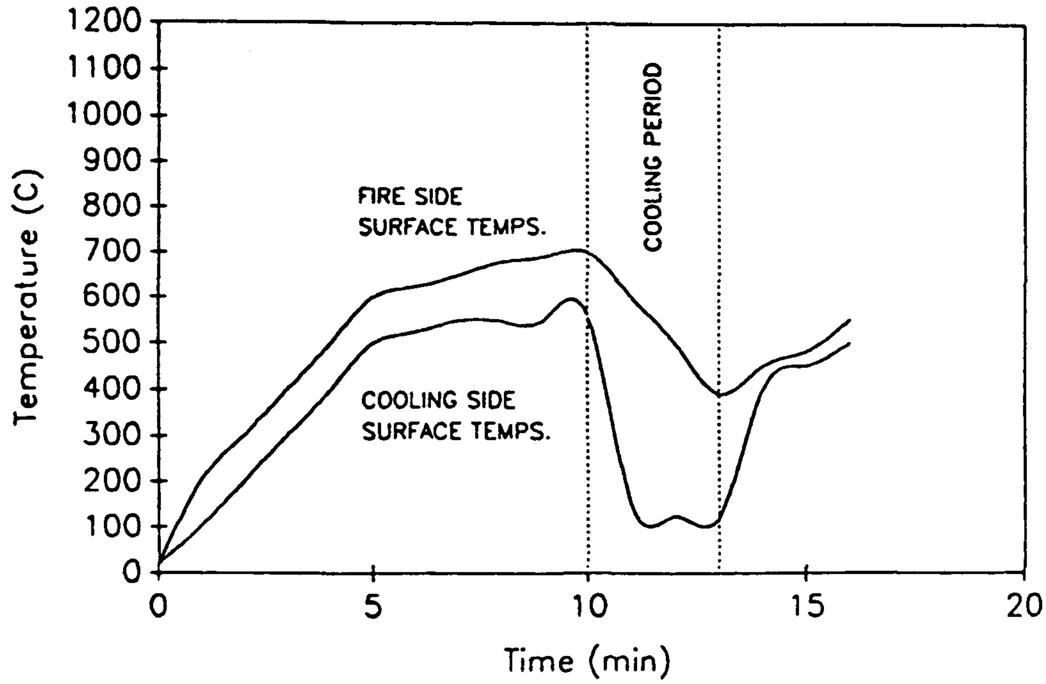


Fig. 14a - Fire compartment east wall average temperatures at low application rate (3 gpm)

