Development of the Smoke Movement Module for the Total Ship Survivability/Fleet Training Model

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Abstract

The Total Ship Survivability/Fleet Training (TSS/FT) Model is designed to be a shipboard damage control training tool for Fleet personnel. The latest update to this model includes the development of a smoke spread "module" that estimates the generation and movement of smoke, resulting from fires caused by a specific weapon impact.

The smoke spread module of the TSS/FT Model incorporates several assumptions and simplifications that allowed for the development of basic equations and guidelines used in describing the generation and movement of smoke. The rate of smoke production and the speed at which smoke spreads throughout a ship are a function of the model's estimated flame spread rate. The primary input for the smoke movement module are the compartment "on fire" times generated by the model's flame spread module.

The TSS/FT Model for the DDG-51 Class is the first to incorporate the smoke spread module. Smoke spread data (model output) for this ship class have been developed and reviewed, with respect to "believability," with favorable results.

Key Words: Damage Control, Ship Survivability, Smoke Movement, Model, Training

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INTRODUCTION

As part of an ongoing effort to provide realistic Damage Control training tools for use by Fleet personnel, the Carderock Detachment of the Naval Surface Warfare Center (NSWC) has developed the Total Ship Survivability/Fleet Training (TSS/FT) Model[1]. The primary function of the TSS/FT Model is to provide shipboard personnel with a means of reviewing possible damage scenarios, resulting from a hit by one of several different weapons types built into the model. Previous versions of the TSS/FT Model addressed only fire (flame) spread. As part of the next phase in the development of this model, a smoke movement module has been integrated with the flame spread module. This report addresses the methodology and assumptions used in developing the smoke movement module.

The total effort associated with the development of the smoke movement module was actually comprised of several "sub-tasks". The initial portion of this effort consisted of a brief review of current smoke production and movement technology, a search for and review of, available (actual) smoke movement data measured during large scale testing, as well as a review of existing smoke movement models with respect to their potential application as tools to assist in making estimates of smoke spread. Based on these initial efforts, it was determined that current, state-of-the-art computer models would not be appropriate, or cost-effective, for use in conjunction with this effort. As such, it was necessary that specific assumptions be made to standardize and simplify the smoke movement estimation process. Subsequently, basic, "rule-of-thumb" guidelines were developed for use in generating the smoke movement data for the TSS/FT. Many of the basic premises used by the smoke movement module are based on assumptions and guidelines developed for the fire spread module. Compartment "on fire" and "engulfment" (or flashover) times, generated by the fire spread module of the TSS/FT Model, are the primary input for the smoke movement module.

The output from smoke movement module consists of "time" data. These data are used to represent two distinct points (times) in the "smoke-filling" process of a shipboard compartment. One time represents the point at which smoke is initially detected ("smoke present") in a compartment, and the second is the point at which the compartment is considered completely filled ("smoke filled") with smoke. Each of these times coincides to a point when the expected visibility in the affected compartment reaches a specified level. A compartment is considered as having "smoke present" when the visibility is reduced to approximately 10 m. At this point in time, it is considered that personnel would be aware of the smoke, but their movements would not be inhibited. A compartment is considered "smoke filled" when the visibility is reduced to approximately 1 m. Upon reaching this level, it is assumed that the compartment is no longer tenable and that movement in (through) this compartment would be severely restricted, if not prohibited. The time required for a compartment to reach these specific levels of visibility is a function of the amount of smoke entering the compartment, as well as the size (volume) of the compartment. The amount of smoke entering a compartment is a function of the number of compartments on fire (smoke generators) that are, in some fashion, connected to the compartment in question. If a compartment is "on fire" (based on fire spread module), it is automatically considered as being "smoke filled". The actual process by which this estimate is made will be discussed in greater detail in subsequent sections of this report.

Upon formulation of the guidelines to be used by the smoke movement module, smoke movement data were generated for a specific ship class, for a variety of weapon scenarios. The DDG-51 Class was identified as the initial ship configuration to be used in generating the baseline smoke movement data. This data was provided to NSWC, Carderock Detachment, for incorporation into the TSS/FT Model. The resulting model output was then reviewed, with respect to plausibility of the estimated smoke spread, with only minor inconsistencies being identified, and ultimately corrected.

SMOKE PRODUCTION AND MOVEMENT TECHNOLOGY REVIEW

Initial efforts of this task included conducting a review of the "state-of-the-art" technology with respect to smoke production and movement. This was done simply to ensure that all available, pertinent data were considered prior to developing the final guidelines to be used by the smoke movement module. The next few paragraphs have been included solely to provide the reader with a brief understanding of some of the complexities associated with smoke production and movement. This, in turn, should assist in the comprehension of why certain assumptions were necessary when developing the final guidelines for the smoke movement module.

Smoke is produced as a result of incomplete combustion. The rate at which smoke is produced, as well as the total amount of smoke produced, is a function of the type and quantity of material involved in the fire, the combustion rate associated with the material(s), as well as the rate at which air is entrained into the plume or the hot smoke layer as it moves from one compartment to the next. The later parameter, air entrainment, is highly dependent upon the geometry of the fire compartment and the surrounding spaces. To "accurately" assess any one of these parameters, it would be necessary to have specific information concerning the expected fire (types and quantity of fuels) as well as the geometry of the fire compartment and surrounding areas.

