Naval Research Laboratory

Washington, DC 20375-5320

NRL/MR/6180--09-9195

Quantitative Assessment of Manned Damage Control Performance

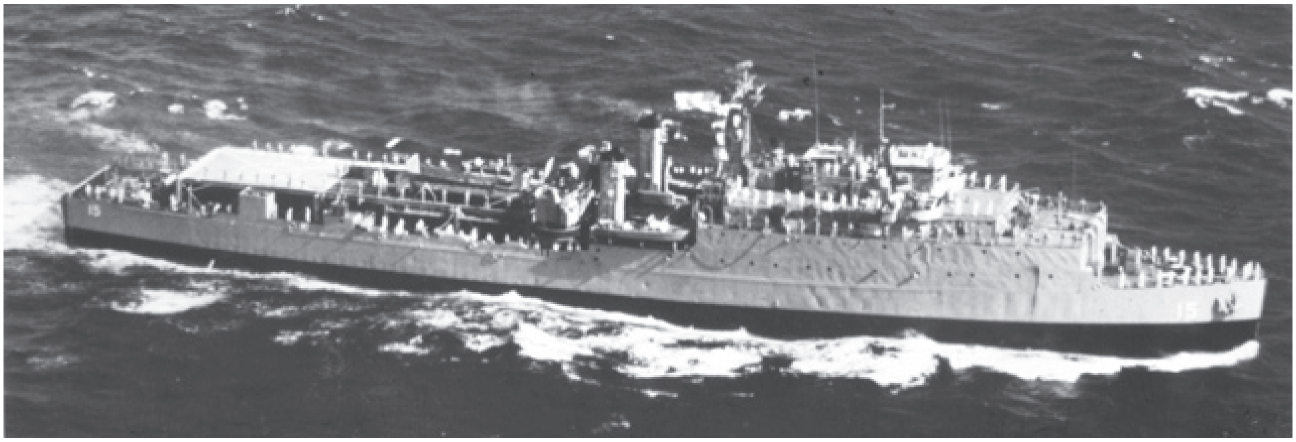
John B. Hoover
John P. Farley
Frederick W. Williams

Navy Technology Center for Safety and Survivability
Chemistry Division

Joseph L. Scheffey
Scott A. Hill
Jason E. Floyd

Hughes Associates, Inc.
Baltimore, MD

July 27, 2009



REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
27-07-2009

2. REPORT TYPE
Memorandum Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Quantitative Assessment of Manned Damage Control Performance

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Johm B. Hoover, John P. Farley, Frederick W. Williams, Joseph L. Scheffey,*
Scott A. Hill,* and Jason E. Floyd*

5d. PROJECT NUMBER
61-8513-A-9-5

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory, Code 6180
4555 Overlook Avenue, SW
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/MR/6180--09-9195

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of the Secretary of Defense
Live Fire Test and Evaluation (OSD/DOTE/LFT)
1700 Defense Pentagon
Washington, DC 20301-1700

10. SPONSOR / MONITOR'S ACRONYM(S)

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

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
*Hughes Associates, Inc., Baltimore, MD

14. ABSTRACT
New ship manning concepts have resulted in new demands and changing roles for personnel assigned to damage control. The changing force structure requires that designers and operators understand the capabilities of damage control teams. This includes the design, equipment, and doctrinal requirements needed for an acceptable level of ship recoverability. Limited formal structures and validated methods for assessing such capabilities exist. Methods to assess readiness and training requirements suffer from a lack of quantitative or validated approaches. This paper describes the use of manned damage control modeling techniques and readiness assessments to provide a more rational basis to assess damage control manning.

15. SUBJECT TERMS
Damage control — Ship fire — Ship manning
Fire fighting — Modeling — Agent-based simulator

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
Unclassified	Unclassified	Unclassified	UL	19

19a. NAME OF RESPONSIBLE PERSON
Frederick W. Williams

19b. TELEPHONE NUMBER *(include area code)*
(202) 767-2476

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

CONTENTS

QUANTITATIVE ASSESSMENT OF MANNED DAMAGE CONTROL PERFORMANCE

INTRODUCTION

On reduced manned ships, the ability to mount an aggressive manned attack on potential conflagrations will be inherently limited. Additionally, advanced concepts, such as SeaSwap, which aim to extend on-station times by rotating crews in mid-deployment, will challenge the ability of newly assigned crews to meet the timeless damage control adage "know your ship." Expert judgment and manpower workload models are currently relied on to assess damage control manning requirements and effectiveness. These methods are lacking, as expert opinion varies between individuals. Manpower workload models designed for watchstander and billet assessment have limited applicability for a relatively short duration, high intensity damage control and recoverability event. These workload models require a scripted set of tasks which is subject to individual interpretation.

An alternative approach is to use an agent-based simulator, the Damage Control Response Simulator (DCRSim). This approach has the capability to simulate the DC response in real-time based on predicted fire and smoke spread data. The DCRSim prototype demonstrates the potential for simulating the response of the DC organization and evaluating the impact of key variables, including the quantity of people, structure of the organization, and the chain of command. The ability to vary key inputs and quickly generate results enables sensitivity analyses that investigate many variables, including DC organization, crew skill level, reliability of the communications system, initial ship condition, and variations in mission priorities. DCRSim addresses limitations of current methods by reducing the time for analysis and explicitly defining parameters and behaviors, which provides a consistent and repeatable prediction.

