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Options for Advanced Smoke Control Onboard Ships

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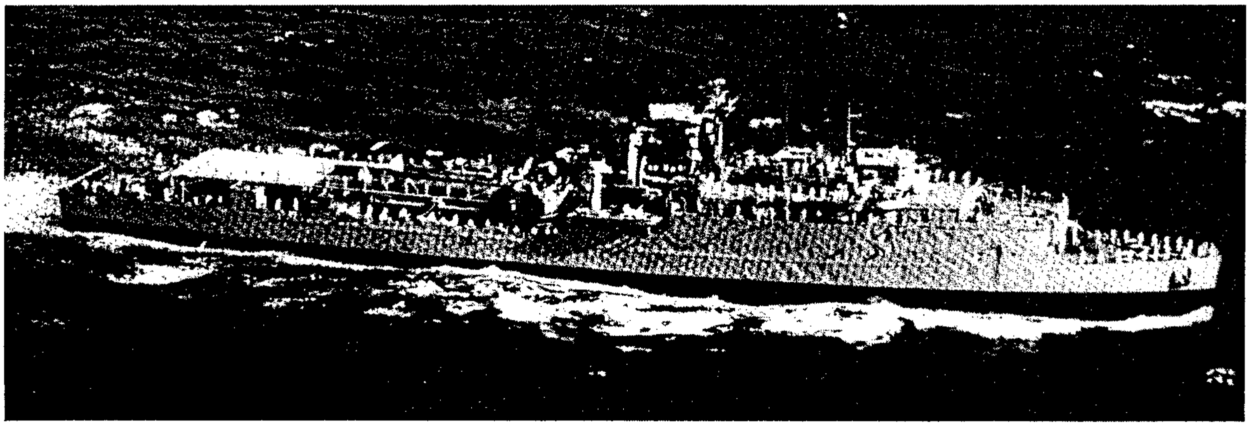

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14. ABSTRACT

The complications posed by smoke disrupt all facets of the damage control (DC) problem onboard ships. Smoke will reduce visibility, which causes disorientation and deterioration of communications among the ship's crew. In turn, the ability of the ship's crew to restore vital ship mission capability will be impeded. In practice, desmoking is generally not implemented until after the fire is under control. With this approach, the benefits gained from minimizing smoke levels in the earlier stages of the event are not realized.

For the design of future Navy ships, it is essential to identify the performance requirements for smoke control and to design systems according to these requirements. Installed smoke control systems will become more important on ships with reduced manning since there will be fewer people available to implement manual techniques. This report describes a shipwide system that could be installed on ships of the future.

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OPTIONS FOR ADVANCED SMOKE CONTROL ONBOARD SHIPS

1.0 INTRODUCTION

1.1 Background

The complications posed by smoke disrupts all facets of the damage control (DC) problem onboard ships. Smoke will reduce visibility which causes disorientation and deterioration of communications among the ship's crew. In turn, the ability of the ship's crew to restore vital ship mission capability will be impeded [1-3]. Currently, manual techniques are used for removing smoke. These techniques require manpower and implementation is time consuming [3]. Firefighting doctrine permits active desmoking for Class A and Class B fires outside of the fire compartment prior to fire extinguishment [4]. In practice, desmoking is generally not implemented until after the fire is under control. With this approach, the benefits gained from minimizing smoke levels in the earlier stages of the event are not realized.

In addition to complicating damage control operations, smoke can contain toxic and corrosive gases. Toxic gases, such as carbon monoxide, may impede the functions of personnel if the smoke spreads to vital compartments remote from the fire. Corrosive gases, such as hydrogen chloride and hydrogen fluoride, can cripple electronic equipment [5-7]. Equipment damage of this nature was realized during a fire on the USS TATTNALL where corrosive smoke "caused extensive damage to electronics equipment [8]."

In order to minimize the problems associated with smoke, the concept of controlling smoke by using ventilation fans, ducting and dampers was evaluated by the United States Navy in testing which occurred in the 1980's [9-12]. Results from these tests showed that smoke spread could be prevented if the ventilation system was configured properly. In practical terms, this required that all normal ventilation be diverted to critical areas in the event of a fire. This change was accomplished remotely by using automated dampers which either opened or closed (depending on their location) when desired. This type of system was named smoke ejection system (SES) [10].

Initially, this research was directed toward developing a system for DDG 51 Class ships. Several design modifications were evaluated in an attempt to reduce air flow requirements and simplify the design. Ultimately, a system was developed that would remove smoke from the DC Deck only by shunting normal supply and exhaust ventilation. This system relied only on the air handling capacity provided by the normal ventilation systems (for example, the collective protection system (CPS)). The design for DDG 51 was eventually rejected due to backfit costs which included substantial redesign/engineering costs from the shipyard.

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More recently, a smoke ejection system was implemented in the design for LPD 17. The system proposed for the DDG 51 Class formed the design basis for LPD 17. The purpose of the system is to desmoke the DC Deck passageways and to prevent smoke infiltration in the Medical Space on the Main Deck in a smoke-filled fire zone. Desmoking of individual compartments or other passageways will not be accomplished with this system. The LPD 17 system was implemented and evaluated on the U.S. Navy full scale research vessel, ex-USS SHADWELL [13-16]. Test results showed that the visibility in the DC Deck passageways was restored from less than 1.5 m (5 ft) to 6.1 m (20 ft) in less than 5 minutes for a representative range of air change rates (once the fire compartment was isolated).

The implementation of a smoke control system on LPD 17 was an important step for damage control. Although this system will accomplish its design goals, it is not a comprehensive ship design. In addition, the system was designed using only the existing ventilation (e.g., CPS ventilation). For the design of future Navy ships, it is essential to identify the performance requirements for smoke control and to design systems according to these requirements. Installed smoke control systems will become more important on ships with reduced manning since there will be fewer people available to implement manual techniques. This report describes a shipwide system that could be installed on ships of the future.

