Naval Research Laboratory

Washington, DC 20375-5320

NRL/MR/6180--04-8738

Lessons Learned from the CG-19 Weapons Effects Test on Mitigating the Effects of a Missile Induced Conflagration

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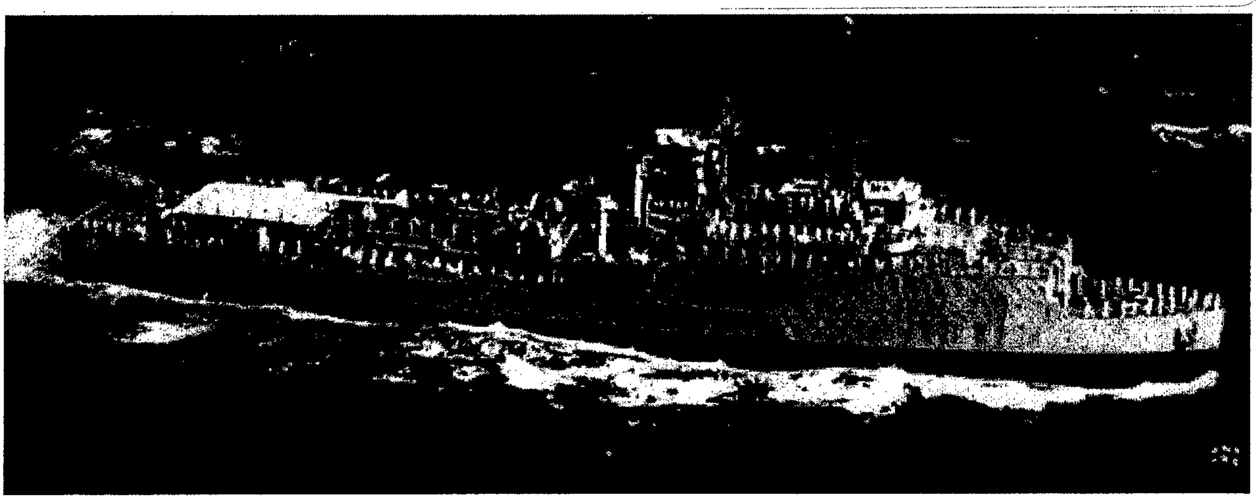
January 16, 2004



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IN REPLY REFER TO:

12 February 2004

To: Distribution
From: Kathy Parrish, Code 3430

Subj: ERRATA: NRL/MR/6180—04-8738, "Lessons Learned from the CG-19 Weapons Effects Test on Mitigating the Effects of a Missile Induced Conflagration

Encl (1) Page 21 of NRL/MR/6180—04-8738

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20040219 214

AH19996

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
January 16, 2004

2. REPORT TYPE
Memorandum Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Lessons Learned from the CG-19 Weapons Effects Test on Mitigating the Effects of a Missile Induced Conflagration

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
61-7878-A-3-5

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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

Naval Research Laboratory, Code 6180
4555 Overlook Avenue, SW
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/6180--04-8738

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

Naval Sea Systems Command
1333 Isaac Hull Avenue, SE
Washington Navy Yard, DC 20376

10. SPONSOR / MONITOR'S ACRONYM(S)

11. SPONSOR / MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

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14. ABSTRACT

Techniques are recommended for reducing the severity of a missile induced conflagration. Evaluate various "fuel load minimization concepts" (reductions in total fuel loading and/or techniques that prevent burnable material from coming in contact with air). Evaluate techniques for reducing the likelihood of fire spread through intact boundaries. Evaluate possible installation techniques for enhancing the survivability of systems (sprinkler, water delivery, and vital systems). Develop/evaluate systems to cool the PDA and cool the PDA boundaries. Develop a network of sensors designed to increase the overall situational awareness and refine the Doctrine for fighting missile induced fires.

15. SUBJECT TERMS

Damage control; Fire; Ships

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Frederick W. Williams
Unclassified	Unclassified	Unclassified	UL	26	**19b. TELEPHONE NUMBER** *(include area code)* 202-767-2476

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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Lessons Learned from the CG-19 Weapons Effects Test on Mitigating the Effects of a Missile Induced Conflagration

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 missiles (ASMs). Efforts to date include; programs to quantify the thermal conditions produced in the ship by the burning of the residual missile fuel in the absence of a warhead detonation [1-3], static detonations of warheads (no motor housings and/or missile fuels) in empty compartments [4], and more recently, a dynamic shot with a live warhead conducted against a fully fitted and instrumented ship (ex-USS *Dale* (CG-19)) [5]. The data collected to date has provided invaluable realistic hazard/threat information and has expanded the knowledge base with respect to the blast and thermal conditions produced in the primary damage area (PDA) during the event. The PDA is defined as the group of compartments/spaces that have been opened-up by the blast and have free communication of fire gases between them.

The CG-19 Weapons Effects Test (WET) made no attempt to evaluate the survivability/effectiveness of either active or passive fire protection systems or measures. The test did, however, demonstrate the potential vulnerability of systems to the blast and also identified areas in the primary damage area (PDA) where systems could transverse with a relatively high probability of surviving the blast/event. The test also re-emphasized the need for systems/measures designed to minimize the threat of the ensuing compartment fire and limit fire spread outside the PDA.

This paper summarizes the lessons learned from the CG-19 WET with respect to both system survivability and techniques to mitigate the threat of the ensuing compartment fire. These lessons are based on the measurements recorded in the ship during the test and a post-test inspection of the compartments in and around the PDA. During this analysis, a limited number of specific references to the conditions on aircraft carriers are made but, as a whole, this information applies to all surface combatants. Techniques that show promise for mitigating the hazard are identified and recommended for inclusion in future weapons effects testing.

2.0 OBJECTIVE

The objective of this report is to identify/discuss approaches to increase the survivability of systems running through the PDA and techniques designed to minimize the threat of fire spread outside the PDA.

Manuscript approved August 19, 2003.

3.0 BASELINE CONDITIONS

Recognizing that there are many variables involved in an anti-ship missile attack (warhead size, trajectory, hit location, residual missile fuel, compartment fuel loading, ventilation conditions, ship construction, etc.), the following analysis/discussion is presented as "food for thought" relative to practical lessons learned from both a doctrine and ship design standpoint. This discussion is based on the analysis of the data collected during the test and the perceptive gained from a post-hit tour of the damaged area.