DCRSim relies on behavioral aspects of damage control personnel for input. This performance, or skill level, may be qualitatively assessed as "high" "medium" or "low." Currently, there is no accepted, objective method for evaluating and comparing the level of expertise and performance of individuals, damage control teams, or damage control organizations. The behavioral science and training literature provide surprisingly little quantitative guidance in this area. As a starting point, it is necessary to develop objective evaluation and comparison methods. The data must then be analyzed to identify specific deficiencies and appropriate training techniques. As a starting point, the Office of Secretary of Defense (OSD) Operational and Test and Evaluation Office initiated a program to develop and test the methodologies and tools needed to assess damage control readiness. The objectives of the program are to:

1) Develop the metrics that will enable objective evaluation of damage control readiness,

---

Manuscript approved May 29, 2009.

2) Develop and apply standard procedures and metrics during full scale damage control evolutions; and
3) Use the tools to identify training, equipment, and procedural deficiencies and improvements.

In addition to providing objective readiness information, the program is expected to provide data which can be used to validate performance aspects of DCRSim.

MOTIVATION TO IMPROVE MANNED DAMAGE CONTROL ASSESSMENT

In the post World War II era, shipboard damage control and fire protection design has been motivated largely by non-combat operating conditions and events. While some of these events have indeed been catastrophic (USS *Nimitz* flight deck fire and ordnance explosions), damage control design was based on more-routine operations and historical lessons learned. Combat incidents and resulting policy changes have altered this thinking. First, the USS *Stark* was severely damaged as a result of hostile missile fire. This led to a rethinking of fire protection containment strategies, as the post missile-hit fire spread unabated through several decks. Second, congressionally-mandated Live Fire Test and Evaluation (LFT&E) has been applied to damage control and recoverability aspects of Navy platforms. This requires that designers consider the response to weapons-induced damage. Third, secretariat level policy to reduce shipboard manning as a cost control measure requires rethinking of damage control response, traditionally a manpower intensive action.

Current LFT&E processes offer insight into progress which has been made in damage control assessment. The three components of survivability are susceptibility, vulnerability, and recoverability. Damage control assessment resides in the vulnerability (primary, secondary, and cascading damage) and, primarily, in recoverability. Recoverability encompasses containment of damage, prevention of loss of ship systems and equipment, and repair and reconfiguration of critical systems so that the ship may continue to fight. Vulnerability assessments to determine primary damage are performed for thousands of scenarios. Secondary damage and the resulting recoverability have been performed using labor-intensive damage analyses for a few selected scenarios. Until recently, ship designs and associated equipment and components were not digitized, and modeling of damage (fire, flooding, CBR) was performed outside the initial damage assessment. A dramatic improvement occurred with the introduction of the Integrated Recoverability Model (IRM), which allows for the development of probabilities of recoverability through the evaluation of numerous, more realistic scenarios. The IRM is shown conceptionally in Figure 1 with DCRSim added. Instead of evaluating selected scenarios, all primary damage predictions are run to obtain probabilities of recoverability. It is a network connected simulation which includes system connections in the digitized ship description such as data, power, and fluids. The simulator imports initial user-defined conditions (e.g., from the ship digital design) and imports damage from a damage model. It coordinates the physics-based predictions of fire and flooding effects from associated models, while determining what equipment is damaged or inoperable due to propagating fire and flooding effects. The outputs are probabilities of degrading or losing mission critical systems over time, along with recovery of these capabilities.

The interconnectivity of the simulator allows for rapid, multiple, physics-based, time-dependent analyses.

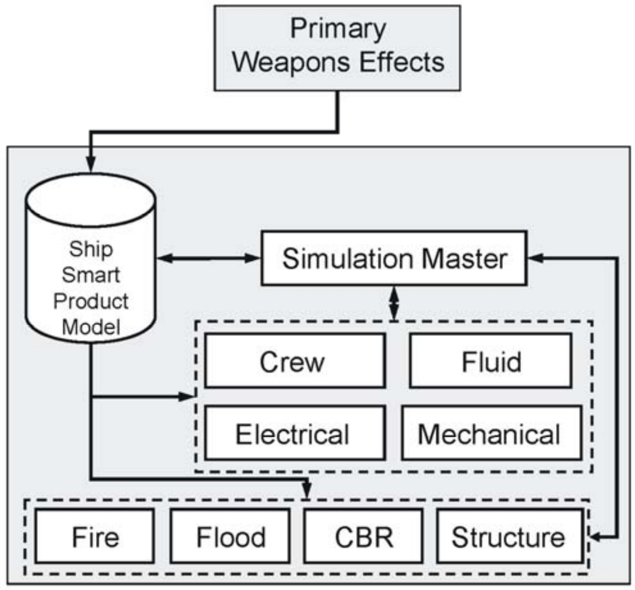


Figure 1. Integrated Recoverability Model Concept

Currently, the DC response analysis is a rules-based, non-interactive process or a manual exercise. Input from subject matter experts forms the technical basis. This approach is time consuming, given the amount of data and number of variables that need to be considered. In addition, several iterations of the damage spread and recoverability model runs may be required to arrive at the final DC response prediction. Often, subject matter experts use "rules-of-thumb" developed based on their experience, which makes documentation of the DC response for peer review difficult. The assumptions may not be well documented, leading to variability in predictions. This is especially true if analyses are performed by different individuals or groups. This precludes repeatability and consistency in the analyses. In addition, since the manual effort is time consuming, it is not practical to conduct sensitivity analyses to determine the impact of specific variables on the effectiveness of the response.