1.2 Terminology

Several terms used throughout this discussion may be unfamiliar, or have several meanings associated with them. For the purpose of this report, the following definitions will apply:

1. Smoke – "The airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass [17]."

2. Fire zone – Ships that are longer than 67 m (220 feet) are divided into fire zones. "Fire zones are physical boundaries designed to retard the passage of flame and smoke and the spread of fire [18]." In new ships, each fire zone has an independent ventilation system. Fire zone boundaries are not more than 40 m (131 feet) apart [18]. Generally, a fire zone will consist of compartments, and longitudinal passageways. The fire zone may be further divided into watertight subdivisions. Typically, there will be three or fewer watertight subdivisions within a fire zone.

3. Smoke control system – A system that provides one or more methods for modifying smoke movement [17]. The primary objective of the system is to prevent smoke from spreading from the fire area to clean areas.

4. Smoke control zone – An area within the ship that is enclosed by smoke barriers and is part of a zoned smoke control system [17]. The smoke control zone defines the area to which smoke will be confined.

2.0 OBJECTIVES

The objective of this analysis is to examine the performance requirements for shipboard smoke control systems and to determine how these requirements will impact the system design. The intent of this evaluation is to develop system options that will achieve the desired goals without specific hardware, monetary or space constraints. This approach differs from that used for previous programs where system designers developed a system using the existing hardware (e.g., CPS ventilation).

3.0 APPROACH

The input from an expert panel (see Appendix A) was obtained over the course of this study. The panel reviewed the history of Navy smoke control, identified system performance requirements and discussed concepts that could be implemented in future shipboard designs. Based on a preliminary evaluation of the capabilities and limitations of these concepts, two concepts were investigated further to determine how the performance options would impact the system design requirements.

4.0 POTENTIAL CONCEPTS

Five concepts were identified as being useful for the control of smoke onboard ships. These concepts are as follows:

1. Compartmentation/Passive Design – This concept relies on the use of vestibules and closures (for hatches and doors) to prevent smoke migration from contaminated areas to clean areas.

2. Smoke Exhaust – The principle of this concept is to remove smoke by exhausting contaminated air and replacing it with clean air. For the purpose of this discussion, smoke exhaust will be categorized as either smoke extraction or desmoking. "Smoke extraction" is used to describe smoke control in situations where the fire has not been extinguished. This type of system would be designed to match a specific smoke generation rate. "Desmoking" is used to describe the removal of smoke after the fire is extinguished or the fire compartment is isolated. While the concept is the same, the design considerations will differ between these two types of smoke exhaust.

3. Pressure Differences – The principle of this concept is to prevent smoke from migrating to clean areas by pressurizing clean areas and venting smoke-filled areas.

4. Counterflow – This concept involves the use of a "critical" air velocity through an Opening such as a doorway, to overcome buoyancy forces that drive smoke movement and hold the smoke at that location (see Fig 1).

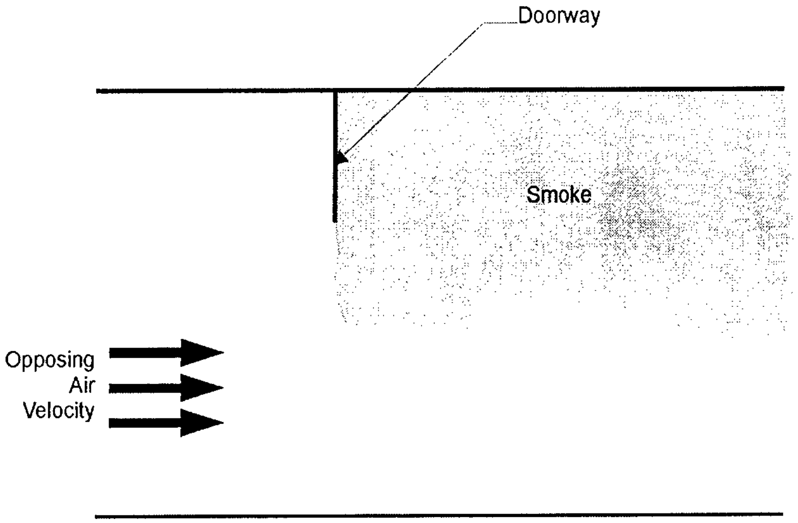

Fig. 1 - Smoke control using the concept of counterflow

5. Smoke Scavenging – The principle of this concept is to use a scavenger (e.g., electrostatic precipitator) to attract smoke particles and facilitate drop out.

Each of these concepts has associated advantages and disadvantages. These qualities are summarized in Table 1. One important distinction between these concepts is that some will provide smoke removal capability while others will only prevent smoke movement. For the purpose of this study, it was assumed that either approach would be acceptable.

Table 1. Advantages and Disadvantages Associated with Smoke Control Concepts

Concept	Advantages	Disadvantages
Compartmentation/ Passive Design	- simple approach - prevents contamination of clean areas	- does not remove smoke - may be manpower intensive unless automated - depends on reliability of closures (if they are even there) - reduced functionality for firefighters - question of "how tight is good enough" becomes critical, may have maintenance issues with doors and hatches
Smoke Exhaust	- can provide means for quickly removing smoke (provided adequate fan capacity)	- may not prevent smoke from migrating to clean areas
Pressure Differences	- limits smoke movement for a given design fire	- may be difficult to design for leakage imposed by firefighters accessing zone - requirement for closures decreases functionality - does not provide means for removing smoke
Counterflow	- limits smoke migration - puts wind at firefighters back when approaching fire	- generally requires large air flow rates - could provide additional supply of oxygen to fire if fire space is unsecured - intended for smoke containment rather than removal
Smoke Scavenging	- may not require the use of an installed system depending on air handling requirements (i.e., may be portable)	- technology not yet completely proven for use in fires - large unit may not offer advantages to using standard ventilation - may not remove toxic gases

The use of compartmentation or passive design is the simplest of these concepts. It will prevent smoke movement to clean areas, but does not provide a means for removing smoke. The reliability of the design will depend on how well the closures are maintained. In addition, it may be manpower intensive to set the proper closures unless they are automated. The integrity of this type of system will be questionable in the event that a manual fire attack is staged. Doors and hatches must be open in order to stage the firefighting equipment. The integrity will also be in question if the ship has been hit by a missile. This concept could easily be incorporated with another concept, rather than relying on it solely.