3.1 Terminology

Describing the conditions in the ship following a weapon hit requires an understanding of the shipboard compartment designations developed for these assessments/evaluations. The compartments are categorized in three ways:

> *Primary Damage Area (PDA) compartments:* These are compartments that have been identified to experience the quasi-steady overpressures produced by blast. It is assumed that there is free communication (open doors, open hatches, passageways, blast holes) between all areas/compartments in the PDA.
>
> *Adjacent to Primary Damage Area (APDA) compartments:* These are all compartments that border the PDA and share some common intact boundary (bulkhead/overhead/deck) with a PDA compartment. There is no free communication between PDA and APDA compartments (i.e., the intervening boundary is intact and connecting doors and hatches are closed).
>
> *Beyond Adjacent to Primary Damage Area (BAPDA) compartments*: These are compartments that border APDA spaces and can be otherwise described as "twice removed" from the PDA. These spaces become a concern as a result of potential fire spread later into the event. It is typically assumed that when the ship is at general quarters, there are no communicable openings (i.e., vents, ducts, open doors, or open hatches) between BAPDA and APDA spaces.

3.2 Conditions Produced by the Blast

There is only limited available data on the structural damage produced by a weapon detonation. Much of this data exists in the form of predictions made using the Ship Vulnerability Model (SVM) developed by the Naval Surface Warfare Center, Carderock Division (NSWC/CD) [6]. The SVM has been used during vulnerability assessment reports (VAR) to predict the damage for a limited number of ship types and a range of attack weapons. Since structural damage resulting from a weapon hit is typically classified information, the following discussion will be general in nature.

There is reasonable degree of consistency between the damage predicted by the SVM and that observed during actual weapon hits/test. In general, the damage typically produced by the detonation is a function of the explosive weight of the weapon. Depending on the explosive weight, the damage can range from one deck to multiple decks in height and vary significantly in length and width. The size of the hull penetration (vent opening to the weather) can vary in size from as small as the missile entry hole to as large as a significant portion of the side shell being opened-up by the blast. The outer perimeter of the PDA is typically bounded by watertight bulkheads (e.g., fire zone boundaries). Generally speaking, the damage tends to be more severe near the detonation location and decrease toward the perimeter of the PDA. In some instances, the most remote areas of the PDA consist of structurally intact compartments that have doors or hatches that have been blown open by the blast.

Inside the PDA, there will be huge mounds of debris and jagged metal spread throughout the space. Electrical cables (some potentially energized) will be hanging down from the overhead. There will be multiple fires in unknown locations at least partially shielded and deep seated within the debris. Horizontal movement throughout the space will be hampered not only by debris and electrical cabling but also by large openings in the decks created by the blast. The ladders and hatches in the space will also be destroyed, preventing vertical movement. These conditions, along with the heavy smoke and high temperatures created by the fire, present a serious obstacle for the fire fighting party.

The detonation of the warhead will effectively destroy all systems (i.e., fire main, electrical power, etc.) located in or running through PDA in the vicinity of the blast. At a minimum, there will be poor visibility in the PDA due to the lack of lighting and there could potentially be power outages throughout the ship.

Access to the PDA will also be hindered by the structural damage created by the blast. The passageways and doors leading into the area may be blocked by ventilation ducts blown apart by the blast. The bulkheads around the perimeter of the PDA may be warped, preventing the doors from being opened. As a result, a cutting torch or crowbar may be required to gain access to the PDA.

3.3 A Description of the Ensuing Compartment Fire

During the CG-19 WET, the detonation of the warhead ignited a fire that burned for at least six hours and eventually consumed almost all of the combustibles in the PDA. These combustibles included berthing, clothing, interior finishes (including painted surfaces), and cable insulation located in the space. The bulkheads and decks in and around the PDA were reduced to basically bare steel with some remnants of white ash left by the burning paint. The bare conductors of the cables hung in the overhead of the space with little evidence that plastic insulation was there before the test. A limited portion of the thermal insulation installed on the interior surfaces remained intact after the test. A majority of the insulation was assumed to have been blown off by the blast. In some areas, the facing material (glass) appeared to have been melted by the fire.

The detonation of the warhead shredded the contents of the space and, in the process, pushed the materials away form the blast location. As a result, there were significant piles of debris against the perimeter boundaries of the blast damage area. Based on this observation, it can be assumed that a substantial portion of the fire occurred near the perimeter of the space.

Observations conducted around the perimeter of the PDA suggest that the fire would have spread both vertically upward and horizontally (forward) to APDA compartments if the adjacent spaces were loaded with combustible materials. The fire could have potentially spread vertically through multiple decks had there been a super structure above the PDA. The fire did not spread in the aft direction due to insufficient fuel loading in the aft section of the PDA. (The fuel loading in this area had been intentionally removed for test purposes (setting fire boundaries)).

4.0 TECHNICAL DISCUSSION

4.1 Compartment Fire Development

4.1.1 Fire Growth Rate

On impact, the detonation of the warhead consumed all of the oxygen in the space and produced a short duration high intensity (high temperature) thermal pulse. On completion of these blast-related effects, the space rapidly cooled and the oxygen concentration in the space gradually increased as air began to flow back into the compartment. As oxygen was replenished, the space became fully involved (a fully developed compartment fire) and eventually consumed the entire PDA. Within 15 to 20 minutes after the hit, the fire reached maximum intensity producing compartment temperatures in excess of 500 °C (932 °F). These trends can be observed in measurements shown in Fig. 1.

During a modeling exercise, the fire growth curve observed during the CG-19 WET was estimated based on the oxygen recovery rate in the PDA [7]. The resulting fire growth curve is considered to be a medium growth rate ($\alpha = 0.011$ kW/sec^2) according to standard t – squared fire growth nomenclature.

4.1.2 Maximum Compartment Temperature

In most scenarios, the size of the opening created by the blast (opening to the weather) governs the maximum heat release rate of the ensuing fire. In a previous study, the Naval Research Laboratory (NRL) bounded the likelihood (and time) for compartments subjected to weapons induced damage to reach flashover [8]. The analysis was conducted for steel compartments with natural ventilation (an opening to the weather). As part of this study, twenty-seven compartment/vent configurations were analyzed using the multi-zone computer model, "Consolidated Model of Fire Growth and Smoke Transport," CFAST [9]. The results show that the likelihood reaching flashover is a function of the ventilation factor to compartment surface area ratio. The ventilation factor, $A\sqrt{H}$ (where A is the area of the vent (m^2) and H is the height