One of the fundamental, and often more quantifiable, parameters necessary in estimating smoke production is the mass burning rate ($\dot{m}$, kg/s). The mass burning rate will be a function of the specific material (fuel) involved, as well as the combustion environment. Different materials are known to burn at different rates and produce varying amounts (per gram of material burned) of smoke. Additionally, the actual volume of smoke produced is also effected by the availability of oxygen within the immediate vicinity of the fuel ("combustion zone"). As stated previously, smoke results from incomplete combustion.

Hence, the degree of "incompleteness" caused by the lack of available oxygen will impact the amount (per gram of material burned) of smoke generated.

To begin to estimate how much smoke is present at any one specific location, it is necessary to understand the means by which smoke propagates. There are two major factors which determine the movement of smoke (hot gases). These are as follows:

(1) the smoke's own mobility, which is due to the fact that it usually consists of hot gases which are less dense than the surrounding air, and

(2) the normal air movement inside the ship, which may have nothing to do with the fire, but which can carry smoke around the ship in a positive fashion.

Smoke movement due to its inherent properties (#1 above) is primarily the result of pressure differentials. These may be developed through the expansion of gases as they are heated by a fire, and/or the difference in density between the hot gases and the cooler air which surrounds them (buoyancy). In the most basic sense, these phenomenon can be accounted for, and reasonable estimates generated. However, this is only true for the fire compartment and the immediate surrounding area. The further the smoke migrates from its source, the greater the possibility for error in assessing its speed and density. This uncertainty is further compounded when attempting to estimate smoke propagation through the complex HVAC ductwork connecting the various shipboard compartments. Smoke movement caused by external forces (#2 above) may be the result of the outside environment (wind, stack effect, etc.) as well as internal HVAC systems. Each can have a significant impact on where, and how fast, smoke will propagate. However, these are often transient effects. When considering a shipboard scenario where conditions do not, necessarily, remain constant, it is not feasible to attempt to account for these effects.

Several computer models are in existence that have both the capability of making cursory predictions with respect to the movement of smoke from a fire compartment, as well as being able to operate on personal computers (PCs). However, all are very limited in their capability to accommodate smoke spread to a large number of compartments, especially when considering complex geometries (deck plans) that include both horizontal and vertical smoke spread. Additionally, there are models designed to predict smoke transport through HVAC ducting, though most are based on "cold smoke" principles where the transport is accomplished by operating fan units. One of the more prominent models, CFAST[2], is touted as being capable of handling both scenarios. The latest version of this model was investigated during the initial stages of this task, but numerous problems were noted that prevented any serious consideration of its use as a tool to assist in this effort. Other computer models, such as CORRIDOR[3], which is designed to predict smoke transport within a corridor (passageway), were also investigated. In all cases, the models were too limited in their capabilities, or too specific in their application, to be of any real (or cost-effective) contribution.

In addition to the lack of capable computer modeling support, there is very little empirical data available to support predictions of smoke spread in an application of this nature. Most of the large scale tests that have been conducted, where smoke movement was measured, consisted of very simple geometries; i.e., smoke flow from the fire compartment into one or two adjoining compartments, or a single, straight corridor. Though these data have provided valuable information and insight concerning the validity of many of the basic principles and algorithms used to predict smoke transport, it is considered to be of limited value when trying to predict shipwide smoke movement.

As noted in the previous paragraphs, there are many factors that can affect both the production and the movement of smoke. This, coupled with the limited availability of empirical data, the lack of viable deterministic computer models, and the fact that the internal configuration of a ship is very complex, makes the development of smoke spread estimates very difficult. For these reasons it was determined that the use of the basic engineering principles associated with smoke production and movement (hand calculations), coupled with the judgement of fire protection engineers experienced in smoke transport, represented the most effective means of developing shipboard smoke spread estimations.

SMOKE MOVEMENT MODULE ASSUMPTIONS AND GUIDELINES

Many of the basic assumptions and guidelines associated with the smoke movement module are a direct correlation to those that were developed for the fire spread module. As stated previously, the smoke movement module derives its input directly from the output of the fire spread module. Specifically, the primary input from the fire spread model is the time at which a compartment becomes "on fire". At that time, within the smoke movement module, the compartment becomes a "smoke generator" and begins supplying smoke to all other compartments to which it is connected. All times are relative to the initial weapon hit, with "Time = 0" equating to the time that the weapon impacts the ship. Additional input data provided by the fire spread module includes the "time to engulfment", or the time required for the compartment on fire to achieve a "flashover" condition. In addition to affecting the speed at which the fire spreads, thereby increasing the number of smoke-generating compartments, the time of engulfment also affects the speed at which smoke begins to spread from the fire compartment to its connected compartments.