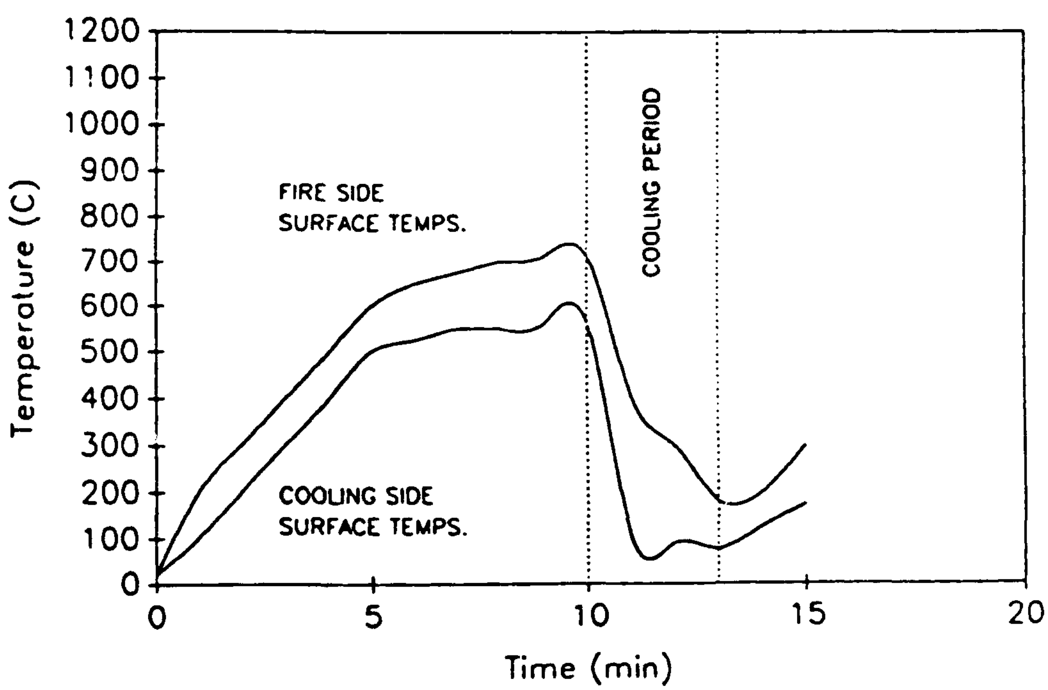


Fig. 14b - Fire compartment east wall average temperatures at high application rate (60 gpm)

Total Periphery Cooling Test. However, if the fire was less severe or had already been extinguished, reducing the exposed surface temperature would reduce the time required to restore the tenability of the fire compartment.

During the tests conducted with application rates of 2.04 lpm/m^2 (0.05 gpm/ft^2), it was observed that when the nozzle was first activated, very little visual steam was produced. As the plate temperature was reduced, the steam production increased. None of the previously incorporated calculation procedures could explain this phenomenon. A literature search on water droplet evaporation on hot surfaces produced an explanation. Water vaporizes by three mechanisms; evaporation, nucleate boiling, and film boiling. Evaporation occurs when the water drop rests on a surface of less than 100°C (212°F). Nucleate boiling which is best described as a uniform rolling boil, produces the highest vaporization rate and occurs when the plate temperature is between 100°C (212°F) and 250°C (482°F) depending on the plate material. The region above 250°C (482°F) is known as the Liedenfrost Transition in which film boiling occurs. In the film boiling range, a thin vapor barrier forms underneath the droplet lifting it off the surface which substantially reduces the heat transferred to the droplet.

Studies conducted by Michiyoshi and Makino [6] for the development of nuclear reactors, illustrated the heat transfer characteristics of a droplet resting on a heated surface as a function of surface temperature and surface material. Figure 15 shows the evaporation time of a single pure droplet of water setting on a heated surface as a function of surface temperature. The nucleate boiling regime is illustrated by the significantly faster evaporation times represented by the minimum values on Fig. 15. Although it appears difficult to take advantage of this phenomenon, the information was incorporated in the development of techniques using standard Navy hardware.

7.4 Manual Cooling Techniques

A total of twelve tests were conducted in this test series. A summary of the results is shown in Table 3. A wide range of application techniques and fire fighter positions were evaluated during these tests. During tests with similar application techniques, the higher flow nozzles produced lower bulkhead temperatures than those nozzles having much lower flow rates. However, along with the lower temperatures came an increase of water build-up in the compartment.

Incorporating the data from these tests on both cooling and reheat rates, a set of application techniques was developed for both the 360 lpm (95 gpm) and 114 lpm (30 gpm) vari-nozzles. These techniques were developed around the criteria of keeping the temperatures of the vertical bulkhead below 250°C (482°F) while applying minimum amounts of water. The vertical bulkhead was selected due to both its strong dependence on application technique and consequently, techniques developed for the vertical bulkhead will work for horizontal decks as well. The selected temperature represents a heat flux from the boundary of less than 5.0 kW/m^2 (0.45 BTU/ft^2 sec) which would be inadequate to spontaneously ignite Class A materials (paper, wood,