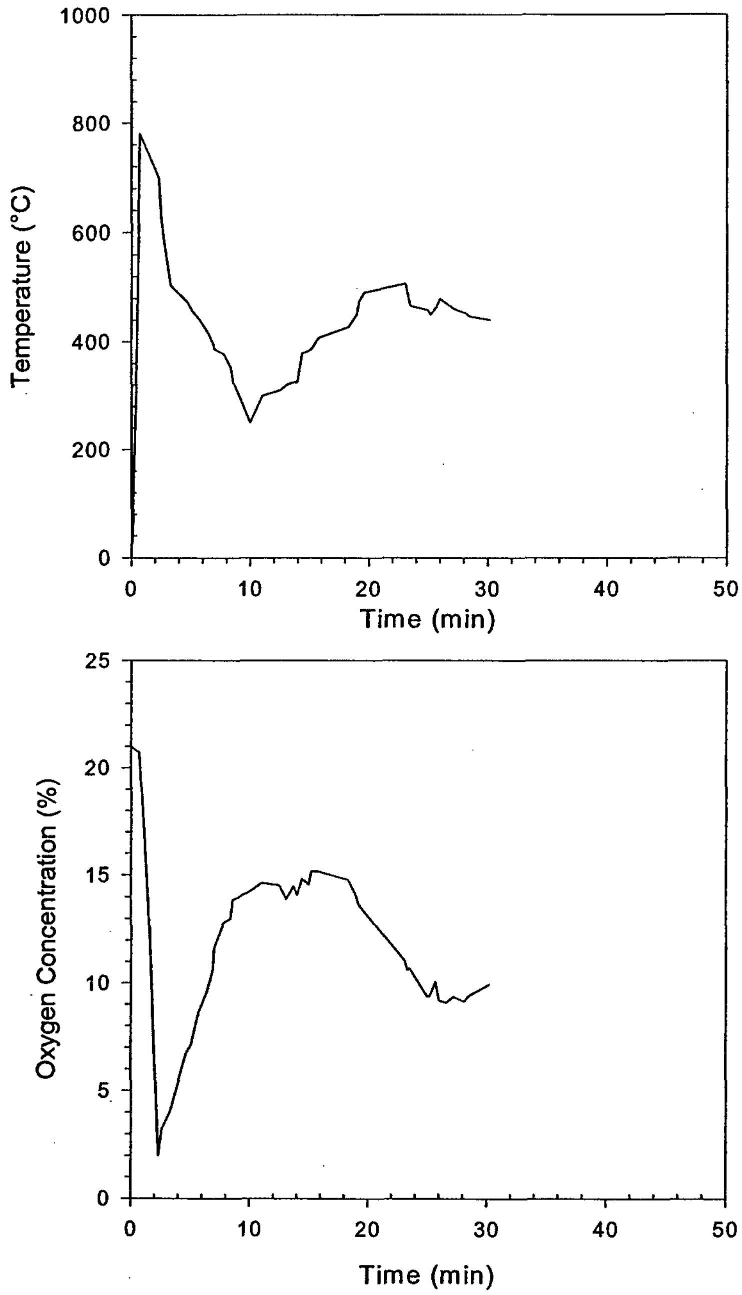

Fig. 1. Conditions produced by the blast

of the vent (m)), defines the maximum heat release rate in the compartment and the energy losses out of the vent openings. The energy losses through the boundaries are a function of the compartment surface area (A_S) defined as the area of the walls and the ceiling and excludes the floor and vent areas. The results suggest that only compartments with ventilation factor to surface area ratios $A\sqrt{H} / A_S$ greater than 0.015 $m^{1/2}$ are likely to produce and sustain flashover conditions. For extremely large vent openings, the fire becomes fuel limited (with the heat release rate governed by the fuel surface area) and the severity of the fire is decreased. These trends are shown in Fig. 2.

The temperatures measured during the CG-19 WET show good agreement with those predicted in Fig. 2. The maximum compartment temperatures (measured during the ensuing compartment fire) approached 650 °C with a ventilation factor to surface area ratio of 0.04 $m^{1/2}$ [7].

4.1.3 Relevance of the Term "Flashover"

The test results suggest that the use of the term "flashover" may not be appropriate or may be misleading for a missile hit scenario. Although flashover is defined as an upper layer temperature between 500-600 °C (932-1112 °F), the term is also associated with a rapid fire growth stage as radiant heat from the upper layer ignites all exposed combustibles in the compartment (filling the compartment with fire). At two times during this test, the temperatures in the space met the definition of flashover, but the heat release of the fire did not significantly increase. This was attributed to either a lack of oxygen or to a lack of fuel surface area. In any case, in order for the fire to rapidly increase to the point where the compartment is filled with flame, both an adequate air supply and ample fuel loading/surface area are needed. In a significant percentage of missile hit scenarios, these conditions may not be met.

Another issue relative to flashover concerns the method by which rapid fire growth can occur. In the classical case of flashover, ignition of exposed fuel surfaces occurs due to the incident radiant heat flux caused by the hot gas layer. As shown during the CG-19 WET, the heat released by a warhead detonation causes an instantaneous temperature spike throughout the blast area well in excess of 500 °C (932 °F). Although the gas temperatures in the PDA are well above the auto-ignition temperature of normal shipboard combustibles, there is a period during which there is insufficient oxygen to allow these materials to burn. If the oxygen recovers while fuel surfaces are above their auto-ignition temperatures, rapid combustion can occur. Auto-ignition temperatures for common materials are on the order of 200-300 °C (392-572 °F) [10] and are much lower than those temperatures associated with flashover. Regardless of whether rapid ignition occurs due to heating via radiation or immersion in hot gases, the effect could be the same.

The significance from a fire fighting standpoint is twofold: (1) given rapid response, fire fighters may be able to extinguish the fire during the lull period while oxygen-deficient gasses are replaced by fresh air, though (2) fire fighters may have to confront a sudden flare-up of