Smoke exhaust, the concept used for the LPD 17 SES, can be highly effective for removing smoke. Depending on the system configuration, some smoke spread may occur. This was shown during LPD 17 SES testing on the ex-USS SHADWELL [13-15]. Since the system was designed for a slight overpressure on the DC Deck, smoke spread to the Main Deck during some tests. In general, smoke spread will be minimal (regardless of the configuration) if the system is activated before smoke can build up. Smoke exhaust is most effective when exhaust terminals are located at the outer edge of the smoke control zone and a supply terminal is located in the center of the zone. This configuration will create an air sweep through the entire zone.

Pressure differences is an excellent technique for use in preventing smoke spread from contaminated areas. This method does not provide for smoke removal. Also, similar to passive design, the proper operation of the system will be dependent on the number of openings in the zone. The larger the number of openings, the larger the pressure losses in the zone. The system can be designed to account for some leakage, but it may not be sufficient particularly in a missile hit scenario.

Counterflow can be useful for containing smoke provided that the opening is relatively small (such as a door). A supply source on the clean side of the opening and an exhaust path on the contaminated side must be provided. As a result, some smoke removal will be achieved. Depending on the geometry of the terminals, smoke removal may be inefficient.

Smoke scavenging using electrostatic precipitators involves using an electric field to charge particulate matter in a gas stream [19, 20]. The charged particles can then be separated from the gas stream. This technology is used in industrial processes to treat exhaust gases from devices such as boilers, furnaces and kilns. In addition, it is used to clean air in offices, hospitals and homes. Properties such as particle size and electrical resistivity will affect the separation efficiency [20]. Electrostatic precipitators have also been integrated into ventilation systems on submarines. The purpose of these units is to collect small particles such as those in tobacco smoke and oil mists. NRL conducted tests in the late 1980s to evaluate the efficiency of these devices for collecting smoke particles from a fire [21, 22]. It was determined that the standard unit would fail when heavy smoke was present [22]. Tests conducted with a prototype precipitator showed that this failure could be prevented. However, this unit, as well as state-of-the-art machines, would not be portable for the air handling requirements discussed in this analysis [23-25]. As a result, no clear advantage over other air handling systems was identified.

Based on these data, counterflow and smoke exhaust were identified as the two concepts that would be least sensitive to the status of closures and the integrity of the smoke control zone. Also, both systems will remove some quantity of smoke. Smoke exhaust will be more effective than counterflow if the goal is to remove smoke quickly.

Both of these concepts require air movement to achieve smoke control. Normally, the air flow rates are generated mechanically using fans. The use of novel ideas for creating air flow may offer an alternative to fans. An example of a novel idea would be to take advantage of the low pressure region that surrounds high velocity flow [26]. This concept has been described in fire fighting manuals as a means for removing smoke from rooms [27-29]. Use of this technique involves setting a fog stream to cover 85 to 90 percent of an opening positioned inside the room directed toward the outside [29]. The fog stream will entrain smoke from the room and push it out the opening. Air flow rates between 284 and 850 m^3/min (10000 and 30000 cfm) have been measured depending on the size, location and pattern of the nozzle [28]. A commercial water mist manufacturer has also used this principle to add smoke removal/scrubbing capability to extinguishing systems [6]. As a result, the use of installed water nozzles at key locations such as doorways and hatches may provide an alternative to fans.

Another useful technique may be to use installed systems, such as CPS ventilation, in an adjacent fire zone to remove smoke from the affected fire zone. This method was demonstrated during the 1998 Damage Control - Automation for Reduced Manning (DC-ARM) tests [30]. An air sweep through the smoke-filled zone may be established by opening the doors between the smoke-filled fire zone and the adjacent fire zone, and a door to weather on the opposite side of the smoke-filled fire zone. By implementing these procedures after the initial fire event, the passageways were cleared of smoke for the rest of the test [30].

5.0 PERFORMANCE OPTIONS

Prior to designing a smoke control system, it is essential to define the appropriate range of performance options. This includes specifying the goal of the system and the zone boundaries. The system can be designed for different levels of performance. The highest level of performance would be to prevent all smoke migration from the contaminated zone to clean zones. By comparison, it may be acceptable to allow a small amount of smoke into clean areas. The amount of smoke that enters the clean zone may be limited by a critical visibility or by a critical layer height (i.e. above head level). If one assumes that the fire is controlled without human interaction, desmoking after the fire may be adequate. As a conservative measure, this analysis considered that the system should prevent all smoke from leaving the affected zone.

The selection of smoke control zone boundaries defines the area where smoke will be confined. It can affect the level of sophistication necessary, requirements for closures, and the air handling requirements (i.e., fan size, ductwork diameter and length of ductwork). With the assumption that future ships will have the same type of architecture as that found currently on ships, three types of zoning were investigated in this analysis. These zones included the compartment, the watertight subdivision, and the full fire zone. Treatment for the watertight subdivision and full fire zone only included the longitudinal and athwart passageways. It was assumed that uninvolved compartments inboard of the passageways would be closed. Also, it is important to identify how many zones must operate simultaneously (as may be necessary in a wartime scenario). If one fan is used to serve multiple zones independently, the number of zones that can be operating at the same time may be limited.

