J. of Fire Prot. Engr., **3** (4), 1991, pp 137-150

FIRESAFETY ANALYSIS OF THE POLAR ICEBREAKER REPLACEMENT DESIGN

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SUMMARY

Fire safety aboard Coast Guard cutters is an important part of their design. In 1987, a project was completed that involved a developmental application of the Ship Fire Safety Engineering Methodology (SFSEM) to the firesafety analysis of the Polar Icebreaker Replacement (PIR) design. The passive and active fire protection was analyzed for every compartment on the PIR in the integrated framework provided by SFSEM. Conventional fire protection engineering was used whenever information necessary for SFSEM was not available. Recommendations for alternative solutions to accomplish performance-based firesafety objectives, as well as guidelines for selected fire protection systems on the PIR, were provided.

This paper describes the framework for the firesafety evaluation, techniques for quantification, and the advantages and limitations identified by this application of the SFSEM for ship firesafety design. The quantification integrated available statistical data with case study analysis, inspection of the operation and fire protection of a similar existing ship, expert opinion, fire science, and engineering practice. The analysis also employed a computer simulation that enabled each compartment of this 405-compartment ship to be studied and evaluated in terms of its intrinsic fire safety, its relative vulnerability to fires starting either within or outside of the compartment, and the effects that each compartment's loss due to fire would have on the ship's mission.

INTRODUCTION

This paper describes the use of the Ship Fire Safety Engineering Methodology (SFSEM) in guiding a comprehensive, performance-based firesafety analysis of the Polar Icebreaker Replacement (PIR) design[1-4]. The PIR is a next-generation polar icebreaker currently planned by the U.S. Coast Guard. The PIR is designed as a multi-mission vessel capable of operating in arctic regions to provide logistical support for defense and scientific installations, search and rescue operations, law enforcement, icebreaking to escort supply ships, and scientific study in arctic waters. The ship design calls for a 460 foot vessel with 405 compartments on nine decks.

The size and complexity of the PIR provided a clear challenge in assessing expected firesafety performance and in designing protective features which allow more reliable operation in severe environments. The application provided an excellent opportunity to test and apply the Ship Fire Safety Engineering Methodology (SFSEM) to the firesafety analysis and design of a vessel of sufficient complexity that made performance evaluations using more conventional intuitive or regulatory-based approaches difficult.

The Ship Fire Safety Engineering Methodology (SFSEM) is the U.S. Coast Guard's ship adapta-

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tion of the Building Firesafety Engineering Method[5-7] developed at Worcester Polytechnic Institute. The methodology is structured fire risk analysis procedure based on systems analysis and risk assessment techniques. The method's flame movement analysis considers ignition, fire growth, passive fire protection, manual fire suppression, and automated suppression using probabilistic analytical networks. The important features of the method are its structured nature, the ability to integrate both engineering judgement and fire science, an ability to use both deterministic and probabilistic information, and the ability to incorporate a wide range of fire prevention and fire protection features in a performance-oriented evaluation. This analysis provides a major enhancement to a conventional firesafety design. The quantification of risk using the SFSEM enables existing codes and standards to be integrated with modern fire science and the experience of engineering practice.

This paper will briefly review the PIR design, the basic elements of the Ship Fire Safety Engineering Methodology (SFSEM), and the firesafety design process for the PIR. The major focus of the paper is the application of the SFSEM to the PIR design.

Ship Firesafety Analysis and Design

The normal procedure for designing Coast Guard cutter firesafety is to design the ship architecturally and, during this process, to ensure that the firesafety requirements comply with the *Naval Engineering Manual*. The *Manual* references many Navy publications, standard practices for shipboard fire emergencies, and applicable published firesafety standards.

Shipboard firesafety and the relationship of its components form a complex system. During a fire, human activities, equipment operation, barrier design, and ship architecture all interact with the products of combustion in a rapidly changing environment. Compliance with codes and standards alone does not ensure that the firesafety system will achieve identified firesafety performance objectives successfully.

The determination of the risk for a Coast Guard cutter due to fire involves an identification of the mission and special needs of the ship, as well as the effectiveness and reliability of the firesafety countermeasures. The mission criticality of different compartments varies considerably, and a wide variety of potential fire scenarios is possible. The effectiveness of passive fire defenses, such as barriers, and of active fire protection, such as detection systems, manual fire fighting, and automated fire protection measures, as well as their interactions must be incorporated. The interconnectivity of the compartments and the operating systems of the ship, such as the electrical system or the ventilation system, make them sensitive to fire. A space may be vulnerable to a fire originating in a compartment far removed from that space.

SFSEM and SAFE 1.0

The SFSEM provides a means by which one firesafety system design may be compared to others. The method integrates all of the separate component interactions in a structured framework, allowing an original firesafety design to be compared with stated mission performance objectives. Thus, suggested alternatives and recommendations may be compared on a consistent basis.

Application of the SFSEM involves three major activities. These are: (1) understanding the functional operation of the ship and identifying the firesafety objectives with regard to life safety, property protection, and mission or continuity of operations; (2) analyzing the initial design as a firesafety system with regard to ignition, flame movement, smoke movement, structural frame performance, and people movement; and (3) comparing the results of the analyses of (2) with the objectives of (1). Weaknesses are identified, and modifications to the initial design may be selected to define an improved firesafety system. These alternatives are then analyzed, and their performances are compared to develop the basis for the most cost-effective firesafety system that will meet the performance objectives.