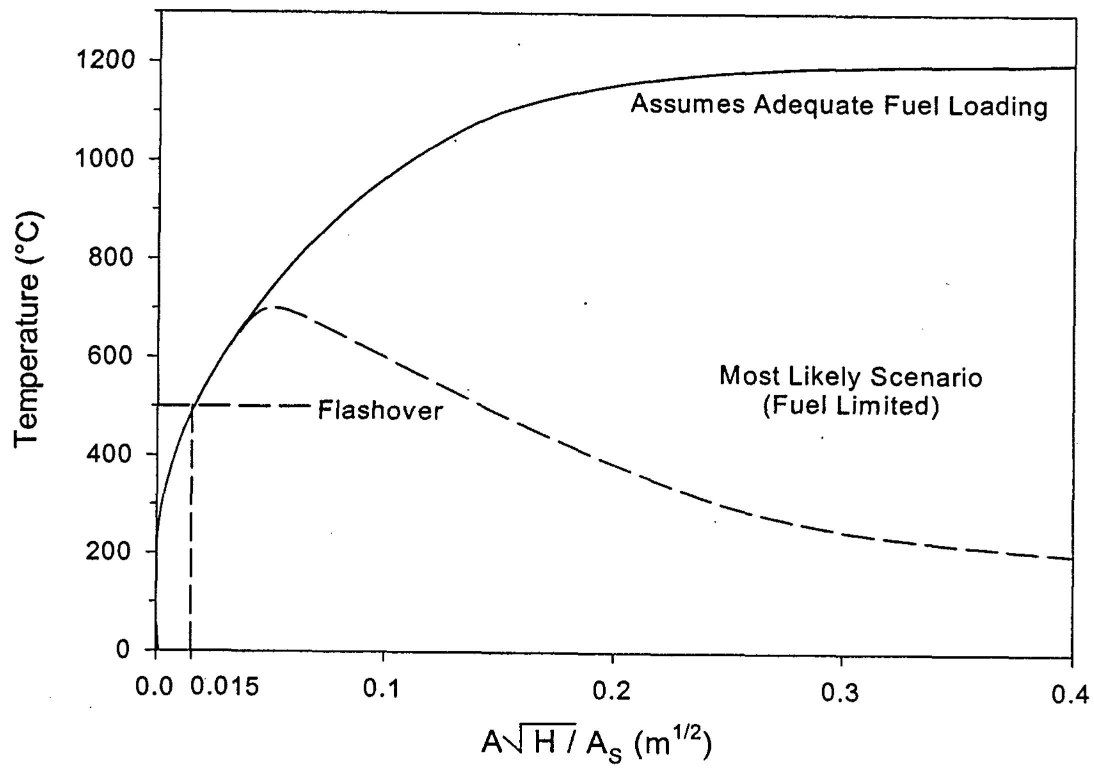

Fig. 2. – Conditions required to flashover the PDA

exposed fuel surfaces as soon as the oxygen level increases. Fire fighting implications are discussed in more detail in paragraph 4.3.

4.2 Design Implications

4.2.1 Bulkheads and Doors

Since the PDA will eventually become fully involved in a majority of weapon hit scenarios, structural improvements can play a major role in reducing the overall fire size. Hardening the hull could potentially reduce the size of the vent opening and the heat release rate of the fire. Bulkheads and doors (especially passageway doors) that remain intact are essential for reducing the size of the PDA and at the same time may minimize secondary fire damage.

Long passageways without doors or other closures which extend through multiple subdivisions of a ship can result in unrestricted fire and smoke spread if they are part of the PDA. The Navy should consider installing doors in long open passageways to limit the size of the PDA and reduce fire and smoke spread throughout the ship.

The heat transfer/insulating characteristics of major watertight subdivisions should also be revisited. Bulkheads and decks (or bulkhead and deck treatments) that could contain the heat in the PDA and prevent fire spread could significantly reduce the outcome of the event. At a minimum, they would reduce the manning required to combat this fire by negating or reducing the need to set boundaries.

Many ships are currently being fitted with fire insulation on fire zone boundaries. Aircraft carriers are currently not equipped with fire insulation on any boundaries. The Navy should consider fitting aircraft carriers with fire insulation on fire zone boundaries and on the boundaries of vital spaces.

Current Navy fire insulation is designed to be installed on the exposure side of the boundary. As a result, many boundaries are insulated on both sides. The current insulation has limited strength characteristics and may be blown off by the blast. As a result, a new innovative approach may be required to address this damage issue and could potentially reduce the weight associated with having to insulate both sides of the boundary. One potential approach would be to sandwich the insulation between two sheets of metal.

When evaluating new insulating techniques and materials, the performance requirements (backside temperature and duration of protection) may need to be reconsidered and selected based on the application. For example, the requirements for magazines and/or vital spaces may be different than the requirements for other applications.

To summarize the previous discussion, the following items should be investigated:

- Consider the installation of doors in long open passageways;
- Measure ability of fire insulation to remain in place after a weapon detonation;
- Evaluate the impact of various bulkhead and deck coverings to prevent fire spread outside the PDA; and,
- Consider new bulkhead designs (e.g., sandwich insulation, composites, etc.).

4.2.2 Minimization of Fuel Loading

Previous fuel loading studies [11-13] have shown that almost every shipboard compartment contains adequate fuel to support a fully developed compartment fire (with a limited few exceptions). Typical fuel loadings for actual shipboard compartments range from 0.2-0.4 kg/m^2 (5-10 lbs/ft^2) with a significant portion of the fuel comprised of cables running through the overhead of the space (Appendix A). Effort should be made to minimize the fuel loading in each compartment and/or develop techniques that prevent burnable materials from coming in contact with air (oxygen).

4.2.2.1 Ordinary Combustibles

The following containment techniques should be considered to reduce the effective fuel loading in the space:

- Stowage of combustibles (clothing, books, paper and office supplies) in self closing metal lockers and cabinets;
- Self closing metal trash receptacles;
- Roll type desks (lid closed when not in use or during potential hostilities);
- Enclosed closet stowage for all linens and towels; and,
- Utilization of "Murphy" beds (when not in use folds up into metal enclosed niche in the bulkhead).

4.2.2.2 Cabling

The CG-19 WET adds credence to previous studies that have shown that electric cableways provide a majority of the fuel loading in a typical shipboard compartment [11-13]. These studies suggest that cabling can be on the order of 70% of the fuel loading for a given space. Since cables are usually installed high in the overhead, they are more likely to become involved in a fire due to exposure from the hot upper layer. Cabling that is difficult to ignite and has a lower heat release rate would reduce the effective fuel loading and should be investigated. A ship design policy that requires all cables to be run in enclosed steel trunks (potentially blast hardened), preferably located at/near deck level on the inside of the hull would also significantly reduce the overall fuel loading/fire severity and would increase the survivability of the cabling/systems.

This would be especially true for the upper decks of an aircraft carrier (03 Level, 2nd and 3rd Decks). Due to regulations preventing cabling from running through the magazines on the lower decks and through the aircraft hangars on the Main deck, the cable loadings on the 03 Level, 2nd and 3rd Decks is significantly higher than analogous compartments on other combatants.

4.2.2.3 Fuel Piping

Although ruptured fuel piping was not an issue during the CG-19 WET, techniques to blast harden flammable liquid piping should be considered/developed. These techniques should include but are not limited to: double wall piping with survivable fittings, excess flow/automatic shut-off valves, remote control fuel shut-off, smart valves, etc.

4.2.3 Fixed Fire Fighting Systems

The CG-19 WET also provided some information relative to the design and utility of water delivery systems (e.g. overhead sprinkler systems) for suppressing combat-induced fires.