6.0 IMPACT OF SUPPRESSION SYSTEM

The presence of a suppression system (i.e., sprinkler or water mist system) may affect the system design since the amount of smoke generated may be lower than if there were no suppression system. Also, the smoke may be less buoyant because the temperature may be lower. While the need for smoke control in conjunction with a suppression system has been questioned, studies have shown that the amount of smoke generated in sprinklered rooms can still be significant [31-34]. The heat release rate will generally decrease when the suppression system is activated (thus producing less smoke). Madrzykowski and Vetturi developed an empirical correlation that describes the exponential decay of heat release rate when sprinklers are operated [34]. The time constant is related to the water flow rate from the sprinklers.

Although it is recognized that smoke control requirements may be reduced when a suppression system is present, it is difficult to predict these requirements. The suppression system may be designed only for fire containment rather than suppression. Such systems include sprinkler systems and a low flow water mist system developed for potential use in the DC-ARM program [35]. This system is specifically designed to prevent a fire from reaching flashover conditions. In contrast, the suppression system may be a high flow water mist system designed to behave similar to a total flooding system (i.e., extinguishing system).

It is important to consider wartime scenarios where missile damage may cripple the suppression system. In this situation, it is possible that large quantities of smoke will be generated. If the suppression system is inoperable, it may follow that the ventilation is also inoperable. As a result, the smoke control zone boundaries would have to extend to the nearest zone where the ventilation is still intact. It is difficult to argue that smoke control would not be necessary in this type of scenario.

7.0 AIR HANDLING REQUIREMENTS

7.1 Smoke Containment Using Counterflow

The air flow requirements necessary to prevent smoke migration can be predicted using Froude modeling techniques. This modeling assumes that migration of smoke will be stopped when the inertial force associated with the opposing air velocity is equal to the buoyancy force associated with the smoke. Experiments have been conducted by Thomas [36], Heskestad and Spaulding [37], and Forssell *et al.* [11] to quantify the Froude numbers necessary for smoke containment. Based on the results of Heskestad, the correlation has been simplified in NFPA 92B, Guide for Smoke Management Systems in Malls, Atria, and Large Areas [17]. This correlation specifies that the critical velocity will be a function of the hot smoke temperature and the height of the opening. As shown in Appendix B, the critical velocity will reach a value asymptotically as the temperature increases (depending on the height of the opening). This asymptotic value is approximately three times larger than that calculated for a hot smoke temperature of 50 C (122 F).

Calculations were performed to determine the velocity that would be necessary to hold smoke at a watertight door. A standard watertight door in the open position with dimensions of 0.7 m wide by 1.7 m high (26 in. by 66 in.) and a sill height of 0.2 m (9 in.) was used (for a total opening height of 1.9 m). The hot smoke temperature was conservatively estimated as 1000 C (1830 F). Using these values, the critical velocity will be 2.4 m/sec (470 ft/min). For this door size, an air flow rate of 180 m^3/min (6200 cfm) would be required. Details of these calculations are described in Appendix B.

These values agree with those recommended by Forssell *et al.* [11]. While it is likely that the smoke temperature in the passageways will be much less than 1000 C, situations may exist where these high temperatures may be present (e.g., the effluent from a very large fire may discharge directly into the passageway). Since these values are difficult to bound, the recommended critical velocity would remain the same for each type of fire zone.

For suppressed fires, the required air velocity may be less since the smoke may be cooler. Since the performance of the suppression system cannot be predicted absolutely, the corresponding temperatures are uncertain. As a conservative measure, the suppression system would contain the fire and prevent flashover from occurring (500 C). With these conditions, the critical air velocity would be 2.1 m/sec (410 ft/min). This velocity equates to an air flow rate of 150 m^3/min (5300 cfm) for a standard Navy door. A less conservative calculation would use the assumption that the suppression system is thermally activated at 75 C (165 F), and that the fire does not grow once the suppression system is on. The required air velocity for 75 C exhaust gases would be 1 m/sec (200 ft/min). This velocity would equate to an air flow rate of 70 m^3/min (2500 cfm) across the door.

7.2 Smoke Removal Using Smoke Exhaust

7.2.1 Smoke Extraction

The requirements for smoke extraction (i.e. fire not extinguished) will depend largely on the fire size and the compartment geometry. The fire size will dictate the plume entrainment (or smoke generation rate) which can be used to estimate the mass flow rate that needs to be extracted. In order to convert the mass flow rate to a volumetric rate, the gas temperature must be estimated. The gas temperatures will be dependent on the compartment geometry (volume, aspect ratio), and heat transfer characteristics (vents, bulkhead and overhead coverings).

Smoke extraction requirements for control at the compartment zone level were calculated using a plume entrainment rate correlation developed by Heskestad [38] (see Appendix B for a further description). The entrainment will be a function of the heat release rate and the height at which the layer is located. This layer should be above the height of the door to prevent smoke from leaving the compartment. As an example, with a fire size of 500 kW and a layer height of 2.0 m (i.e., slightly above the height of the door), an exhaust gas mass flow rate of 2.7 kg/sec would be expected. The mass flow rate for a 1 MW fire would be 4.1 kg/sec. Assuming a hot gas temperature of 350 C (660 F), the 500 kW fire would require an extraction rate of approximately 280 m^3/min (10000 cfm), and the 1 MW fire would require approximately 430 m^3/min (15000 cfm). With a hot gas temperature of 500 C (932 F), the extraction rates would be 350 m^3/min (12500 cfm) and 540 m^3/min (19000 cfm), respectively. Higher gas temperatures would require even higher extraction rates.

Smoke extraction at the subdivision or full fire zone level may be a more feasible option. By allowing the layer height in the fire compartment to descend below the door, the smoke generation rate will be lower. As a result, less extraction capability will be required to maintain the same layer height in the subdivision passageway than in the fire compartment.

