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Submarine Hydraulic Fluid Explosion Mitigation and Fire Threats to Ordnance

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14. ABSTRACT

Previous work has shown that leaks in submarine hydraulic systems can produce sprays and mists that are highly flammable and potentially explosive. To evaluate the feasibility of using currently available fire extinguishing technologies for preventing or mitigating these explosions, large-scale tests were conducted in the SHADWELL/688 test area aboard ex-USS *Shadwell*. PKP, AFFF, carbon dioxide, and water (applied with a Vari-Nozzle, a Navy applicator, and a water mist spray system) were evaluated. PKP prevented the explosions; the other agents were ineffective.

Additional testing was performed to characterize the fire threat to ordnance located in the torpedo room. It was found that the temperature produced, even by small spray fires, exceeded the maximum safe temperature limits for the Mk-48 torpedo.

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SUBMARINE HYDRAULIC FLUID EXPLOSION MITIGATION AND FIRE THREATS TO ORDNANCE

1.0 BACKGROUND

The fluid used in the interior hydraulic systems of US Navy submarines, identified as 2190 TEP hydraulic fluid, is, by design, relatively non-flammable in bulk, having a minimum allowable flash point, as specified by MIL-PRF-17331H [1], of 204 °C (400 °F). However, when atomized, 2190 TEP is known to be highly flammable and, under some conditions, may be explosive [2]. The long history of fires and explosions associated with hydraulic fluids bears this out. Examples include:

1. a hydraulic spray fire in a Titan II missile silo that resulted in 53 fatalities [3];
2. an explosion on an oil drilling platform triggered by a static discharge [4]; and
3. a hydraulic fire in a wheel assembly plant where the ignition source was an electric light bulb [5].

The common thread in the above incidents was the production of a fine spray or mist, due to a leak in a pressurized hydraulic line, and the subsequent ignition of that spray. To date, no hydraulic system fires or explosions have been reported aboard modern, US nuclear submarines. However, due to the high operating pressures of submarine hydraulic systems (approximately 3000 psi for the USS Los Angeles class) hydraulic system casualties are likely to produce such mist clouds and the possibility that they could be ignited should not be ignored. Furthermore, it should be noted that no US nuclear submarine has ever seen hostile action. It is reasonable to suspect that the probability of occurrence of a hydraulic system fire or explosion might be higher, perhaps significantly higher, for submarines involved in hostilities than the peacetime record may suggest.

As a result of these concerns, the Naval Research Laboratory (NRL) submitted a proposal to the Department of Defense Office of Live Fire Test and Evaluation (LFT&E) to investigate submarine hydraulic fire and explosion hazards. LFT&E funded the proposed work, which was carried out, in accordance with the test plan [6], in the SHADWELL/688 submarine test area aboard ex-*USS Shadwell.*

During Series 1 (4 — 7 August, 2003) fire tests and explosion scoping tests were conducted; more detailed explosion hazard testing was done in Series 2 (17 — 21 November, 2003). NRL published two reports, the first of which documented the hazards associated with hydraulic spray fires [7] while the second focused on hydraulic fluid explosion hazards [8].

Both reports documented potentially serious consequences in the event that ignition of hydraulic fluid sprays should occur and, based on this confirmation, a follow-on study was proposed to investigate possible methods of preventing or mitigating explosions. A Phase 2 test plan was published [9] and the tests were conducted during the period 14 — 25 June, 2004. As before, the SHADWELL/688 test facility was used. This report documents the results and conclusions of the Phase 2 study.

Manuscript approved November 5, 2004.

2.0 PROGRAM PLAN

Initially, we had hoped to evaluate the feasibility of using quick-reaction installed systems to suppress explosions because only systems of that type can be relied upon to react quickly enough to respond to an explosion after the fact. However, as the test plan was developed, it became evident that, due to the significant, and very expensive, alterations that would be required to install such systems in existing ships, that was not a realistic goal. Consequently, the Submarine Hydraulic System Explosion and Fire Mitigation program focused on determining whether existing tools could be used to prevent, or reduce the intensity of, mist explosions. Note that the existence of an hydraulic casualty and the presence of an ignition source were assumed — issues related to the causes of the original casualty or to the probability of ignition were outside the scope of these tests.

2.1 Objectives

The primary objectives of this study were to investigate the possible use of on-board fire extinguishing agents for prevention of explosions in the event that a casualty resulted in the formation of a cloud of hydraulic fluid mist. The systems to be tested were:

1. carbon dioxide extinguishers;
2. PKP extinguishers;
3. AFFF extinguishers; and
4. hoselines with Vari-Nozzles.

Secondary objectives were to

1. study the effects of a torpedo room fire on dummy ordnance;
2. obtain video documentation of the appearance of hydraulic mist clouds;
3. investigate the effects of compartment clutter on the explosion intensity; and
4. evaluate other fire suppression systems (such as water mist), as time permitted.

2.2 Approach

The approach to these tests was to first develop a "standard explosion" that could generate reproducible overpressures sufficient to be easily measured but small enough so that the pressure relief panel (having a nominal burst pressure of 1.5 psi) was not ruptured. This was done by adjusting the number of nozzles and the spray time, with the constraint that the minimum fuel flow time had to be slightly greater than the discharge time of the slowest extinguisher in order to allow time for application of the agent and securing of the compartment.

Using this scenario, extinguishing agents were applied during the fluid spray period followed by an attempt to ignite the mist using an electric arc igniter. Two metrics for quantifying the success of the test were used. The first was: does the method successfully prevent the hydraulic spray from exploding? In the event that there is an explosion, the second criteria was used: does the method reduce the intensity of the explosion? Explosion intensity is estimated based on the peak overpressure produced.

Explosion tests were conducted with and without the presence of dummy ordnance (representing MK-48 torpedoes) in order to estimate the effects of clutter, which has been reported to amplify the explosive intensity under some conditions [4]. Fire tests were also carried out, using three different fire sizes, and the thermal effects on the dummy ordnance was measured with thermocouples and radiometers.

3.0 EXPERIMENTAL

Testing took place in the SHADWELL/688 test area (Figure 1) and, as in the Phase 1 tests, the fires and explosions were located in the torpedo room. 2190 TEP hydraulic fluid was stored in a pressure vessel at approximately 1450 psi and was introduced into the torpedo room via an array of Bete P24 spray nozzles, as illustrated in Figures 2 and 3. The fuel vessel had a capacity of approximately 190 liters (50 gal) of fuel and was connected to the nozzle array by 1.3 cm (0.5 in.) diameter welded stainless steel pipe. Pressurization of the vessel was provided by a 12-cylinder nitrogen manifold.

Two electrical heater bands were wrapped around the circumference of the pressure vessel and electrical heating tape was used to prevent cooling of the fluid in the delivery pipe. The heating system was adjusted to maintain the fluid temperature at the nozzle at approximately 45 — 50 °C (113 — 122 °F), which is near the upper end of the normal operating temperature range for submarine hydraulic fluid.

Fuel flow was toggled by a solenoid valve, with manual valves as safety backups. The fuel flow rate was controlled by the fluid pressure and the flow characteristics of the nozzles. Using the manufacturer's data [10], and correcting for the difference in density between the standard fluid (water) and 2190 TEP, the nominal flow rate for each nozzle is

$$Q_{hyd} = K\, P^{1/2}\, S_{hyd}^{-1/2} \text{ liters/min} \qquad \text{Eqn. 1}$$

where K, the nozzle flow coefficient (0.0598), relates the flow rate to operating pressure, P is the nozzle operating pressure (in psi) and S_{hyd} is the specific gravity of the hydraulic fluid (0.865). At a nozzle pressure of 1450 psi, this gives to a flow rate of approximately 2.4 liters/min (0.65 gal/min).