Pertinent Fire Spread Model Assumptions/Guidelines

During the inception of the original fire spread module, several basic assumptions were made concerning the manner in which a fire would grow within a compartment, and ultimately spread to surrounding compartments. These original assumptions were subsequently modified to better reflect what was considered realistic values, based on data obtained during actual, full scale fire tests.[4] The following paragraphs highlight those assumptions, and resulting guidelines, which had a direct impact on the development of the guidelines used for the smoke movement module.

One of the significant assumptions made by the fire spread module is that the various compartment fires will always have sufficient oxygen to sustain their maximum (assumed) heat release rates. This is a very conservative assumption, especially when taking into account the compartmentalization of Navy vessels. It does, however, allow for simplification of the fire growth (spread) process and, in light of the fact that this is a training tool, presents a "worst case" scenario. The implication of this assumption, with respect to smoke production, is that it allowed the utilization of smoke production data based on "open burning" tests. Data from tests of this nature are much more prevalent and, as such, included a wider range of materials from which to base estimates.

Of the guidelines that were developed for the fire spread module, those having the greatest significance to the smoke movement module are the time estimates for fire growth within a compartment and subsequent fire spread to adjoining compartments. As mentioned previously, these are the basis for determining when adjoining (to original fire compartment(s) resulting from the weapon hit) compartments become "smoke generators". Of primary interest are the time estimates for a compartment "on fire" to become "engulfed". These times are based on the type (utilization) of compartment and the expected fuels contained therein. Table 1 represents a listing of the Engulfment Times used by the fire spread module.

Table 1 - Compartment Engulfment Times

Compartment Type	Engulfment Time	Fire Growth Rate
Electronic Spaces	5 Minutes	Slow
Office Spaces, Storerooms, Berthing Spaces	3 Minutes	Moderate
Fuel Storage and Engineering Spaces	1 Minute	Fast
Magazines	Instantaneous	N/A
Voids	Indefinite	N/A

The times presented in Table 1 represent slow, moderate, and fast fire growth rates. They are based on calculations using an exponentially growing fire, or what is commonly termed a "T-squared" fire, as indicated by equation (1).

$$Q = \alpha \cdot t^2 \tag{1}$$

where Q - is the Heat Release Rate of the fire (kW),
α - is the fire growth coefficient (kW/s), and
t - is the time (s).

The fire growth coefficient (α) is a function of the type and quantity of fuel that is expected to be present in the fire compartment. The coefficients used in determining the fire growth for the spaces listed in Table 1 are as follows;

Fast Growing Fire - α = 0.42 kW/s,
Moderate Growing Fire - α = 0.0464 kW/s, and
Slow Growing Fire - α = 0.0116 kW/s.

These values were utilized when calculating the times associated with the onset of smoke production in, or passage through vents to, adjoining compartments. This will be discussed further in the following section. Although the time required for the fire to spread to adjoining compartments is also important to the smoke movement module, these data (times) were direct input from the fire spread module ("on fire" time) and had no other ramifications on the development of the smoke movement guidelines.

Another assumption, inherent to the TSS/FT Model and having a major impact on the smoke spread, is that the ship(s) would be at a condition of combat readiness known as General Quarters (GQ). In this configuration, all doors and hatches would be closed. It is also assumed that the HVAC systems would not be in operation, although the systems would not be isolated through the actuation of installed dampers. As such, initial smoke spread from the fire compartment(s) can only be accomplished via smoke transport through the ventilation ducting and openings (vent areas) associated with joiner (non-tight) doors.

There are other assumptions, guidelines, or separate modules associated with the TSS/FT Model that will affect the smoke spread. However, since these are indirect impacts caused by changes in a compartment's "on fire" time, they will not be addressed in this report.

Development of Smoke Movement Module Assumptions and Guidelines

To develop the smoke movement module, it was necessary that three primary issues be addressed:

1) smoke production,
2) smoke spread from one compartment to the next, and
3) smoke measurement (quantification).

Associated with each of these issues, is a set of assumptions that had to be made to allow for the development of basic guidelines (rules) that could be used in defining how the smoke movement module was to function.

Smoke Production

Smoke production in the various compartments is assumed to occur through one of two mechanisms. The first, is through the combustion of the fuel(s) in the fire compartment(s). The second, is the result of heat being transferred through the bulkheads of the fire compartment(s) and causing material on the unexposed sides to begin to pyrolize. The latter mechanism allows for the generation of smoke in compartments adjacent (with adjoining bulkheads) to a compartment "on fire".

To accommodate the multiple fuel types (fire growth rates) associated with the various shipboard compartments, while continuing to allow for the utilization of basic hand calculations, it was assumed that smoke production in a fire compartment would be expressed as a function of the fire growth rates. As stated in Section 2.0, one of the more fundamental, and quantifiable, parameters associated with smoke production is the mass burning rate of the fuel(s). As such, a mass burning rate was estimated for each of the three fire growth rates (fast, moderate, and slow) listed in Table 1.

NOTE: Burning rates are not required for either the Magazines or Voids. The model terminates upon fire spread to a Magazine, and since Voids have no "vent" connections, there is no mechanism for "internally-generated" smoke to exit one of these compartments.