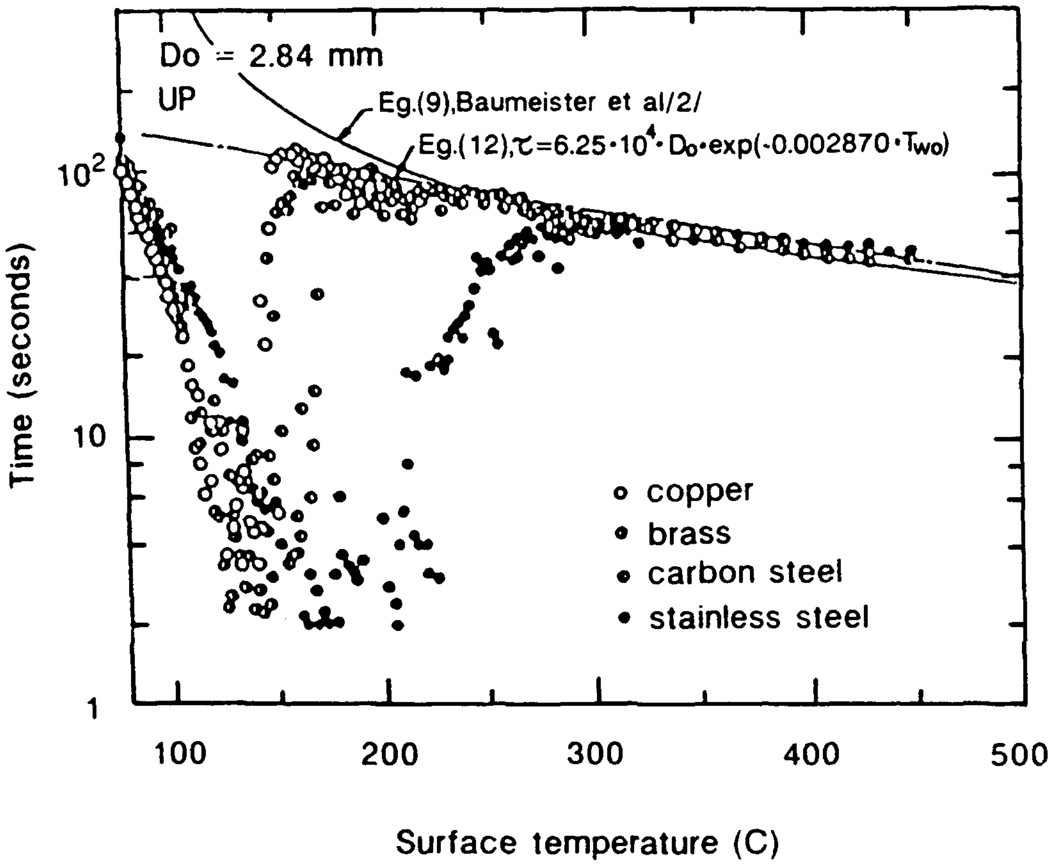


Fig. 15 - Vaporization rate as a function of plate temperature (Ref. 6)

Table 3. Manual Cooling Techniques

Test #	Nozzle/ Orientation	K Factor	Nozzle Pressure MPa (psi)	Flow Rate lpm (gpm)	Application Rate lpm/m² (gpm/ft²)	Avg. Comp. Temp. Before °C (°F)	Avg. Comp. Temp. After °C (°F)	Avg. Deck Temp. Fire Comp. °C (°F)	Avg. Deck Temp. Adj. Comp. °C (°F)
103	95 gpm Vari	9.5	0.28 (41)	230.9 (61.0)	38.7 (0.95)	220 (428)	50 (122)	100 (212)	50 (122)
115	30 gpm Vari	3.0	0.17 (25)	56.8 (15.0)	9.4 (0.23)	230 (446)	50 (122)	450 (842)	100 (212)
116	3/4" Cap w/Holes	1.0	0.31 (45)	25.4 (6.7)	4.1 (0.10)	220 (428)	120 (248)	500 (932)	200 (392)
118	3/4" Cap w/Holes	1.0	0.23 (34)	22.0 (5.8)	3.7 (0.09)	230 (446)	130 (266)	375 (707)	110 (230)
119	Garden Hose	0.71	0.34 (50)	18.9 (5.0)	3.3 (0.08)	230 (446)	160 (320)	520 (968)	180 (356)
120	3/4" Cap w/Holes	1.0	0.19 (28)	20.1 (5.3)	3.3 (0.08)	220 (428)	150 (302)	375 (707)	170 (338)
121	30 gpm Vari	3.0	0.30 (44)	75.7 (20.0)	12.6 (0.31)	220 (428)	100 (212)	250 (482)	75 (167)
122	95 gpm Vari	9.5	0.32 (47)	2[illegible]6 (65.0)	41.6 (1.02)	220 (418)	100 (212)	120 (248)	50 (122)
123	3/4" Cap w/Holes	1.0	0.18 (26)	1[illegible].7 (5.2)	3.3 (0.08)	230 (446)	150 (302)	400 (752)	150 (302)
126	95 gpm Vari	9.5	0.28 (41)	2[illegible]0.9 (61.0)	38.7 (0.95)	240 (464)	70 (158)	120 (248)	80 (176)
127	30 gpm Vari	3.0	0.30 (44)	75.7 (20.0)	12.6 (0.31)	240 (464)	70 (158)	140 (284)	90 (194)
128	3/4" Cap w/Holes	1.0	0.19 (27)	19.7 (5.2)	3.3 (0.08)	230 (446)	90 (194)	320 (608)	100 (212)