3.1 Explosion Tests

In order to prevent the spread of potentially hazardous mist clouds throughout the test area, the torpedo room was isolated by closure of the access hatches and doors (H8, H13, H14, D10, D11, S1 and S2 in Figure 1) during the explosion tests. In addition, the frame bay ducts that connect the torpedo room and the combat systems space (not shown in Figure 1) were blocked off at the lower end. Due to the restricted volume available, this also had the effect of boosting the overpressures produced during the explosions, thus making the effects of suppressive agents easier to detect.

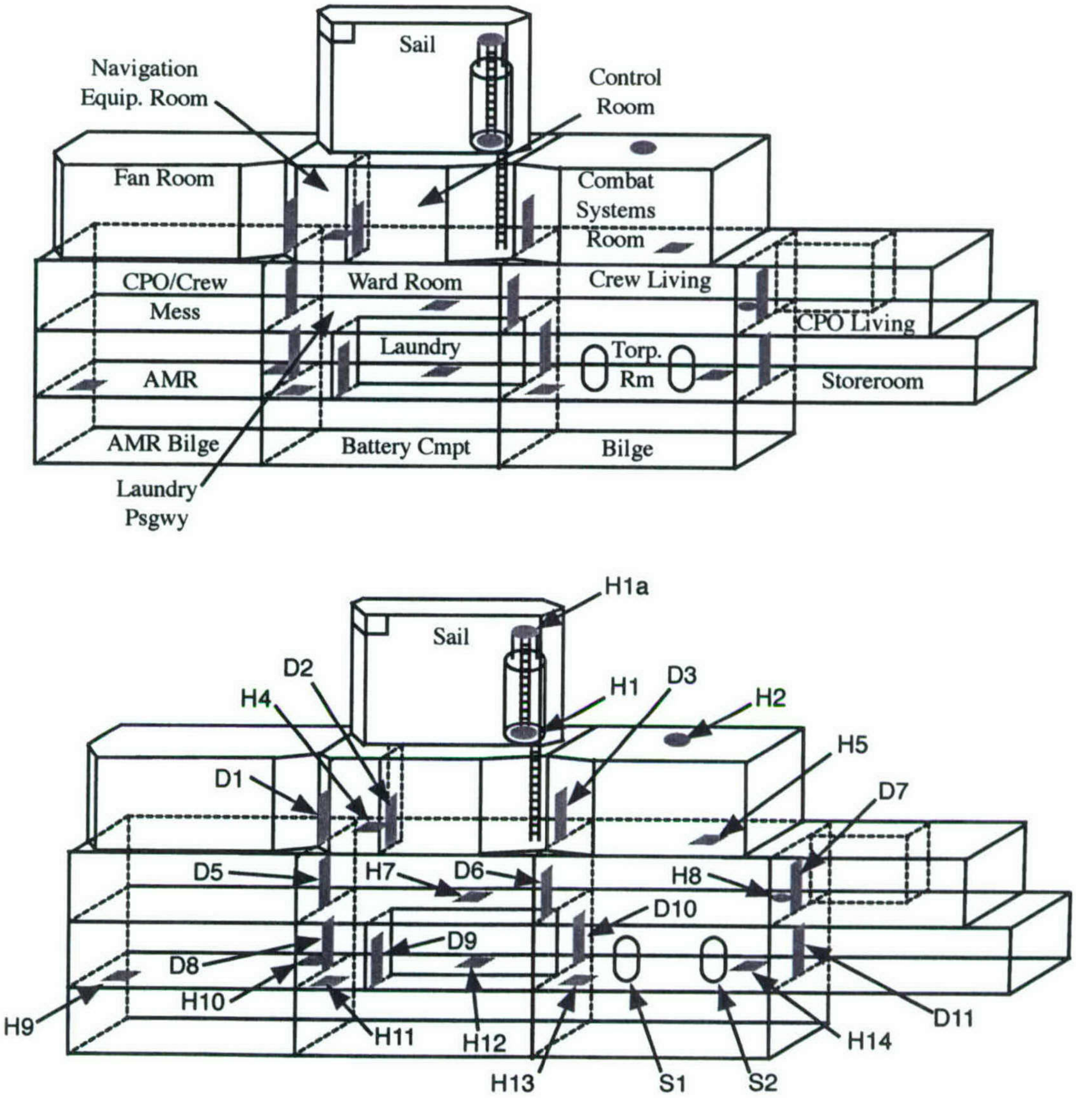

Figure 1. SHADWELL/688 Test Area

The compartments (upper diagram), and closures (lower diagram) within the SHADWELL/688 test area are shown. Closure designations are the same as those used in the Submarine Ventilation Doctrine tests, with the addition of the safety doors (S1 and S2). Closures H3, H6 and D4 were not used in the current test program and, for clarity, were deleted from this diagram.

Agents were manually applied by test personnel through the forward safety door (S2). In order to limit the escape of hydraulic mist and agent, aluminum foil strips were hung inside the safety door and the agent nozzles were inserted between the edges of the foil. Immediately after the agent discharge was completed, the safety door was secured and the igniter was then activated. The extinguishers were standard, Navy-issue types having the agent capacities shown in Table 1. Nozzles pressures and flow rates for the hoseline and water mist tests are given in Table 2 and descriptions of the explosion test conditions are listed in Table 3.

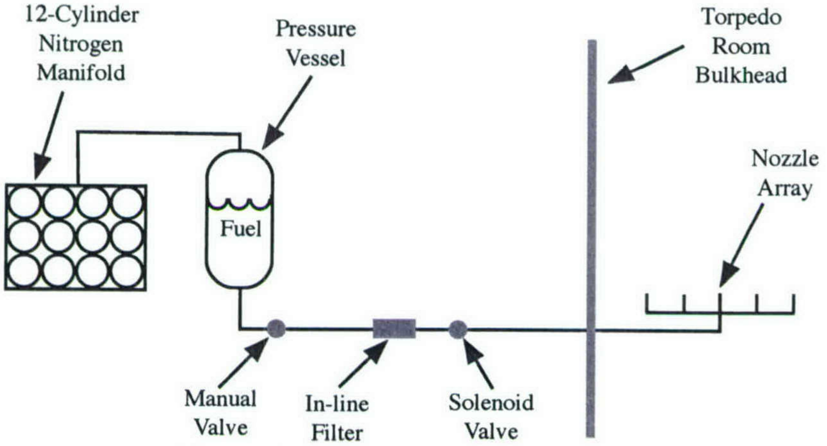

Figure 2. Fuel System Configuration

Hydraulic fluid was stored in a vessel (rated at 1500 psi) that was pressurized by a nitrogen manifold. Fuel flow was controlled by on-off valves; the flow rate was dependent on the pressure and the nozzle characteristics. An in-line filter removed particulates to prevent clogging of the nozzles or solenoid valve.

For each experiment, fuel flow began at minus 65 seconds, relative to ignition (which was defined to be zero seconds). Because the extinguisher discharge times varied, depending on the agent, the start of agent application was adjusted so that the discharge ended at approximately minus 15 seconds, allowing enough time to secure the safety door before attempting to trigger an explosion. For AFFF, the discharge time was about 50 — 60 seconds while the times for carbon dioxide and PKP extinguishers were approximately 25 seconds. In the former case, agent was applied starting at minus 65 seconds; in the latter two cases, it was delayed by about 20 seconds after the start of the fuel flow. For tests in which water hoses were used (including the high pressure mist system), there was no characteristic discharge time. Therefore, water application began when the fuel was turned on at minus 65 seconds and continued until approximately minus 10 seconds.