7.2.2 Desmoking

Desmoking performance can be quantified more easily since it is assumed the fire is extinguished and there is a finite amount of smoke to remove. Assuming the air is well-mixed, the amount of smoke that is present will decrease exponentially with time. The decay rate will be dependent on the air change rate (purge rate) within the volume. Using optical density as the measure of the smoke quantity, the rate of smoke removal can be expressed as [39]:

$$\frac{OD}{OD_o} = \exp^{-at}$$

where

OD = optical density at time t (m^{-1}),
OD_0 = initial optical density (prior to desmoking) (m^{-1}),
a = purge rate (air changes/minute), and
t = time (minutes).

Using this equation and data relating optical density to visibility [40-43], the amount of time needed to restore visibility from 1 m (3.3 ft) to 6.1 m (20 ft) can be calculated. These values are tabulated in Table 2 for three air change rates (50, 80 and 110 air changes per hour). Table 2 also includes the volumetric air flow rate that would be required to achieve these air change rates for either a subdivision or for a full fire zone as the smoke control zone. For demonstration purposes, the volumes of the subdivision and fire zone were estimated using approximate dimensions for DDG 51 passageways. The volume used for the subdivision was 37 m^3 (1300 ft^3) (9.1 m long by 1.5 m wide by 2.7 m high (30 ft by 4.8 ft by 8.9 ft)). The volume used for the fire zone was 130 m^3 (4400 ft^3) (31 m long by 1.5 m wide by 2.7 m high (100 ft by 4.8 ft by 8.9 ft)).

Table 2. Effect of Air Change Rate on Smoke Removal Time and Air Flow Rate Requirements

Air Change Rate (air changes/hour)	Time Needed to Improve Visibility from 1 m (3.3 ft) to 6.1 m (20 ft) (minutes)	Air Flow Rate Required for Subdivision Zone (m^3/min (cfm))	Air Flow Rate Required for Full Fire Zone (m^3/min (cfm))
50	2.4	31 (1100)	100 (3600)
80	1.5	49 (1700)	170 (5800)
110	1.1	68 (2400)	230 (8000)

As with counterflow, the presence of a suppression system will reduce the air flow rate requirements for smoke extraction and desmoking. Again, the requirements will be dependent on the type of suppression system that is installed and how effective it is.

7.3 Impact of Design on Overall Air Handling Requirements

Calculation of the air handling capacity only addresses a portion of the ventilation system design. The ductwork and control requirements are also part of this design. The length and diameter of ductwork that is required for each type of design is important. Space and weight limitations onboard ships mandate a careful consideration of tradeoffs. Duct diameter will be dependent on the ventilation capacity that is required as well as the size of the zone (i.e., length of ductwork). Higher air flow rates require larger duct diameters in order to minimize the pressure drop. Also, the pressure drop will be directly related to the length of ductwork used.

Calculation of specific duct size needed for different capacities is beyond the scope of this analysis. It will be dependent on how the ductwork is routed (including number of elbows and tees), and how many feet are required. As a guideline, approximate duct sizes can be calculated using the standards provided in Section 512 of the General Specifications for U.S. Navy Ships [44]. Maximum duct velocities of 18 m/sec (3500 ft/min) are permitted provided that noise levels do not exceed those specified in Section 073 [44,45]. With this requirement, ductwork handling 280 m^3/min (10000 cfm) would require a diameter of 0.6 m (1.9 ft). Ductwork carrying 140 m^3/min (5000 cfm) would require a diameter of 0.4 m (1.3 ft).

In order for the system to operate automatically, automated dampers would be necessary. Since one fan may serve numerous smoke control zones, automated dampers will be required for each zone. In addition, if ventilation from normal systems (such as CPS) were used, automated dampers would be needed to shut off ventilation to the normal terminals. In general, the larger the number of individual smoke control zones, the larger the requirement for automated dampers. The relationship between the number of automated dampers necessary for smoke exhaust is demonstrated in Figs. 2 and 3. These Figures show a rough representation of a DDG 51 fire zone. Figure 2 shows a schematic of the ductwork and controls needed for compartment zoning. Figure 3 shows a schematic of the ductwork and controls needed for subdivision zoning.