The design of such systems (and other systems running through the ship) should consider the likely blast pattern from and anti-ship missile as observed during this test and during the attack on USS *Stark* in May of 1987 [14] where only one side of the ships hull was damaged by blast. This suggests that water distribution piping running along the interior of the hull (on both sides of the ship for redundancy) may survive the blast.

This test might also suggest that an overhead water delivery system (suppression system) will have limited utility in a combat induced fire. To achieve cooling and/or suppression in the PDA, more survivable system designs need to be developed and tested.

The recently completed Damage Control-Automation for Reduced Manning (DC-ARM) program helped to identify and develop the systems, equipment and techniques that will be required to significantly reduce the manning requirements for damage control (DC) and improve DC performance on Navy ships [15-17]. The DC-ARM technologies demonstrated included a high-pressure (HP) water mist fire suppression system.

In the design of the DC-ARM water mist system, the concept of improved survivability was introduced with an architecture that included HP sidewall water mist nozzles [18]. The concept was to provide a design where some nozzles survive the blast in the PDA. Since the damage in the PDA tends to be less around the perimeter, the sidewall nozzle concept has significant merit. Water discharged from these nozzles would then cool the PDA and prevent fire spread to adjacent compartments. This would reduce the manpower required to perform an indirect attack on the PDA. This survivable sidewall concept could be adapted to other systems as well (e.g. conventional sprinkling).

The ability of a sidewall water mist system to cool the PDA has been bounded analytically and validated during full scale testing [19, 20]. The results suggest that 40-80 Lpm

(10-20 gpm) of water mist could potentially cool the PDA to less than 100 °C and prevent fire spread to adjacent spaces for the likely range of battle damage conditions included in this analysis.

For combat scenarios, fixed boundary cooling systems at major subdivisions may have considerable merit. Previous studies have identified the relatively low water delivery rate necessary to prevent fire spread through intact boundaries [21]. A perforated pipe (or other water delivery systems/nozzles) on each side of a major boundary should be considered, especially in a minimally manned ship where conventional fire party boundary men may not be available.

4.3 Fire Fighting Implications

4.3.1 Increased Situational Awareness

The DC-ARM program [15-17] developed and demonstrated technologies that enable significant reductions in DC manning by automating selected DC functions. The purpose of the program was to evaluate the capabilities of the advanced systems and technologies developed to date, demonstrate improved situation awareness by DC Central personnel, and evaluate the modified DC Manning organization.

While not associated with the CG-19 WET, the DC-ARM program made significant steps in reducing the DC manning required for a wartime casualty (missile induced conflagrations). For shipboard implementation, a first step to applying this knowledge to an actual ship may be to focus on the situation awareness aspect of the problem. A video monitoring system or a simple Commercial Off-the-Shelf (COTS) heat and/or smoke detector system installed throughout the ship could be used to define the PDA and to track the progression of the fire through the ship. Since there appears to be a trend towards installing video monitoring systems on new ships for security purposes (watch standing), the same system could also be used to increase the situational awareness during a missile-induced conflagration.

4.3.2 Fire Fighting Procedures

Prior to a discussion on fire fighting doctrine and procedures, the adverse conditions produced by the blast need to be restated. It is these conditions that will dictate the success of the fire fighting efforts.

In a majority of missile hit scenarios, the fire main will in all probability need to be realigned prior to conducting manual fire fighting. Access leading into the PDA will also be hindered by the structural damage created by the blast. As a result, a cutting torch or crowbar may be required to gain access to the PDA. Once inside the PDA, there will be huge mounds of debris and jagged metal spread throughout the space. These conditions, combined with the heavy smoke and high temperatures created by the fire, will present a serious obstacle for the fire fighting party. As a result, the first decision will be to determine whether to access the space and begin a direct attack or to prevent fire spread outside the PDA by setting boundaries

It should be emphasized that the following discussion, which minimizes the importance of entry and a direct attack on the PDA, presumes the immediate demise of all personnel within the space negating the need for search and rescue within the PDA. It is assumed that immediate lethality will result in the blast area from the fireball, blast wave and overpressure, primary and secondary fragmentation, immediate consumption of all oxygen, elevated temperatures, and copious quantities of toxic combustion products. The issue of potential human survival and the role of search and rescue efforts can have significant impact on tactics to be followed. To validate this assumption on lethality, it is suggested that an in-depth analysis be conducted focusing on human survivability in the blast environment.

4.3.2.1 Attack Options

The "Operational Objectives for Fire Fighting" [22] were developed to establish the fire fighting capabilities required for a ship to survive a hit from a modern anti-ship missile. That report, which was based primarily on testing conducted with solid propellant (such as that used in EXOCET), concluded that the compartment of origin (PDA) would become fully involved within 3 minutes of the detonation as shown in Fig. 3. The experimental and incident data used to develop those conclusions have various interpretations raising questions about the likelihood and timing of this event. The results of the CG-19 WET add additional data concerning the time required to reach the fully developed fire stage.

The time-temperature curve recorded during the CG-19 WET is similar in shape to the one presented in the "Operational Objective for Fire Fighting." The difference between the two curves lies in the time scale of the event. A comparison between the two curves for the first twenty minutes after the hit is shown in Fig. 4. As indicated in this figure, the duration of the initial thermal pulse created by the warhead detonation and the time required to reach full involvement may have been previously underestimated by a factor of four to five. The conditions produced by the initial thermal pulse lasted in some degree for over 5 minutes. The compartment fire did not reach full involvement until 10 minutes later (15 minutes after the hit). This data perhaps suggest that in some instances there is more time than previously thought to initiate fire fighting actions in an attempt to slow fire growth in the PDA.

The temperature curve from the CG-19 WET suggests a possible "window of opportunity" lasting several minutes where it might be possible to automatically (through the use of a survivable system) or manually attack the fire directly to prevent or slow the transition into the fully developed compartment fire. Previously testing on the ex- USS *Shadwell* as part of the Attack Team Workshop [23] showed that fully protected fire parties can function in air temperatures as high as 250-300 °C (482-542 °F) for several minutes. On the *Shadwell*, fire fighters with breathing apparatus, full ensemble, flash hoods and gloves (i.e., no exposed skin area) were able to enter a compartment with the air temperature at head height about 300 °C and extinguish multiple fires involving wood cribs, particle board, and cardboard filled boxes using an "offensive fog" attack method. The *Shadwell* results would clearly suggest that, between five