The SFSEM integrates event trees and fault trees used in conventional risk analysis into an organized, structured systems framework. An event tree is an inductive, forward logic framework that identifies a process. It has a major advantage of being able to incorporate time and sequential conditionality into a scenario, somewhat analogous to a motion picture. It has the major weakness of an inability to identify the causal details that contribute to the outcomes.

Fault trees, on the other hand, provide a deductive, backward logic framework for an event. The major strength of a fault tree is its ability to structure hierarchical details and causal relationships into a logical framework. The principal disadvantage is that an evaluation must be for conditions that relate to a single instant of time, analogous to a photograph or one frame of the event tree "motion picture." Consequently, sequential time and certain interdependency conditions cannot be incorporated into a fault tree.

A theoretical description of the method, the details of the hierarchical systems framework, and the manner by which the event trees and the fault trees are integrated may be found in Reference 5.

This paper focuses on the application of the method to a complex ship. The analysis provided a major enhancement to the conventional fire-safety design of the PIR. The quantification of risk using the SFSEM enables existing codes and standards to be integrated with modern fire science and the experience of engineering practice.

The Ship Applied Fire Engineering (SAFE) computer programs implement the theory and structure of the flame movement components of the SFSEM. The computer package stores a description of the architectural layout of the ship and permits this layout to be changed as necessary. The programs contain a routine that identifies the interconnectivity of all compartments via their common barriers. Information such as use, frequency of established burning, fuel load, ventilation parameters, detection, and fire protection equipment is stored for each compartment. The thickness, density, specific heat, and thermal conductivity, as well as the barrier performance characteristics as expressed by its $\underline{T}$ values and $\underline{D}$ values, are stored for each barrier. In addition, accommodation doors and hatches are identified for the barriers so that different scenarios of fire propagation with doors or hatches opened or closed may be considered.

The final functions of the programs involve the calculation of the probability of the paths of

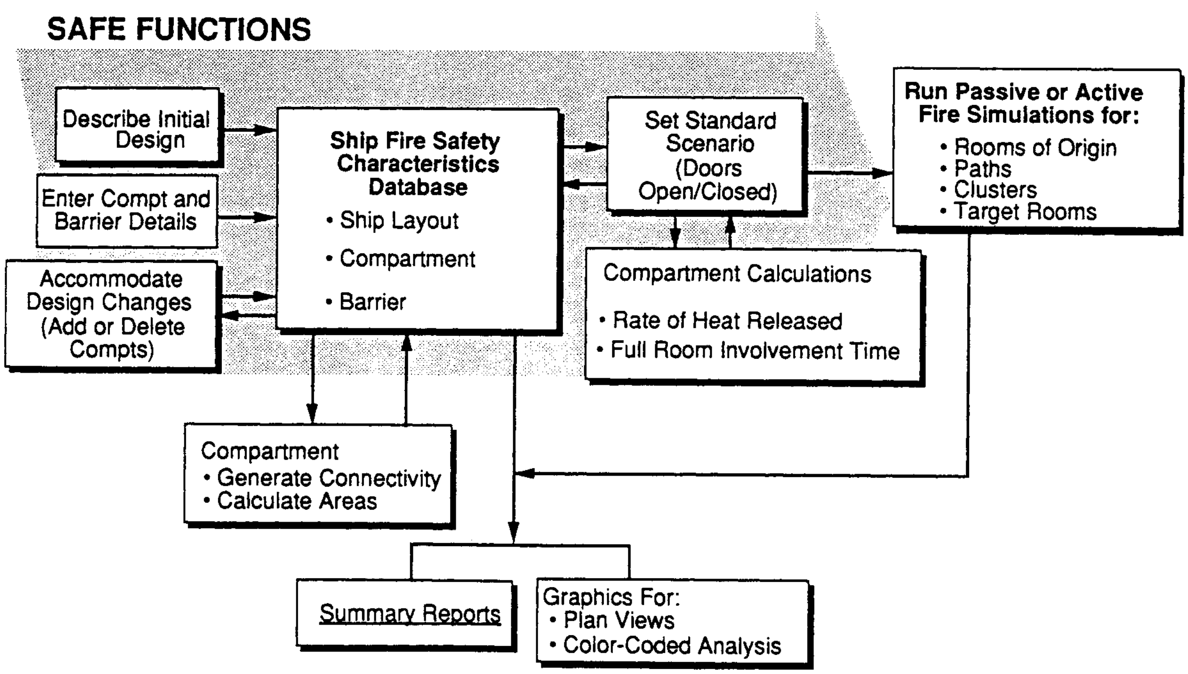


Figure 1. Ship Applied Fire Engineering (SAFE) Program System.

flame movement from any specified room of origin through the ship, as well as a variety of output formats. The output can display a variety of component performance descriptors so that specific aspects of weakness may be identified more easily. In addition, the cumulative probability of success of paths, clusters of rooms, and target rooms in limiting flame movement is available. Summary reports and graphics for color-coded analyses are also available. Figure 1 shows the functions of SAFE 1.0.