clothing) in dry air, much less when the combustibles are saturated with water. This temperature is also the lower limit for the Liedenfrost Transition region, where, for any higher temperatures, water itself begins to lose efficiency in cooling as stated earlier.

Temperature measurements recorded during the cooling of the boundaries using the two developed techniques are shown in Fig. 16. These techniques are described as follows.

The cooling technique developed for the 360 lpm (95 gpm) vari-nozzle is stated as follows. While staying low or lying on the deck (if appropriate) a tolerable distance from the heated surface, the nozzleman should begin wetting the combustibles in the compartment by sweeping with a 30° fog pattern. It is recommended that the fire fighter position him or herself either in a doorway spraying into the heated compartment or behind a large piece of equipment to help protect the fire fighter from direct exposures to heat and steam. During the sweeping of the combustibles, short sweeps of the heated surface should be conducted until the amount of steam produced begins to make the space untenable for the fire fighter. In many cases, a natural inflow of cool air and outflow of steam will be established allowing the compartment to remain tenable. If the position of the fire fighter is not jeopardized, the nozzleman should aggressively cool the boundary for approximately two and one-half minutes. This, in most cases, will reduce the boundary surface temperature to below 150°C (302°F). Short 15 second water bursts sweeping a 30° fog pattern across the bulkhead or deck every three minutes will ensure that the surface temperature never rises above 250°C (482°F).

The technique developed for the 114 lpm (30 gpm) vari-nozzle is similar to the one developed for the 360 lpm (95 gpm) vari-nozzle. Initiating the cooling as previously described, the nozzleman should aggressively cool the boundary for five minutes using a 30° fog pattern. Short 15 second water bursts every two minutes will maintain the boundary surface temperature below 250°C (482°F).

An analysis was also conducted on two low flow nozzles (a garden hose nozzle and a "homemade" nozzle made from a 1.9 cm (0.75 in.) pipe cap). Both nozzles had K factors in the range of 0.5-1.0. The garden hose nozzle was selected for this evaluation due to its availability onboard ships for cleaning purposes. The homemade nozzle was designed to simulate a low flow vari-nozzle. The homemade nozzle was made from a 1.9 cm (0.75 inch) threaded pipe cap with nine 0.13 cm (0.05 inch) diameter holes drilled into it. The holes were oriented to simulate the 30° fog pattern of the vari-nozzle. The garden hose provided adequate cooling reducing the surface temperature to 180°C (356°F) but suffered in reach characteristics. The garden hose nozzle only had a reach of 2-3 meters (6.7 feet) while producing a 30° water spray pattern. The homemade nozzle proved to have a greater reach, 5 to 6 meters (15-20 ft), and had a much better cooling efficiency. The homemade nozzle cooled the bulkhead to 110°C (230°F). Although these two nozzles provided adequate cooling at low flow rates for this application, both of these nozzles would be ineffective against substantially larger bulkheads or decks.