3.1.1 Dummy Ordnance

Since real torpedo rooms are filled with ordnance and supporting equipment, it was desirable to simulate these conditions by installing dummy ordnance. In addition to increasing the realism of the tests, this permited the effects of clutter to be estimated by comparison of tests with and without dummy weapons. In an actual SSN 688-class torpedo room, weapons are stored on two levels, 0.2 m (0.6 ft.) and 1.27 m (4.2 ft.) above the deck, with the racks divided into three sections (port, starboard and center) separated by 0.7 m (2.4 ft.) aisles. The torpedo room of *USS*

Montpelier (SSN 765) is shown in Figure 4.

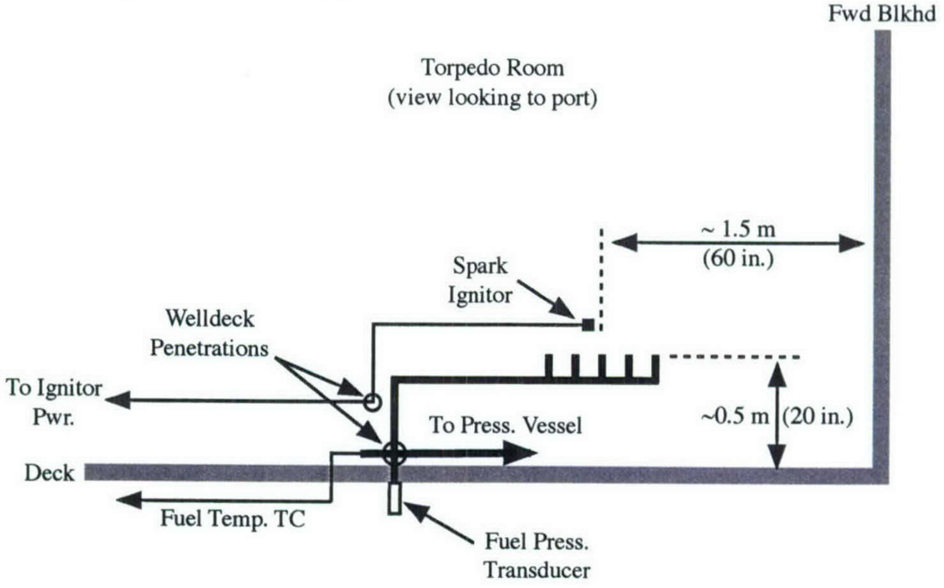

Figure 3A. Side View of Torpedo Room Nozzle Array

Five nozzle positions were provided. A pressure transducer and a fuel temperature thermocouple were installed outside the test compartment near the bulkhead penetration.

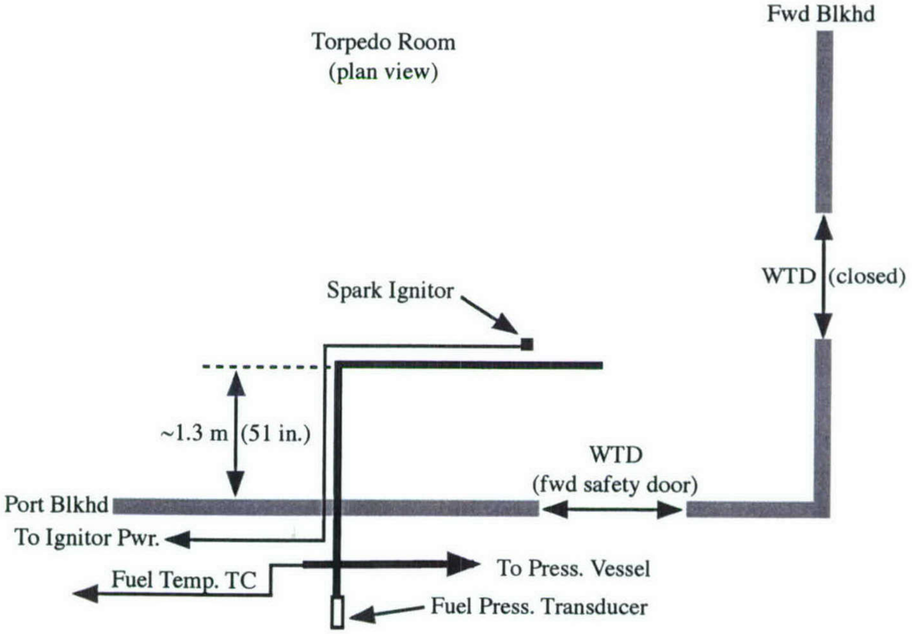

Figure 3B. Plan View of Torpedo Room Nozzle Array

The watertight door (WTD) in the forward bulkhead was always closed and the forward safety door in the starboard bulkhead was either dogged down or covered with a smoke blanket. The aft WTD (not shown) was always closed.

Agent	Nominal Capacity
CO2	6.8 Kg (15 lbs)
PKP	8.2 Kg (18 lbs)
AFFF	9.5 l (2.5 gal)

Table 1. Nominal Extinguisher Sizes

Nominal agent capacities for the standard extinguishers used in the explosion mitigation tests.

System	Specifications
Vari-Nozzle	~ 300 liters/min (80 gpm) @ 100 psi, wide pattern
Navy Applicator	~ 300 liters/min (80 gpm) @ 100 psi
Water Mist	~ 14 liters/min (3.6 gpm) @ 2700 psi

Table 2. Water System Parameters

The nominal flow rates and operating pressures are shown for each of the water systems used.

For our experiments, this configuration was simulated by two racks loaded with dummy MK-48 torpedoes (empty 55-gallon drums placed end-to-end). Because the SHADWELL/688 torpedo room is much narrower than an actual torpedo room, only two racks were used with a 0.7 m (2.4 ft.) aisle between them. The port rack had two levels with seven drums on each level. Due to obstructions in the compartment, the starboard rack had only the upper level and was limited to four drums. The dummy torpedoes are shown in Figure 5.

3.2 Fire Threat Tests

For the fire tests, the scuttle from the torpedo room to the crew living space (H8) and the door to the laundry passageway (D10) were opened to simulate normal submerged conditions aboard a submarine. The door to the storeroom (D11) was closed to protect the instrument trunk, which is located in the aft, port corner of the latter compartment.

Based on the heat of combustion of the hydraulic fluid (Table 4), and assuming complete combustion of the fluid, the nominal fire size was estimated to be 1.8 MW (1.4 BTU/sec) per nozzle. Using one, three or five nozzles, the fire sizes were as shown in Table 5.

Test Number	Agent	Application Method	Discharge Delay (sec)	Remarks
HXT-01	None	NA	NA	Scoping test; 40 sec fuel flow, 1 nozzle; smoke curtain
HXT-02	None	NA	NA	Scoping test; 65 sec fuel flow, 1 nozzle*
HXT-03	None	NA	NA	Scoping test; 65 sec fuel flow, 2 nozzles (cluttered space)
HXT-04	CO_2	2 extinguishers	20	Mitigation test*
HXT-05	None	NA	NA	Baseline test (cluttered space)*
HXT-07	CO_2	2 extinguishers	20	Repeat HXT-04*
HXT-08	PKP	2 extinguishers	20	No ignition*
HXT-09	PKP	2 extinguishers	20	Repeat HXT-08; no ignition*
HXT-11	PKP	1 extinguisher	20	Mitigation test*
HXT-13	AFFF	2 extinguishers	0	Mitigation test*
HXT-14	Water	Vari-Nozzle	0	Mitigation test*
HXT-16	Water	Navy applicator	0	Mitigation test*
HXT-17	Water mist	Pressure washer	0	Mitigation test*
HXT-18	None	NA	NA	Baseline test (empty space)*
HXT-20	None	NA	NA	Baseline test (empty space)*

Table 3. Explosion Test Descriptions

The Table shows the agent, the agent application method and the agent discharge time for the explosion mitigation tests. The asterisks indicate tests conducted at standard conditions: one nozzle, 65 second fuel spray and ~1450 psi fuel vessel pressure.