Quantification Overview

Quantification of hazards and countermeasures using the SFSEM serves two major functions. The most obvious is to provide the numerical basis for comparing alternatives to the initial firesafety design. The second, and possibly more important role, is to serve as a mechanism to understand, evaluate, and describe the expected performance and reliability of the firesafety subsystems. The analytical framework of network diagrams forces the engineer to identify the potential failure models of active and passive fire defenses with regard to the expected behavior of the products of combustion. The organization incorporates the relationships and interactions with the other parts of the system.

The quantification of hazards and the related fire protection countermeasures is based on the probability of success in limiting the fire. There are two accepted, yet fundamentally different, views of probability that are used with risk assessment. One is the classical or objective view. The second is the personal or subjective view. Both agree on the basic principles of probability and on the mathematical interrelationships and manipulations. However, the interpretation of the meaning of the numerical values and the methods to obtain them are vastly different.

The objectivist views probability as a characteristic of an identifiable physical process. These probabilistic values may be established either as a measure of a relative frequency or as a condition of symmetry. The subjectivist views probability as a degree of belief held by an individual. For example, a subjectivist would have no difficulty in assigning a degree of belief for the likelihood that Candidate "X" will be elected as the next President or that a particular barrier will be able to withstand a complete burnout in a specific compartment without allowing any ignition into the adjacent compartment.

Subjectivists base their beliefs on the information that is available. This may include such acquired knowledge as mathematically calculated results from deterministic relationships, results from computer models, physical or chemical relationships and theory, experimental results, failure analyses, available statistics, and personal experience. The probabilistic assessments are based on the full spectrum of information that seems relevant to the assessment. It is very common for engineers to base judgments and solutions on subjective procedures, although the articulation of the degree of belief in probabilistic terms is not usually done.

The SFSEM makes use of both methods of determining probability. The probabilities of ignition and established burning are estimated by objective methods. Statistical data pertaining to performance of equipment and configurations needed to evaluate the specific firesafety systems initially proposed for the PIR are nonexistent. Subjective probabilistic assessments based on the information available and engineering judgment were the basis of quantification of the other components of the SFSEM. This use of subjective probabilistic assessments is a useful method by which modern research results can be integrated into the analysis and different alternatives can be compared on a consistent basis.

Probabilistic Assessment for the PIR

The evaluation of the performance of the firesafety system incorporates the function of the ship with the many independent, dependent, and conditional events in the firesafety system. This is easier to do on existing ships because as-built conditions can be observed. The PIR was in the planning stage, and reasonable estimates had to be made of construction and active and passive fire systems behavior. To enhance the information base for the subjective judgement assessments, the following activities were undertaken.

1. Extensive, detailed studies were made of the USCG Cutter *POLAR SEA* to obtain first-hand information on icebreaker characteristics necessary for evaluations using SFSEM. Included in the study was a fire drill to provide specific information for manual fire fighting evaluation.
2. Additional studies were made on 270-foot cutters under construction at Newport, RI to obtain information on the most current forms of construction, fire protection systems, and accommodation materials.
3. Fire incidents on 36 U.S. Navy ships and Coast Guard cutters were examined. Timelines were constructed to compare suppression results. Problem areas and recommendations were studied to gain further insight into characteristics of shipboard fire behavior and safety.
4. Documentation from active and passive fire protection tests including compartment burnout studies conducted at the U.S. Coast Guard's Fire and Safety Test Detachment, as well as experience of test personnel provided an additional knowledge base for the required evaluation.

In addition to the information cited above, individuals at the U.S. Coast Guard's Marine Fire and Safety Research Division, Worcester Polytechnic Institute, and Rolf Jensen & Associates provided additional engineering experience and judgement on a wide variety of topics. The subjective engineering judgements used in SFSEM were based on selection of the most appropriate information available for each component within the time constraints.

PERFORMANCE OBJECTIVES

The establishment of performance objectives is one of the first activities of the SFSEM. Performance objectives are most appropriately developed through a cooperative effort of the user, the design team, and the firesafety engineering team. They are essential in applying a performance-based engineering method. In this case, objectives were identified by the PIR design team and the SFSEM engineering team through a round-table discussion of the mission criticality of each compartment of the ship. The objectives were expressed in terms of a tolerable level of compartment damage and an acceptable frequency of compartment loss.

This exercise proved to be valuable in that it identified a major weakness in design for mission-sensitive structures with regard to firesafety. It became obvious that clear recognition of the impact of equipment and support systems on the mission sensitivity to different fire sizes is needed. Although it was not done here, the objective models should be augmented by economic and operating systems analysis. The issue of defining performance objectives are discussed in Reference 8.

FREQUENCY OF ESTABLISHED BURNING

The SFSEM can deal with fire hazards in a number of ways. The frequency of fire can be decoupled from its subsequent fire growth hazard potential. In this way, the "what if" questions relating to fire performance given ignition can be addressed in an engineering manner.

The SFSEM normally evaluates the probability of ignition separately from the probability of reaching established burning. Established burning is the size of fire that starts the recognized established combustion process. For most rooms, this is a fire of about 5 kW. While this concept is useful from an engineering viewpoint, when dealing with the level of detail found in most mishap reports, it is difficult to separate ignition from established burning. Recognizing that all ignitions are not reported, but established burnings are quite likely to be reported, it was conservatively assumed that the statistical data described as "ignition" more properly represents the frequency of established burning.

In this study, fire frequency — expressed as the number of fires per year of exposure — was used. Fire frequencies were determined for each type of shipboard compartment and calculated from historical data covering a 10-year period for U.S. Navy vessels selected as similar to the PIR design.