This was accomplished by using existing fire spread module assumptions, by making additional assumptions with respect to the expected fuel types, and subsequently "backing into" an estimated mass burning rate. An assumption provided by the fire spread module is that a fire compartment will achieve "flashover" (engulfment) when the internal temperature reaches 500°C. This, coupled with the assumed "times to engulfment" for the three fire growth rates and the use of equation (1), allows for the development an estimated heat release rate (Q) at the time of flashover. Subsequently a second, basic equation was utilized to develop estimated mass burning rates, specifically;

$$Q = \dot{m} \cdot \Delta h_c \tag{2}$$

where Δh_c - is the Heat of Combustion of the Fuel (kJ/g).

Obviously, since the actual fuels for the various compartment types are not known, it was necessary to assume a heat of combustion for each of the three primary compartment types, based on the type of fuel(s) that would be anticipated. Table 2 provides a listing of the estimated combustion parameters associated with the three fire growth rates, using equations (1) and (2).

Table 2 - Estimated Fire/Combustion Parameters

Compartment Type	Heat Release Rate (at time of flashover) (Q)	Heat of Combustion (Δh_c)	Mass Burning Rate ($\dot{m}$)
Electronic Spaces	1044 kW	35 kJ/g	30 g/s
Offices, Storerooms, Berthing Areas	1503 kW	30 kJ/g	50 g/s
Engineering & Fuel Storage Spaces	1512 kW	45 kJ/g	34 g/s

To estimate the total amount of mass burned (combustion by-products generated), as a function of time, it was necessary that other assumptions be made. The fire spread module assumes that fires will grow exponentially. As such, the mass burning rate will not be constant during the growth phase of the various fires. This requires complex calculations to allow for the estimation of the total mass burned (ultimately the smoke generated) at any point during the growth phase of the fire. To simplify this calculation, the smoke movement module assumes that the fires did not grow exponentially, but at a constant rate. Thus, it is possible to use simple calculations to estimate (versus integrate) the area (total mass generated) under the curves during the growth periods of the various fires. Further, it is assumed that upon reaching the time of engulfment (flashover), the heat release rates, and thus the mass burning rates, remain constant. In light of the fact that the growth period for all fires is relatively short, coupled with the fact that these are very rough approximations to begin with, this assumption is quite reasonable and should not have any detrimental impact on the overall performance of the model. Figure 1 represents the growth rate curves for the three fire types. The "shaded" areas under the curves represent the total mass burned during the growth periods.

The second means by which smoke can be generated involves the pyrolization of materials, in compartments adjacent to a fire compartment, due to heat being transferred through the adjoining bulkhead(s). This is accomplished through a very general approximation. Very little data, concerning the pyrolization of paint and/or other materials on the unexposed side of steel bulkheads, were available. However, the objective was to utilize an average value that was considered reasonable, when accounting for the complexity of what was being estimated. Paint was considered the most likely candidate fuel. Based on this assumption, and the review of some limited test data, a value of 0.05 $g/m^2/s$ was developed as the mass burning rate. As can be discerned from the units, the total amount of smoke generated (mass burned) within a "target" compartment, at any point in time, will be a function of the area of the affected bulkhead.

Other assumptions associated with the production of smoke include the following:

1) Smoke production from bulkhead heating does not commence immediately. It is a function of the time required for a compartment to become "engulfed". Smoke production of this nature commences midway between the time a compartment becomes "on fire" and the time at which it becomes "engulfed". This allows for a time "lag" to account for bulkhead heating.

2) Smoke production from bulkhead heating does not occur in freezer or chill compartments. It is assumed that the insulation, coupled with the bulkhead lining materials, would prevent this from occurring.

Smoke Movement

Section 2.0 highlighted the primary factors that both cause and affect smoke movement. To accommodate the goal of developing a simple method for estimating smoke transport between shipboard compartments, it became readily apparent that it would not be possible (practical) for the smoke movement module to address these factors in any detailed fashion. When coupled with the fact that the ships are assumed to be at GQ (highly compartmentalized), it was determined that the best means of accommodating smoke transport would be through a very simple "mass balance", with each compartment being addressed as a simple "control volume". An assumption was made that when a compartment