An automated method for simulating the DC response is desirable to ensure consistency in analysis and decrease analysis time. An automated simulation has many benefits over methods that have been used in the past. A simulator will provide repeatable predictions for a specific set of conditions in a timely manner, which will enable analyses of specific changes to the DC organization and/or ship design. An automated simulator can ultimately be integrated with other vulnerability models and operate concurrently (e.g., within an IRM-type environment as proposed in Figure 1), which will greatly reduce the time required to generate the DC response timeline and reduce the number of model iterations required for each scenario during recoverability and vulnerability assessments. This will permit many more scenarios to be addressed. An automated method will also yield documentation on assumptions and the basis for specific parameters and variables that affect the DC response.

Current methodologies for simulating DC response rely on rules-based approaches for very specific actions, such as boundary cooling, or pre-scripted actions before a simulation run. Besides being unavailable for peer review in the public literature, these methods lack continuous interaction between damage events and the defined personnel response. Furthermore, non-ideal responses resulting from communication failures, decision making errors, or potential improper or failed performance are not addressed. Not accounting for this variability plus the inherent bias introduced by case-by-case application of subject matter experts essentially guarantees that DC personnel will always "win" in their approach.

There are two particular aspects for developing improved analysis of DC response. First, a tool is required which interactively addresses key DC actions to primary damage and changing secondary damage. Second, because many of these actions relate to human behavior, some means must be provided to address the proficiency of DC personnel in the modeling and simulation effort.

DAMAGE CONTROL RESPONSE SIMULATOR (DCRSIM)

An effort was initiated to develop an agent-based simulator with the capability to simulate the DC response in real-time based on predicted fire and smoke spread data. The prototype Damage Control Response Simulator (DCRSim) was developed to demonstrate the feasibility and application of this approach and to identify the key variables and functionality required.

The DCRSim is a multi-agent based simulator, where each member of the DC organization is represented as an agent that has a unique skill level and attributes. In an agent based simulation, each entity (e.g. crew member) is represented by its own set of internal state variables and behavioral rules for changing those states. Each member of the DC organization, or agent, interacts with the environment and can communicate with others to report specific information. Information is reported up through the organization until the information reaches the appropriate decision maker, typically the Damage Control Repair Station (DCRS) Leader or Damage Control Assistant (DCA). The DCRS Leader or DCA then makes decisions and issues orders based on the information available, which can include information from DC personnel reports, sensor output, and fixed system status.

Although the DC response is controlled by the DCA, the use of intelligent agents in DCRSim allows individuals to make decisions and take immediate action based on local conditions. For example, investigators can decide to extinguish small fires discovered during the investigation process without any direction from the DCA. The ability and amount of time required to complete a specific DC activity vary depending on the environmental conditions, personnel protective equipment (PPE), and skill/training of the individuals. Injuries to DC personnel can be simulated as a function of the environmental conditions, the skill/training of the individuals, and the activity of the personnel. The times for specific DC actions and other model parameters were derived from experimental evaluations of DC responses [1], Fleet doctrine [1], data in the literature and input from subject matter experts.

The structure of the DC organization can be varied in DCRSim so changes in the number of personnel and command structure can be evaluated. Similarly, changes in the communication architecture can be evaluated by adjusting the communications map, which defines how members of the DC organization communicate with one another. In addition, DCRSim can evaluate the impact of initial ship conditions and can provide mission-based responses through adjustment of the importance of critical spaces with respect to specific types of damage for different missions.

General Approach

The overall approach in developing DCRSim was to provide an agent-based simulation, where the responses of DC personnel would be based on the conditions and information known to the individual agents. Agent-based simulators have been previously considered for damage control, but these efforts were limited to interactions of the members of an attack team [2]. DCRSim provides a flexible framework that accounts for variations in the DC organization, communications architecture, concept of operations, and presence of fixed sensor, suppression, and other damage control systems. DCRSim also includes the potential for missed or dropped communications between individuals.

Agent-based simulators provide a means for evaluating complex human systems by modeling the responses of individuals, or agents, within the system [3]. Agents individually make decisions based on their own assessments of the conditions that influence their decision. Collectively, these decisions can produce complex behaviors that result from the interactions of individuals. Agent-based simulations are inherently flexible because attributes and behaviors of individuals can be modified or added to enhance the simulation. Another benefit of this approach is that the simulator is a natural description of the system that is being analyzed, which makes the simulator seem closer to reality.

The simulation process, shown in Figure 2, begins with setting the initial conditions for the ship, personnel, and equipment. At each time step in the simulation, the compartment and damage conditions are updated with information from other models; for example, fire, smoke and temperature data from the physics-based Fire and Smoke Simulator, FSSIM [4]. The status of personnel is then updated to reflect their new condition, location, and awareness. Information, such as damage reports, is communicated between personnel. The person coordinating the DC response, typically the DCA or DCRS Leaders, prioritizes the damage reports they receive and assigns tasks to respond to the damage. Task assignment is based on the priority of the damage and the availability of personnel and equipment. This process is repeated for the duration of the simulation.