Full Room Involvement Time

The event trees that relate time with the fire growth and the active and passive fire defenses require an estimate of the time to full room involvement (FRI). Clearly, the ability of manual and automated fire suppression efforts are much more likely to succeed during the pre-FRI period. The time to full room involvement can be estimated using simple correlational methods available in the literature[9-12]. These methods require a knowledge of the fire growth rate, the ventilation, and the thermal properties of the compartment boundary materials. Unfortunately, these methods have been developed using experimental data from compartment fires with boundaries quite unlike steel bulkheads. That is, the materials on which test data exist are much better insulators.

The methods of handling wall heat losses in these correlational methods are not appropriate for use with highly conductive wall materials. The correlations assume that the resistance to the flow of heat is associated only with conduction within the wall. This is, of course, not the case for highly conductive materials. The radiative/convective processes, along with the heat capacity of the wall, determine the heat losses. Attempts to use these correlational methods for ship compartments yield quite erroneous and recognizably incorrect results.

Another possible route to predicting full room involvement times involves the use of compartment fire models. Unfortunately, most compartments in the PIR have forced ventilation from above. There are no zone-type fire models which can handle both forced ventilation from above and steel bulkhead heat transfer. Even several years after development, there still are no zone models which can address this type of fire situation. As a result, it was necessary to rely on engineering judgement to estimate full room involvement times.

Based on the contents of the compartments, fire growth rate estimates for each compartment were made. Burning rate data from the literature for materials and items similar to the contents of each space were used to estimate compartment burning rates. Of course, for a single compartment, there does not exist a single expected fire growth rate. The estimates of burning rate were intended to reflect a reasonable design fire for the space. As such, the burning rate estimates were derived from the burning rate for the compartment fuels with the most rapid growth rates.

The burning rate estimates, the ventilation rate information, and the wall material properties were used to guide the estimation of the full room involvement time using engineering judgment. Experimental data for compartment fires with steel bulkheads and decks are clearly needed.

Duration of Fully Developed Burning

The duration of fully developed burning defines the time period over which the barriers are challenged. Given the ventilation openings and total fuel load, the duration of fully developed burning can be estimated by assuming ventilation limited burning. The air inflow rate is approximately given by:

$$\dot{m} = 0.5 A \sqrt{h} \tag{1}$$

where A is the vent area and h is the vent height. All units are kg, s, or m. For multiple vents, the relationship becomes far more complex. For purposes of this investigation, it was deemed sufficiently accurate to use simple methods for estimating an equivalent single vent. The limitations of these methods are well known. The following expressions were used:

$$A = \Sigma A_i \tag{2}$$

$$h = \frac{1}{A} \Sigma (A_i h_i) \tag{3}$$

where A's are the individual vent areas, and h's are the individual vent heights. This method will work well when vent heights are approximately the same. When the vents included ceiling or floor openings, the height used was the compartment height. This represents a crude estimate for these conditions.

Using the equivalent vent characteristics, the heat release was estimated using:

$$\dot{Q} = 1500\, A\sqrt{h} \tag{4}$$

where the heat release is in kW and vent dimensions are in m. The duration of burning, t, was then determined from the burning rate and the total energy content of the fuels in the compartment.

$$t = \frac{Q}{\dot{Q}} \tag{5}$$

where Q was found from the estimated fuel load of the compartment and the appropriate heats of combustion.

Evaluation of Fire Protection Countermeasures

The evaluation of the active and passive fire protection features for the initial design required a detailed study of each of the compartments as they were designed and specified for the ship. For example, the barrier effectiveness, the manual fire fighting effectiveness, and the automated suppression system's effectiveness are major components that are evaluated for each compartment. They are evaluated in the context of the anticipated fire growth in the space, the fire protection equipment that is involved, human intervention, and ship conditions. In other words, the performance of the people and equipment on the ship are evaluated in the context of the function that must take place. The SFSEM organizes these components so that they may be integrated into the evaluation in an orderly, consistent manner.

To illustrate the process, the elements that were involved in evaluating the fixed fire suppression component of a single compartment will be described. Engine Room No. 1 will serve as the example. In the actual analysis, eight typical compartments were evaluated in detail. The values for the other 394 compartments were estimated by extrapolation from these representative compartments.

Engine Room No. 1 contains the diesel engine/generator sets and auxiliary machinery. This compartment normally is not occupied in port, and it is assumed to be occupied approximately 15% of the time when underway. The compartment is three decks high (30 ft), and the floor area is 2400 ft^2. Entry is made at the third deck level.

Three fire scenarios were considered for this space.

1. An oil spray fire (either lubricating or fuel oil) at a flow rate of less than 1 gpm. The oil spray will stop when the machinery being served by that oil is shut down.
2. An oil spill fire (either lubricating or fuel oil) at a flow rate of over 1 gpm. The fuel spill will continue after the associated machinery is shut down.
3. A fire in bundled cables located in the compartment overhead.

These fire scenarios were evaluated for two conditions. They were for the ship underway in calm seas and the ship underway in heavy seas which causes severe rolling motion.

The probability for the fixed systems to suppress each of these fires successfully was evaluated as Automated Suppression (the A value in Table 1). In this compartment, the automated systems consisted of a manually operated Halon 1301* total flooding system and a manually operated AFFF sprinkler system with sprinklers installed in the bilge.