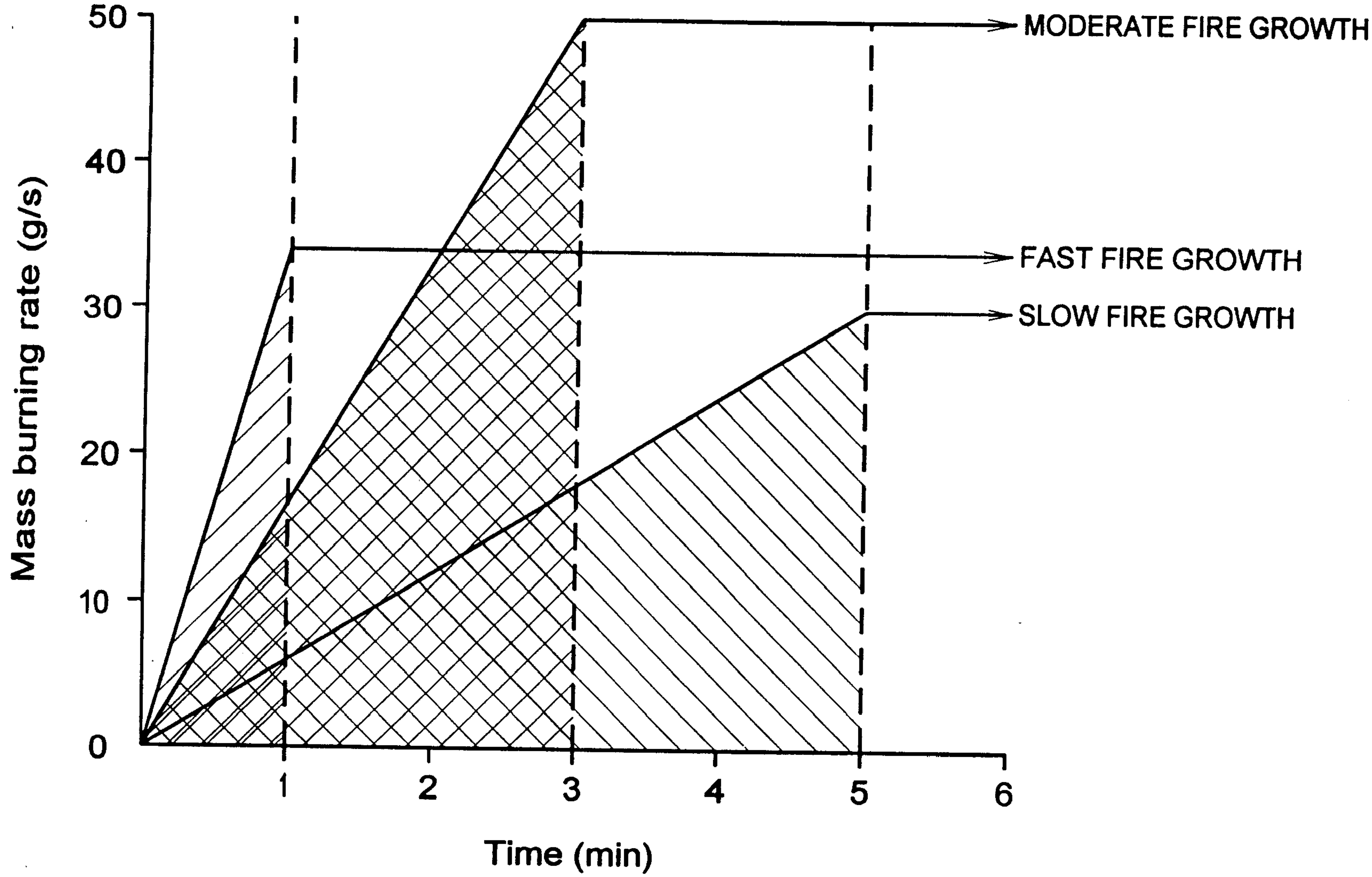

Fig. 1 - Mass burned versus fire growth rates

became "on fire", it was instantaneously "filled" with smoke. When coupled with the assumption that the compartment's internal pressure remains constant, the amount of mass (smoke) being generated by the fire would equal the amount of mass that was leaving the compartment. The only means by which smoke can leave the compartment is through a connection (vent) with another compartment or the outside environment. It was additionally assumed that no smoke would begin to leave a compartment until it was filled with smoke; i.e., the volume of smoke that had entered a compartment was equal to the compartment's total (empty) volume.

The actual smoke spread from a fire compartment to its connected compartment(s) was determined through a simple ratio of the vent area, to the connected compartment, to the total vent area of the fire compartment as shown in the following equation:

$$\dot{m}_v = \dot{m}_T \cdot (A_v / A_T) \tag{3}$$

where $\dot{m}_v$ - is the mass (smoke) flow through the connecting vent (g),
$\dot{m}_T$ - is the total mass (smoke) produced by the fire (g),
A_v - is the area of the connecting vent (m^2), and
A_T - is the total area of all vents in the fire compartment (m^2).

No factors were applied to account for potential losses due to friction, heat transfer, or accumulation of smoke particulate on bounding surfaces; i.e., smoke in = smoke out. Where a fire compartment was connected to several compartments via the HVAC ducting, the smoke flow to each individual compartment was equal to the smoke flow through the specific vent of the fire compartment ($\dot{m}_v$), divided by the number of connected compartments. Smoke flow through doorways and hatches was based on predetermined vent areas. The assumed vent area for both water-tight and non-tight (joiner) doors is 0.0094 m^2. However, since the water-tight doors are also considered (under non-fire conditions) to be smoke-tight, the vent area for these doors did not become effective until one minute after the compartment, in which the door was installed, became "engulfed". This assumption was based on data resulting from full scale fire tests of water-tight doors.[5] This assumption was also applied to those scenarios where a water-tight hatch was involved. The only difference being that a vent area of 0.0135 m^2 was assumed for all water-tight hatches.

