Naval Research Laboratory

Washington, DC 20375-5320

NRL/MR/6180--99-8423

Thermal Insult Produced by the Residual Liquid Fuel in a Missile Hit Scenario

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December 23, 1999

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20000104 038

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (*Leave Blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 23, 1999	Final 1993

4. TITLE AND SUBTITLE

Thermal Insult Produced by the Residual Liquid Fuel in a Missile Hit Scenario

5. FUNDING NUMBERS

PE — 0603514N

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/6180--99-8423

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Chief of Naval Operations
Code N86DC
Washington, DC 20350-2000

Naval Sea Systems Command
Code PMS 500
Arlington, VA 22242-5160

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

*Hughes Associates, Inc., Baltimore, MD
**GEO Centers, Inc., Rockville, MD

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

Shipboard fires that result from residual liquid missile propellant were studied in this collaborative work with the Italian Navy.

Penetration of a ship compartment by a shaped charge jet by itself, i.e., in the absence of entrained missile propellant, will not cause ignition of Class A materials due to the extremely short duration of the thermal pulse. However, hot fragments generated by the warhead could result in ignition if the fragments happened to land on easily ignited Class A material. If the shaped charge jet entrains missile propellant, there is a potential for a serious fire or explosion depending on the quantity of propellant ingested into the compartment and the volume of air available.

14. SUBJECT TERMS

Shipboard fire
Liquid fuel
Missile propellant
Class A material
Thermal pulse

15. NUMBER OF PAGES

44

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

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Thermal Insult Produced by the Residual Liquid Fuel in a Missile Hit Scenario

1.0 INTRODUCTION

Since the EXOCET missile attack on the USS STARK (FFG-31) in May of 1987, the U.S. Navy has been studying the incendiary aspects of anti-ship missile (ASM) systems weapons. Efforts to date have focused on solid propellant ASM systems. Large scale tests have been conducted to quantify the thermal environment generated by combustion of up to 300 lb of solid propellant in ship compartments [1-3]. Data obtained from these tests have provided invaluable realistic threat/hazard information and expanded the knowledge base with respect to quantification of thermal environments and the propensity of fire spread beyond the compartment of origin. There is a need, however, to expand the present knowledge base by including characterization of liquid propellant based ASM's.

During the spring of 1993, the U.S. and Italian Navies conducted a series of shipboard blast tests designated as the Martest Trials. The Martest Trials consisted of a series of ship survivability/vulnerability experiments conducted aboard the Italian ship ex-MARGOTTINI near La Spezia, Italy. The trials were initiated to evaluate both underwater explosion (UNDEX) and air explosion (AIREX) scenarios. These trials provided a unique opportunity to further expand the present database to include ASMs utilizing liquid propellant and shaped charge warheads..

In preparation for these liquid propellant trails, a series of scoping tests were conducted at Naval Weapons Center, China Lake, CA. These tests were designed to characterize both the thermal environment produced by the shaped charge alone and the additional insult produced by residual liquid rock propellant that might be entrained by the shaped charge jet [4]. The results of the China Lake tests indicated that, while the thermal insult produced by the blast was of high intensity, the duration of the exposures were so short that the probability of ignition of combustible materials in the target compartment was highly unlikely. The Martest trials were conducted to verify these results in an actual shipboard compartment.

Manuscript approved November 16, 1999.

2.0 Threat

It is known that various anti-ship missiles are in the hands of potentially hostile countries. In some of these missiles, the shaped charge warhead is located behind the liquid fuel tank creating a potential blast enhancement effect known as shaped charge jet follow through (SCJFT).

When the warhead fires, the warhead jet must pass through the fuel tank before it strikes the target. In theory, the SCJFT concept creates a unique coupled effect between the shaped charge and the residual fuel: as the SCJ passes through the fuel and penetrates the ship's hull, it creates a negative pressure in the hole which tends to suck the remaining fuel behind it. Of course, any residual oxidizer would also be forced in the ship. To further enhance fuel injection into the ship, the pressure wave from the warhead tends to push to remaining fuel into the entrance hole. The result of this effect, depending on exact warhead-propulsion system design, is to produce an internal compartment fire or possibly to create an "inefficient" fuel-air explosion (FAE). It has been theorized that these systems could generate significantly enhanced incendiary and/or blast enhancement effects [5]. The goal of this project was to quantify the unique thermal and/or blast enhancement effects produced by the SCJFT concept.

3.0 OBJECTIVES

The objectives were as follows:

- Measure the thermal insult produced solely by the detonation of a shaped charge as the jet passes through a ship's compartment;.
- Measure the additional threat produced by unspent liquid rocket fuel in the above scenario; and
- Investigate the likelihood of ignition of combustibles within the compartment in both of the above scenarios.

4.0 TEST SETUP

Two tests were conducted on board the decommissioned BERGAMINI Class frigate, the ex-MARGOTTINI (Fig. 1). The ship is approximately 95 m (311 ft) long, 11.3 m (37 ft) wide and displaces 1500 metric tons (1650 English tons). The test compartment was located on the Corridoio Deck between frames 36 and 48 as shown in Fig. 2. The size and shape of the compartment had to be modified due to damage sustained during a previous blast test. The final compartment dimensions are shown in Fig. 3.

The charges were mounted on platforms on the exterior of the starboard hull at locations shown in Figs. 2 and 3. The warheads were fired horizontally through the compartment at a height of approximately 1.3 m (50 in.) above the deck. A 5 cm (2 in.) thick steel plate was fastened to the port side of the ship to contain the blast. The warhead was initially aligned using a laser.

4.1 Shaped Charge

The shaped charge consisted of a 6.3 kg (14.0 lb) of C-4 plastic explosive with a 100 g (0.2 lb) 50/50 Pentolite booster. The explosive was housed in a 18.4 cm (7.25 in.) diameter cylinder (OD) by 17.5 cm (6.9 in.) In length as shown in Fig. 4. The casing was 1.0 cm (0.4 in.) thick and was made of 1008 steel. The charge was activated using a J-2 or RP-80 detonator.

The liquid rocket propellant was simulated using commercially available diesel fuel which was selected for this application because of its availability and similar heat of combustion (42.6 kJ/g for diesel versus 42.0 kJ/g for liquid rocket propellant) [6]. Approximately 4.0 liters (1 gal) of diesel was used during these tests. The diesel was housed in a standard one-gallon paint can. The can measured 16.5 cm (6.5 in.) in diameter by 20.3 cm (8.0 in.) in length. The can was fastened to the front of the shaped charge as shown in Fig. 5.

4.2 Instrumentation

The instrumentation scheme was designed to measure both the thermal insult produced by the warhead and to provide information for predicting the time and likelihood of ignition of combustible materials. Instruments were installed to measure air temperatures, radiant and total