The evaluation of this component involved the capabilities of these systems as they were specified, including considerations for performance reliability. The review included not only the systems themselves, but also the support systems such as the detection system, pumping system, seawater main and agent storage, and proportioning equipment. These systems were evaluated as specified for their strengths and weaknesses with regard to performance.

*The Halon 1301 total flooding has been replaced in updated designs because of ozone depletion concerns.

Table 1

Compartment Firesafety Summary for Polar Icebreaker Replacement

(drawings dated 5/12/1987)

Compartment: 5-100-0-E

Engine Room No. 1 (Tank Top Level)
Zero strength barrier above.

USE: E — Machinery areas which are normally occupied.

AREA: 2391 ft^2 **DECK HEIGHT:** 8.0 ft **VOLUME:** 19,135 ft^3
UNACCEPTABLE LOSS: Code 3 (Full compartment lost to fire)
THRESHOLD FREQUENCY OF UNACCEPTABLE LOSS: 0.0330 per ship year
FREQUENCY OF ESTABLISHED BURNING: 0.0474/year
FUEL LOAD: 18,916 Btu/ft^2 Cable, paint, etc. (40 gpm x 6 m/compartment area)
VENTILATION: 19,135 ft^3/min **EXCHANGE TIME:** 1.0 min.
VENT AREA: 2100 $in.^2$ **VENT HEIGHT:** 70 in.

FIRE STARTED DUE TO:	I	FRI Time	A	M
$\underline{F}$ire Origin	0	6	85	10
$\underline{T}$ Failure	5	6	20	40
$\overline{D}$ Failure	5	*	0	0

*calculated as (100 – % Heat Release)/100 x FRI Time or 2 min., whichever is greater.
Assumes a fuel or lube oil line rupture; No line rupture as adjacent compartment

DETECTION:

Manual: Occupied 0% of time in port and 15% of time at sea
Automatic: Rate of temperature rise detection system (RR)
Photo electric smoke detection system (P)
Flame detection system (UV or IR) (F)

FIRST AID FIRE PROTECTION

2 hand portable carbon dioxide fire extinguisher
4 hand portable dry chemical fire extinguisher (PKP)

AUTOMATED FIRE PROTECTION SYSTEMS

1 Halon 1301 total flooding system - remotely actuated
1 AFFF (3%) bilge sprinkler system - remotely actuated

MANUAL FIRE FIGHTING EQUIPMENT

1 1-1/2-in. seawater hand line with "all purpose nozzle" 50 ft
2 1-1/2-in. AFFF (3%) hand line with SFL variable nozzle 50 ft

BARRIERS (Adjoining Compartments ID and Name)		MAT ID	D/H	AREA ft^2	$\overline{T}$	$\overline{D}$	% HEAT Rel
5-100-1-F	Oil Tank	W8	0	491.2	80	100	5
5-100-2-F	Oil Tank	W8	0	491.2	80	100	5
4-162-0-#	Engine Room No. 2	W8	0	336.0	80	100	5
5-76-0-E	Bow Thruster Machinery Rm.	W8	0	288.0	80	100	5
4-100-0-E	Engine Room No. 1	C0	0	2390.6	0	0	100

1 ft = 0.3048 m
1 BTU/ft2 = 11.34 kJ/m^2

The information in Table 1 utilizes the nomenclature and concepts of the SFSEM. It may be useful to explain a few of the terms in order that the concise description may be identified.

A fire may originate within this space, or it may be caused by a fire in an adjacent space that results in an ignition across one of the barriers. In concise form, the table FIRE STARTED DUE TO describes a number of conditions that are used by the computer program SAFE 1.0. When the fire originates in the space (line "Fire Origin"), the fire may self-terminate (I), may be suppressed by fixed systems (A), or may be extinguished by manual action by the ship's fire party (M). The probability of success of each of these three components is listed under I, A, and M for the line "Fire Origin." The A and M values were influenced by the time to FRI estimated for this space.

If the fire had fully involved an adjacent space, ignition could occur through a barrier. The expected performance of the barriers is reflected by the $\overline{T}$ and $\overline{D}$ values of the barrier part of Table 1. Briefly, $\overline{T}$ indicates a small, hot spot ignition failure, and $\overline{D}$ indicates a large, massive ignition failure. The values of $\overline{T}$ and $\overline{D}$ are time dependent because of the continuous heat released by a fully involved fire in the adjacent space. The SFSEM incorporates this time dependency in the selection of appropriate $\overline{T}$ and $\overline{D}$ performance relationships in addition to the heat release rate and fuel quantity of the adjacent space. The other tabular information in the "Barriers" part identify the specific barrier construction (e.g., W8 and C0) and its dimensional characteristics.

The percent of heat release section estimates the heat energy that is expected to be transferred into the adjacent space when a $\overline{D}$ failure occurs. SAFE 1.0 has a protocol to adjust values when several barriers fail sequentially or simultaneously.

If an adjacent barrier allows a $\overline{T}$ ignition in the space, a different set of environmental conditions will exist than if the fire had originated in this compartment. Consequently, the I, A, M, and FRI time values for the table FIRE STARTED DUE TO reflect the differences expected in the termination of a fire when this space is a successive space, rather than a space of origin. Similarly, $\overline{D}$ values for I, A, M, and FRI time reflect the expectations of success for termination within the space when the barrier exhibits a $\overline{D}$ failure.