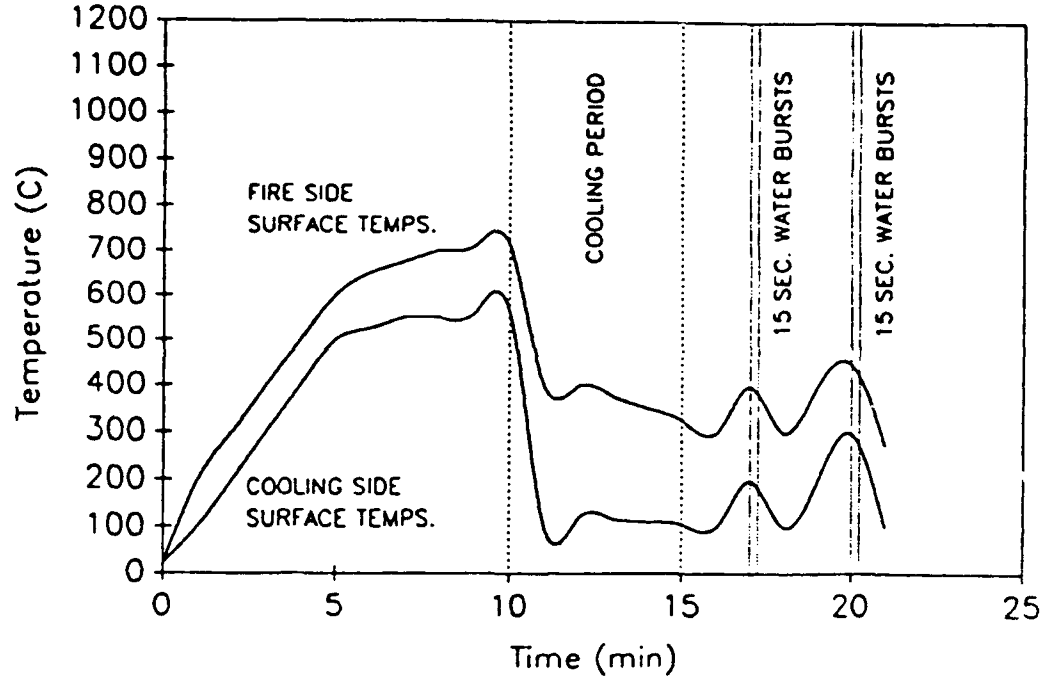


Fig. 16a - Fire compartment east wall average temperatures when cooling with 30 gpm vari-nozzle (Test 121)