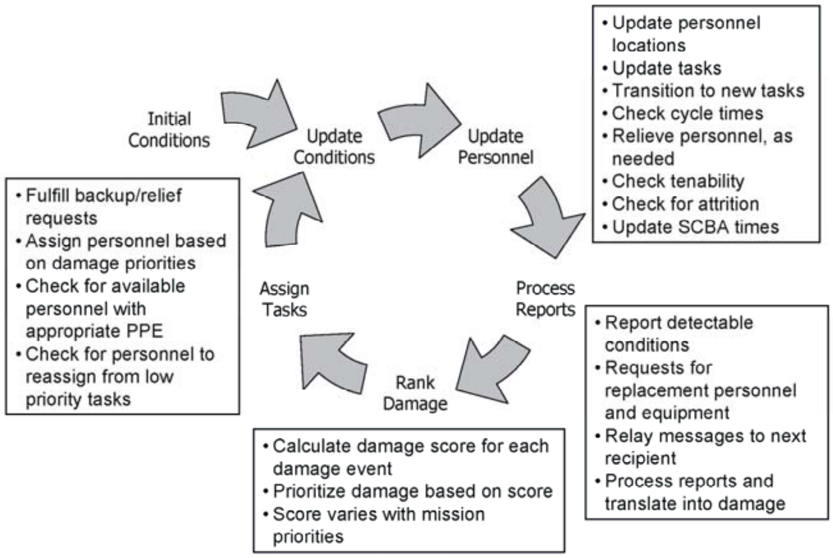


Figure 2. DCRSim Simulation Process

Reported information is prioritized and then used to determine the specific DC actions that are required to mitigate the reported damage. Orders for the required DC tasks are communicated to the organization and personnel are dispatched, provided they are available. Since the level of personnel protection equipment (PPE) is tracked for each agent, only personnel that are properly equipped for the assigned task are dispatched. The simulator accounts for the time required to dress out, gather necessary equipment, travel, and complete the activity. If conditions in a compartment exceed the tenability thresholds for a particular individual and their level of PPE (visibility, temperature, flooding level), then either an alternative approach is adopted or the task is abandoned and the person returns to the DCRS. Personnel are relieved as the duration of their task exceeds the time they can spend engaged in the task (stay time). Relieved personnel exit the area to rest and recover. After a period of recovery, these personnel become available for a new task assignment. During the response, DC personnel may be injured such that they are no longer available to perform DC tasks. The response continues until all damage has been mitigated or the simulation reaches its defined duration, whichever occurs first.

The primary outputs from DCRSim are an event log, a manning summary, and a personnel timeline. The event log is a list of important events in the DC response that are marked with a time stamp. Examples of events included in the log are task assignment, start of a task, end of a task, when access to compartments is gained, when backup personnel take over a task, and when personnel are lost to attrition. A description of the simulation that provides additional information regarding the personnel, task, and location of the damage is also logged.

The manning summary provides a representation of the overall manning of the DC response as a function of time. The output file includes the number of personnel being simulated, number of personnel available, number of personnel assigned to tasks, number of replacement personnel available, number of personnel resting, number of personnel injured, and the number of personnel performing tasks.

DCRSim also provides more detailed information on the current task of each individual simulated as a function of time. If personnel have not yet been assigned a task they are shown as available. Likewise, once a person is injured they are identified as such.

The current model does not include DC plotting tools or supervisory control systems as variables; there is a need to quantify the impact of these variables.

Technical Basis for Model Parameters

The times to complete specific DC activities were established based on the results of: full-scale tests involving firefighting and damage control responses; a review of DC doctrine and tactics [1]; and other literature. Examples of some of these parameters, as well as the technical basis for each parameter, are summarized in Table 1. The time to complete a task varies with the skill level of the individuals performing the tasks. The skill levels, currently assigned qualitatively are identified as high, medium, and low. High skill level would indicate an individual with significant experience and training for the specific task. Medium skill would indicate personnel who have been properly trained in the function and have some experience. Low skill level would apply to personnel with little or no training or experience for the particular task. These parameters were not fully vetted for the prototype and further review of the parameters is anticipated. It is expected that data from the planned Readiness and Proficiency project, discussed in the next section, will provide quantitative input into these skill levels.

Specific tenability thresholds were established for the different levels of personnel protection as described in the literature [5]. For example, an area is considered to have a heavy smoke condition if visibility is less than five feet.

Clearly, these parameters need refinement: firefighting and boundary cooling times should have some sub-categorization for different size threats. Boundaries may have fire insulation which should retard fire spread, and other passive features may be provided. Some sensitivity to size/geometry of the impacted area should be included. Quantification of skill levels is required. An approach to provide this quantification is described in the next section.

DAMAGE CONTROL READINESS AND PROFICIENCY

The need to account for variability in manned performance was identified in a fire hazard analysis for a new platform. Traditionally, "standard" manned response characteristics (e.g., response time, time to combat a specific type of fire) were established using expert opinion. In the hazard analysis, times for the onset of critical secondary damage events (fire spread between decks, time to critical ordnance temperatures) were found to be sensitive to firefighting response. Where it was assumed that manned performance was optimum, critical events could be averted. However, even modest degradations in personnel response (e.g., longer transit times to reach a fire) resulted in the onset of potentially catastrophic secondary damage. The need to address the variability of performance over the entire duration of the response was clearly established.