The remaining information in Table 1 identifies use codes, fuel load, ventilation, and active and passive equipment in the space. In addition, an unacceptable loss code is assigned to reflect the performance objectives discussed under "Performance Objectives" above.

Detection is a major component of the automated suppression evaluation because the fixed systems are manually activated. Table 2 describes the various types of detectors and the estimated times for detection that were used in the analysis. These times are used to relate the timeline of fire growth with the timeline necessary for agent application in either automated or manual suppression.

Both the AFFF sprinkler system and the Halon 1301 total flooding system were evaluated. Time for fire growth was considered in combination with time to agent application. Initially, the estimated fire suppression effectiveness for this compartment was evaluated in terms of the four levels of performance shown in Table 3. These categorical estimates were converted into numerical values of probability of success for the compartment A-value in the SAFE 1.0 computer analysis by subjective judgement considering the expected environment, ship architecture, and operating procedures.

One of the benefits of this process is that the evaluation is organized, and specific elements can be clearly identified. Furthermore, the tracking of the process is guided by the network diagrams which enable specific weaknesses to be identified. These recognized weaknesses became the basis for the recommendations for improvement to the firesafety system.

THE FIRESAFETY (FLAME MOVEMENT) ANALYSIS

The firesafety analysis for the PIR involved both a flame movement analysis and a smoke movement analysis. However, in this paper, only the flame movement analysis is discussed. The flame

Table 2

Estimated Detection Times – Engine Room No. 1

Detection System	Class B Fire	Bundled Cable Fire
1. Rate of rise detection system	5 seconds	5 minutes +
2. Flame detection system	1 second	5 minutes +
3. Photoelectric smoke detection system	Not reliable	Not reliable
4. Fixed temperature detection system	10 seconds	5 minute +
5. Line-type fixed temperature detectors in cable bundles	Not detected	15 to 120 seconds
6. Crew within compartment	0 to 5 seconds	5 minutes +
7. Crew outside compartment	*2 to 5 minutes +	5 minutes +

*Crew may observe unusual engine or engineering plant operating conditions, causing them to enter the compartment to investigate.

movement analysis incorporates the frequency of ignition and established burning with the fire growth hazard potential, the active fire protection measures of manual and automated suppression, and the passive resistance of barriers.

The limit of flame movement, L, is the probability that the fire will be limited, or terminated, before fully involving the compartment or compartments being considered. The limit, L, may be calculated using the basic network of Figure 2. Details on the procedure may be found in Reference 5. Its complement, $\bar{L}$, is the probability that the flame will not be limited, and thus, the compartment will reach full room involvement and be lost. For a target compartment, k, and a fire propagating along a fire path j, due to a fire originating in compartment i, this may be

Table 3

Estimated Fire Suppression System Effectiveness – Engine Room No. 1

System Type	Spill Fire: Ship Steady	Spill Fire: Ship Unsteady	Spray Fire: Ship Steady	Spray Fire: Ship Unsteady	Bundled Cable Fire
Portable Fire Extinguishers	X	X	P	D	D
AFFF Hand Hose	D	X	E	P	P*
AFFF Sprinkler and Hand Hose– No Sprinklers Below Obstructions	P	D	E	E	P
AFFF Sprinkler and Hand Hose– Complete Sprinkler Protection	E	D	E	E	P
Halon 1301*	P	E	E		
Halon 1301 and AFFF Sprinkler Combined	E	P/E	E	E	P

This evaluation assumes that diesel engines are shut down, ventilation system secured, electrical equipment de-energized prior to fire fighting activity.

* Personnel safety hazard if electrical cables are not de-energized.

Explanation Key	Symbol	Meaning
	E	System is expecting to be effective in fire fighting.
	P	System will probably be effective but may not be effective under adverse conditions
	D	System effectiveness is doubtfül, but the system may be effective under favorable conditions.
	X	System is not expected to be effective.

expressed as:

$$P_k\left(\bar{L} \mid EB_i\right) = 1 - P_k\left(L \mid EB_i\right) \tag{6}$$

In order to compare the ship performance to its objectives, the frequency of expected loss for each compartment must be determined. The expected loss probability for a target compartment, k, is the sum of the $\bar{L}$ values for compartment k for fires in all rooms of origin including target compartment k. The computer simulation, SAFE 1.0, calculates the probability that the target room will be lost. The probability of target room loss due to a fire originating in room i is determined by summing $\bar{L}$ over all available fire paths, j. This may be expressed as

$$P_k\left(\bar{L} \mid EB_i\right) = \sum_j P_k\left(\bar{L}_j \mid EB_i\right) \tag{7}$$

The frequency of loss of the target is found by multiplying this value of P_k by the frequency of EB for each compartment of origin. This is expressed as:

$$f_k\left(\bar{L} \mid EB_i\right) = P_k\left(\bar{L} \mid EB_i\right) f\left(EB_i\right) \tag{8}$$

The total frequency of the target loss is found by summing over all compartments of origin. This becomes:

$$f_k\left(\bar{L}\right) = \sum_i f_k\left(\bar{L} \mid EB_i\right) \tag{9}$$

This frequency can be compared to the threshold loss frequency objective. The term $f_k\ (\bar{L})$ is the relative frequency of failure given fire free status. For convenience, the output lists the ratio of this value to the unacceptable loss frequency. If this fraction is greater than 1.0, changes are required to meet the objective.