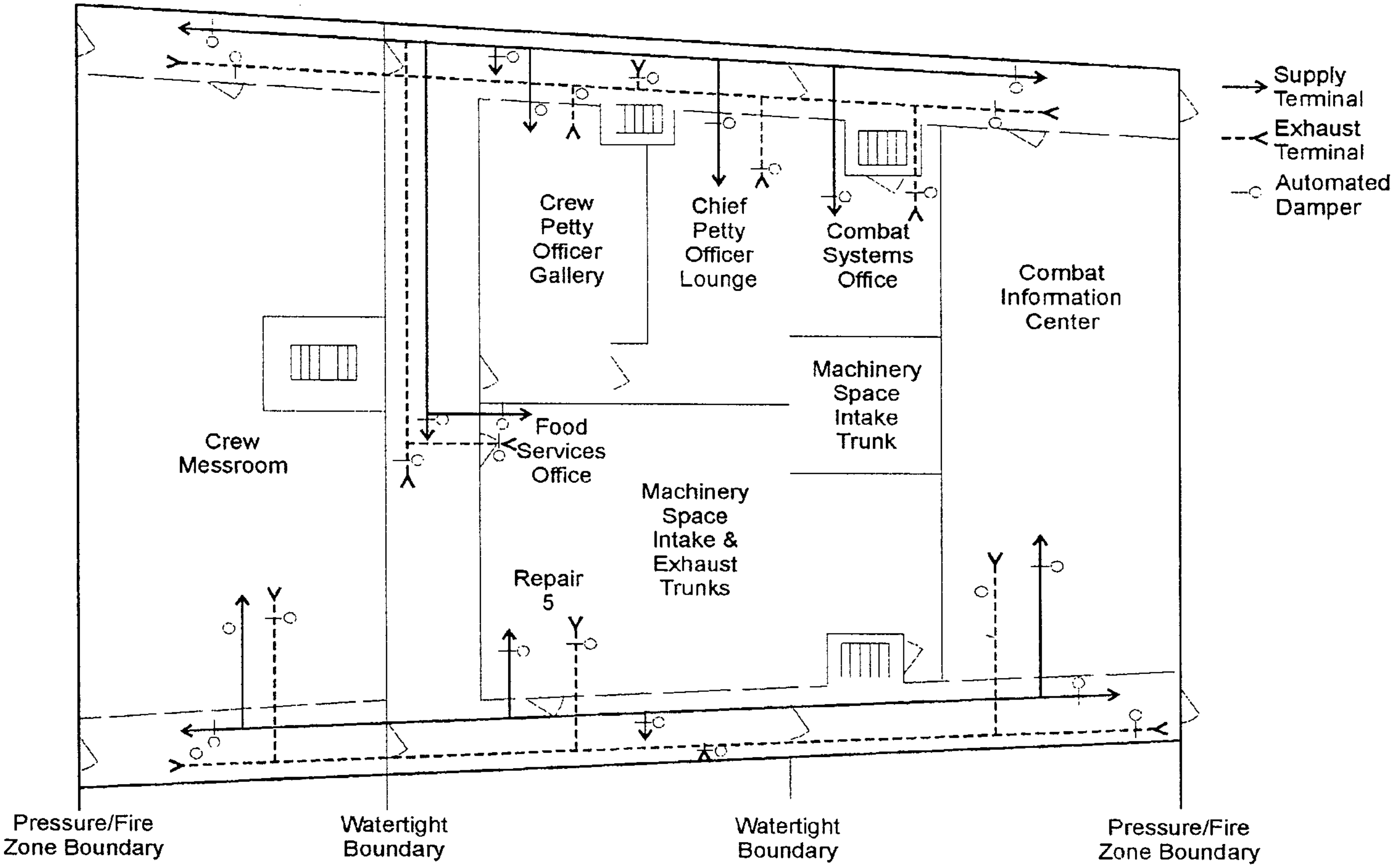

Fig. 2 - Schematic of a typical DDG 51 fire zone with smoke exhaust at the compartment level (NOTE: normal separation distances between supply and exhaust terminals are not shown on drawing)

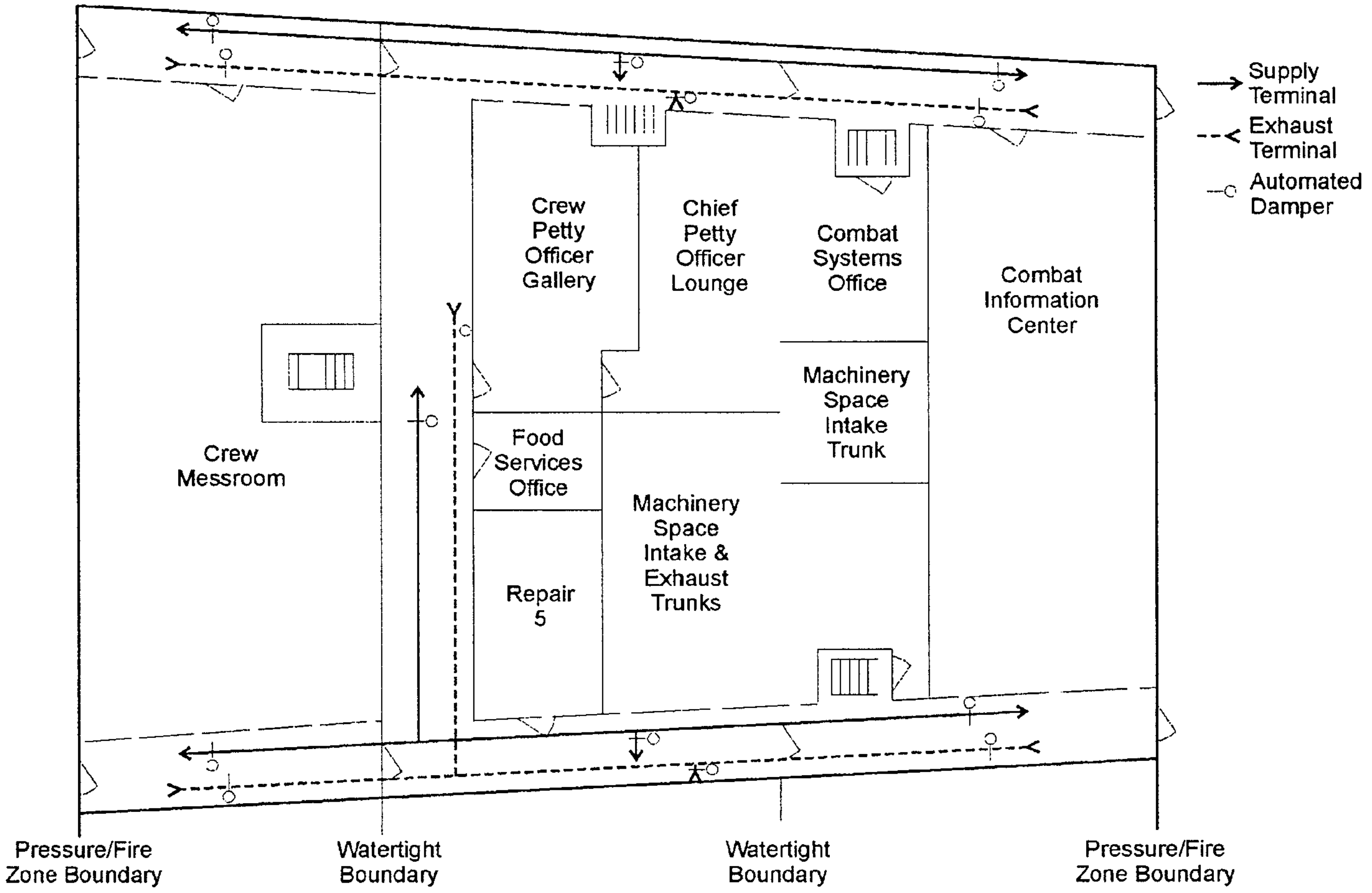

Fig. 3 - Schematic of a typical DDG 51 fire zone with smoke exhaust at the subdivision level (NOTE: normal separation distances between supply and exhaust terminals are not shown on drawing)

Twenty-eight automated dampers are shown for compartment zoning as compared to fourteen for subdivision zoning. Fewer dampers would be required for a full fire zone.