Smoke produced as a result of bulkhead heating is assumed to affect only that compartment in which it was produced. During the initial development of the smoke movement module it was planned that, upon filling the original compartment, smoke produced in this fashion would then migrate to surrounding compartments. However, subsequent to initial implementation of the basic smoke movement guidelines, it was noted that the instances where smoke filling occurred solely from this mechanism were rare. This is, in part, due to the rapid nature by which the model spreads fire. Thus, most of the compartments become involved with fire well before they have a chance to fill with smoke generated solely by bulkhead heating. Also of note, is the fact that the effort required to address smoke spread beyond compartments adjacent to the compartment of origin, is very time-intensive. In light of these two facts, it was determined that this feature would not be included in this version of the TSS/FT Model.

Other assumptions associated with the movement of smoke include the following:

1) Smoke spread through the HVAC ducting will not occur in the "downward" (between decks) direction. Downward smoke propagation will only occur where there is a vent opening directly in the deck.

2) Adjoining compartments that are "on fire" will not "exchange" smoke. It is assumed that their internal pressures would be equal, and thus, no smoke movement would occur between the two compartments.

Smoke Measurement

The previous two sections discussed the processes used in estimating both the production and movement of smoke, or more specifically the mass of the combustion by-products. However, for these estimates to be of any value, it is necessary to have a means by which to measure the amount of smoke in the various compartments. Additionally, this must be accomplished in terms that can be easily quantified and compared. It is equally necessary to have units of measure that are in a format that can be readily understood by all personnel.

Smoke, which is basically particulate matter suspended in combustion gases, is known to have numerous properties (heat, toxicity, etc.) that can be detrimental to exposed personnel. However, these are very difficult to predict and quantify in terms that readily lend themselves to establishing defined exposure limits. The one property associated with smoke that is most often used to quantify its presence, is that of light attenuation. Because the ability to see through smoke and identify objects requires the transmission of light from the object to the observer, it is expected that there would be a direct relationship between the degree of light attenuation (obscuration) and the maximum visibility distance. The loss of visibility will greatly increase the time required for, if not totally prevent, the performance of tasks in, or egress from, the affected compartment. If smoke comes between a light source and a detector, the intensity of the light arriving at the detector will decrease from its original intensity. This decrease in light intensity will be, in part, a function of the mass concentration and the light absorption characteristics of the smoke. It is through this relationship, known as the Beer-Lambert Law or Bouguer's Law, that it is possible to quantify the level of smoke present in a compartment. Equation (4) is used to represent this relationship and is the basis for the development of all equations used in measuring smoke obscuration:

$$I = I_0 \cdot e^{-\epsilon M L} \tag{4}$$

where I - is the reduced light intensity (smoke present),
I_0 - is the original light intensity (no smoke present),

ϵ	-	is an absorption coefficient,
M	-	is the mass concentration of the smoke, and
L	-	is the path length.

To simplify this expression, and provide units of measure that are easy to comprehend, equation (4) can be reformatted to reflect the ratio, I_0/I. This, in turn, is converted to represent a unit called "optical density"(D). This is accomplished through the following equation:

$$D = \log_{10}(I_0/I) = \epsilon ML/2.303 \qquad (5)$$

Using data obtained through experimentation, it is also possible to estimate the optical density by having knowledge of the mass optical density (D_m), which is specific to the material(s) burned. The optical density is then estimated using the following equation:

$$D = \frac{D_m \cdot \Delta M}{V_c} \qquad (6)$$

where D_m	-	is the mass optical density for a material (m^2/g),
V_c	-	is the volume of the smoke chamber (compartment) (m^3), and
ΔM	-	is the total mass loss of the material(s) burned (g).

The optical density can then be related to visibility (S) through the following relationship[6]:

$$S = 1.3 \cdot D^{-1} \qquad (7)$$

As stated earlier in this report, smoke is assumed to be "present" when the visibility is reduced to ten meters (10 m). This equates to an optical density value of: D = 0.13. A compartment is assumed to be smoke "filled" when the visibility is reduced to one meter (1 m). This equates to an optical density value of; D = 1.3. Using equations (6) and (7), an optical density value was calculated for all compartments connected to a fire compartment. Based on experimental values available for the mass optical density for several representative materials, an average value of; $D_m = 0.5\ m^2/g$ was assumed. The total mass loss (ΔM), used by equation (6), was developed by "summing" the mass flow ($\dot{m}_v$) into the target compartment from all vents connected to fire compartments. The total mass flow into a target compartment was calculated at multiple time steps to account for the fact that different vents became effective (active) at various times, with respect to the time-line of the fire. Subsequently, a time was calculated when each compartment would reach the two critical values of D = 0.13 and D = 1.3. These time values, for all affected compartments, represent the "output" of the smoke movement module.

IMPLEMENTATION OF THE SMOKE MOVEMENT MODULE

Subsequent to the development of the final assumptions and guidelines to be used by the smoke movement module, a set of smoke movement data were developed using the DDG-51 Class as the "test case". It should be noted that the development of the assumptions and guidelines for this module was very much an iterative process. Many of the assumptions and guidelines were developed in response to the identification of a specific limitation or a need to simplify a process that was considered too time-intensive in light of little, or no, real benefits gained.