Figure 4. USS Los Angeles-Class Submarine Torpedo Room

This photograph of the USS Montpelier (SSN 765) torpedo room, looking aft, shows the port and center torpedo racks, separated by a narrow passageway. There is a similar passageway between the center and starboard rack (part of which is visible at the far left). Note the mattresses used to provide temporary bunks on the lower level. The aft end of a MK-48 torpedo is visible on the far right.

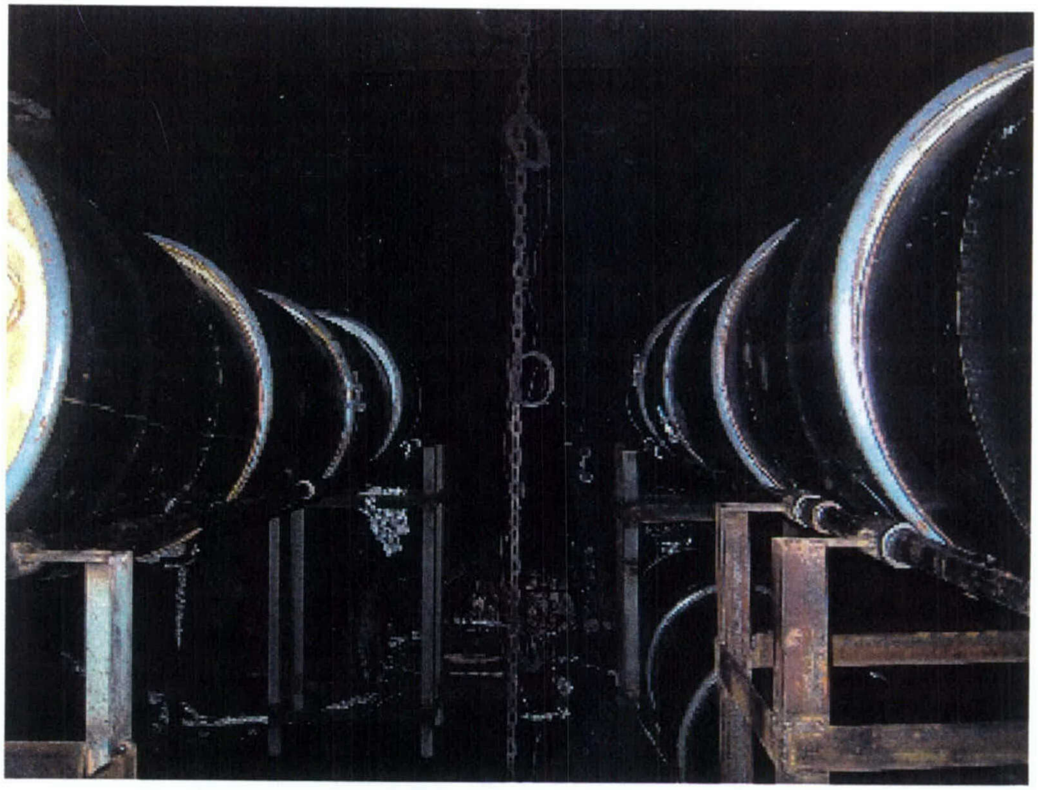

Figure 5. Dummy Torpedoes

Three dummy torpedoes, as viewed from the forward end of the torpedo room. The diameter, elevation and spacing between dummy torpedoes are similar to the values found on actual submarines.

Fuel Property	Property Value
Composition	>99% Heavy paraffinic distallates
Absolute Viscosity (cP)	69.0 @ 40 °C; 8.4 @ 100 °C
Flash Point (°C)	246
Boiling Point (°C)	>315
Specific Gravity	0.86 - 0.87
Heat of Combustion (MJ/Kg)	42.7

Table 4. Selected Properties of ChevronTexaco 2190 TEP Hydraulic Fluid

These properties of ChevronTexaco 2190 TEP hydraulic fluid have been excerpted from the manufacturer's product data sheet and MSDS.

Nozzles	MW (BTU/sec)
1	1.8 (1.4)
3	5.3 (4.2)
5	8.9 (7.0)

Table 5. Nominal Fire Sizes

> Fire sizes for one, three and five nozzles, calculated from the nozzle flow data provided by Bete Fog Nozzles [10] and the hydraulic fluid heat of combustion, with the assumption of complete combustion.

The fire tests are listed in Table 6. The shakedown tests were the first tests conducted during this series and were used to verify operation of the instruments and of the fuel and data acquisition systems. The actual fire threat to ordnance tests were carried out later in the series, after the dummy ordnance had been installed in the test space. The ordnance configuration for the fire threat tests was the same as that used for the "cluttered space" tests, described above.

Test Number	Number of Nozzles	Nozzle Positions	Ordnance Present	Remarks
HFT-01	1	3	No	Shakedown test
HFT-02	1	3	No	Shakedown test
HFT-03	3	2 – 4	No	Shakedown test
HFT-04	5	1 – 5	No	Shakedown test
HFT-05	1	3	Yes	Fire threat test
HFT-06	3	1, 3, 5	Yes	Fire threat test
HFT-07	3	1, 3, 5	Yes	Fire threat test

Table 6. Test Parameters for Fire Effects Tests

> The initial shakedown tests were used to verify proper operation of the fuel system, instruments and data acquisition systems. During the fire threat tests, the thermal conditions were measured at the locations of the dummy ordnance.

3.3 Instrumentation

Because this test phase focused on events within the compartment of origin, the primary instruments of interest were those located in the torpedo room, as indicated in Figure 6. These included thermocouple trees, a gas analysis loop (for oxygen, carbon monoxide and carbon dioxide), pressure transducers and radiometers. Data from several other compartments were also obtained for the fire tests. Both visible light and near IR video cameras were placed in thetorpedo room and the fuel system was instrumented for temperature and pressure in the pressure vessel and close to the nozzles.