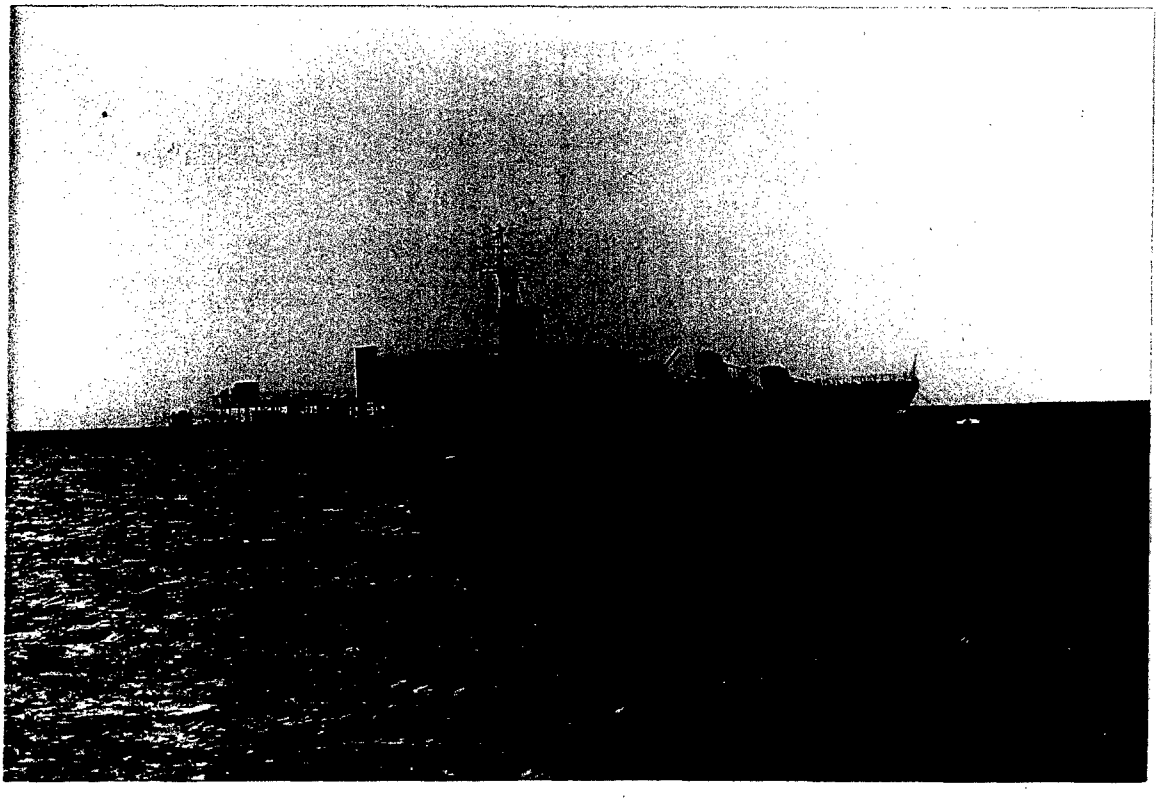


Fig. 1 - ex-Margottini

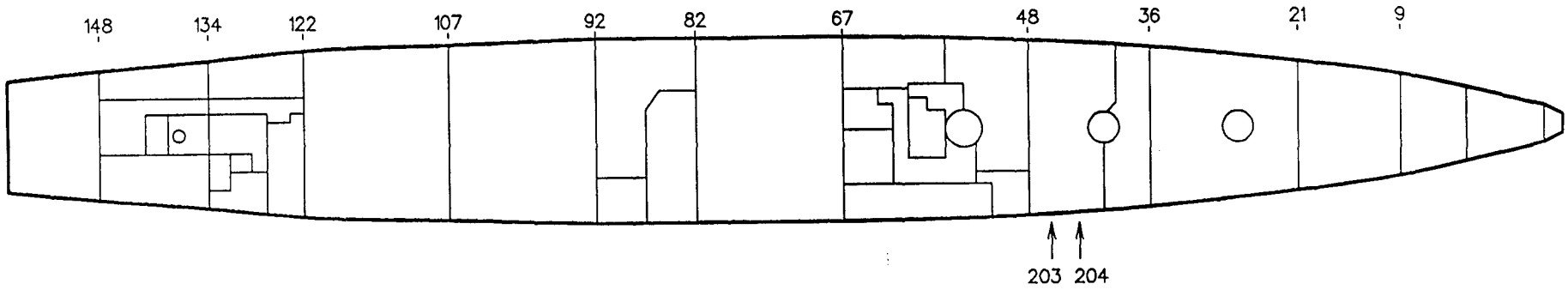


Fig. 2 - Test compartment location - Corridoio deck

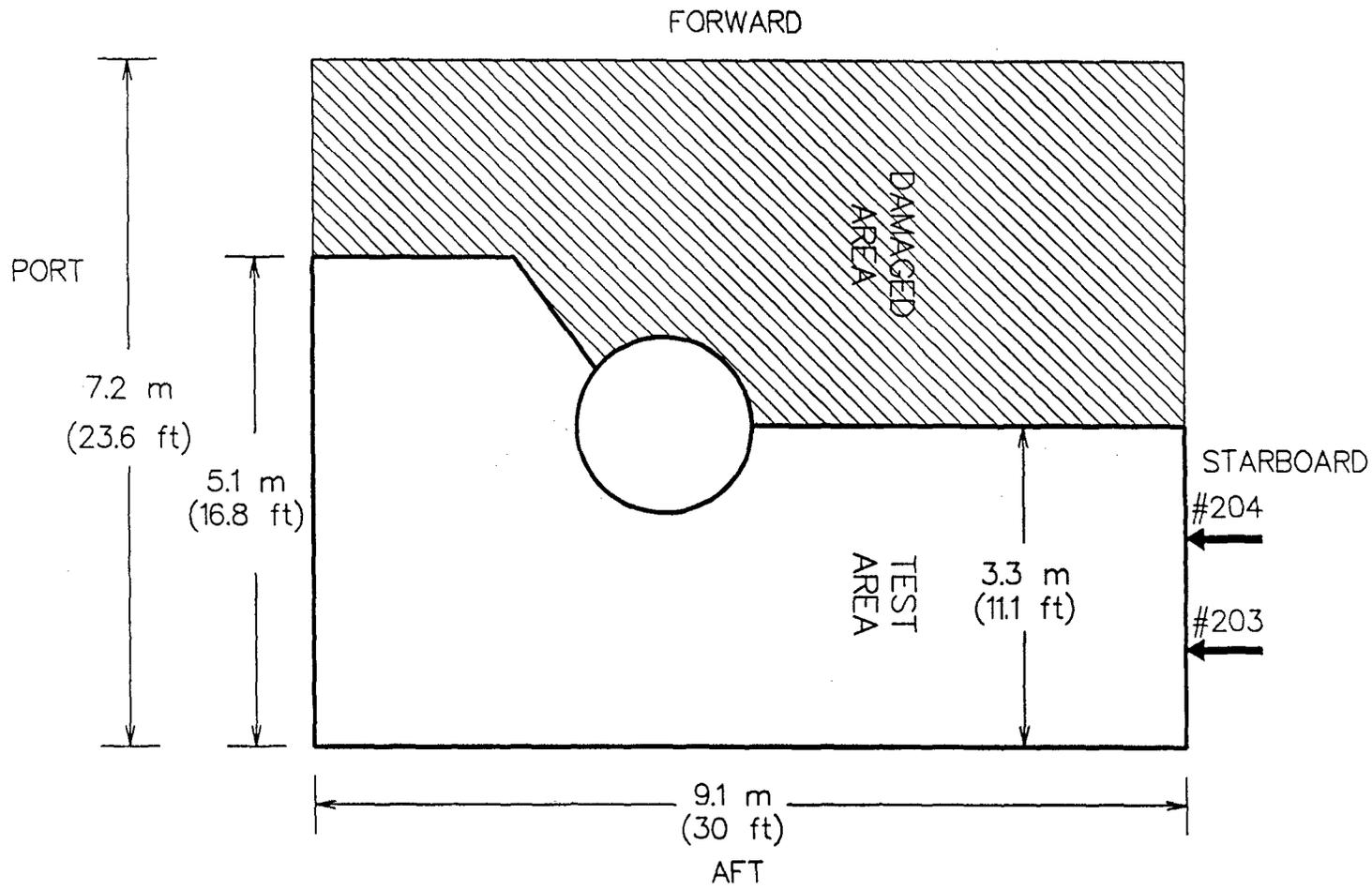
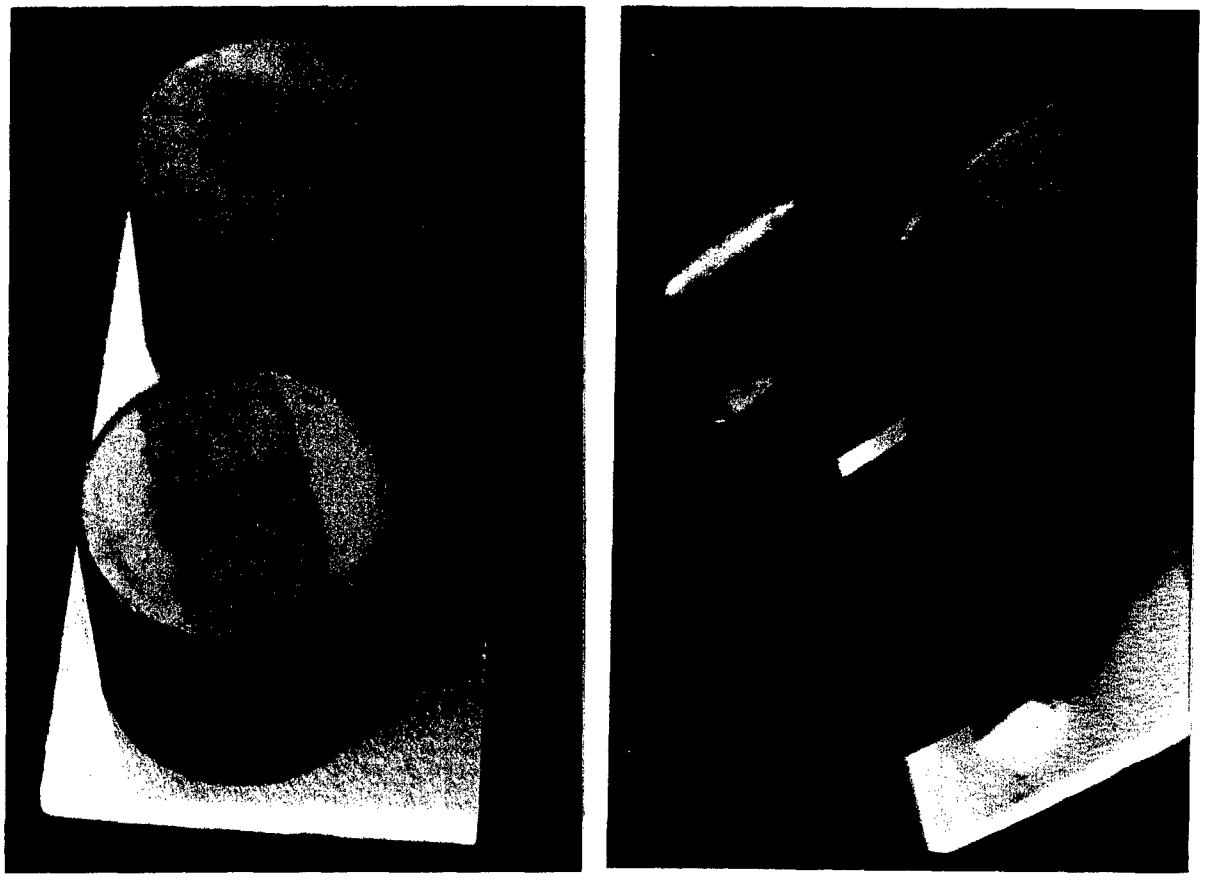


Fig. 3 - Test compartment



MATERIALS LIST		
PART	DESCRIPTION	MATERIAL
1	CASING	18.4 cm (7.2 in) OD x 17.1 cm (6.7 in) ID TUBING
2	DISC	16 ga. MILD STEEL
3	LINER	AISI 1008 STEEL
4	EXPLOSIVE FILL	14 lb HBX-1
5	BOOSTER	100 g 50/50 PENTOLITE

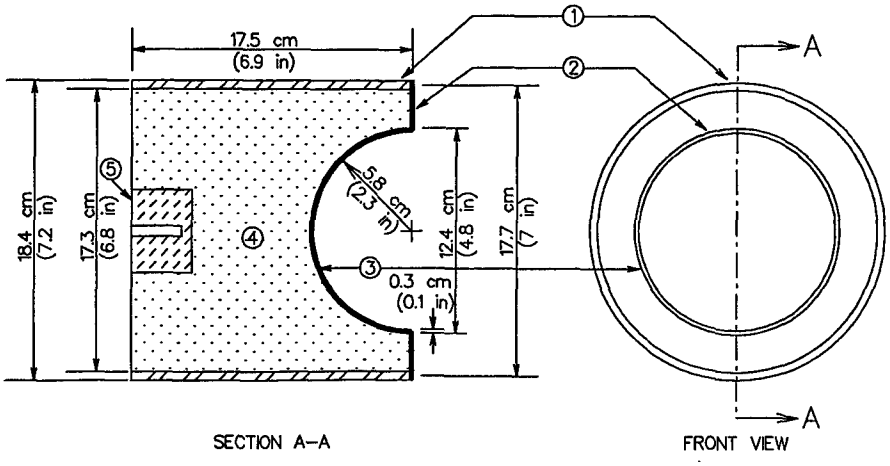


Fig. 4 - Shaped charge

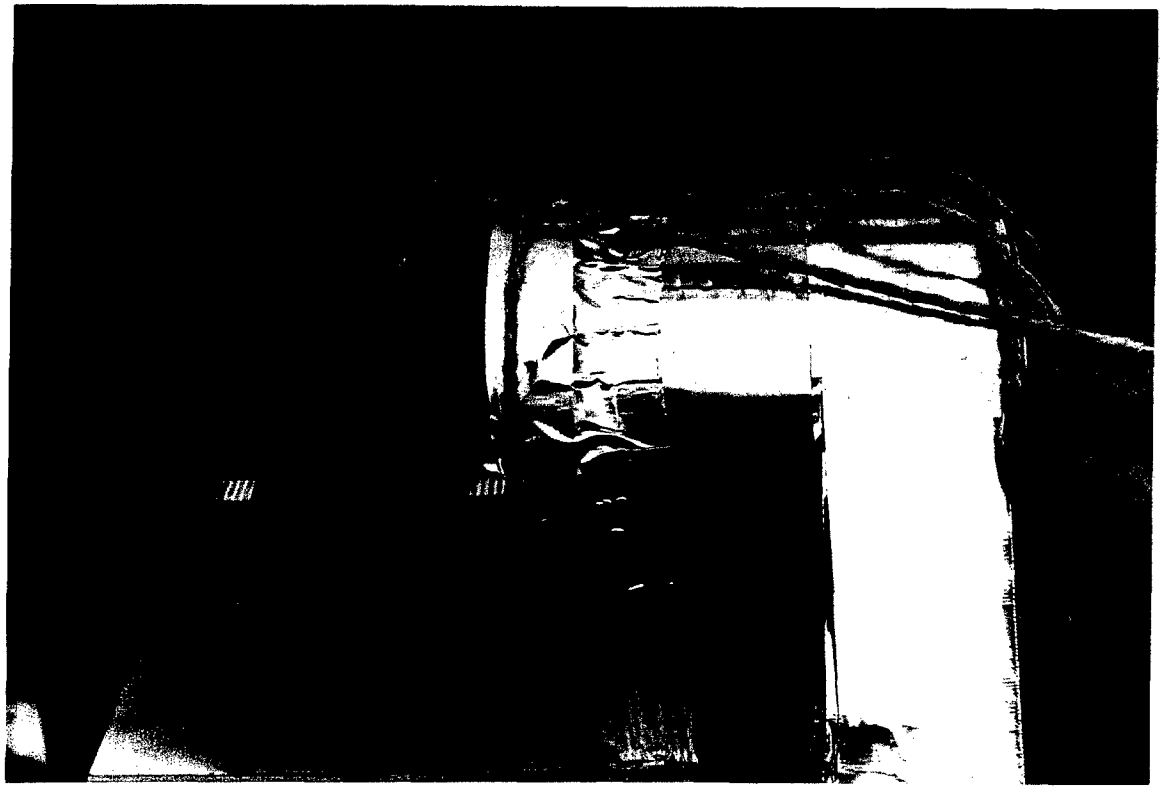


Fig. 5 - Shaped charge with liquid propellant

heat flux, oxygen concentrations, and compartment blast pressures. The instrumentation scheme is shown in Fig.6. Due to safety requirements, the data acquisition systems were activated remotely from a control room located on the hanger deck well aft of the test compartment. A further description of the instrumentation is as follows.

4.2.1 Thermocouples

Four Type "K" thermocouple trees (arrays) were placed in the test compartment. Three trees were positioned equidistant from port to starboard along the centerline of the compartment. The fourth tree was positioned in a void forward in the compartment. These trees consisted of three thermocouples, each spaced 0.6 m (2 ft) apart at heights of 0.6, 1.2, and 1.8 m (2, 4, and 6 ft) above the deck. The thermocouples were glass braided, 36 gauge wires having a response time/time constant of approximately 0.15 seconds.

4.2.2 Ignition Indicators/Targets

Four ignition indicators were fastened to the thermocouple trees at charge level, i.e., 1.25 m (50 in.) above the deck. These indicators were 0.3 x 0.3 m (12 in. x 12 in.) sheets of paper (chemical wipes) each instrumented with a thermocouple. The intent of this configuration was to expose combustibles to the thermal insult produced by the blasts to determine if ignition would occur and to measure the temperature and time that ignition occurred.

4.2.3 Total Heat Flux Transducers (Calorimeters)

Three Medtherm Schmidt-Boelter fast response (0.05 s response time) total heat flux transducers (Model 64-10F-205B) were mounted in the fire compartment. These transducers were installed at charge level, i.e., 1.25 m (50 in.) above the deck, on the aft bulkhead equidistant from port to starboard. From these measurements, the likelihood and time to ignition of various combustibles can be estimated.

4.2.4 Radiometers

Three Medtherm Schmidt-Boelter fast response (0.05 s response time) radiometers (Model 64-10F-205B, 1SW-1C-150) were also installed along side of the total heat flux transducers. These instruments measure the radiant exposures in the fire compartment. The

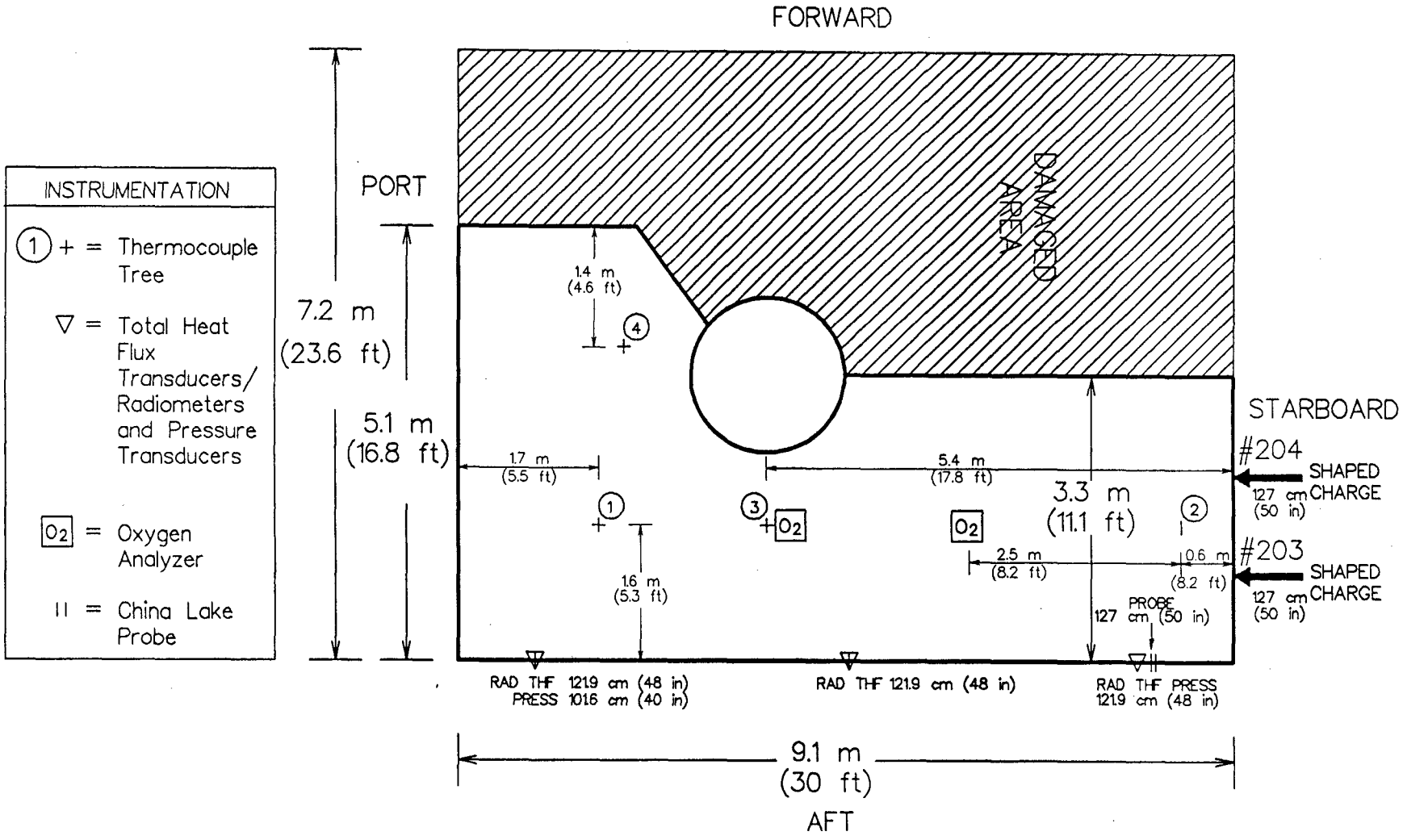


Fig. 6 - Instrumentation layout

approach of installing the radiometers and calorimeters side by side aids in determining the radiant and convective components of the overall exposure.