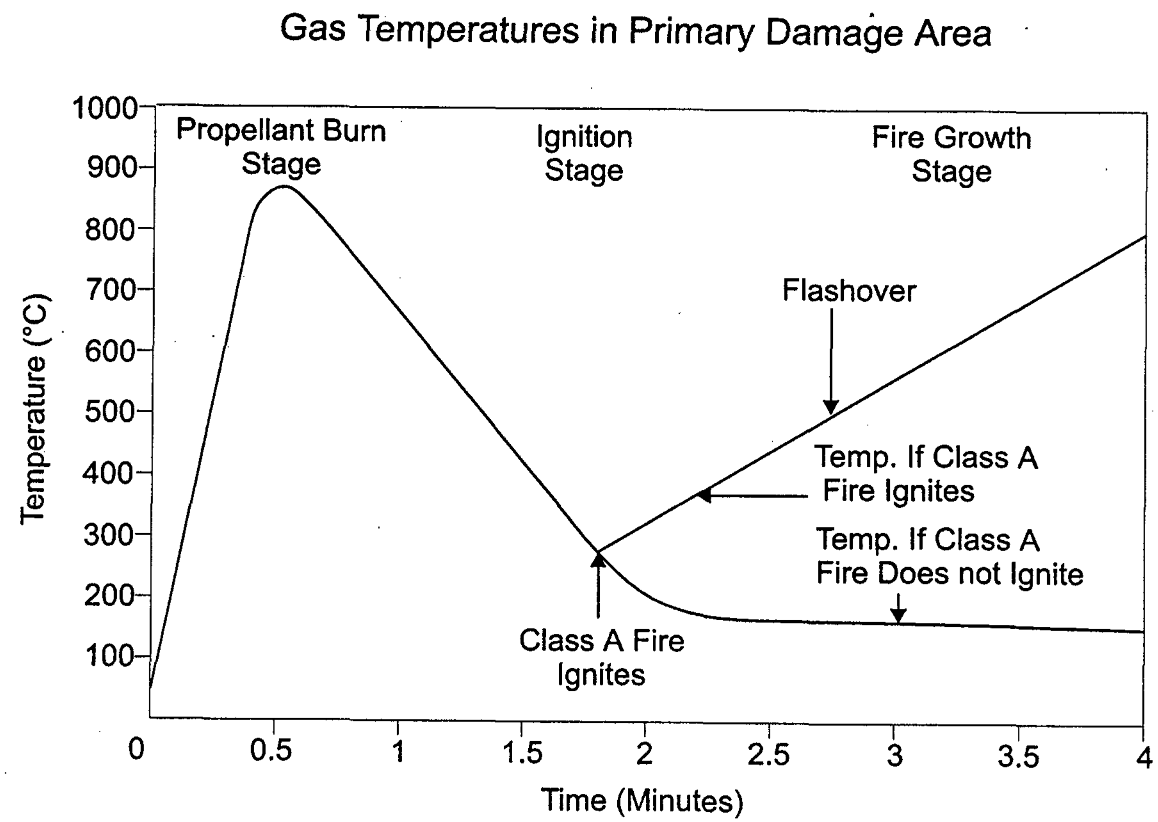

Fig. 3 – Assumed time temperature curve for a missile induced conflagration [22]

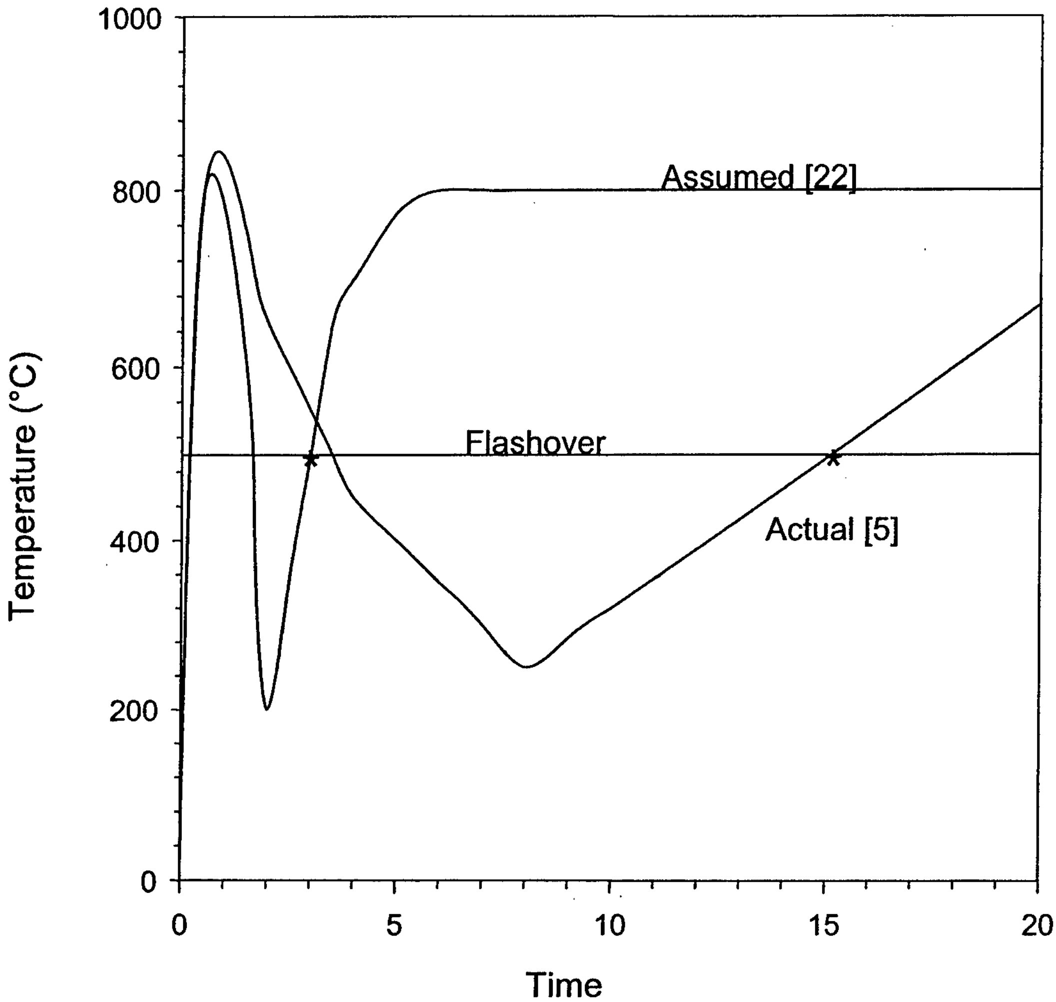

Fig. 4. – Measured time temperature curve for the CG-19 WET

to ten minutes after the hit, the temperatures might be low enough to permit such an attack (assuming the fire party can quickly gain access to the PDA).