To address this need and establish more quantitative methods to determine Fleet readiness, the OSD has initiated an assessment project. This project, the Evaluation of Fleet

Table 1. Examples of Damage Control Activity Times

Task ID	Task	Time to Complete Based on Skill Level (minutes)			Technical Basis
		High	Medium	Low	
ANOR	Normal compartment access	3.5	7.5	11	The average time for teams to access fire compartments for a direct or indirect attack during 1993 FDE tests was 7.5 minutes [6]. During manned tests, the time to access the fire ranged from 3.5 to 11 minutes [7].
BLR	Bulkhead repair	14	30	To be determined	Assumes the use of a K-type shore to brace damaged bulkhead. High and medium times are average times to construct K-shores in DC tests [8,9], 1996a and 1996b). The differences in performance between the two series of tests were attributed to difference in shipboard training prior to tests.
DA	Direct attack on a moderate size fire (<500 kW)	3.5	18	To be determined	The time to extinguish moderate size fires once a direct attack had been initiated ranged from 3.4 to 17.8 minutes during fleet doctrine tests [10].
FMI	Manual firemain isolation	3	10	22	The time to manually isolate the firemain ranged from 3 to 22 minutes during the 1998 DC-ARM tests [11]. The average time was 10.2 minutes.
GEAR	Time to complete dress out, activate SCBA, and gather equipment prior to leaving DCRS	2	4	To be determined	The time to don an ensemble and OBA were 2.8 and 3.4 minutes respectively during a series of submarine firefighting tests [12].
REST	Rest/recuperation after firefighting	—	20	—	NSTM 555 [13] indicates that recuperation time shall be at least twice as long as the on-scene firefighting time. On-scene firefighting time is limited to 10 minutes; the rest time is 20 minutes (NAVSEA, 2004).
VBC	Vertical boundary cooling	10	20	29	The time to set vertical boundaries ranged from 5 to 41 minutes in previous firefighting tests [14,15,16]. The average time was 19.8 ± 19.6 minutes. The stay time for personnel engaged in vertical boundary cooling was 7 to 14 minutes during full-scale tests with personnel wearing ensembles [17].

Damage Control Readiness, is intended to develop the metrics that will enable objective evaluation of the overall damage control readiness of a ship. The data derived from this evaluation can then be used as input to DCRSim and to optimize onboard and shore side training.

Current shipboard DC team training proficiency is affected by a number of factors, including:

- The realism of drill scenarios – This is limited by training methods available (for example, limited live fires) and the policy to limit risk to personnel and equipment.
- Repair party proficiency – Personnel assignments to DC repair parties are continuously in a state of flux. This lack of continuity in functional teams, such as firefighting attack teams, shoring, pipe patching, and others, may make it difficult to maintain quality proficiency within the repair locker.
- Reinforcement of basic survivability skills – Self-contained breathing apparatus (SCBA) use and basic familiarization with damage control and firefighting equipment are but a few of the skills that need continuous reinforcement.
- Availability of advanced tactics training and shore-based team training.

There is considerable anecdotal evidence suggesting that many, if not most; sailors have insufficient expertise in damage control skills. After-action investigations of many of the Navy's shipboard fire and damage conflagrations (such as those aboard USS *Stark* and USS *Forrestal)* also revealed a lack of basic damage control and firefighting skills that not only increased the response times but also contributed to personnel casualties. Similar problems have repeatedly been observed during full-scale damage control exercises conducted by the Naval Research Laboratory (NRL) aboard the ex-USS *Shadwell* during the past 20 years. Fleet personnel have frequently participated in these tests, performing actual damage control evolutions involving fire fighting and flooding control. Recurring observations, supported by statements from the test participants, reveal that, upon arrival at ex-USS *Shadwell*, many of the participants were not adequately prepared for real-world casualties. Qualitative performance assessments have been made, based on Fleet doctrine evaluation tests; team effectiveness has been found to be highly variable, as shown in Table 2 [18]. Table 2 also illustrates the large degree of variability among ships. Qualitatively, no correlation is apparent between prior experience working as a team and overall performance.

Table 2. Qualitative Assessment of Damage Control Training Effectiveness

NRL Test	Year	Team	Prior Team Experience	Effectiveness
Electrical cable [19]	1985	Navy fleet instructors	No	Poor
Smoke curtain [20]	1986	Active destroyer crew	Limited	Poor
Submarine hose reel & quick response doctrine [12]	1987	Instructors & operators	No	Good - Excellent
Mass conflagration [10]	1991	Senior instructors & officers	No	Poor
Heat & smoke management [15]	1992	Senior instructors & officers	No	Fair
Vertical entry [6]	1993	Active reserve ship crew	Yes	Excellent
Attack team workshop [21]	1994	Surface ship pre-commissioning unit	Limited	Fair
Attack team workshop [22]	1994	Surface ship crew	No	Poor
Attack team workshop [23]	1994	PEB officers	Yes (evaluation team)	Good
SCBA [24]	1996	Aircraft carrier crew	Yes	Good
Submarine ventilation doctrine [25]	1997	Operators	No	Good
DC-ARM/ISFE [11]	1998	Surface ship pre- commissioning unit	Limited	Fair

In order to quantitatively evaluate performance, tasks must be reduced to some manageable and measurable level. Conceptually, the damage control organization can be divided into three hierarchical levels: individuals, teams (for example, a hose team) and managers (such as the on-scene leader or the Damage Control Assistant). Associated with each level are tasks that must be accomplished. Each task, in turn, requires specific knowledge, skills and abilities (KSAs) that must be learned and practiced in order to ensure that those tasks are carried out quickly and efficiently.

Each of these levels will be addressed using a phased approach. Within each phase, the KSAs required for the corresponding level will be identified. Based on the core requirements identified in an initial task analysis, methods will be developed to measure the degree to which these tasks are successfully accomplished and to quantify the skill levels of the participants. These methods will include sets of specific test scenarios, metrics (essentially, a scoring system for measuring performance in the test scenarios) and techniques for applying the metrics to the scenarios. Once the above framework for performance measurement has been established, exercises will be designed to demonstrate the required tasks and skill sets under realistic conditions.