Ship's drawings for the DDG-51 were used to develop the required "connectivity" between a fire compartment (supplied by the fire spread module) and the surrounding compartments. Possible connections between a fire compartment and other compartments were via actual openings (vents), through the degradation of gasket materials associated with water-tight fittings, connecting HVAC ducting, and having a common bulkhead. The drawings were also used to develop volume estimates for all compartments involved. Based on the data provided by the fire spread module, the type of fire (fast, moderate, or slow) was classified for each fire compartment, thus providing the data necessary in estimating the mass flow from each fire compartment. This, coupled with the mass generation from the pyrolization of fuel(s) on the unexposed side of common bulkheads, provided the data necessary for calculating the total mass (smoke) flow into the various target compartments. All pertinent data was entered into a large database (spreadsheet) that was used to automatically calculate the times required for the target compartments to reach the two critical values associated with "smoke present" and "smoke filled". Smoke movement data was developed for a total of 41 different weapon scenarios for the DDG-51 Class. These data were submitted to NSWC, Carderock Detachment, personnel for integration into the TSS/FT Model.

During the course of this effort, several anomalies were noted with respect to the identification of numerous shipboard compartments. It is realized that the compartmentation scheme used by the fire spread module does differ from what is presented by the actual ship drawings; e.g., many of the larger compartments have been subdivided into several "subcompartments", and numerous small compartments have been combined to form a single, larger compartment. However, after reviewing the listing of compartments associated with the fire spread module, numerous errors were still noted. These errors included areas where compartment numbers did not match the compartment name, compartment numbers were wrong, or listed compartments simply did not exist. For the majority of the instances, it was possible to identify a likely substitute, or proper compartment. It was noted that these errors were common to, and identical in, all weapon scenarios. Appendix A of this report is a listing of the problem areas identified as well as what actions were taken with respect to their inclusion in the smoke movement module.

Another area of potential concern, though not directly related to the smoke movement effort, was noted during the review of the output data from the fire spread module. There appears to be a propensity for compartments that have already transitioned from "on fire" to "engulfed," to re-appear on the list of "on fire" compartments at a time subsequent to their having become "engulfed." In general, this anomaly was primarily noted during those scenarios of longer duration (30+ minutes). This event, other than being somewhat of a nuisance, did not affect the development of the smoke movement data. Any instance, when a compartment was inadvertently entered (as a fire compartment) more than once, was easily highlighted during the final analysis (sort process) of the smoke movement data. However, it may be prudent to investigate the cause of this phenomenon to determine if it has any detrimental impact on the performance of the fire spread module.

SUMMARY AND RECOMMENDATIONS

Subsequent to the integration of the smoke movement data into the TSS/FT Model, the model's output was reviewed with respect to the "believability" of the smoke movement throughout the ship. It was noted that the speed at which compartments filled with smoke (the time from "smoke present" to "smoke filled") did appear to be rather quick. However, in light of the speed at which fire is spread, via the fire spread module throughout the ship, this was expected, if not somewhat forced. It is well known in the fire community that smoke is a major factor that must be addressed when combating a fire, and that it will usually precede well in front of the fire spread. For this reason, efforts were made to ensure that, at least to a minimal degree, the model's estimated smoke propagation did precede that of the fire. However, all efforts were made to ensure "realism", and it was recognized that smoke spread would be significantly impacted as a result of the assumption that the ship was at General Quarters. Taking all of this into account, the smoke spread portrayed by the model does appear to be reasonable.

The output of the model is presented in one-minute time steps. As such, the actual data (times) generated by the smoke movement module are "rounded" up to the next full minute. It is for this reason that compartments will go from "uninvolved" to "smoke filled" in a single step. In most instances, assuming the compartment does not become "on fire," this situation is limited to relatively small compartments that fill very quickly. However, this can also occur in larger compartments that are connected to more than one fire compartment.

It has been stated several times in this report that the smoke movement estimates developed by this module (model) are considered "reasonable". However, this must be taken in the context under which the smoke movement module was developed. These estimates are meant to represent likely "worst-case" scenarios and are for training purposes only. Though all the assumptions and guidelines generated in conjunction with this module are based on actual engineering principles and experimental or historical data, they should, in no way, be construed as being definitive. In the future, should it be desired that this model be used as something other than a simple training tool, significant modifications would be required to incorporate many of the complex parameters, associated with smoke movement, that have been simplified for this module.

REFERENCES

1. Pocock, M., Fulton, J., and Tinker, C., "Analysts Manual/Documentation for Total Ship Survivability/Fleet Training (TSS/FT)," Carderock Division SSM-68-94/01, Survivability, Structures, and Materials Directorate Research and Development Report, January 1994.

2. Peacock, R., G. Forney, P. Reneke, R. Portier, and W. Jones, "CFAST, The Consolidated Model of Fire and Smoke Transport," NIST Technical Note 1299, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, February 1993.

3. Nelson, H., and S. Deal, "CORRIDOR, A Routine for Estimating the Initial Wave Front Resulting from High Temperature Fire Exposure to a Corridor," NISTIR 4869, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, July 1992.

4. DiNenno, P., J. Scheffey, P. Tatem, and F. Williams, "Review of Fire Spread Parameters for Total Ship Survivability/Fleet Training (TSS/FT) Fire Spread Model," NRL Ltr Rpt 6180-107, 22 April 1992.