The SFSEM and its related computer program, SAFE 1.0, allow the compartments to be uncoupled to identify sensitivity of the protective measures. Table 4 illustrates the use of projected loss data. For example, the passive loss of Engine Room No. 1 for passive measures (i.e., only fuel control (I) and barriers with no automated or manual suppression) is 1.4364. The value is greater than 1.0, indicating an unacceptable level. However, when automated suppression only is included, the loss ratio is reduced to 0.2155. This is clearly well within acceptable levels. When both automated and manual suppression are combined, the loss ratio is reduced further to 0.1939. Ratios of this type allow both unacceptable fire protection measures to be identified easily in a complex structure, as well as a means by which cost effectiveness comparisons for alternatives to be made. Figure 3 shows that this information also can be displayed in graphical form for rapid visual inspection and comparison.

A detailed evaluation using SFSEM can enable the fire protection engineer to identify potential recommendations for improvement of the active or the passive fire protection. Incorporating the changes in the probability of success into SAFE 1.0, the relative effect of any changes can be evaluated with regard to practicality and cost.

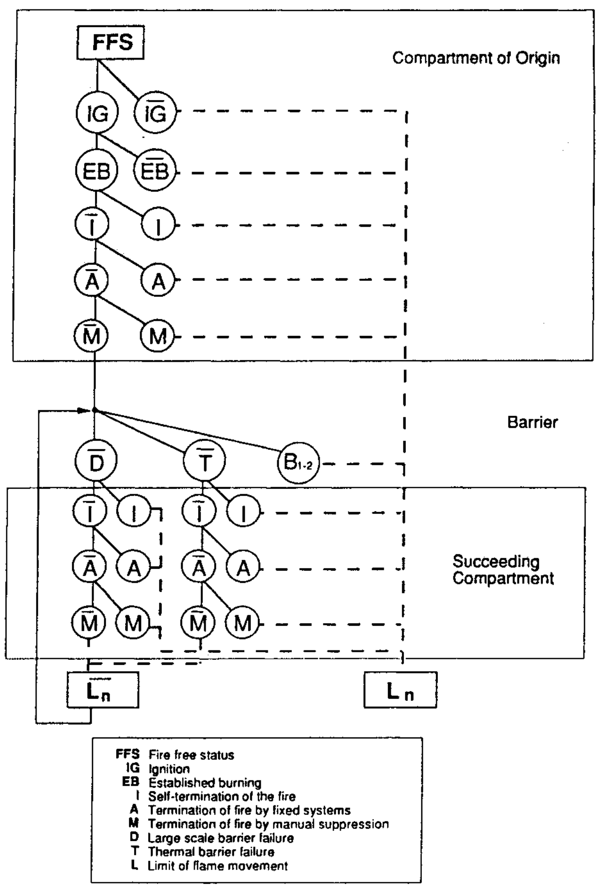


Figure 2. Flame Movement Analysis Used for the PIR.

Table 4

Flame Movement Results for Passive, Automated, and Manual Fire Protection

Compartment Number	Compartment Name	Passive	Passive & Automated	Passive Automated, & Manual
		Fraction of Unacceptable Loss Frequency*		
3-100-0	Engine Room No. 1	1.4364	0.2155	0.1939
4-100-0	Engine Room No. 1	1.4364	0.2155	0.1939
5-100-0	Engine Room No. 1	1.4364	0.2155	0.1939
3-162-0	Engine Room No. 2	1.4364	0.2155	0.1939
4-162-0	Engine Room No. 2	1.4364	0.2155	0.1939
5-162-0	Engine Room No. 2	1.4364	0.2155	0.1939
1-178-1	Boiler Room No. 1	1.3697	0.2739	0.2465
2-178-1	Boiler Room No. 1	1.3697	0.2739	0.2465
1-178-2	Boiler Room No. 2	1.3697	0.2739	0.2465
2-178-2	Boiler Room No. 2	1.3697	0.2739	0.2465
02-178-0	Emergency Generator Room	0.6182	0.0927	0.0835
03-178-2	Auxiliary Generator Room	0.4327	0.0649	0.0584
2-361-1	Steering Gear Room	0.2079	0.1894	0.1881
2-361-2	Steering Gear Room	0.2079	0.1894	0.1881

$$\text{* Fraction of Unacceptable Loss Frequency} = \frac{\text{Relative Frequency of Failure} \mid \text{FFS}}{\text{Unacceptable Loss Frequency}}$$

Discussion

The principal goal of this project was to evaluate firesafety design for a proposed new polar icebreaker and to recommend improvements where appropriate. The SFSEM was used to accomplish this task for two main reasons. One is that the SFSEM does incorporate in a systematic, disciplined manner the elements of the complete system of fire protection within its scope. The second is to test and challenge SFSEM and SAFE 1.0 with regard to practicality and usefulness of application.