After an acceptable set of metrics has been developed and an initial group of damage control personnel have been evaluated, recommendations will be made regarding ways to improve damage control readiness in the Fleet. These may include suggestions for changes in the training curriculum, improvements in shipboard training evolutions or better tools for maintenance of individual proficiency.

During the team and management phases, the effects of unequal individual skills among different teams must be addressed. The issue is that the presence of a few people having less than satisfactory individual skills may degrade the performance of the team to the extent that the entire team scores poorly. Conversely, a particularly strong individual may have a positive impact on the team, leading a team to an unrealistically high score.

One possible approach being considered is the development of weighting factors that would normalize the team scores to correct for individual scores. In a similar fashion, the overall management scores might be corrected for the effects of differences in the team scores. This would probably require the application of statistical methods to resolve the contributions due to different factors.

Prior testing has provided some indications of potentially useful statistical techniques for problems of this type. For example, in 1989, NRL conducted full scale fire fighting doctrine and tactics tests in simulated submarine compartments [11]. Firefighter effectiveness (as measured by their response and extinguishment times) was believed to be a function of many variables, including:

- The fire threat (including thermal and smoke density);
- The fire fighting appliances used (portable extinguisher, hose reel, or hand line);
- The level of personal protection available (coveralls, breathing apparatus, full protective ensemble);
- The specific fire fighting tactics; and
- The experience of the firefighters.

A statistical approach, using analysis of variance (ANOVA) [26,27], was applied to analyze the response and extinguishment time performance measures. ANOVA apportions the variations in the measured data to the hypothesized variables and can be used to determine whether there is a statistically significant correlation between the variables and the results. For example, in the submarine tests, visibility was found to be a statistically significant variable affecting performance whereas the temperature of the passageway leading to the fire, the fire location and the type of equipment used were found to be statistically insignificant variables [28]. A similar ANOVA analysis is expected to be useful in determining which of the many training-related parameters produce statistically significant effects and which do not.

Fortunately, the number of variables associated with firefighting proficiency can be culled using the substantial data from the ex-USS *Shadwell [1]*. Experience shows that, in test after test, certain findings are consistently identified. Examples of these findings, for the three groupings of interest, include the following:

Individuals

1. The greater the degree of protective clothing worn by an individual, the more aggressive the boundary cooling tactics can be. Head protection is required to protect against hot, dripping water from steam condensation [13] (55-6.1.1).

2. Water should only be used when needed. Water should not be applied to a hot boundary unless there is an imminent fire spread hazard [13] (555-7.2.6).

3. It has been repeatedly found that the hands, wrist, neck, and feet are the "weak links" in terms of susceptibility to steam burns. Steam can be driven into clothing where it joins, i.e., glove to sleeve [13] (555-6.1.2).

4. Removal of combustibles from fire boundaries is an effective boundary maintenance technique [13] (555-7.2.6).

5. Investigators and boundarymen should focus on their duties. The limitations of manned investigation and boundary maintenance have been observed; sometimes the personnel perform their job, e.g., remove combustibles, sometimes they don't.

Teams

1. It was easier to locate fires vertically, i.e. from above the fire, by locating hot spots.

2. Vertical boundary cooling evolutions are very difficult to perform without a vent path for the steam buildup.

3. There is a need to emphasize the short water burst tactic for steam management when boundaries are very hot [13] (555-7.2.7.1.1).

4. Cooling in the repair locker (e.g., with moving air or cool compresses) appears to be an effective technique to reduce post-firefighting heat stress [13] (555-7.5.10).

5. Indirect firefighting opportunities and effectiveness should be emphasized.

6. The firefighter's ensemble provides protection for the maximum heat threat. The potential for heat stress should be recognized. Other protection (e.g., coverall protection with flashhood, gloves, and breathing apparatus) may be sufficient for lower heat threats (e.g., boundary cooling situations) [13] (555-6.1.5).

7. Specific doctrine, tactics, and procedures should be drafted for active desmoking during firefighting [13] (555-7.7.3.5).

8. DC Team members should be flexible in their assignments. The plugman can be used for utility purposes (e.g., helping with desmoking equipment and passing messages). However, the plugman should stay in close proximity to the plug [13] (555-5.2.3.4).

9. Access requirements will differ depending on the fire [13] (555-7.5.4 & 555-7.6.2).

10. Active desmoking increases visibility and decreases heat stress. The key to desmoking evolutions is flexibility [13] (555-7.7.1).

11. The use of chemlights for identifying equipment and personnel in the dark is effective [13] (555-7.5.12).

12. The need for rapid rotation of attack team members, in particular, the team leader and nozzleman, has been repeatedly verified [13] (555-7.5.10).

13. The ability for personnel to navigate through smoke improves with improved knowledge of a space layout.

14. When a properly protected attack team enters a fire space, they typically put the fire out within a few minutes after entering. In many situations, neither fire severity nor attack team techniques are major factors in not meeting performance goals.

15. Nozzlemen should adopt "stream management" techniques including a short water burst tactic, use of straight, narrow angle, and wide angle streams, and use of water only when necessary. This must be integrated with other factors including personnel protection, desmoking, and venting of the fire area [13] (555-7.5.5.a).