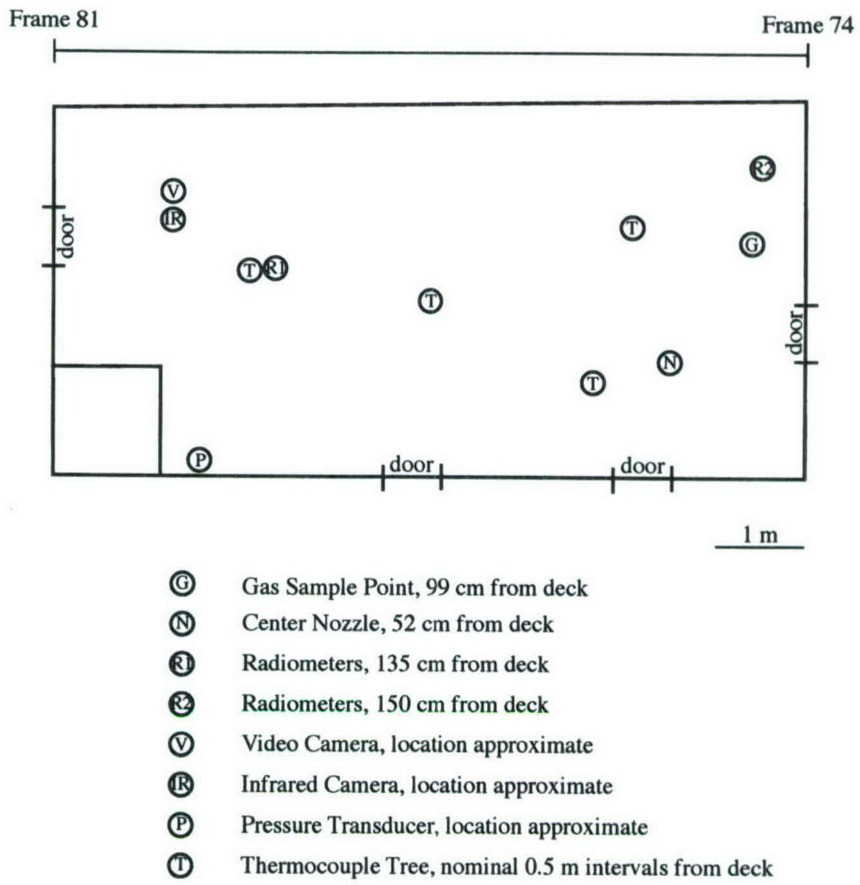

Figure 6. Torpedo Room Instrument Configuration

The layout of torpedo room instruments for the explosion and fire mitigation tests.

For the tests of fire effects on ordnance, the forward drums on both levels of the port rack were instrumented with surface and air temperature thermocouples. The drums were positioned so that the thermocouples were located on the side facing the fire. Figure 7 shows the overall thermocouple configurations and Figure 8 is a close-up, showing the method of attachment used for the thermocouples. The thermocouples used on the ordnance were taken from the thermocouple tree located near frame 3-75.

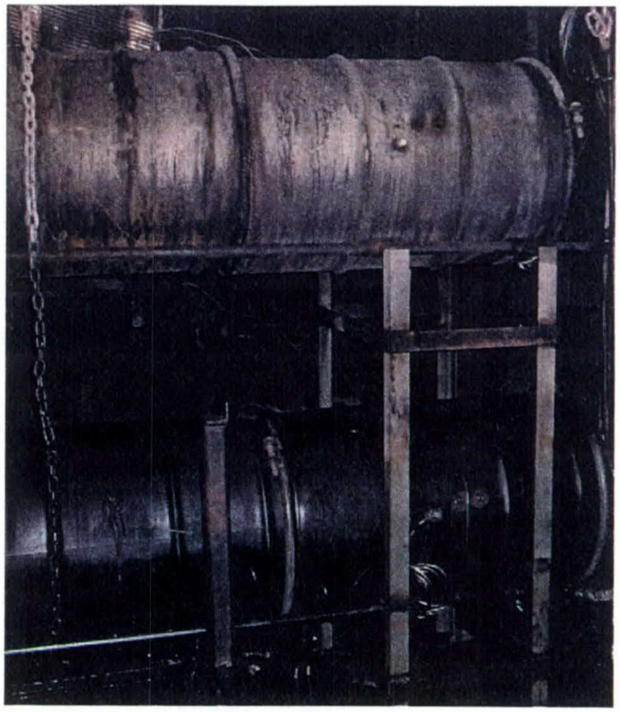

Figure 7. Torpedo Instrumentation

The forward sections of both dummy torpedoes on the port side were instrumented with air and surface temperature thermocouples as shown in more detail in the Figure 8.

Figure 8. Torpedo Instrumentation Detail

A surface temperature thermocouple (white arrow) was clamped to the dummy torpedoes using bolts screwed into a nut welded to the surface. Air temperature thermocouples (black arrow) were wrapped around the bolt and adjusted to be about 1.0 cm (0.5 in.) from the surface.

3.3.1 Fast-Response Pressure Transducers

A 0 — 2 psi pressure transducer was installed in the well deck outside the torpedo room and connected to a short, large bore [approximately 0.25 m (0.8 ft.)] length by 2.5 cm (1 in.) diameter)] stainless steel tube that penetrated the well deck bulkhead into the aft portion of the torpedo room. By eliminating the long run of small diameter tubing that is normally used with pressure transducers located in the node room (which is in the storeroom near door D11), this arrangement reduced the time constant for the measurements and permitted measurements of fast pressure transients during the explosion tests.

3.4 Data Acquisition

The standard MassComp data acquisition system was used for all tests to capture general environmental data, including temperatures, gas composition and heat fluxes. However, this system, which is limited to a scan rate of one hertz, was not fast enough to characterize the explosions. Therefore, a National Instruments SCXI system, controlled by a custom LabVIEW application, was used for the pressure data, which were recorded for approximately 10 seconds at a one kilohertz rate, starting about five seconds before the ignition attempt. The transducer output voltage was converted to pressure using a linear calibration curve obtained in the laboratory.

4.0 DATA ANALYSIS

4.1 Explosion Tests

4.1.1 Pressure Transients

The output of the LabVIEW data acquisition software was a tab-delimited ASCII file with each column containing data, in engineering units, from a single instrument. The only data source that was actually used in these tests was the 2 psi pressure transducer discussed above. These data were analyzed off-line as described below.

Because the data acquisition rate (one kHz) was controlled by hardware in the SCXI chassis, each output row was known to represent a one millisecond time step. A time track was created by adding a column containing sequential numbers, with the zero position corresponding to the initiation of the explosion. The pressure data were smoothed by averaging over a 50 millisecond sliding window. In order to ensure that all of the data was plotted on the same scale, the mean pre-explosion value was calculated and subtracted from every point in each experiment. This had the effect of converting from absolute pressures, which varied with the ambient pressure, to pressure differentials.

4.2 Fire Threat Tests

4.2.1 Ordnance Temperatures

For tests HFT-05 and HFT-06, the surface and air temperature data were processed and plotted for both of the instrumented dummy weapons. Processing involved adjusting the time scales so that zero time corresponded to the time of ignition and correcting for the differences in ambient temperature between tests using Eqn. 2

$$T_{cor} = T - T_0 + 25°C \qquad \text{Eqn. 2}$$

where T_{cor} is the adjusted temperature, T is the uncorrected temperature and T_0 is the mean pre-ignition temperature.

4.2.2 Oxygen Concentrations

Torpedo room oxygen concentrations were also recorded for these tests. Gas samples were drawn through a filter and cold trap (to remove particulates and condensable vapors, respectively) and transported via tubing to remotely located analyzers. Because there was a transit delay between the time that the sample was drawn from the test space and the time that it reached the analyzer, data for the gas analysis channels were logged at a time later than the data for other sensors. In principle, this time offset would be expected to vary for each sample point, due to differences in the lengths of the tubing, the characteristics of the individual filters and traps and the speed of each pump.

To correct for this delay, the transit time for the torpedo room sample was measured, as shown in Figure 9. The system was run until the oxygen concentration stabilized, nitrogen was vented from a compressed gas cylinder at the sample inlet position and the time delay between the introduction of the nitrogen and the initial response of the oxygen analyzer was measured. The test was repeated, with identical results — a 58 second delay. The oxygen data from the fire effects experiments were adjusted by subtracting the above delay from the elapsed times. After this correction, the oxygen data can be directly compared with the temperatures.

5.0 RESULTS & DISCUSSION

5.1 Explosion Tests

5.1.1 Explosion mitigation

The results of the explosion mitigation experiments are presented in Figure 10. It is evident that only PKP had a significant effect on the peak overpressure while carbon dioxide caused a small reduction in the maximum pressure. Water applied with the Vari-Nozzle and the Navy applicator resulted in a very slight increase in pressure and water mist had no effect — the graph is superimposed on the baseline case.