4.2.5 Oxygen Analyzers

Oxygen concentrations were measured at two locations in the overhead of the test compartment. These measurements served two purposes. The first was to aid in the prediction of ignition of Class A materials, and the second was to assist in estimating the energy released during both tests.

4.2.6 Pressure Transducers

Two Endevco piezoresistive (Model 8530C-50) pressure transducers were used to measure the compartment blast pressures during these tests. Black silicon grease (high carbon content) was used to cover the face of the transducer to negate radiative effects.

4.2.7 Data Acquisition Systems

Two data acquisition systems were used to collect data during these tests. Both systems consisted of an MS-DOS based 50 MHZ/486 computer and computer interface produced by Metrabyte Corporation.

One system was designed to collect data from the pressure transducers at high speed (5 kHz). This system consisted of the above computer, a Metrabyte DAS-16F interface, and a STA-16 terminal board.

The second system was used to scan all of the instruments at a slower rate (50 Hz). This system consisted of the above computer, a Metrabyte DAS-8 interface, and three EXP-16 multiplexer cards.

A commercially available software package (Labtech Notebook) was used to drive both systems. Each system also contained a break-wire positioned in the fire compartment to flag the detonation of the warhead.

4.2.8 Video and 35-mm Still Cameras

Photographs, both still and motion, were made of each test. These records served as the means to analyze conditions inside and outside the fire compartment and were archived to serve as a visual record.

5.0 RESULTS AND DISCUSSION

Two tests were conducted on July 15, 1993 approximately 21 kilometers (13 miles) off the coast of La Spezia, Italy. The first test (Martest 203) consisted of the shaped charge without liquid fuel, and the second (Martest 204) consisted of the shaped charge with four liters (~1 gal) of diesel fuel to simulate a liquid rocket propellant. The results from these tests are summarized in Table 1, which shows the peak values for temperature, heat flux and pressure and minimum values for oxygen.

Table 1. Summary of SCJ Tests

	Martest 203 Test #1 No Fuel	Martest 204 Test #2 with Fuel
Temperatures (°C), Peak		
Starboard Tree	150	350
Center Tree	165	140
Port Tree	190	125
Forward Tree	50	165
Ignition Indicated	No	No
Exposures (kW/m^2), Peak		
Starboard Radiant Heat Flux	3.7	60.0
Starboard Total Heat Flux	4.7	65.0
Center Radiant Heat Flux	4.5	12.0
Center Total Heat Flux	8.5	13.0
Port Radiant Heat Flux	---	---
Port Total Heat Flux	22.5	---
Oxygen Concentrations (%), Minimum		
Starboard	20.0	17.0
Port	19.0	18.5
Pressure (psi)		
Starboard	---	---
Port		
Peak	7.5	7.0
Steady	4.5	7.0/4.0

5.1 Test 1/Martest 203

A series of photographs capturing the blast sequence for Test 1 is shown in Figure 7. The charge did not pass directly through the ship as anticipated. Instead the shaped charge entered the ship through the 1.25 cm (0.5 in.) thick hull on the starboard side and continued across the ship striking the aft bulkhead approximately three-quarters of the way across the compartment as shown in Fig. 8. The warhead cut an almost perfect circular opening through the starboard hull as shown in Fig. 9a. The blast fragment pattern was approximately 1.0 m (~ 3 ft) in diameter and consisted of holes and deep pits on the aft bulkhead as shown in Fig. 9b. Other than the area in the blast pattern and the hole through the hull, the compartment was relatively unaffected by the blast.

The thermal insult to the compartment resulting from the shaped charge jet was of low intensity and extremely short duration. The temperatures measured along the line of the shot (Figs. 10a - 10d) were found to increase rapidly, reaching a peak value of up to 190°C, depending on the height, and then rapidly decay, i.e., within two seconds the temperatures were back to baseline, i.e., 30°C. The center thermocouple tree (tree #3 - Figure 10b) was hit with blast fragments during this test resulting in a longer period of time for the thermocouples to return to ambient temperatures. The highest temperature recorded on each tree was measured at the approximate height of the shot (1.2 m (4 ft)). The overall thermal pulse was found to be higher on the port side of the ship than on the starboard side (where the jet originated). This may be attributed to two factors: (1) the convective heat transfer may have been greater on the port side due to the spreading of the blast pattern with increased distance from the charge; and (2) when the fragments (molten metal) struck the port bulkhead, small amounts of materials (paint, etc.) may have briefly ignited. On the other hand, the temperature rise in the area remote from the blast (Tree 4) was negligible.

The radiant and total heat flux measurements also followed the same trend with the fluxes increasing with increased distance from the blast (Figs. 11a-c). The peak values were reached in less than 50 ms. In this case, this higher exposure on the port side may not only be attributable to the spreading of the pattern or localized ignition but may also be a function of the distance between the radiometers and the plasma jet. The jet struck the aft bulkhead near the port side of