5. Durkin, A., F. Williams, and J. Wong, "Failure Analysis of Door Gasket Materials Subjected to a Post-flashover Fire," NRL Ltr Rpt Ser 6180/547.1, 17 November 1993.

6. Mulholland, G.W., "Smoke Production and Properties," Chapter 1-25, *The SFPE Handbook of Fire Protection Engineering*, DiNenno, P.J., Editor-in-Chief, National Fire Protection Association, Quincy, MA, 1988, pp. 1-368 - 1-372.

Appendix A

Fire Spread Module Compartment No.	**Fire Spread Module Compartment Name**	**Problem**	**Action Taken** (changes highlighted in **Bold**)
1-69-2-Q	Security Force Issue Room	No such compartment number exists	Used Compartment No. from dwg for Security Force Issue Room "**1-54-1-A**"
2-97-2-T	Access Trunk	Compt. No. is incorrect	Used "**3**-97-2-T"
01-110-2-Q	Fan Room	Compt. No. does not exist	Used Compt. No. for Fan Room "01-110-**3**-Q"
01-118-1-L	Passage	Compt. does not exist	Used "Passage", "01-**110**-1-L"
01-118-4-L	Passage	Compt. No. does not exist	Used Compt. No. for Passage - "01-118-**2**-L"
1-126-3-L	Passage	Compt. does not exist	Used "**Air Lock**" "1-126-**1**-L"
1-126-4-L	Passage	Compt. does not exist	Used "**Pressure Lock**", "1-126-**2**-L"
01-158-1-L	Passage	Compt. does not exist on dwg	Used Passage, "01-**162**-1-L"
1-191-0-Q	CPO Living Space	Improper Compt. Name & No.	Used "CPO **Galley**", "1-191-**01-L**"
1-220-5-L	Crew Messroom	Compt. Name & No. do not match	Compt. "1-220-5-L" is a "Passage". The "Crew Messroom" is Compt. "1-220-01-L". **Ignored this Compt. Name/No. combination.**
1-255-2-Q	Electric Load Center	Compt. does not exist	**Ignored this No.** since "1-254-2-Q" is an "Elect. Load Ctr" and is listed as well.

Fire Spread Module Compartment No.	Fire Spread Module Compartment Name	Problem	Action Taken (changes highlighted in Bold)
01-300-3-A	Helo Crash & Salvage	Compt. No. does not match dwg	Used "01-**304-1**-A" (01-300-3-A is a Boat Gear Locker)
1-356-6-L	Stateroom	Compt. does not exist	Used "**Dept. Hd** Stateroom", "1-356-**2**-L"
1-370-2-F	SSGTRB Intake	Compt. Name & No. are incorrect	Used "SSGTRB **Fuel Tank**", "1-**374**-2-F"
1-370-4-F	SSGTRB Intake	Compt. Name is incorrect	Used "SSGTRB **Fuel Tank**"
02-158-3-L	Stateroom	Compt. Name does not match dwg	Used Compt. Name from dwg "**Officers WR/WC & Shwr**"
02-158-6-Q	Galley	Compt. Name & No. are incorrect	Used "02-158-**8-L**" which is the "**Wardroom** Galley"
02-158-7-L	Stateroom	Compt. Name does not match dwg	Used Compt. Name from dwg "**Passage**"
2-161-1-T	Access Trunk	Compt. does not exist	Used Access Trunk "**3-162-1-T**"
02-166-2-L	Stateroom	Compt. Name does not match dwg	Used Compt. Name from dwg "**Wardroom WR & WC**"
2-246-2-A	Laundry	Compt. Name & No. do not match dwg	Used "Laundry **Annex**", "2-**426**-2-**Q**"
2-338-2-L	CPO WR	Compt. No. incorrect	Used "2-338-3-L"
2-422-4-Q	Bathythermograp h Room	Compt. No. does not match dwg	Used "2-442-4-Q"

Fire Spread Module Compartment No.	Fire Spread Module Compartment Name	Problem	Action Taken (changes highlighted in Bold)
03-128-1-C	Array Room	Compt. No. suffix is incorrect	Used suffix listed on dwg "03-128-1-**Q**"
03-158-3-Q	Array Room	Compt. No. does not match dwg	Used Compt No. from dwg "03-158-**1**-Q
3-381-2-Q	Electrical Shop	Compt. No. does not match dwg	Used "**2**-381-2-Q"
4-220-4-E	Fuel Service Tank	Improper Compt. No. suffix	Used "4-220-4-**F**"
4-410-0-A	Bos'n Storeroom	Compt. Does not exist	**Ignored this Compt. No.** ("Bos'n Storerooms -410-1-A and -410-2-A are listed)
05-131-0-Q	EOFCS Barbette	Compt. No. does not match dwg	Used Compt. No. from dwg "05-13**0**-0-Q
1-300-01-C	Passage	Improper Compt. No. suffix	Used "1-300-01-**L**"
3-220-01-A	Supply Dept. Storeroom	Compt. No. does not match dwg	Used "3-**230**-**0**-A"