8.0 SYSTEM CONTROL (INTEGRATION INTO DC-ARM)

In order for the smoke control system to operate automatically, sensors will be needed to provide information feedback. Data provided by these sensors will be used to identify where there is smoke, and to verify that the smoke control system is functioning properly. In the event that the system does not function properly, these data could be used to reconfigure it accordingly.

There are several candidate sensors that could be used to provide this information. The most logical data to use for identifying the affected zone would be smoke sensors. Commercially available smoke detectors have little to no capability for monitoring smoke levels after the threshold is reached. As a result, they would not provide any information about how conditions are improving or worsening. More versatile smoke data can be obtained from a laser and photodiode setup, but these sensors are not available commercially in a compact package. The sensor package being developed for DC-ARM could provide a continuous read-out of this condition [46].

Pressure transducer data may be useful to map the direction of air flow throughout the affected area. This would rely on the concept that air flows from a higher pressure to a lower pressure. Information about the direction of flow could be useful for determining whether the system is operating properly and anticipating areas of contamination. Experimental data of this type should be analyzed to gain a better understanding of the capabilities and limitations of this technique.

As an example, data from the Submarine Ventilation Doctrine experiments could be analyzed to provide this type of insight [47]. Part of the test procedure was to spread smoke generated by a pan fire so that the entire test area was filled prior to examining ventilation tactics. Test data included pressure transducer and optical density meter measurements located in each compartment within the test area. These data would be useful to assess whether the pressure measurements provided a responsive and reliable indication of smoke transport.

Flow sensors should be installed in the ductwork to verify the presence of flow. The use of these sensors would be especially important in a wartime situation. Sections of ductwork may be destroyed in the event of a missile hit leaving some branches inoperable. Analysis of ductwork flow data would allow the control system to determine which sections were inoperable and make adjustments accordingly.

An integrated feedback control system would be used to continuously analyze data and assess the status of the system. Using the DC-ARM concept, the control system could be interfaced with or incorporated into the overall supervisory control system to obtain information about where fires have been detected and suppression has been activated. The control system should have the ability to update itself and reconfigure the smoke control system as conditions change. For instance, if an adjacent zone begins to fill with smoke, the system should reconfigure the zone boundaries to include treatment to the extended area.

9.0 SUMMARY

There are numerous tradeoffs associated with the performance options for a smoke control system. The size of the zone will impact the length of ductwork that is required and the diameter of the ductwork. Longer lengths of ductwork will impose larger pressure drops, thus larger diameter ductwork may be required. In addition, the control network will become more complicated as the zone size decreases.

Table 3 summarizes the tradeoffs for counterflow and smoke extraction relative to each other. Effects from suppression are not reflected in this Table. In general, the smaller the smoke control zone, the larger the requirements for air handling capacity, ductwork and number of automated controls. The exception to this generalization is for counterflow where medium flow rates (i.e. approximately 170 m^3/min (6000 cfm)) would be sufficient for each zone type. In all respects discussed, smoke extraction at the compartment level has the largest number of requirements. The protection of only key compartments, such as spaces with a high fuel load, would reduce these requirements if smoke control by compartment were desired.

Table 3. Summary of Tradeoffs Associated with Performance Options

Concept	Zone Size	Air Flow Rates Required	Amount/Size of Ductwork	Number of Controls
counterflow	compartment	medium	large	high
	subdivision	medium	medium	medium
	fire zone	medium	small	low
smoke extraction	compartment	large	large	high
	subdivision	medium	medium	medium
	fire zone	medium to small	small	low

It is likely that the ventilation provided by the CPS system would be sufficient for supplying the "medium" air flow rates in the event of a small casualty. Collective Protection System fans are sized according to the amount of leakage in the fire zone (such as air purges through airlocks). As a result, the CPS fan capacities may vary from zone to zone, and ship to ship. These fans would probably not have enough capacity to serve multiple smoke control zones. Smoke control for multi-deck or multi-zone casualties would require more powerful fans.

The presence of a suppression system may reduce the smoke control system requirements. This effect will depend largely on the type of suppression system that is installed. Higher smoke generation rates would result from a low flow rate suppression system (intended for flashover suppression) than for a high flow rate suppression system. It is important to recognize that the suppression system may not be functional in a wartime situation. For this reason, a smoke control system design that does not weigh heavily on the effects of the suppression system may be justified.

Since the smoke control requirements for a particular ship will be dependent on parameters such as the ship architecture/configuration and the manning, future work in this program should include a ship specific evaluation. The future destroyer class DD X, currently being used as the template for the DC-ARM program, could be used for this evaluation. This assessment would be necessary in order to link specific performance requirements that are needed to different approaches for smoke control.

10.0 RECOMMENDATIONS

Based on this analysis, the following recommendations were developed.

1. Experiments should be conducted for the purpose of assessing the smoke control requirements when a suppression system is installed in the fire compartment. These results will provide more data on how suppression systems will affect smoke generation. Different types of suppression systems (i.e. flashover suppression versus suppression) should be considered since the type of system will likely affect the resulting smoke generation rate. These experiments should include the use of highly obstructed fires that would only be limited by the suppression system rather than extinguished. Small-scale tests (i.e., single compartment) could be used to measure the corresponding smoke generation rates. Experiments using multiple compartments would also provide information about smoke transport and how it is affected by reduced gas temperatures.