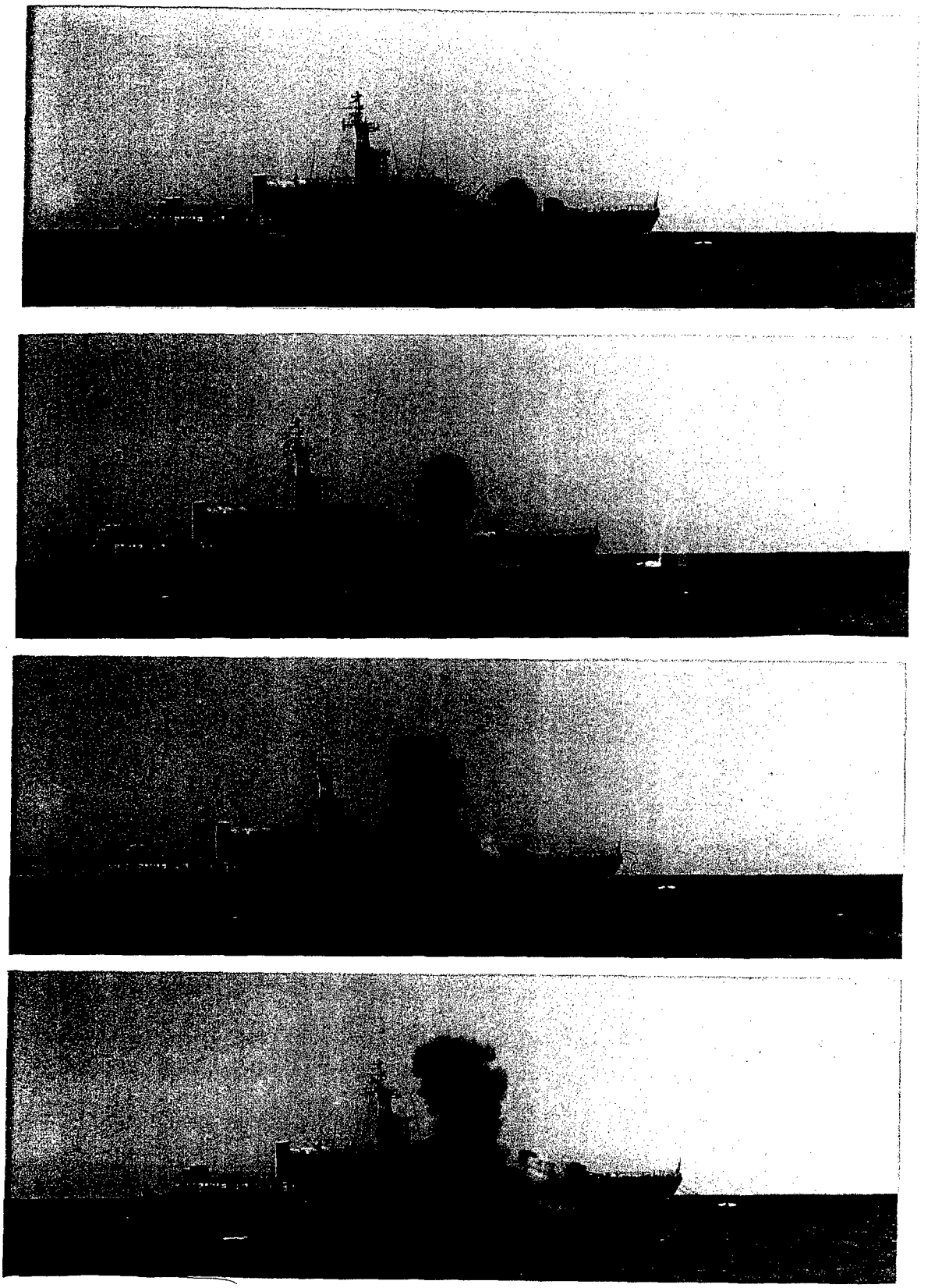


Fig. 7 - Martest 203 blast sequence

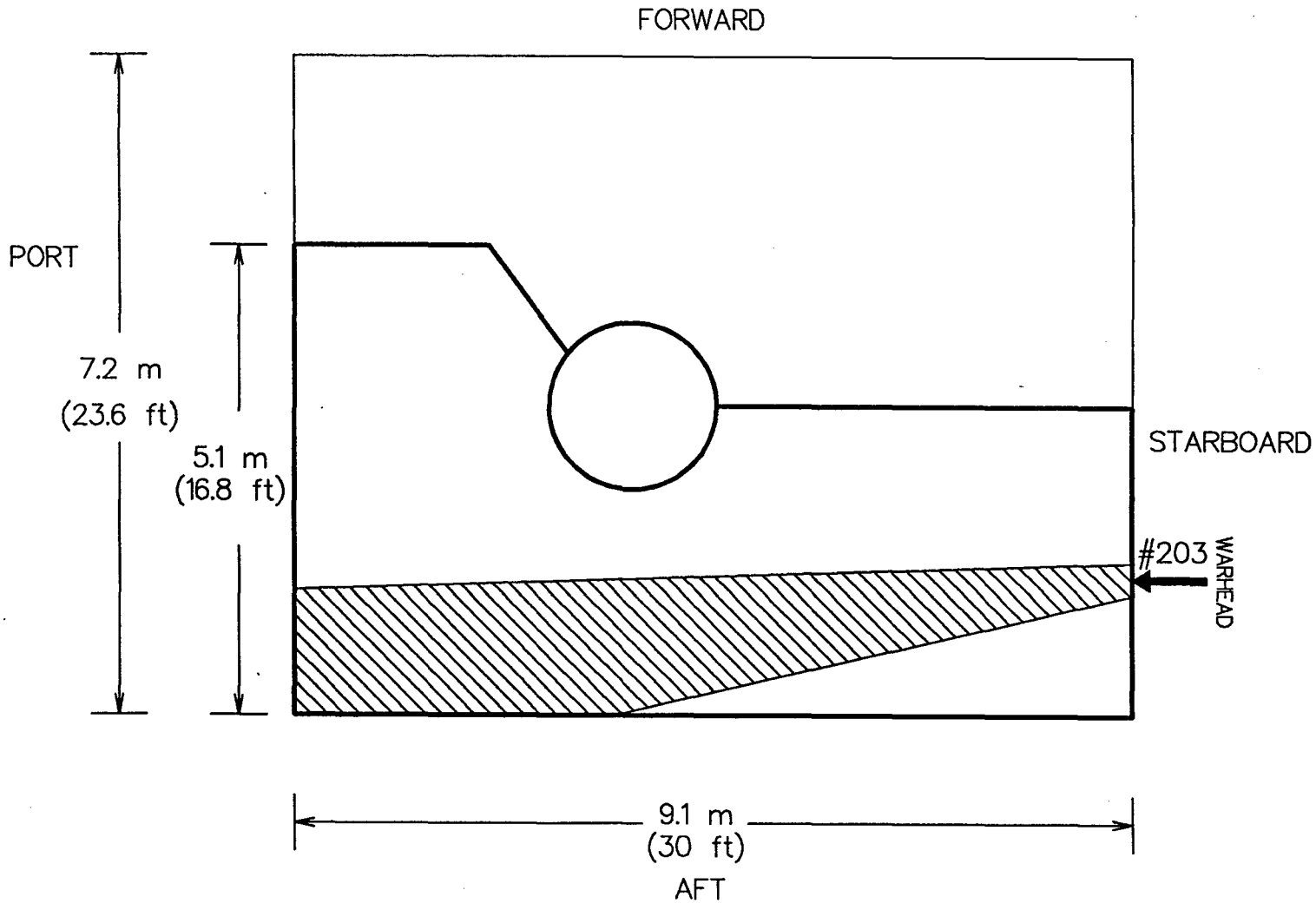


Fig. 8 - Martest 203 blast path

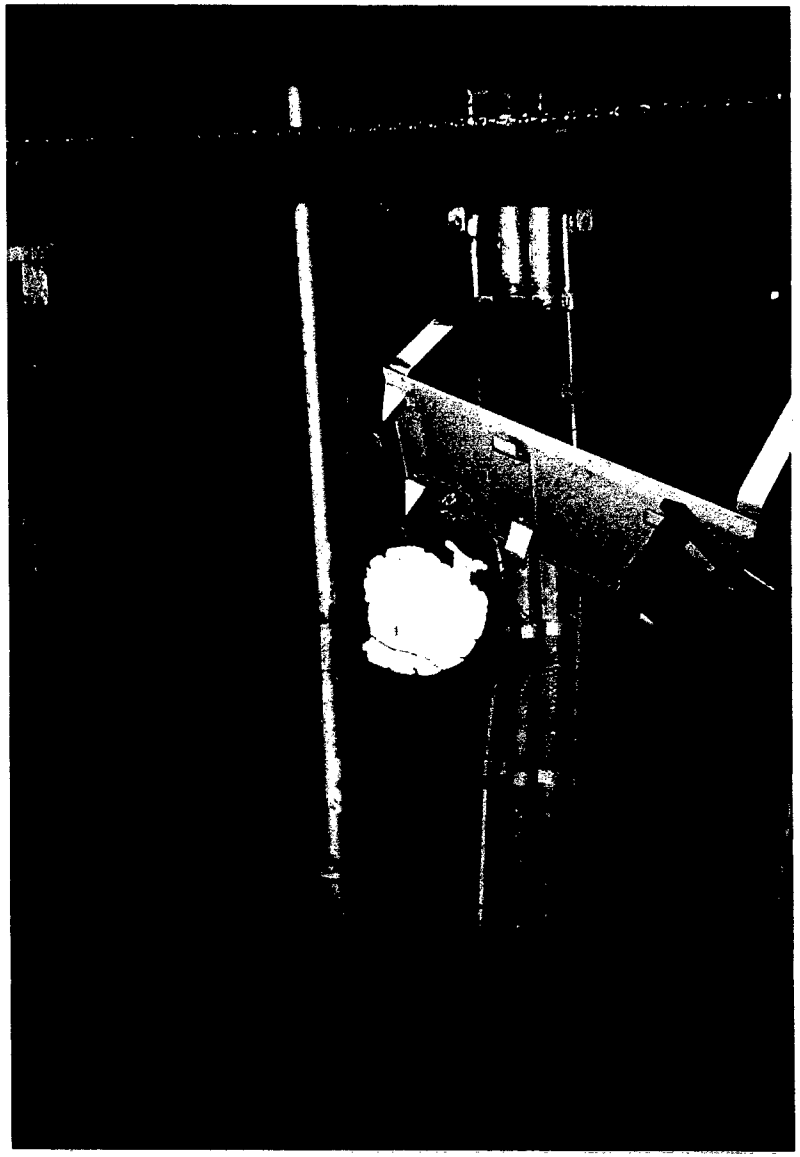


Fig. 9a - Martest 203 blast

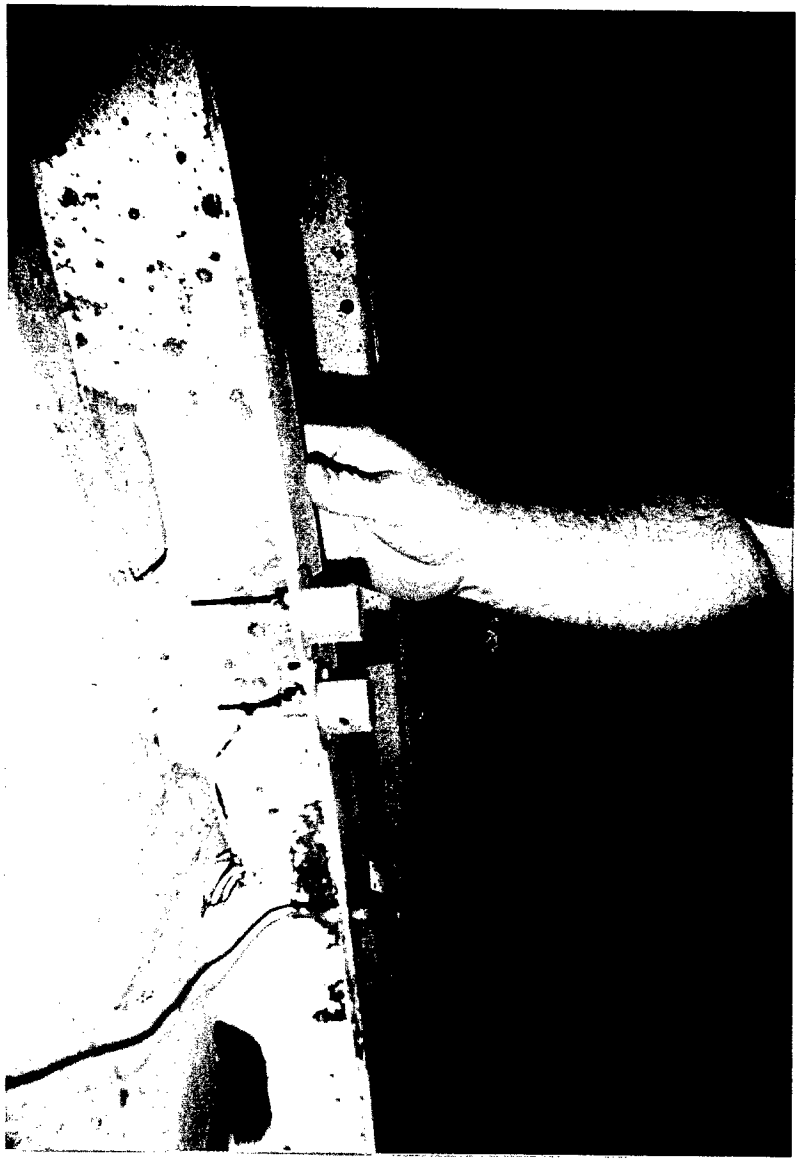


Fig. 9b - Martest 203 fragment illustrations

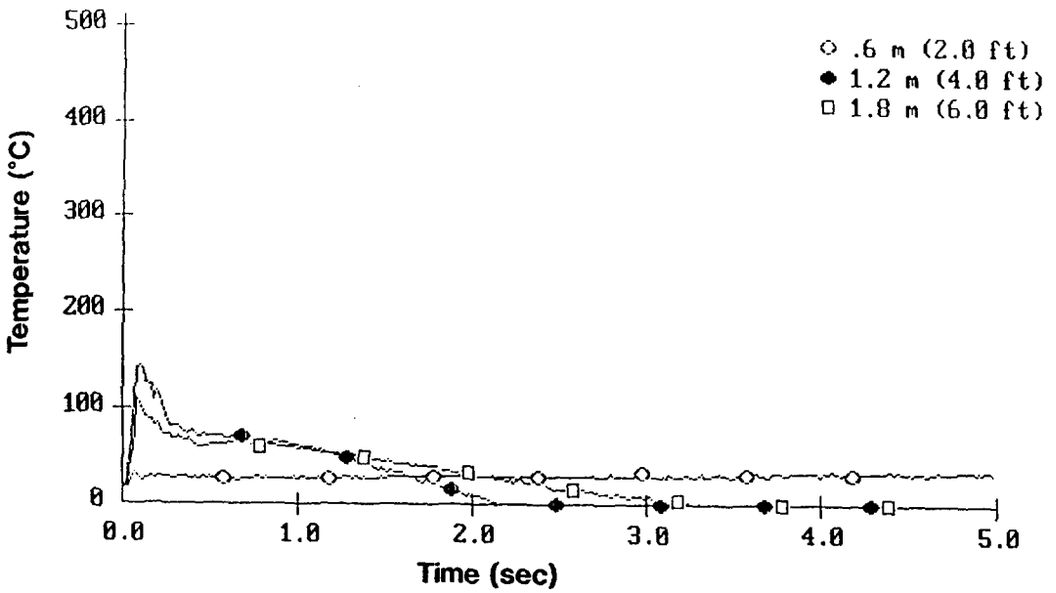


Fig. 10a - Fire compartment temperatures (starboard tree #2) Test #1

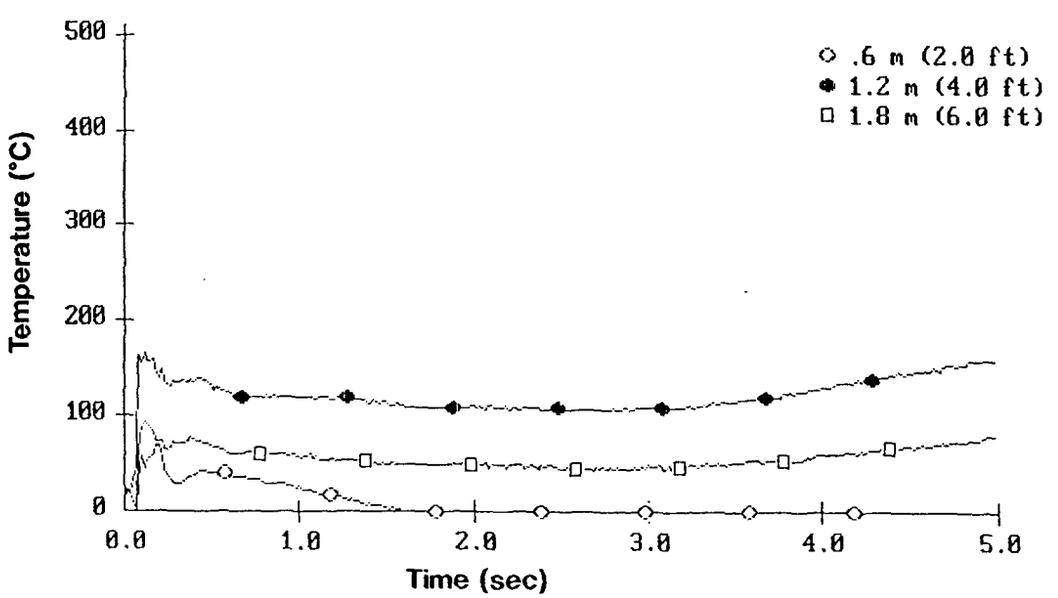


Fig. 10b - Fire compartment temperatures (center tree #3) Test #1

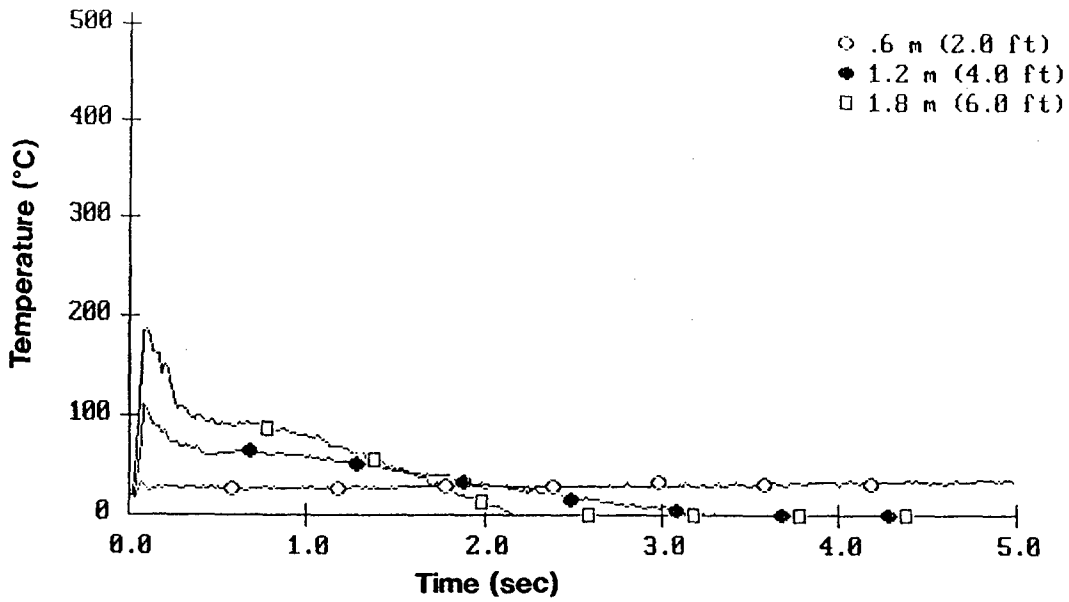


Fig. 10c - Fire compartment temperatures (port tree #1) Test #1

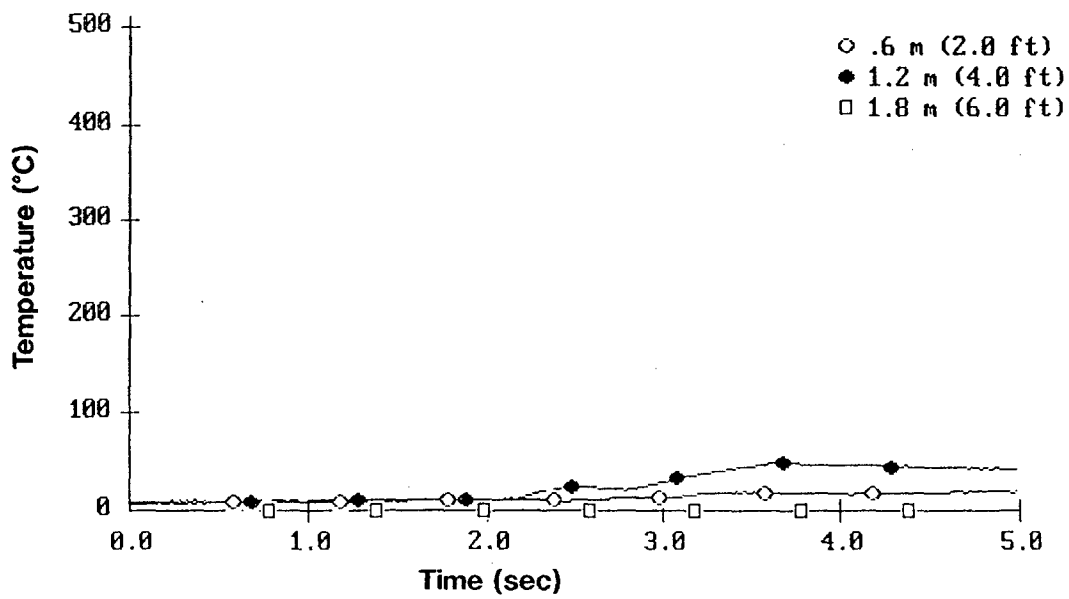


Fig. 10d - Fire compartment temperatures (forward tree #4) Test #1

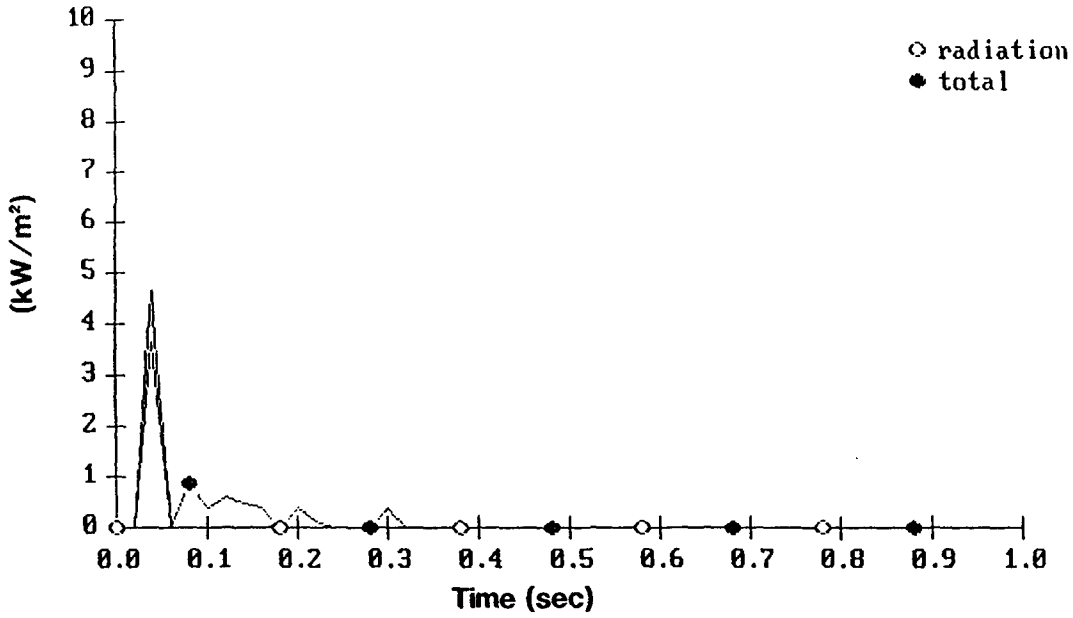


Fig. 11a - Fire compartment exposures (starboard) Test #1

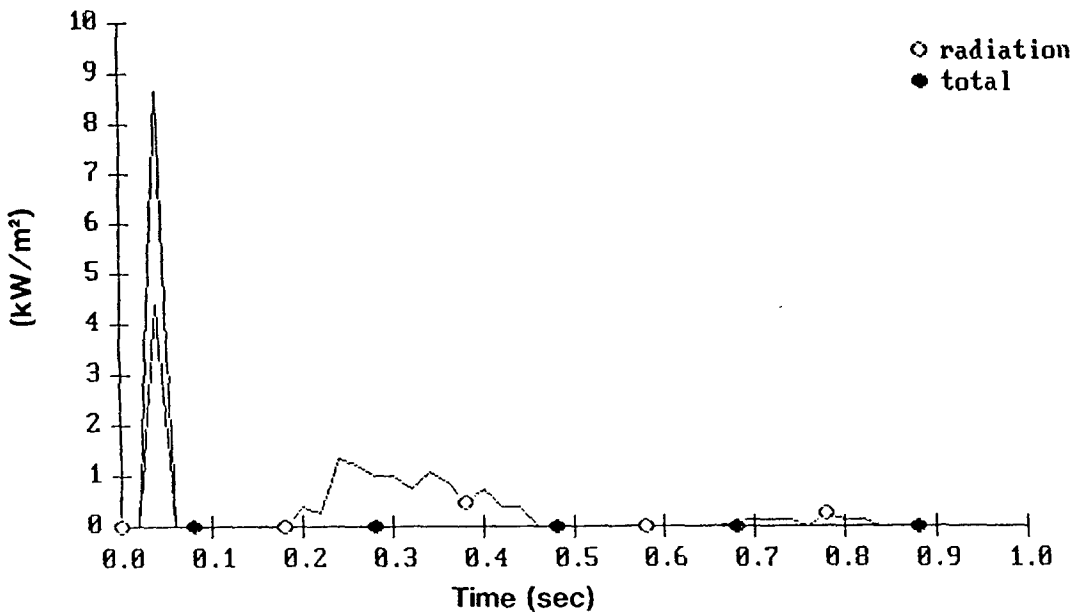


Fig. 11b - Fire compartment exposures (center) Test #1

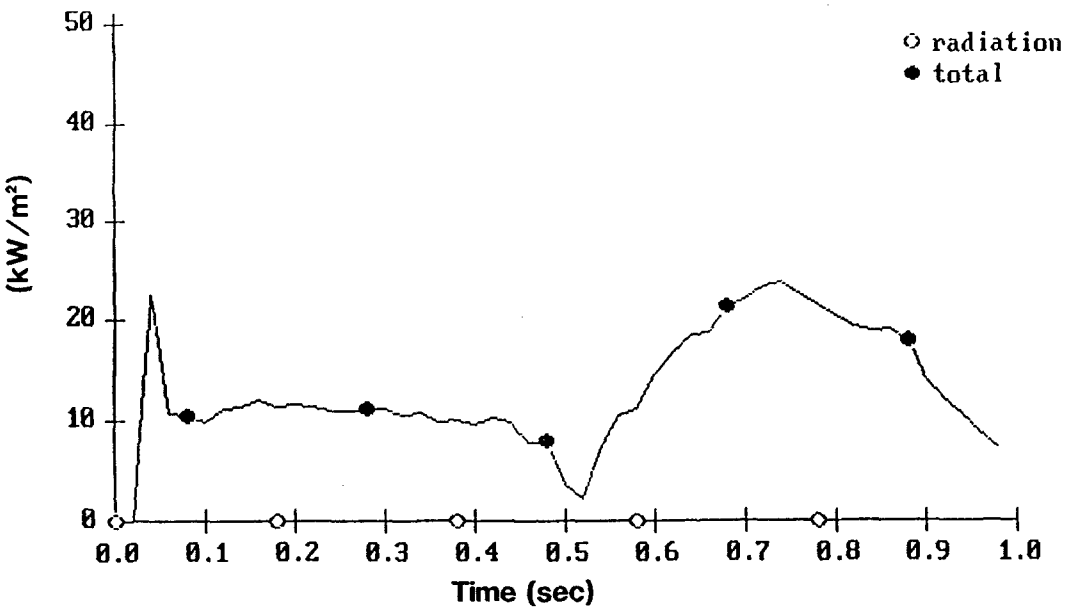


Fig. 11c - Fire compartment exposures (port) Test #1

the ship shortening the distance between the jet and the radiometers at this location. The maximum total heat flux was recorded as 22.5 kW/m^2 (2.0 Btu/ft^2 sec). The maximum radiant flux was measured as 4.5 kW/m^2 (0.4 Btu/ft^2 sec). For comparison, it was shown in separate test that a total exposure on the order of 150 kW/m^2 sec is required to ignite paper [7]. When considering the thermal/radiant exposure produced by the charge only lasts 0.1 seconds, a heat flux of 1500 kW/m^2 would be required to cause ignition, far in excess of the peak value of 22.5 kW/m^2 recorded in this run.

The oxygen concentrations during this test (Fig. 12) remained fairly constant at about 20 percent although there was a slight momentary drop to 19 percent on the port side, suggesting some minor burning in this area. At any rate, the oxygen concentration in the compartment was high enough throughout the test to support combustion if any Class A material had been ignited.

The low intensity short duration thermal pulse had no effect on the four ignition indicators as shown in Fig. 13. The thermocouples positioned in/above the materials recorded temperature increases of less than 30°C. For comparison, the accepted spontaneous ignition surface temperature of Class A materials is 400-500°C [4], almost three times that recorded anywhere in the compartment.

Although the ignition indicators did not ignite, another possible source of ignition could have been hot fragments resulting from the SCJ. If hot fragments had landed on a Class A material, this too could have caused ignition. However, in this case, the hot fragments did not land on the ignition indicators, but rather impacted the bulkhead on the port side of the compartment.

Although two pressure transducers were also installed for this test, the transducer on the starboard side of the ship was damaged by the blast, and hence, no readings were obtained at this point. However, the port pressure transducer worked properly and recorded a peak pressure of 51.7 kPa (7.5 psi) 19 ms after the blast (Fig. 14). The duration of the pressure wave was measured to be 5 milliseconds (ms). This relatively high pressure, but short duration pulse