The experience did demonstrate that SFSEM and SAFE 1.0 can be used in a large, complex structure such as the PIR. A substantive insight was gained in the value of its strengths and the clear identification of the next level of improvement that is needed. The principal observations are as follows:

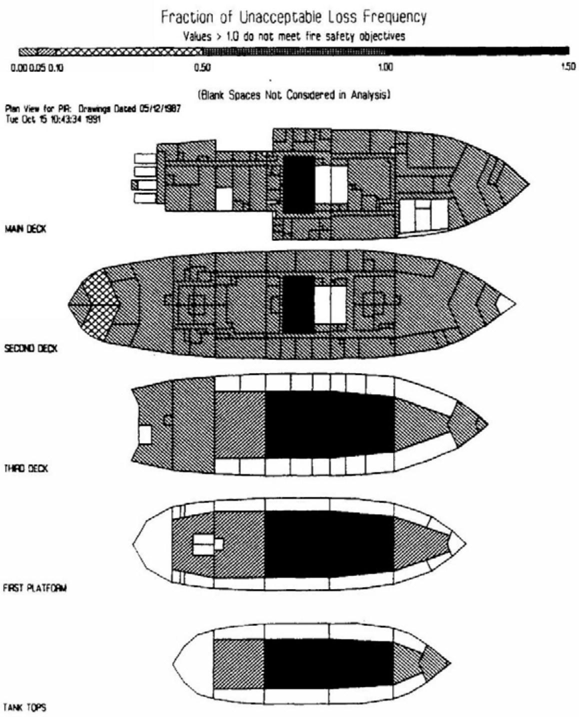
a. Existing performance statements for objectives do not exist in a quantitative sense. Although quantitative performance criteria were established, techniques for identifying objectives in a more realistic, definitive manner must be developed.

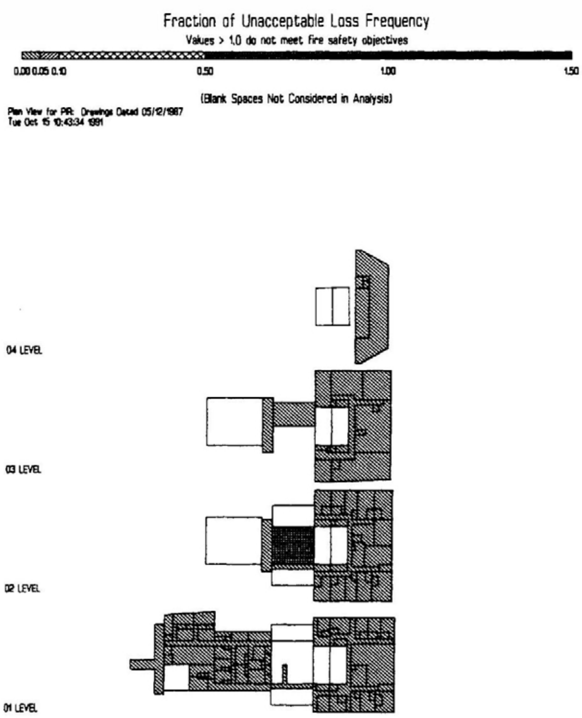
b. The target room concept for identifying the potential loss rate due to all fire paths through the target which originate in every room was successful. The "weak links" can be identified and corrective alternative measures selected for improvements on a selective basis.

c. It is possible to compare numerically the effectiveness of different proposed alternatives.

d. The SFSEM focuses on the strategic view of the problem and is not dominated by computer hardware. For example, the analytical procedures clearly identify the weakness of manual extinguishment in certain spaces and may recognize its strength in other spaces.

e. Recommendations for firesafety improvements can be articulated on a





performance basis.

f. The analysis requires a variety of technical fire protection engineering skills. The method is not appropriate for use by untrained individuals. However, it may be possible to automate the process to give non-fire protection engineers a sense of proportion for some selected preliminary planning schemes.

g. The method is appropriate for use on existing ships to identify existing weaknesses and modification alternatives. If it is to be used throughout the planning, design, and construction completion process, it must be applied in different ways by different users for different functions. For example, the exact routing of electrical cables is established by the contractor during construction. A seemingly low importance compartment may have the electrical "umbilical cord" for important ship functions pass through that compartment. Consequently, the compartment loss could have unanticipated consequences unless attention is given to firesafety during construction. Complete attention to the firesafety system would include this type of analysis. It is not possible to do it during the design stage although it can be done when construction drawings become available.

h. The evaluation of barriers required a special awareness of a complex theory and physical relationships. A simpler, more automated procedure for barrier evaluation is needed.

i. The question of what and how much information to automate in the analysis is important. The relationship between deterministic calculations that may be used in the analysis and the human assessment of their quantitative reasonableness is always a concern. More consideration must be given to simplifying the evaluation while retaining the sensitivity that is gained through the SFSEM analysis. This study is continuing.

This first major attempt to apply the SFSEM to

a large, complex ship was a valuable test of the method. It demonstrated that the method has evolved from a conceptual academic procedure to one that has potential merit in applications that deal with mission-based performance needs. It demonstrated that quantitative comparisons of firesafety alternative designs can be made in complex situations.
The exercise also identified the need for better methods of quantifying certain compartments. In some cases, this weakness is due to the inadequacy of the information base. In other cases, SFSEM identified weakness in the processing of the available information. At the present time, the SFSEM should be used by a team of individuals who possess a broad range of fire protection engineering skills.

The method did allow a strategic view of the performance of the ship with regard to its firesafety capabilities. The SFSEM proved to be a useful bridge to integrate existing knowledge into a useful, practical application procedure.

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