2. In order to develop more specific design requirements for smoke control systems, the ship architecture/configuration and the manning must be known. Future work for this program should include a ship specific design evaluation.

3. Pressure data collected during the Submarine Ventilation Doctrine tests onboard the ex-USS SHADWELL should be analyzed to determine how useful these measurements are for control of smoke control systems.

4. It is believed that significant air velocities can be generated by using water spray. Experiments should be conducted to assess the performance of water spray nozzles to control smoke movement. These experiments could be conducted in a single compartment with water spray nozzles located in and/or near the doorway to the compartment. Test variables should include water flow rate and nozzle geometry.

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Appendix A

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Appendix B

Calculations for Counterflow and Smoke Extraction

B.1 COUNTERFLOW CALCULATIONS

The critical air velocity was calculated using the following equation from NFPA 92B Guide for Smoke Management Systems in Malls, Atria, and Large Areas [B1]:

$$v = 0.63\,[gH\,(T_f - T_o)\,/\,(T_f + 273)\,]^{1/2}$$

where

v = air velocity (m/sec),
g = gravitational constant (9.81 m/sec^2),
H = height of the opening (m),
T_f = heated smoke temperature (C), and
T_o = ambient air temperature (C).

A standard watertight door with dimensions of 0.7 m wide by 1.7 m high (26 in. by 66 in.) with a sill height of 0.2 m (9 in.) was assumed (for a total opening height of 1.9 m). Assuming a hot smoke temperature of 1000 C (1830 F):

$$v = 0.63\,[9.81\,m/s^2 * 1.9\,m\,(1000 - 25)\,/\,(1000 + 273)\,]^{1/2} = 2.4\ m/sec$$

For this door size, the required air flow rate would be 2.9 m^3/sec (6200 cfm).

The effect of the heated smoke temperature on the critical velocity is shown in Figure B-1. As the temperature increases, the counterflow velocity approaches an asymptote of approximately 2.5 m/sec (490 ft/min).

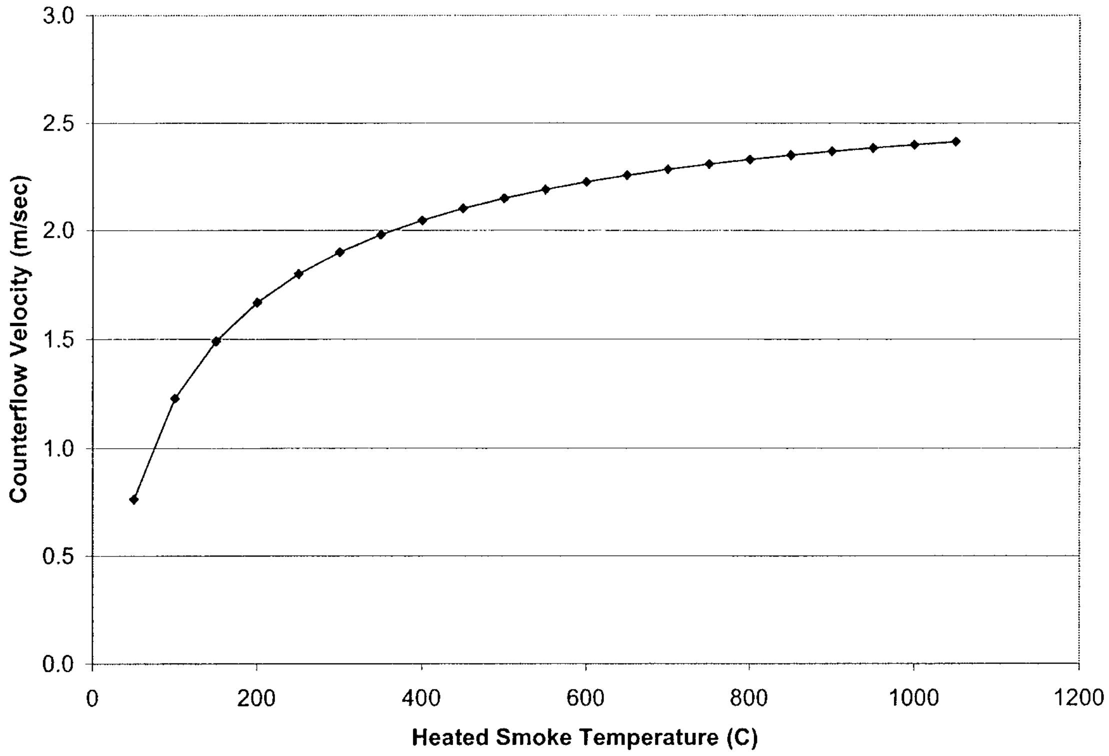

Figure B-1. Relationship between heated smoke temperature and counterflow velocity required to prevent smoke movement

B.2 SMOKE EXTRACTION CALCULATIONS

The smoke production rate (or plume entrainment rate) was calculated using the following equation from Heskestad [B2]:

$$\dot{m} = 0.071\, \dot{Q}_c^{1/3}\, z^{5/3}\, [1 + 0.026\, \dot{Q}_c^{2/3}\, z^{-5/3}]$$

where

$\dot{m}$ = smoke production rate (kg/sec),
$\dot{Q}_c$ = heat release rate (kW), and
z = layer height (m).

With a heat release rate of 500 kW and a layer height of 2.0 m, the production rate will be as follows:

$$\dot{m} = 0.071 * 500\,kW^{1/3} * 2.0\,m^{5/3}\,[1 + 0.026 * 500\,kW^{2/3} * 2.0\,m^{-5/3}] = 2.7\ kg/sec$$

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