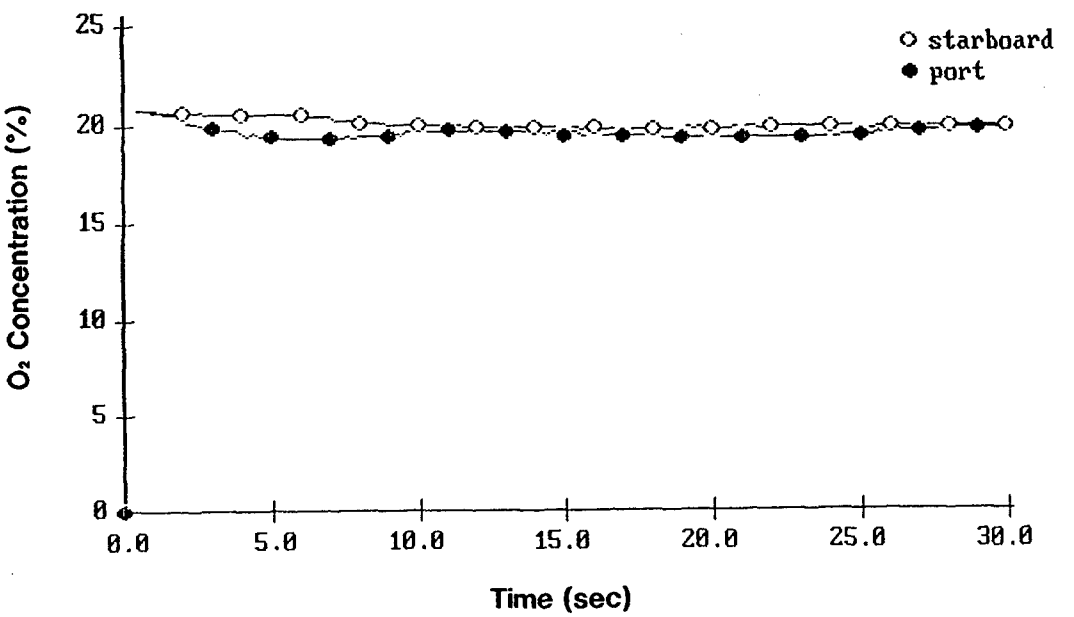


Fig. 12 - Fire compartment oxygen concentrations Test #1

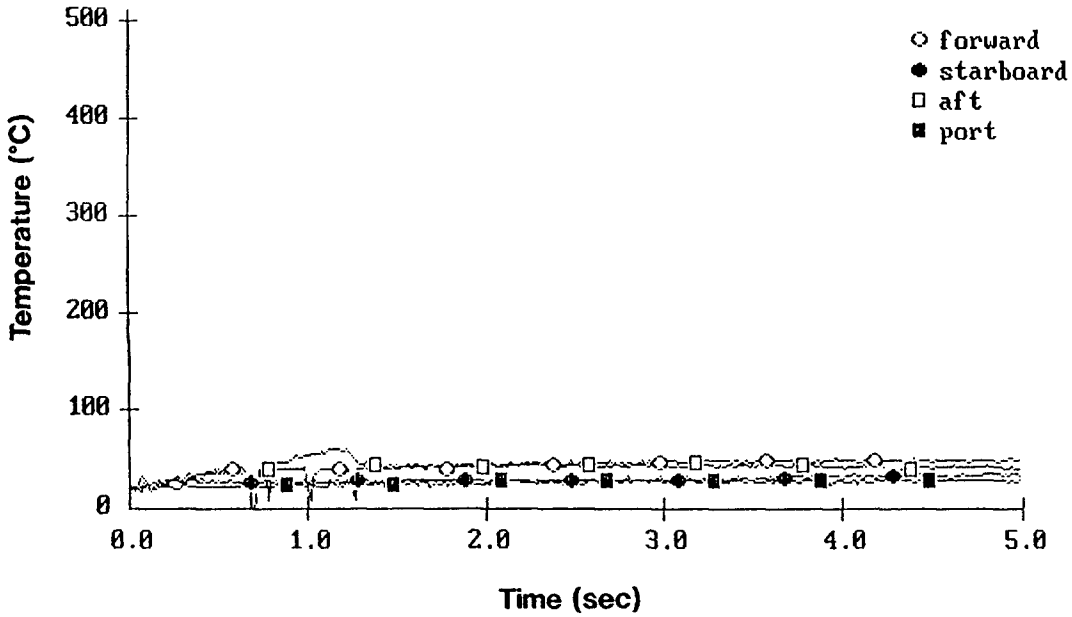


Fig. 13 - Ignition indicator temperatures (all) Test #1

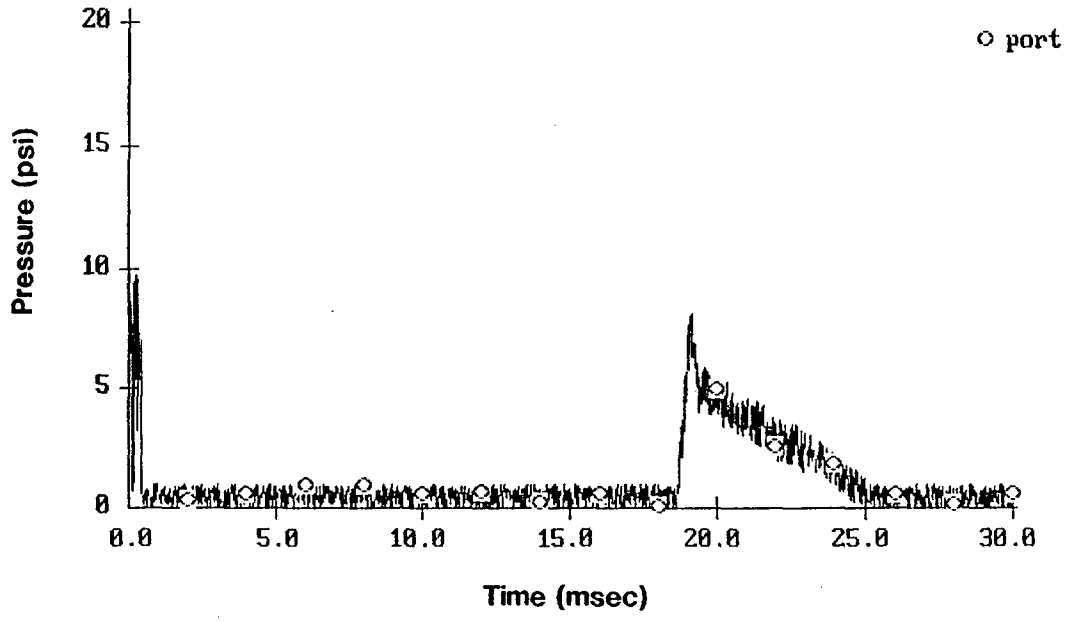


Fig. 14 - Fire compartment pressures in Martest 203

inflicted no visible damage on the compartment. (The initial pressure spike at < 1.0 ms was attributed to the detonation of the warhead.)

5.2 Test 2/Martest 204

A series of photographs capturing the blast sequence in Martest 204 is shown in Fig. 15. The jet did not cut cleanly through the hull as in Martest 203, but rather left two semicircular openings which served to deflect the jet towards the overhead and towards the deck (Fig. 16a). The same types of openings (Figs. 17a and 17b) were observed in the China Lake tests [2], namely a clean hole when no fuel tank was used (Fig. 17a) and a partially cut hole when the fuel tank was placed in front of the SSCJ warhead. In Martest 204, it appeared that the majority of the diesel fuel carried by the blast was entrained through the upper opening, producing an inefficient fuel/air explosion at this location. This is evident by the residue/char pattern observed on the overhead at this location (Fig. 16a). A portion of the jet did, however, pass through the entire ship exiting the port bulkhead. The presence of the fuel tank significantly altered the conditions in the compartment.

The temperature profiles obtained for the second test (Martest 204) are shown in Fig. 18a-d. The most severe thermal conditions occurred on the starboard side of the ship rather than on the port as in the previous test (compare Figs. 18a and 10a). This was attributed to the inefficient fuel/air explosion. The temperatures measured during this test reached 350°C on the starboard side decreasing across the compartment to 125°C on the port side. The duration of the pulse was also lengthened from less than a half-second to over a second by the combustion of the fuel as shown in Fig. 18a-d.

The radiant and total heat flux measurements were also dramatically higher for the second test (compare Figs.11a-c and 19a-c). The maximum exposures were measured on the starboard side of the ship with both the radiation and total heat flux levels reaching values over 60 kW/m^2 (Fig. 19a). This increase was well over an order of magnitude greater than those measured during the first test. The exposures in the center of the compartment were also observed to increase a factor or two from the first test (averaged from 6.5 kW/m^2 to 12.5 kW/m^2) (see Fig. 19b). Although the heat fluxes recorded in Martest 204 were higher than in Martest 203 and of longer

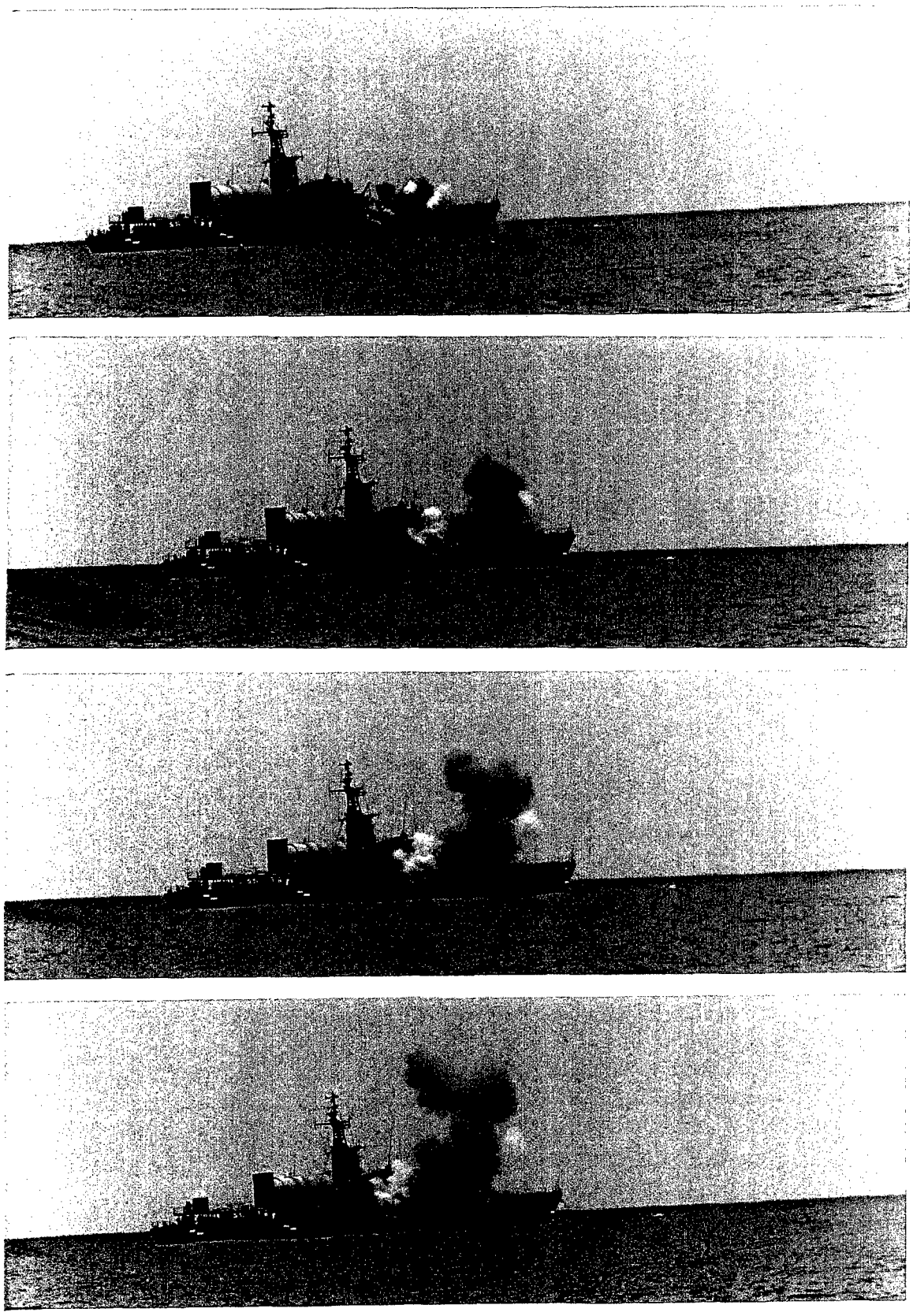


Fig. 15 - Martest 204 blast sequence

Fig. 16a - Martest 204 blast and fragment illustrations (cable that deflected the jet)

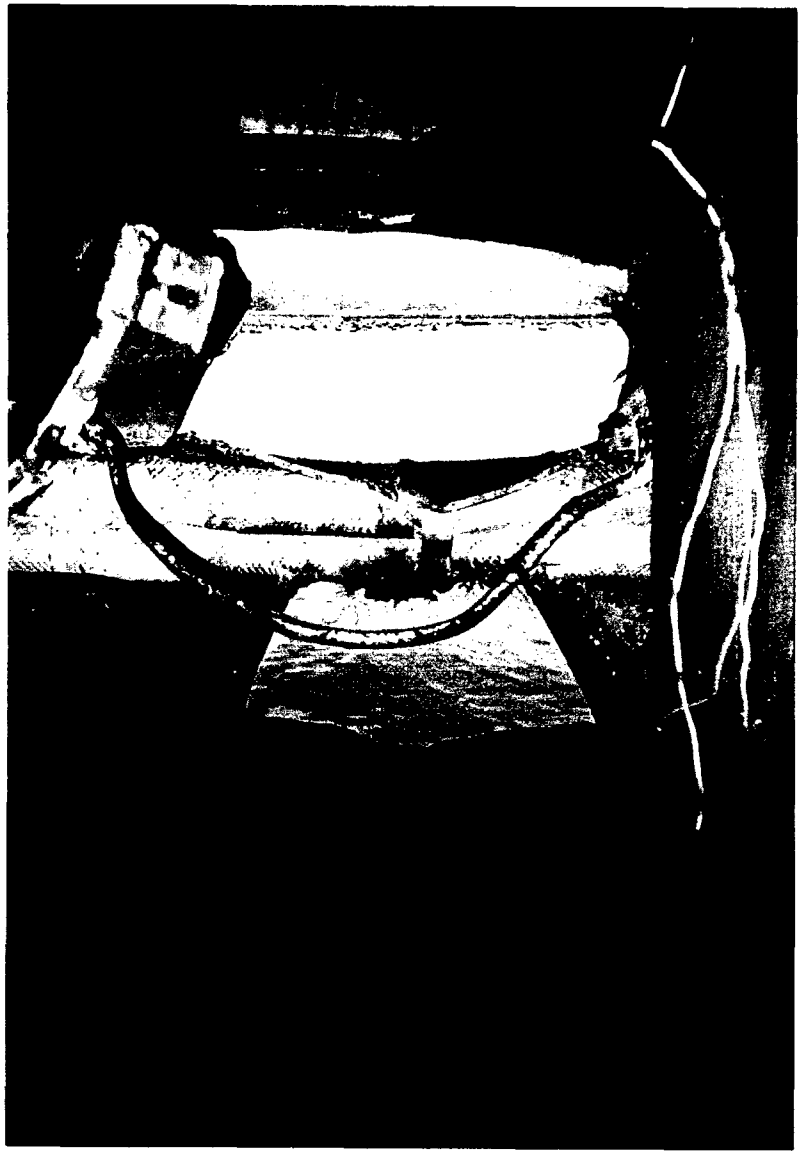


Fig. 16b - Martest 204 blast and fragment illustrations (char pattern on overhead)

Fig. 17a - Clean hole cut by SCJ in absence of fuel tank [2]

Fig. 17b - Partially cut hole obtained when fuel tank was placed in front of SCJ [2]