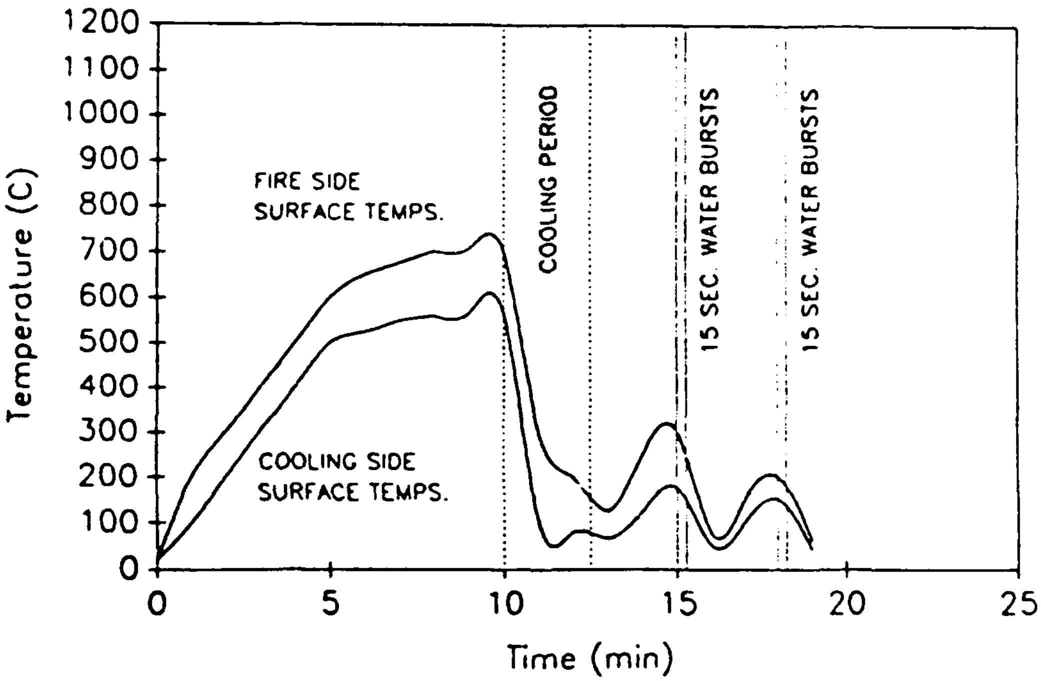


Fig. 16b - Fire compartment east wall average temperatures when cooling with 95 gpm vari-nozzle (Test 122)

8.0 SUMMARY AND CONCLUSIONS

1. An application rate of 2.04 lpm/m^2 (0.05 gpm/ft^2) was verified to be minimum for cooling surface temperatures of both horizontal and vertical boundaries to 100°C (212°F).

2. The temperature of the fire compartment was not reduced by aggressively cooling (high application rates) of all fire compartment boundaries as long as the fire remained burning.

3. A low flow water curtain (11.4 lpm (3 gpm)) was found to reduce radiant heat by 75%.

4. At application rates of 2.04 lpm/m^2 (0.05 gpm/ft^2) or above, cooling of horizontal decks was independent of application technique.

5. Vertical boundary cooling was strongly dependent on application technique. Maximum cooling efficiency was achieved when the water was applied in sheets or continuous sprays tangentially to the heated surface. The nozzle must also be oriented to provided complete surface coverage by the water spray and the water must remain on the surface a sufficient time to absorb the required energy. A nozzle producing a fan shaped water spray pattern mounted at the side of the bulkhead, one-half the vertical distance up the wall, spraying across the heated surface produced superior results in this test series. Nozzles producing a conical shaped water spray pattern applied perpendicular to the surface provided inadequate cooling for low application rates but improved with increased application rates. The higher application rate was required due to the water droplets (streams) bouncing off the heated surface. Fine atomizing nozzles applied perpendicular to the heated surface proved to be inadequate for cooling of steel bulkheads. The fine drops lacked the needed momentum to penetrate the thermal updraft of steam and hot gases to adequately impact the heated surface.

6. Water was found to be more efficient at removing heat energy when wall surface temperatures were between 100°- 250°C (212°- 482°F), i.e., in the Leidenfrost Transition region.

7. At low application rates, only the front surface of the boundary was cooled. Minimum visible steam was produced. At high application rates, both the front and back surfaces of the boundary were cooled and significant amounts of steam were produced. The increased steam production was attributed to the ability to remove the heat stored in the steel plate.

8. Techniques for effectively cooling boundaries to prevent fire spread were developed for two standard Navy vari-nozzles and are listed as follows:

360 lpm (95 gpm) vari-nozzle - After the wetting of the combustibles in the compartment, aggressively cool the boundary by sweeping with a 30° fog pattern for two and one-half minutes or until conditions become untenable for the fire fighter. Short 15 second water bursts every three minutes should be more than adequate to keep the bulkhead cool and prevent fire spread.

114 lpm (30 gpm) vari-nozzle - After the wetting of the combustibles in the compartment, aggressively cool the boundary by sweeping with a 30° fog pattern for five minutes or until conditions become untenable for the fire fighter. Short 15 second water bursts every two minutes should be sufficient to keep the bulkhead cool and prevent fire spread.

9.0 RECOMMENDATIONS

It is recommended that the results of these tests, as summarized in Appendix B, be included in the next revision of NSTM 555.

10.0 REFERENCES

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