The small effect of carbon dioxide was likely due to dilution of the available oxygen, resulting in reduced combustion. Water, when applied as relatively large droplets via a Vari-Nozzle or Navy applicator, appears to have increased turbulent mixing of the fuel and air, increasing the burning efficiency and thereby slightly increasing the observed overpressure.

During the first two PKP tests (HXT-08 and HXT-09), there was no ignition of the fuel mist but,

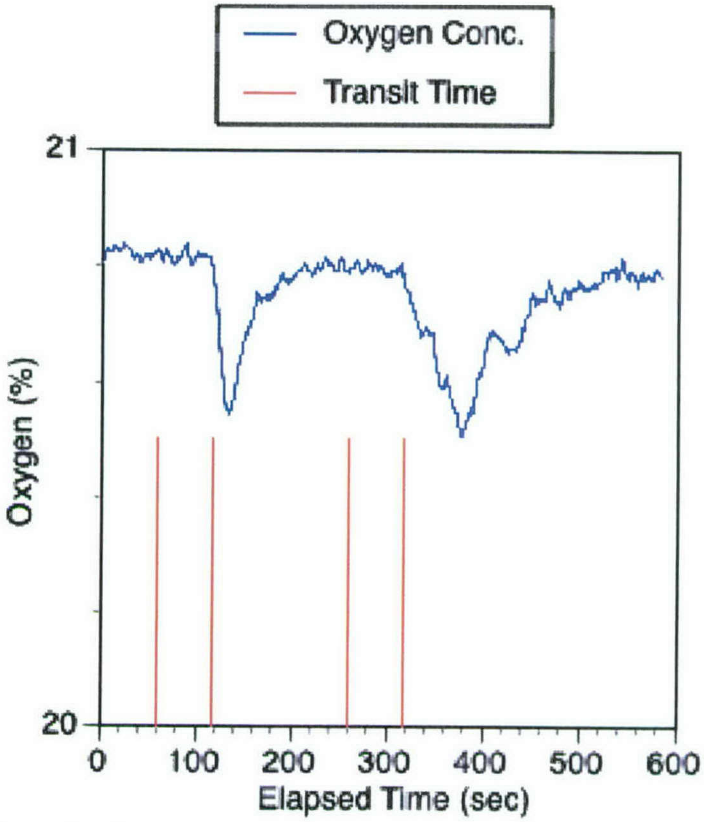

Figure 9. Gas Sample Transit Time for the Torpedo Room

The gas transit time was measured by venting nitrogen gas (from a cylinder) at the inlet and measuring the oxygen concentration in the sampled gas. The time at which nitrogen was introduced and the time at which the oxygen analyzer first responded were noted, as indicated by the vertical lines. Two replicates were run.

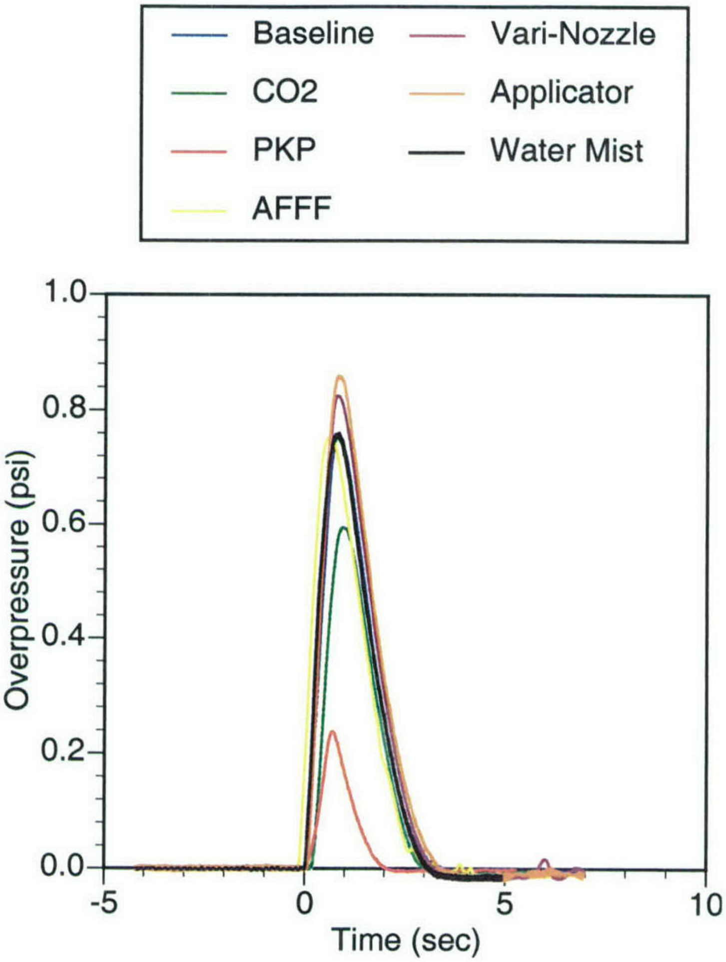

Figure 10. Overpressures during Explosion Mitigation

> The overpressures obtained during the baseline (no mitigation) and mitigation tests are shown. The plot from the water mist case is superimposed on the baseline.

due to the optical density of the powder suspended in the torpedo room, it was not possible to visually confirm whether the igniter had functioned properly. In HXT-09, the igniter was triggered three times while fuel mist and PKP were present and again immediately after ventilating the space. There was no ignition during the first three attempts, but the post-ventilation test confirmed that the igniter was working.

In HXT-11, the spacing between electrodes was reduced from the normal value of about three centimeters (1.2 inches) to one centimeter (0.4 inches) and the amount of agent was reduced by using only one extinguisher. Under those conditions, an explosion did occur, but it was very weak relative to the unsuppressed case — the overpressure was reduced to less than one third of the baseline value.

5.1.2 Effects of clutter

In order to determine whether the presence of clutter had an appreciable impact on the overpressure, explosion tests were run with and without the dummy ordnance. Two replicate tests of each configuration were conducted and, for each configuration, the mean overpressures of the replicates were calculated. The results, presented in Figure 11, show that there was no significant difference between the results when dummy ordnance was present and when it was not.

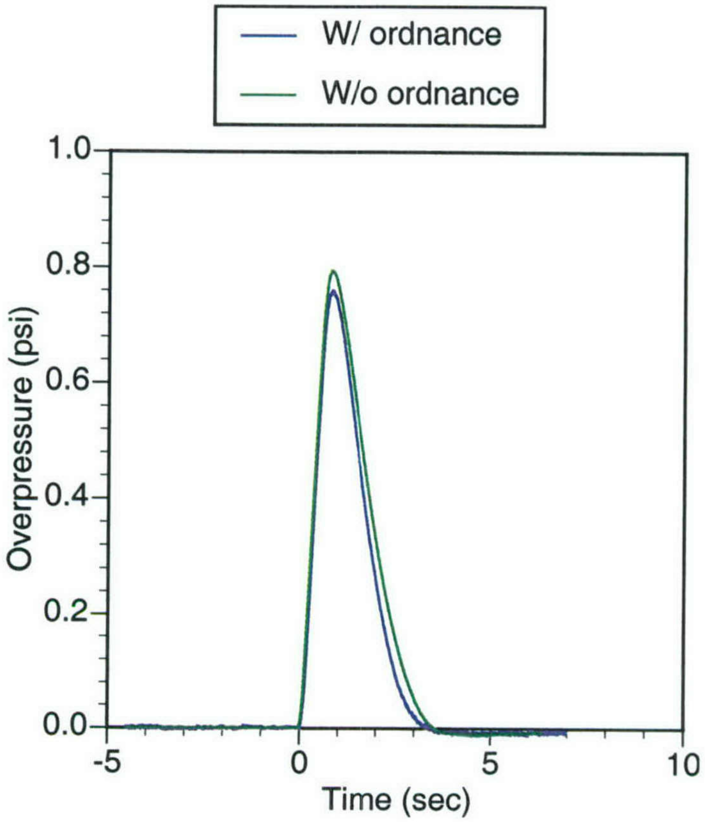

Figure 11. Effects of Dummy Ordnance on Overpressure

Comparison of the mean overpressures obtained during tests with and without the dummy ordnance shows no significant effect.