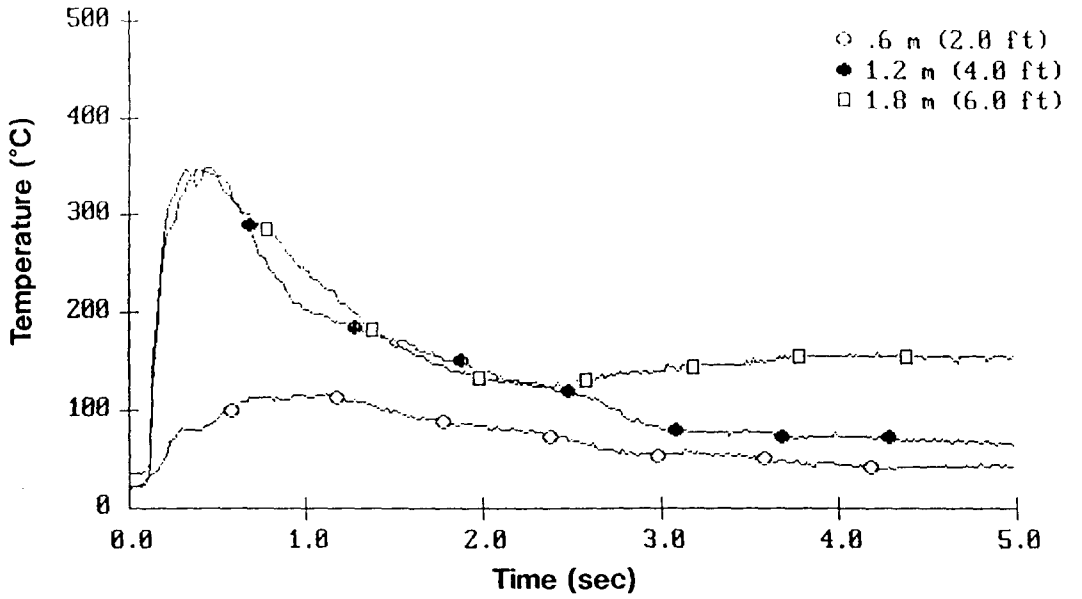


Fig. 18a - Fire compartment temperatures (starboard tree #2) Test #2

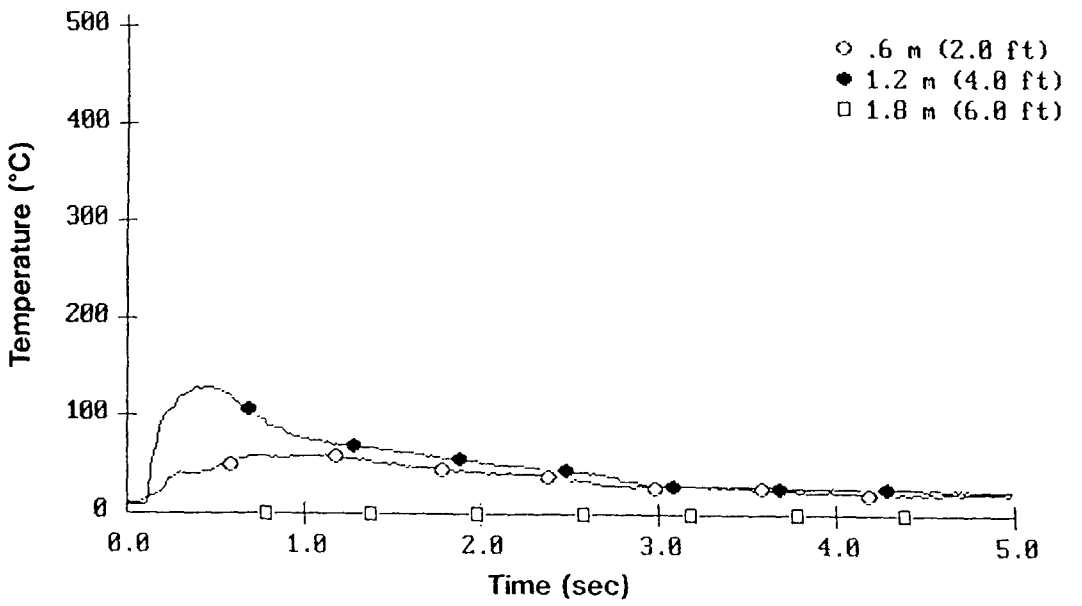


Fig. 18b - Fire compartment temperatures (center tree #3) Test #2

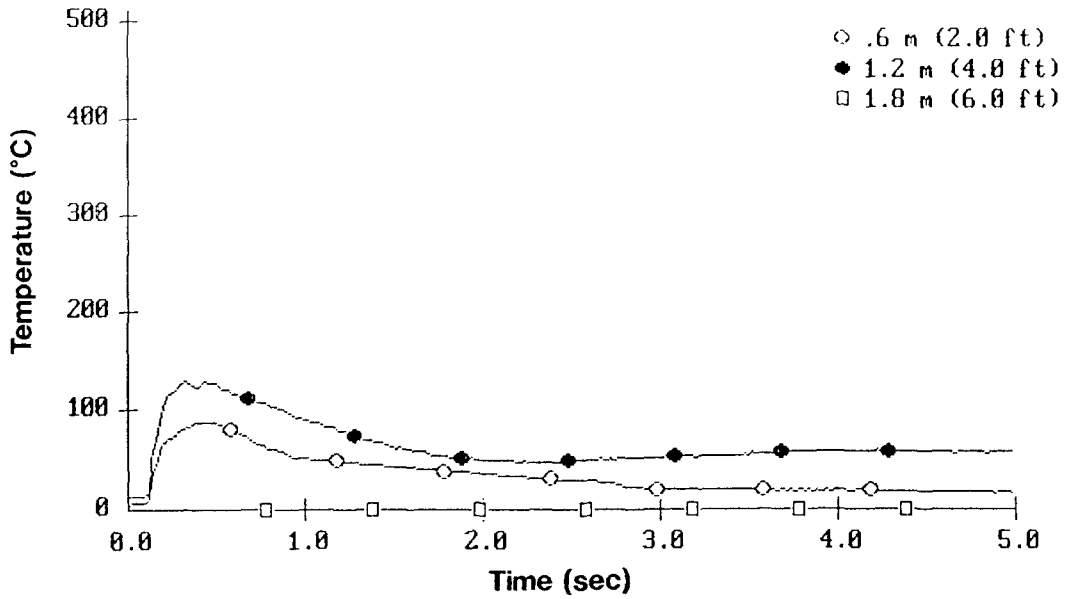


Fig. 18c - Fire compartment temperatures (port tree #1) Test #2

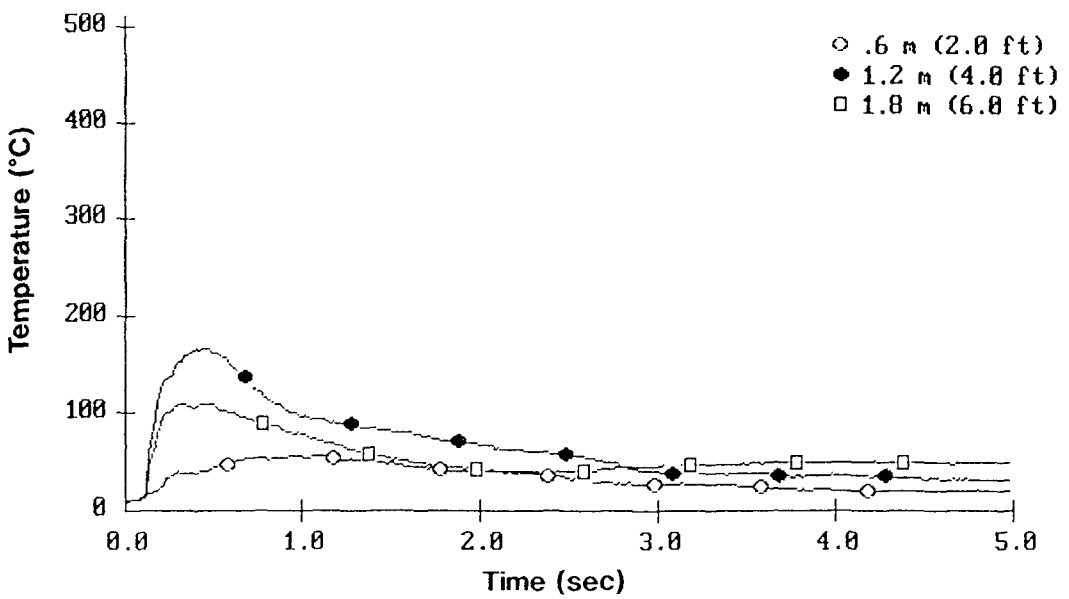


Fig. 18d - Fire compartment temperatures (forward tree #4) Test #2

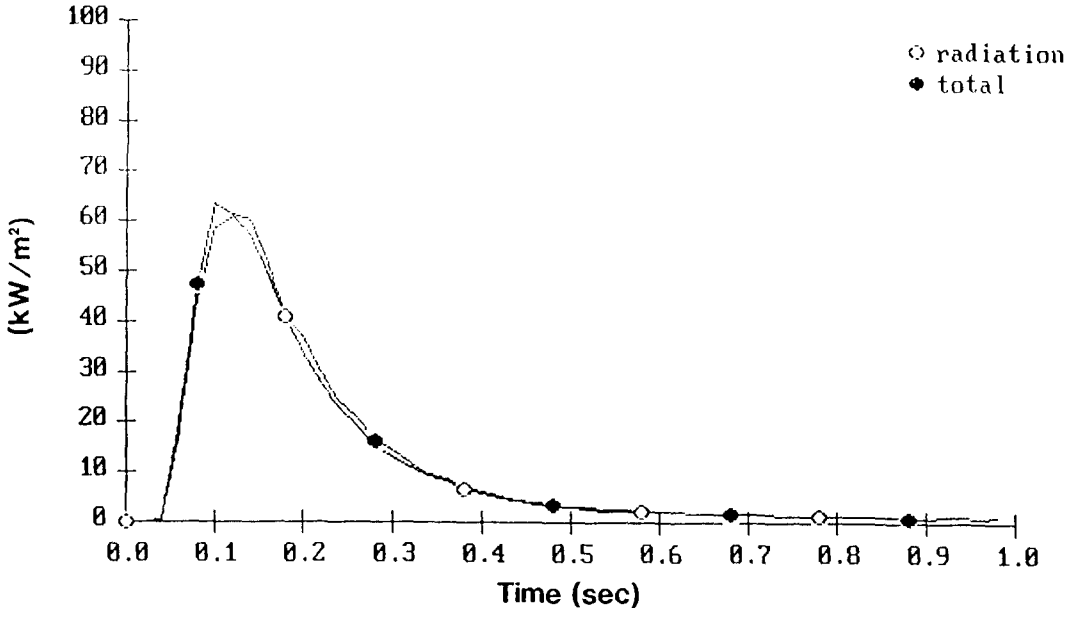


Fig. 19a - Fire compartment exposures (starboard) Test #2

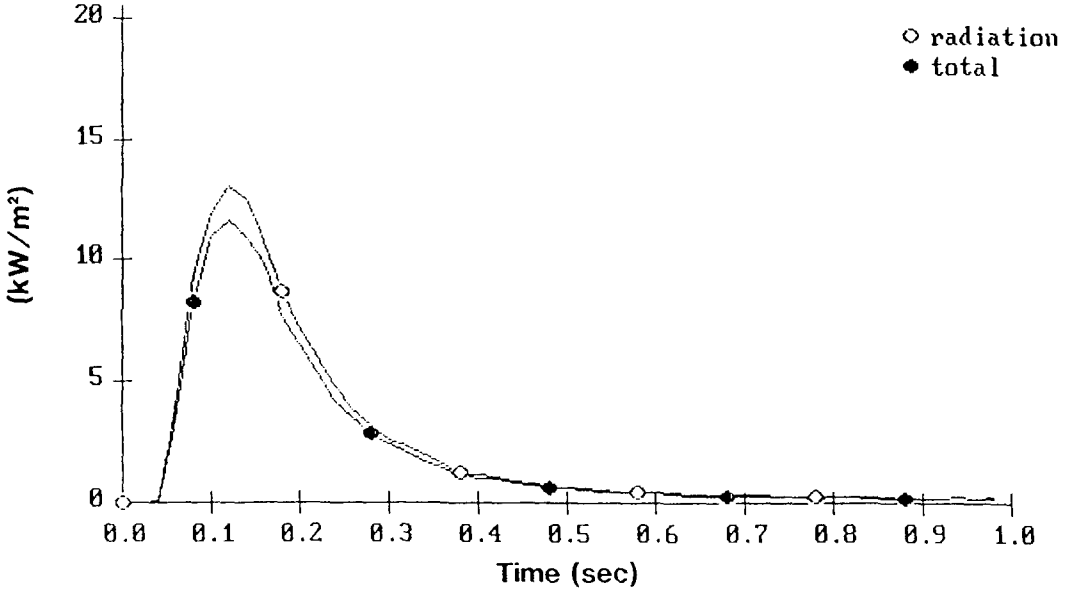


Fig. 19b - Fire compartment exposures (center) Test #2

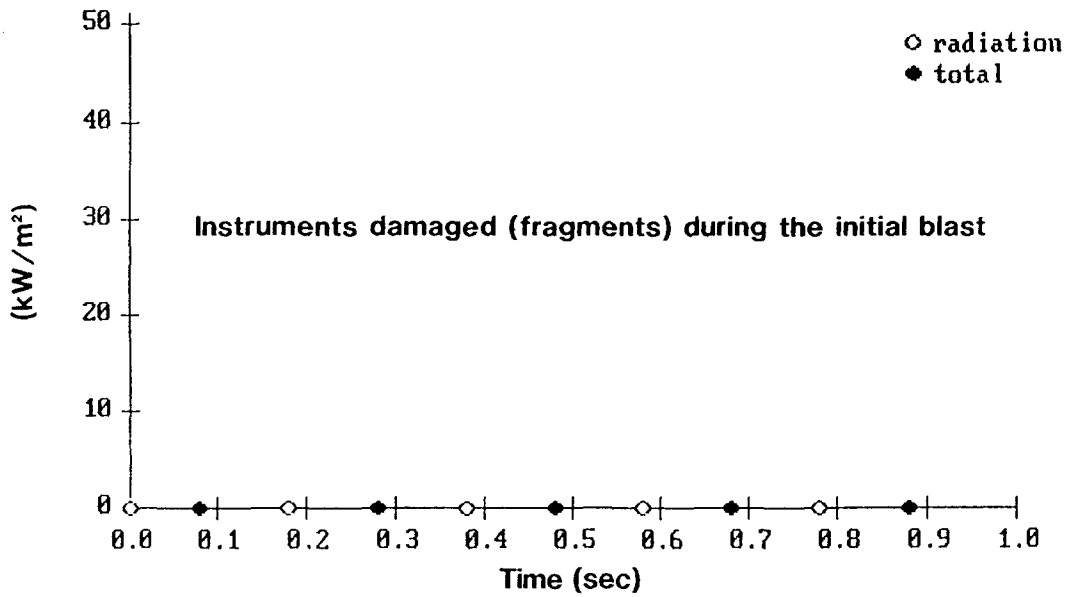


Fig. 19c - Fire compartment exposures (port) Test #2

duration, they were still below the threshold required for ignition of Class A materials. For example, the peak value of 60 kW/m^2 in Fig. 19 would have to be sustained for 2.5 seconds in order to cause ignition compared with only 0.05 seconds in Fig. 19a.