Another approach would be to conduct an indirect attack on the PDA by cutting holes in the deck above and inserting a hose line nozzle set for a wide angle fog pattern. This type of indirect attack was shown to be very effective during the DC-ARM program [16, 17]. It is recommended that the holes be cut 6-9 m (20-30 ft) forward and aft of the estimated point of detonation. Other techniques and hardware such as cellar nozzles or hi-expansion foam generators should also be considered/investigated.

4.3.2.2 Setting Boundaries

Even if the temperatures are not excessively high, attempts to enter the PDA for direct fire fighting will be arduous, time consuming, and most likely futile in terms of salvaging the contents of the space. The data indicates that for a considerable period of time (at least 15 minutes) the fire should be confined to the PDA. Within this area, human survival is unlikely and blast damage is extensive.

For practical purposes, it may be best from a fire fighting standpoint to assume that the contents in the PDA have been completely destroyed by the blast. As a result, the threat from the fire is the likelihood of spread to adjacent spaces. This suggests that the primary goal of fire fighting efforts should be to cool boundaries and prevent spread (set boundaries around the PDA).

Another factor supporting the need to focus on boundary cooling is illustrated in Fig. 5. The blast tends to shred the contents of the space and pile a significant portion of the contents around the perimeter of the PDA. This piling of combustible debris around the perimeter could cause direct flame impingement on the bulkheads, facilitating rapid heat transfer (and fire spread). Previous studies have shown that heat transmission through an intact bulkhead can cause ignition of combustibles on the non-fire side in less than 10 minutes [24].

4.3.2.3 Smoke Curtains

A less conventional approach to combating a missile induced fire is to reduce the oxygen available for combustion. As discussed in the CG-19 Final Report [5], a typical "wood stove" airflow pattern was created on the CG-19 by the missile penetration and warhead detonation. Throughout the duration of the fire, fresh air entered through the hole created by the missile while smoke and combustion products exited the overhead "chimney" through hatches on the main deck that were blown open by the blast. In some respects, the high vent path is an anomaly relative to typical blast damage. If these hatches had not been located above the blast area, there may not have been a topside hole to the weather. This would have significantly reduced the oxygen available for combustion as well as the size of the ensuing fire. A technique such as covering the missile entry hole (or any other opening between the PDA and the weather that provides air to the fire) with a smoke curtain could considerably reduce the size of the fire. In

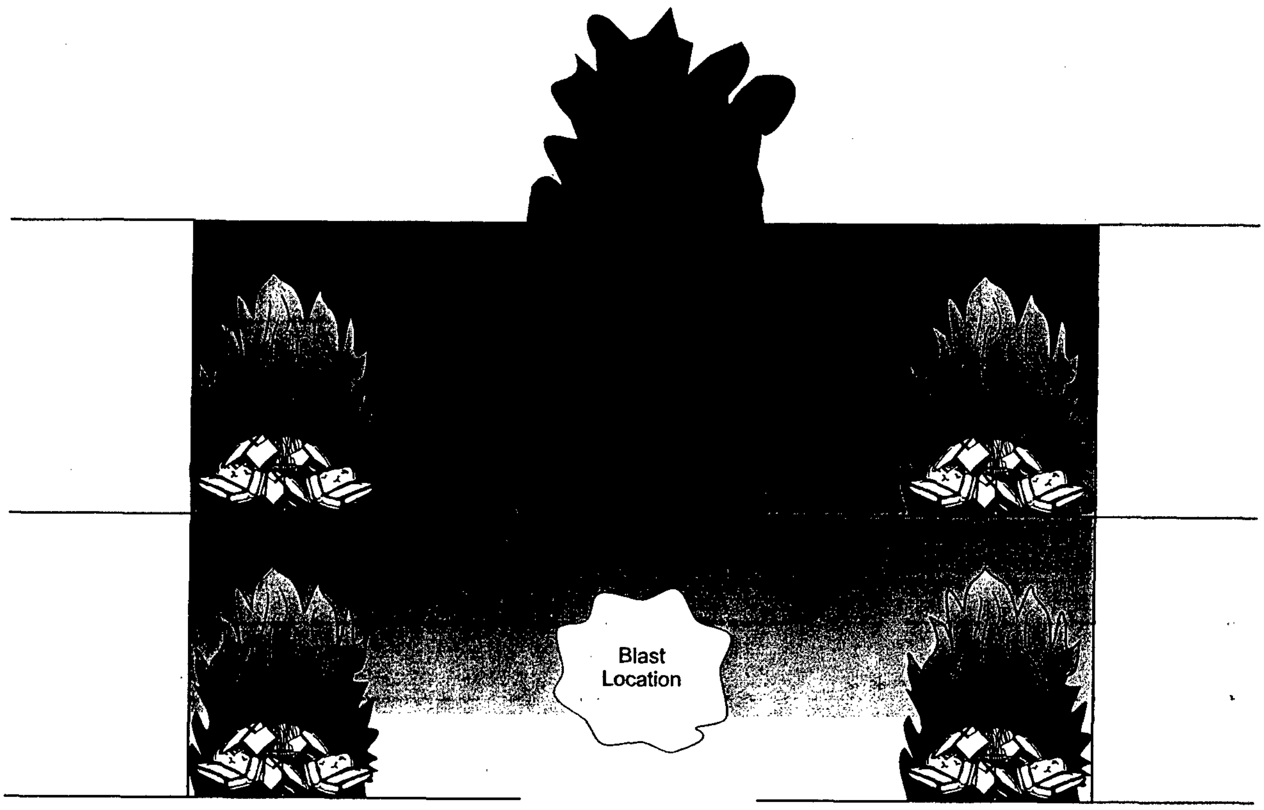

Fig. 5 – Relocation of combustibles caused by the blast

this particular case, the entry hole was small and could have been easily covered. Quantification of the merits of such a procedure should be considered as a future R&D study.

4.3.2.4 Suggested Fire Fighting Doctrine

The essential lessons learned from a procedural standpoint are as follows:

- It is important to readily determine the perimeter of the PDA. This will aid in deciding whether to enter the PDA or to set boundaries in adjacent spaces.

- Boundary setting, including boundary cooling as necessary, should be established around the perimeter of the PDA with special attention given to vital spaces.

- If accessible, the missile entry hole should be covered with smoke curtain (or other means) to restrict airflow into the compartment.

- Lateral entry into the PDA for purposes of direct or indirect fire fighting may be attempted subject to the following constraints:

  - Access will probably be blocked by blast damage. Time and effort should not be wasted on forcible entry at the expense of setting boundaries;

  - Entry will require full protective clothing and breathing apparatus;

  - To be successful, entry must be made within the first ten minutes; and,

  - Fire fighters should be alert to the possibility of a very rapid temperature rise as the oxygen level in the compartment begins to recover.