5.2 Fire Threat Tests

In Figures 12 and 13, the surface and adjacent air temperatures are shown for test HFT-05 and HFT-06, respectively. The air and surface temperature curves followed the same trend, but the surface temperatures lagged behind due to the heat capacity effects.

Test HFT-05 used a single nozzle, producing a nominal 1.8 MW (1.4 BTU/sec) fire, whereas HFT-06 used three nozzles to achieve 5.4 MW (4.2 BTU/sec) fires. The Ships' Systems Manual for the SSN 688-class submarine states that the MK-48 torpedo warhead can explode after

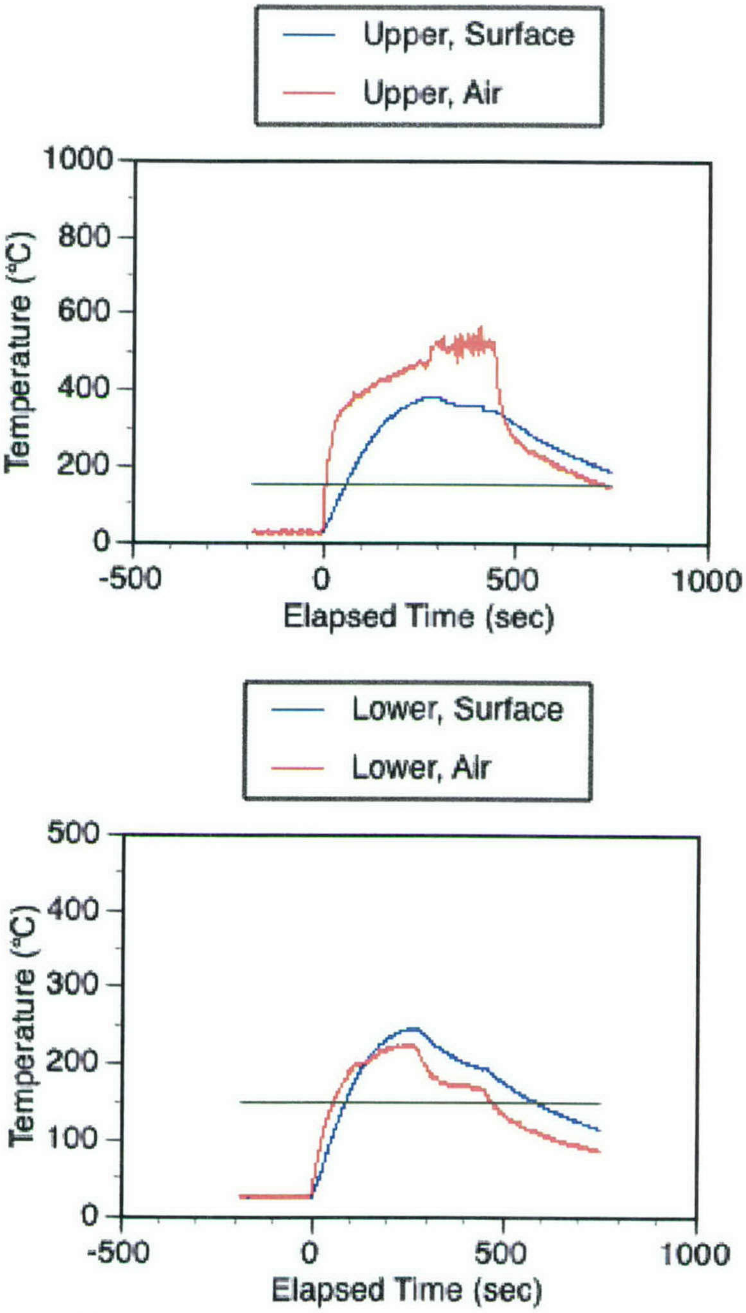

Figure 12. Weapon Temperatures for HFT-05

The temperatures measured at the surface of the dummy torpedoes and in the adjacent air layers are shown for the upper and lower weapons during test HFT-05. As discussed in the text, the horizontal lines indicate the maximum safe sustained temperature for a MK-48 torpedo [149 °C (300 °F)].

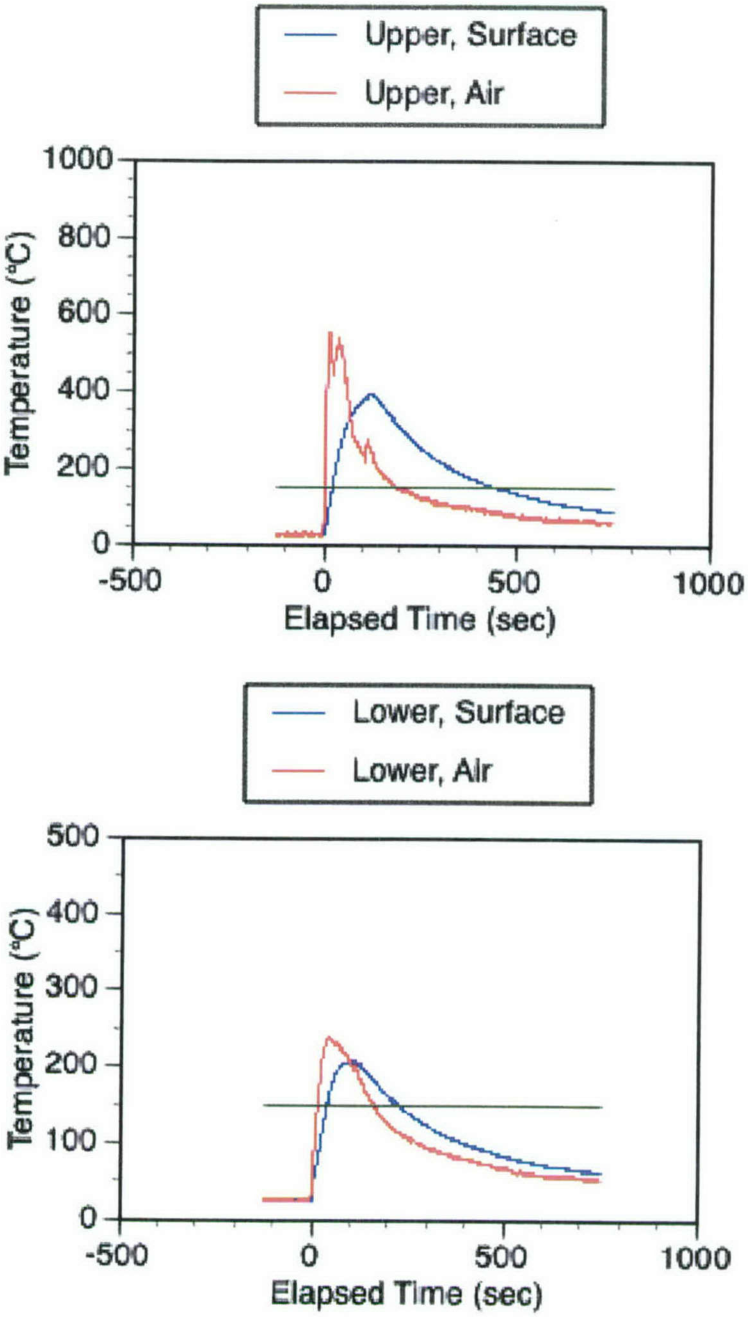

Figure 13. Weapon Temperatures for HFT-06

The temperatures measured at the surface of the dummy torpedoes and in the adjacent air layers are shown for the upper and lower weapons during test HFT-06. As discussed in the text, the horizontal lines indicate the maximum safe sustained temperature for a MK-48 torpedo [149 °C (300 °F)].

sustained exposure to temperatures of 177 °C (350 °F) and that the torpedo fuel tank can rupture at temperatures above 149 °C (300 °F) [11]. Accordingly, we have used the latter value as an estimate of the maximum safe environmental temperature. In Figures 12 and 13, horizontal lines have been drawn to represent this threshold.