The oxygen concentrations were measured to be lower on the starboard side of the compartment than on the port (Fig. 20). The starboard oxygen concentration was observed to drop to 17% as compared to 18.5% on the port side of the ship. The localized oxygen depletion was the result of liquid fuel burning inside the ship. Although these concentrations were lower than those of the previous test, there was still enough oxygen remaining in the compartment to support ignition and combustion of Class A materials.

Although the intensity of the thermal pulse recorded in the second test (Martest 204) was substantially greater than in the first (Martest 203), the ignition indicators still did not ignite (see Fig. 21). As in the first test, the thermal pulse was of too short a duration to cause ignition of the paper ignition indicators even though there was evidence of combustion of liquid fuel in the compartment.

The combustion of the liquid fuel had very little effect on the shape of the pressure curve. A comparison of the pressure readings for Martests 203 and 204 (Figs. 14 and 22) shows that the peak pressures were approximately the same in both tests (8 psi in Martest 203 and 7 psi in Martest 204), but the pressure was drawn out for an additional 5 ms in Martest 204. The shape of the pressure pulse indicates an initial spike in pressure due to the hull penetration and then a sustained pressure as the fuel/air cloud ignited. The only explanation for the similarity in magnitude between the two tests was the presence of the opening produced during the first test which may have served to vent a portion of the pressure pulse in the second test.

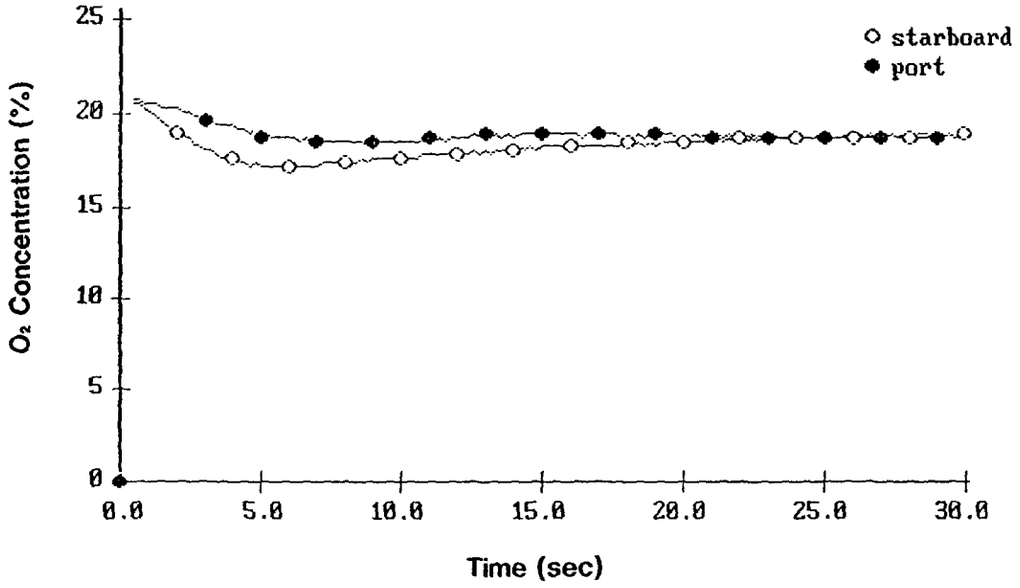


Fig. 20 - Fire compartment oxygen concentrations Test #2

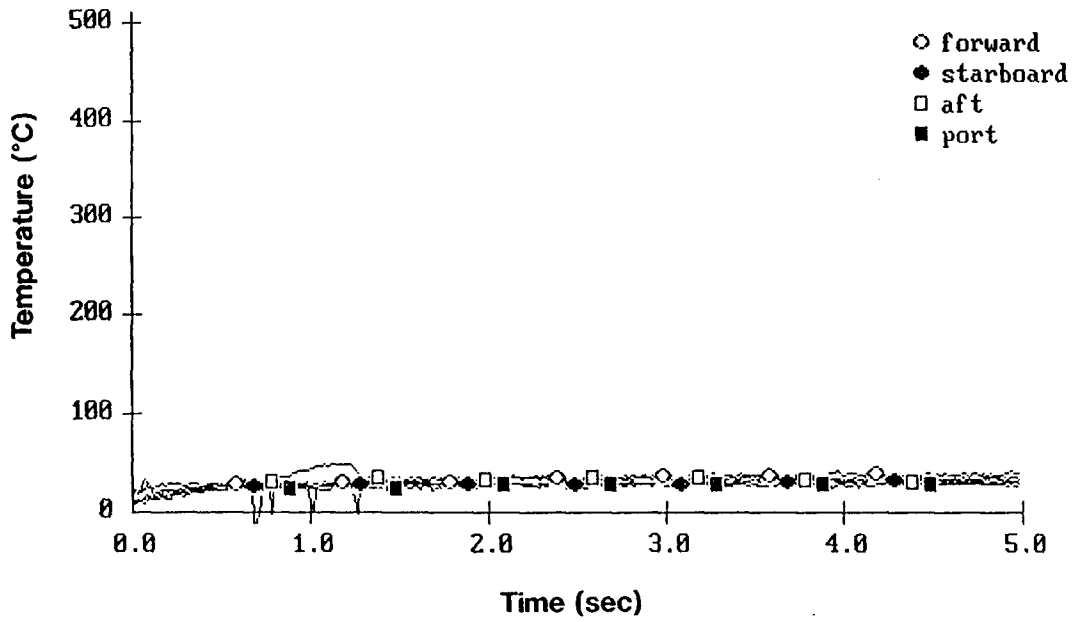


Fig. 21 - Ignition indicator temperatures (all) Test #2

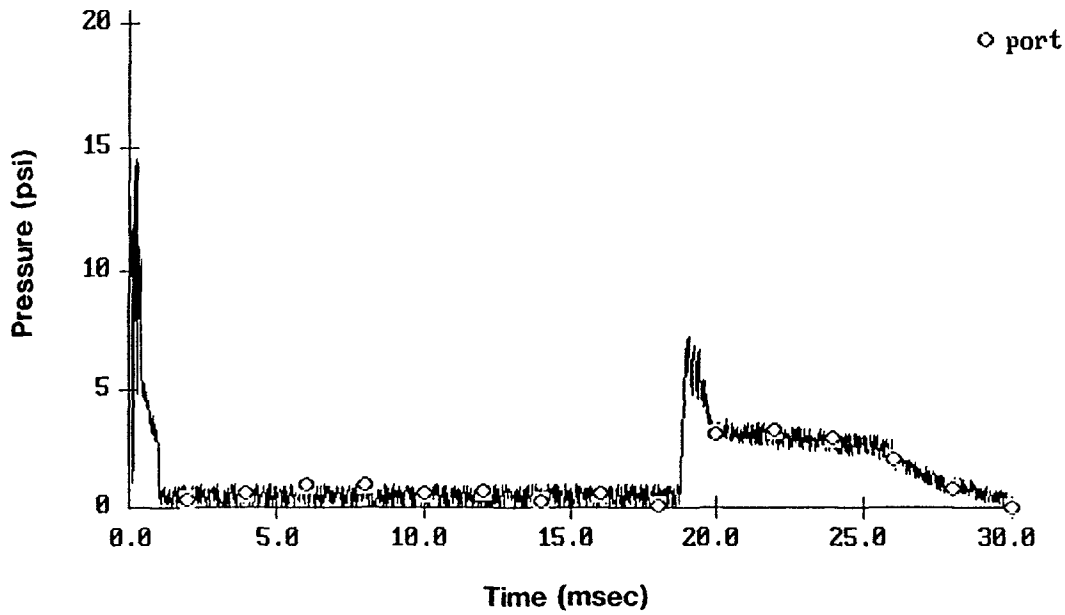


Fig. 22 - Fire compartment pressures in Martest 204

5.3 Contribution of Liquid Fuel

The presence of the liquid fuel in Martest 204 had a significant impact on the conditions in the compartment. Although the conditions dramatically changed between the two tests, the amount of fuel entrained by the charge appears to be relatively low.

The amount of fuel entrained by the blast can be estimated in two ways. The first is based around the amount of energy required to heat the air in the compartment to the measured temperature. These calculations are shown as follows:

$$Q = m\, C_p\, (\Delta T) \qquad \textbf{(1)}$$

where m = mass air $\approx \rho_A V_A \approx 100$ kg;

V $\approx$ volume of the compartment (air), $90 m^3$

ρ_A = density of air, 1.1 kg/m^3;

C_p = specific heat of air, 1040 J/kg K and

ΔT = (100 K) (average difference of all thermocouples between the two tests)

yields Q = 10.4 MJ.

The mass of the liquid propellant can then be estimated as follows:

$$Q = m\, \Delta H_c \qquad \textbf{(2)}$$

where ΔH_c = heat of combustion of the liquid propellant, 42.5 MJ/kg (3.5 kg/gal) (150 MJ/gal) and

m = $Q/\Delta H_c$ = 10.4/150 = 0.07 gal

$\approx$ 7% of the fuel was entrained.

The second approach is based on the oxygen depletion measured in the compartment. The decrease in oxygen concentration is directly proportional to the amount of energy released and consequently the amount of fuel consumed. This calculation is shown as follows.

An average 1.5% O_2 drop was measured between the two tests. Assuming a well mixed compartment, the amount of fuel combusted in the compartment can be estimated as follows:

$$V = \text{volume of the compartment, } 90\ m^3;$$

$$V_{O2}\ \text{consumed} = 90\ m^3 \times 1.5\% = 1.35\ m^3 \text{ or } 1.5\ kg\ (STP);$$

$$Q = (m_{O2})\ (H_{c\text{-}O2}) = (1.5\ kg)\ (13\ MJ/kg) = 19.5\ MJ;$$

$$m = Q/\Delta H_c = 19.5\ MJ/150\ MJ/gal = 0.13\ gal$$

$$\approx 13\% \text{ of the fuel was combusted.}$$

The oxygen depletion approach should overestimate the amount of fuel entrained due to the assumption of a well mixed compartment. In actuality, the compartment was not well mixed with the oxygen depletion occurring only in a localized area. Both approaches estimated the amount of fuel entrained by the blast to be on the order of 10%.

5.4 Overall Threat to Ship

In the present tests, only a small amount, i.e., 0.4 L (0.1 gal) of fuel was entrained by the SCJ and subsequently combusted in the test compartment. Accordingly, the thermal impact on the test compartment was minimal. However, under more practical conditions, the amount of fuel entrained by the warhead depends on several factors, such as at what point during the impact does the warhead detonate; and second, how does the body of the missile and missile fuel momentum affect the entrainment of the fuel. Both of these uncertainties would dramatically affect the outcome of the incident.

However, if we assume that under the worst case conditions, enough fuel was entrained in the compartment to consume all of the available oxygen, the amount of energy released can be estimated as follows.

$$V = 90\ m^3 \approx m_{air} = 100\ kg$$

$$Q = (m_{air})\ (Hc_{air}) = (100\ kg)\ (3\ MJ/kg) = 300\ MJ$$

The amount of liquid propellant required to consume all of the oxygen in the compartment is a relatively small quantity (7.5 L (2.0 gal)). Using Equation (1), the resulting air temperature could be estimated as follows (ignoring dissociation of products):

$$Q = m\,Cp\,\Delta T$$

where $\Delta T = Q/m\,Cp = (300{,}000\ \text{kJ})/(100)\ (1.04\ \text{kJ/kg K})$

$\Delta T = 2885\ \text{K}$

This temperature rise would relate to a pressure pulse of 160 psi (based on the ideal gas law). This magnitude of both the temperature and pressure pulse would severely damage the ship. Temperature increases of 2000 K and pressures of 120 psi have been widely observed in confined fuel/air explosions. Of course, larger compartments could contain more available oxygen and hence could combust significantly greater quantities of entrained fuel.

6.0 CONCLUSION

The following was concluded from the present study:

- Penetration of a ship compartment by a shaped charge jet by itself, i.e., in the absence of entrained missile propellant, will not cause ignition of Class A materials due to the extremely short duration of the thermal pulse. However, hot fragments generated by the warhead could result in ignition if the fragments happened to land on easily ignited Class A material.

- If the shaped charge jet entrains missile propellant, there is a potential for a serious fire or explosion depending on the quantity of propellant ingested into the compartment and the volume of air available.

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