Managers

1. Leadership and communications are critical in mass conflagrations [13] (555-8.11.1.3 & 555-8.11.1.4).

2. Communications have repeatedly been identified as a major limitation to effective operations:

   a. The use of the 1MC to pass important messages has been repeatedly advocated. The 1MC is effective for relaying information when other communication systems break down. It also is psychologically beneficial, particularly to those personnel out of direct contact with the repair party (e.g., boundarymen).

   b. There are problems with WIFCOM and there is a need for back-up communications (e.g., sound powered phones). Problems include dropped or garbled signals [13] (555-7.14.5).

c. Coordination between and within teams is important. “Local” communications (i.e., between the scene leader and hose team leader) are important [13] (555-7.6.1).

d. The need for written messages between the scene and the repair locker should be evaluated.

e. Communication among the team members improves with repeated training over the course of a test week on ex-USS *Shadwell*. Poor communication directly impacts the amount of time required to locate the fire and rig firefighting equipment.

3. The benefits gained from operating installed smoke ejection systems (SES) before initiation of investigation procedures have been shown. The use of SES also dramatically reduces the amount of time required for personnel to prepare for fire extinguishment [13] (555-7.7.7.1].

4. In combat damage scenarios, reduced manning recovery goals were not met because of:

   a. Long delays in investigations and poor communications between investigators and the scene leader, DCRS Leader, and DCA;

   b. Delays in isolating firemain ruptures and the ensuing confusion about which fire plugs had water available; and

   c. The failure of the chain of command to grasp the overall situation and act accordingly.

Associated with the test findings is guidance in the “program of record” for surface ship fire fighting. Many of the ex-USS *Shadwell* findings are, in fact, embodied in NSTM 555. Citations to NSTM 555 are provided with findings outlined above. It now remains to be seen whether recommended practices are implemented in the Fleet. There are also indications that this information is not filtering down into the Fleet [29]. The approach in the proficiency testing will be to use the identified doctrine, tactics, and procedures known to be accurate, effective, and necessary, as documented in the program of record, and see if individual personnel, teams, and managers are proficient.

SUMMARY

Scientifically-based modeling and simulation of damage control physics (fire development, smoke spread, flooding) continues to be developed and implemented into vulnerability assessments and design analysis [30]. Scientific rigor in assessing the human element, that is, the manned damage control response, has been lacking. This report has proposed a modeling and simulation framework, DCRSim, whereby manned damage control response may be more rigorously analyzed. The key improved features of this simulation are: real-time interactivity with other simulation elements, ability to vary key manning parameters including quantity of people, team command structure and doctrine, and, ability to incorporate personnel proficiencies to identify the sensitivity of the human response to meeting recoverability performance requirements.

A parallel testing effort should provide the process (measures of performance) and outcomes (measures of effectiveness) necessary to judge the proficiency of individual damage control personnel, teams, and command structures. This will allow quantification of DCRSim skill levels, and identify where current training is effective and ineffective. This will lead to more accurate and valid assessments. Policy makers can then balance fixed capital design costs (e.g., installed suppression systems, passive insulation, and supervisory control systems), versus manning requirements and recurrent human costs, including training.

REFERENCES

1. Williams, F.W., "ex-USS *Shadwell* Bibliography," in preparation

2. Andrade, S.F., "An Intelligent Agent Simulation of Shipboard Damage Control," Naval Postgraduate School Thesis, Monterey, CA, June 2000.

3. Bonabeau, E., "Agent-based Modeling: Methods and Techniques for Simulating Human Systems," in *Adaptive Agents, Intelligence, and Emergent Human Organization: Capturing complexity through Agent-Based Modeling*, Proceedings of the National Academy of Sciences, Stanford University Highwire Press, May 14, 2002.

4. Floyd, J., S. Hunt, F. Williams, and P. Tatem, "A Network Fire Model for the Simulation of Fire Growth and Smoke Spread in Multiple Compartments with Complex Ventilation", *Journal of Fire Protection Engineering*, 15, No.3, 2005, pp. 199-229.

5. Purser, D.A., "Toxicity Assessment of Combustion Products," *The Society of Fire Protection Engineering (SFPE) Handbook of Fire Protection Engineering*, 3rd Edition, National Fire Protection Association, Quincy, MA, pp. 2-83 – 2-171, 2002.

6. Williams F.W., J.L. Scheffey, J.T. Wong, T.A. Toomey, and J.P. Farley, "1993 Fleet Doctrine Evaluation Workshop: Phase I - Class A Fire/Vertical Attack," NRL/MR/6180--93-7429, Naval Research Laboratory, Washington, DC, December 30, 1993a.

7. Luers, A.C., S.A. Hill, J.L. Scheffey, H.V. Pham, J.P. Farley, and F.W. Williams, "The Evaluation of the Autonomic Fire Suppression System Concept of Operations and PDA Cooling Effectiveness," NRL/MR/6180-03-8709, Naval Research Laboratory, Washington, DC, September 30, 2003.

8. Hill, S.A, J.L. Scheffey, C. Campbell, R. Breaux, H. Kuzma, and F.W. Williams, "Evaluation of Damage Control Tactics and Equipment – Phase I, Baseline Tests," NRL/MR/6180--96-7902, Naval Research Laboratory, Washington, DC, December 30, 1996.

9. Hill, S.A, C. Campbell, H. Kuzma, and F.W. Williams, "Evaluation of Damage Control Tactics and Equipment– Phase II, Baseline Tests," NRL/MR/6180--96-7903, Naval Research Laboratory, Washington, DC, December 30, 1996.