The two fire sizes produced approximately the same maximum air temperatures but the smaller fire took a longer time to reach the maximum and remained at higher temperatures for a longer period. This is due to the fact that the larger fires were oxygen limited. Figure 14 shows that the larger fire consumed significantly more of the available oxygen and used it at a much greater rate.

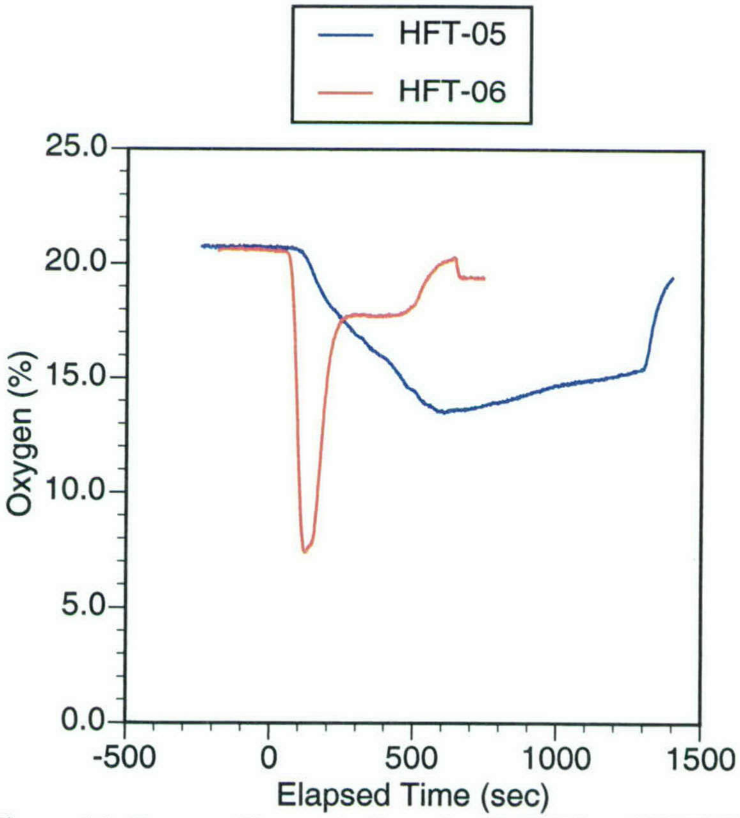

Figure 14. Oxygen Concentrations for HFT-05 and HFT-06

The oxygen concentration dropped much faster and to a much lower level in the 5.4 MW (4.2 BTU/sec) fire (HFT-06) than in the 1.8 MW (1.4 BTU/sec) fire (HFT-05).

6.0 CONCLUSIONS & RECOMMENDATIONS

6.1 Explosions

The explosion test results indicated that only the PKP extinguisher had the ability to significantly suppress the explosion. In some cases, there was no explosion at all and, when there was an explosion, the maximum overpressure was reduced by more than a factor of three. The fact that

PKP did have an effect should not be a surprise because commercially available explosion suppression systems use similar chemicals [12]. Unfortunately, of the agents tested, PKP is probably the worst in terms of cleanup costs and potential harm to electrical and mechanical systems.

Two hypotheses were advanced to explain the lack of explosions in those tests that involved the discharge of two PKP extinguishers. One theory was that the PKP interfered with the igniter so that it did not function in the presence of large concentrations of agent. The second possibility was that the igniter did work, but the presence of the agent prevented ignition of the mist. We believe that the former is more likely because there is no indication of an arc in any of the visible or IR video and safety personnel on the scene reported that they could not hear the igniter, which was very loud.

During these tests, two common igniter failure modes were observed. In the first, a short circuit was caused by breakdown of the cable insulation after repeated use. This produced a permanent failure, requiring that the cable be replaced. The second failure mode, in which arcing was prevented by a buildup of agent on the igniter, could be cleared simply by wiping the contaminant off of the electrodes.

However, the ignition failures during the PKP tests was of a different nature, as demonstrated by the fact that the igniter worked perfectly, without cleaning the electrodes or replacing the cable, after the PKP was vented from the compartment. This suggests that PKP prevented ignition by some other mechanism, possibly by increasing the breakdown voltage of the air. This is further supported by the observation that the igniter functioned properly when the gap width and PKP concentrations were reduced. Small-scale experiments should be conducted to definitively resolve this issue.

Due to the time constraints for responding to an explosion after the fact, manual systems can not be used in a reactive mode. However, an automated system could circumvent the inherent problems of dry powder by responding only after an explosion has actually occurred. We recommend that the feasibility of dry powder-based automatic suppression systems be investigated.

Carbon dioxide extinguishers showed a small effect, reducing the explosive overpressure by about 22%. However, CO_2 extinguishers are well known for producing static discharges so we must consider the possibility that a extinguisher could actually trigger an explosion that would not have otherwise occurred. We conclude that the relatively small reduction in intensity, should an explosion occur, does not justify the increased risk of causing the explosion.

Based on the results reported above, it appears that the use of hoselines can actually magnify the explosion under some conditions, possibly due to increased turbulent mixing of the hydraulic mist with air. Although this effect was small in these tests, it could potentially be large in a real world situation, where the amount of mist is not carefully constrained to ensure safety. Additional testing should be performed to determine whether this effect is general or was an artifact of these particular experimental conditions.

The pressures observed using water mist were indistinguishable from those obtained with no mitigation. This was likely due to the small amount of mist that was delivered with the handheld mist system and to the localized application volume. The difference between water mist and water spray (delivered with a hoseline) is attributed to the differences in the size distributions of the droplets.

Based on simple thermodynamic considerations, it seems likely that water mist would be capable of absorbing large amounts of energy from a developing explosion if the mist can be delivered, in sufficient quantity, to the point of origin of the explosion. Accordingly, it is recommended that further work be carried out, initially on a small scale, to investigate the applicability of both local and total flooding water mist for suppression of hydraulic mist explosions for submarines.

We also note that the scope of these tests was limited and the results strictly apply only to a small range of mist droplet sizes, mist concentrations and agent:mist ratios. Agents that show promise for explosion suppression should be tested over a much broader range of conditions to ensure that they are generally applicable.

6.2 Fires

The results obtained during this work indicate that the hydraulic spray fires can very quickly heat weapons to dangerously high temperatures. One interesting observation is that smaller fires can be more dangerous than larger ones due to their longer duration. Of course, this would be true only if the oxygen is limited, as in a closed boat (submerged) scenario. In the case of a fuel-limited fire, the larger fire would be more energetic and, therefore, would present the greater cook off hazard.

It should be noted that, due to differences in material properties between the dummy weapons and actual torpedoes (different alloys and thicknesses, for example), the surface temperatures and heating rates seen in these tests are not expected to be identical with those that would occur with a real torpedo. However, in all cases, the air temperatures attained were well in excess of the 149 °C (300 °F) threshold temperature so it must be assumed that the weapon temperatures would ultimately reach unsafe levels.

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