- If direct entry into the PDA is not possible, an indirect attack should be conducted by discharging water into holes cut in the overhead of the blast damage area. Holes should be cut approximately 6-9 m (20-30 ft) forward and aft of the estimated point of detonation.

4.3.2.5 Additional Considerations

There is also the question of whether the impact location (general area in the ship) would alter the fire fighting tactics. It can be rationalized that there are at least three different scenarios associated with the impact location. These scenarios/locations include: low in the ships hull, high in the ship's hull, and in the super structure. In all three scenarios, the blast damage (and openings to the weather), the ability to access the compartment, the approach/need for an indirect attack, and the potential need for dewatering may be significantly different. It is recommended that a blast damage model be used to bound the range of potential conditions for each of these scenarios. The predicted blast damage used in conjunction with current fire modeling techniques would bound the likely thermal conditions produced by the fire and aid in the development of tactics and doctrine to combat the various scenarios. The effect of the types of compartments in the PDA (i.e., magazines, flammable liquid storerooms, vital spaces, etc.) as well as the ship status prior to the blast (i.e., set zebra) should also be included in the sensitivity analysis.

5.0 SUMMARY

The following techniques are recommended for reducing the severity of a missile induced conflagration and should be considered for inclusion in future weapons effects testing.

I. Evaluate various "fuel load minimization concepts" (reductions in total fuel loading and /or techniques that prevent burnable material from coming in contact with air) including:
   - Stowage of combustibles (clothing, books, paper and office supplies) in self closing metal lockers and cabinets;
   - Self closing metal trash receptacles;
   - Roll type desks (lid closed when not in use or during potential hostilities);
   - Enclosed closet stowage for all linens and towels;
   - Utilization of "Murphy" beds (when not in use folds up into metal enclosed niche in the bulkhead);
   - Investigate cabling with reduced/lower burning characteristics;
   - Installation of electrical cable in conduit, protected chases or box beam girders; and,
   - Blast hardened flammable liquid piping (double wall piping with survivable fittings, excess flow automatic shut-off valves, remote control fuel shut-off, smart valves, etc.).

II. Evaluate techniques for reducing the likelihood of fire spread through intact boundaries including:
   - Measure ability of fire insulation to remain in place after a weapon detonation;
   - Evaluate the impact of various bulkhead and deck coverings to prevent fire spread beyond the blast damage area; and,
   - Evaluate other insulation techniques (e.g. sandwiched insulation between two sheets of metal).

III. Evaluate possible installation techniques for enhancing the survivability of systems (sprinkler, water delivery, and vital systems) including:
   - Piping and cabling at the hull rather than distributed throughout the overhead;
   - Piping run in steel box beam girders (armored pipe runs);
   - Cabling run in steel box beam girders (armored cable runs);

- Recessed sprinklers heads; and,
- Sidewall heads.

IV. Develop/evaluate systems to cool the PDA and cool the PDA boundaries.

V. Develop a network of sensors designed to increase the overall situational awareness.

VI. Refine the Doctrine for fighting missile induced fires including:
- Develop/evaluate techniques for accessing the space after the hit;
- Develop/evaluate techniques for conducting an indirect attack;
- Develop/evaluate techniques for setting boundaries around the PDA; and,
- Quantify the utility of air-starving the fire by covering vent holes to the weather using smoke curtains as a possible fire fighting tactic.

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APPENDIX A

FUEL LOADINGS OF TYPICAL SHIPBOARD COMPARTMENTS

FUEL LOAD ESTIMATES FOR TYPICAL SHIPBOARD COMPARTMENTS

As an aid in determining fuel load quantities for the ex-SPRUANCE WET tests, three references that estimate typical fuel loads were reviewed. Reference [A1] was based on visits to two CG-47 Class ships as well as a detailed review of DDG-51 design drawings. Reference [A2] was prepared to estimate fuel loads in spaces on the USS *Stark*. Reference [A3] was funded by NRL as a means of quantifying ship fire hazards based on compartment material contents. The tables below provide summaries from each reference of estimated fuel loads for selected spaces.

Table 1. Fuel Loads from Reference [A1]

Space Designation	Normal Contents (lbs/ft^2) (1)	Typical Cable Fuel Load (lbs/ft^2) (2)	Typical Total Fuel Load (lbs/ft^2) (3)
Crew Living	5-7.5	2-2.5	7-10
WR, WC & Shr	1-2	1-2	2-4
IC & Gyro	2.5-5	5-7.5	7.5-12.5
Ships Store Room	5-7.5	2-2.5	7-10
A/C Mach Pump Rm	1-2	2-2.5	3-4.5
Fan Room	1-2	5-7.5	6-9.5
Tool Issue Room	1-2	1-2	2-4
Linen Locker	5-7.5	1-2	6-9.5
Laundry	5-7.5	1-2	6-9.5
Crew Rec/Trng	1-2	2.5-5	3.5-7
General Workshop	2.5-5	1-2	3.5-7
Passageway	0	2-10 (4)	2-10

Notes: (1) Fuel load of contents (not including cables) based on space designation. All fuel loads based on pounds of "wood equivalent" (8000 BTU/lb)
(2) Typical fuel load presented by cables passing thru or serving space
(3) Typical total fuel load (contents plus cables)
(4) Overhead cable fuel load in passageways varied widely. Highest fuel load occurred when longitudinal passageways were used for main fore-aft cable runs.

Table 2. Fuel Loads from Reference [A2]

Space Designation	Normal Contents (lbs/ft^2)	Typical Cable Fuel Load (lbs/ft^2)	Typical Total Fuel Load (lbs/ft^2)
Crew Living	6.4	3.2	9.6
WR, WC & Shrs	.3	1.4	1.7
Ships Store	6.3	2.1	8.4
Electronics (CIC)	1.0	14.1	15.1
Passageway	0	6.3	6.3

Table 3. Fuel Load for Crew Berthing from Reference [A3]

(Calculations based on 500 ft^2, 18 man bunk room)

Item	Fuel Load
Per Person (40 lbs bedding, 60 lbs personal property) 18 persons x 100 lbs/person	1800 lbs
Cable Passing Through (50 linear ft x 2 ft^3 per linear ft x 20 lbs/ft^3)	2000 lbs
Floor Tiles (500 ft^2 x 1 lb/ft^2)	500 lbs
Paint on Bulkheads	70 lbs
Trash in Cans	30 lbs

Total 4400 lbs

Fuel Load per ft^2 4400 lbs/500 ft^2 = 8.8 lbs/ft^2

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