10. Scheffey, J.L., F.W. Williams, J.T. Wong, T.A. Toomey, and J.P. Farley, "Results of Fleet Doctrine Evaluation (FDE) Tests," NRL Ltr Rpt Ser 6180/412.1, Naval Research Laboratory, Washington, DC, June 29, 1992.

11. Parker, A.J., B.D. Strehlen, J.L. Scheffey, J.T. Wong, R.D. Darwin, H.V. Pham, E. Runnerstrom, R. Lestina, R. Downs, M. Bradley, T.A. Toomey, J.P. Farley, F.W. Williams, and P.A. Tatem, "Results of 1998 DC-ARM/ASFE Demonstration Tests," NRL Rpt Ser 6180/0032, Naval Research Laboratory, Washington, DC, March 12, 1999.

12. Scheffey, J.L., L.A. Jonas, T.A. Toomey, R. Byrd, and F.W. Williams, "Analysis of Quick Response Fire Fighting Equipment on Submarines – Phase II, Full Scale Doctrine and Tactics Tests," NRL/MR/6632, Naval Research Laboratory, Washington, DC, July 10, 1990.

13. Naval Sea Systems Command, Naval Ships' Technical Manual NAVSEA S9086-S3-STM-010, Chapter 555, Volume 1, "Surface Ship Firefighting," Revision 11, 1 October 2004.

14. Williams, F.W., J.L. Williams, M.G. Toscano, J.L. Scheffey, J.T. Wong, and T.A. Toomey, "Results of Fleet Doctrine Evaluation Workshop-Psychological Stress," NRL Ltr Rpt Ser 6180/102.2, Naval Research Laboratory, Washington, DC, June 1, 1993.

15. Williams, F.W., J.T. Wong, J.P. Farley, J.L. Scheffey, J.T. Wong, and T.A. Toomey, "Results of Heat and Smoke Management/Firefighting Tests," NRL Ltr Rpt Ser 6180/31, Naval Research Laboratory, Washington, DC, February 4, 1993.

16. Peatross, M.J., A.C. Luers, H.V. Pham, J.L. Scheffey, J.T. Wong, J.P. Farley, F.W. Williams, P.A. Tatem, X. Nguyen, and S.L. Rose-Pehrsson, "Results of FY2000 DC-ARM Demonstration," NRL Ltr Rpt Ser 6180/0029, Naval Research Laboratory, Washington, DC, February 7, 2001.

17. Scheffey, J.L., T.A. Toomey, R.L. Darwin, and F.W. Williams, "Post-Flashover Fires in Shipboard Compartments Aboard Ex-USS *SHADWELL*: Phase VI - Boundary and Compartment Cooling," NRL/MR/6183--94-7455, Naval Research Laboratory, Washington, DC, March 28, 1994.

18. Williams, F.W., P.A. Tatem, X. Nguyen, A. Durkin, A.J. Parker, B.D. Strehlen, J.L. Scheffey, H. Pham, J.T. Wong, R.L Darwin, E. Runnerstrom, T. Lestina, R. Downs, M. Bradley, T.A. Toomey, and J.P. Farley, "Results of 1998 DC-ARM/ISFE Demonstration Tests," NRL/FR/6180--00-9929, 25 April 2000.

19. Williams, F.W., "Fire Fighting Tests for Cable Fires," NRL Ltr Rpt 61800-564 of 2 July 1985

20. Williams, F.W., "Navy Smoke Curtain Tests," NRL Ltr Rpt 6180-994:FWW:cak of 18 September 1986

21. Gottuk, D.T., Beyler, G.L., Toomey, T.A., Scheffey, J.L. and Williams, F.W., "1993 Fleet Doctrine Evaluation Workshop: Phase II, Class B Fire Dynamics Test Series," NRL Ltr Rpt 6180/0148.1 of 23 March 1994

22. Farley, J.P., Scheffey, J.L., Siegmann III, C.W., Toomey, T.A. and Williams, F.W., "1994 Attack Team Workshop: Phase II – Full Scale Offensive Fog Attack Test," NRL Ltr Rpt 6180/0798.2 of 17 November 1994

23. Hill, S.A., Scheffey, J.L., Campbell, C., Breaux, R., Kuzma, H. and Williams, F.W., "Results of Damage Control Tactics and Equipment Tests: Phase 1 – Baseline Tests," NRL Ltr Rpt 6180/0557.1 of 05 September 1995

24. Hill, S.A., Scheffey, J.L., Farley, J.P. and Williams, F.W., "Results of the 1996 Firefighting and Damage Control Equipment Evaluation Tests (SCBA)", NRL Memorandum Report NRL/MR/6180—97—7936, March 31, 1997

25. Parker, A.J., Scheffey, J.L., Hill, S.A., Farley, J.P., Tatem, P.A., Williams, F.W., Satterfield, D.B., Toomey, T.A. and Runnerstrom, E., "Full-Scale Submarine Ventilation Doctrine and Tactics Tests," NRL Memorandum Report NRL/MR/6180—98—8172 of June 30, 1998

26. Spiegel, M.R., Statistics, Schauin Publishing Co., New York, NY, 1961

27. Pan, B., *Basic Statistics*, Doubleday & Co., Inc., Garden City, NY, 1967.

28. Scheffey, J.L., and F.W. Williams, "The Extinguishment of Fires Using Low-Flow Water Hose Streams — Part II," *Fire Technology*, 27 (4), November 1991, pp. 291-320.

29. Scheffey, J.L., C.W. Siegmann, T.A. Toomey, F.W. Williams, and J.P. Farley, "1994 Attack Team Workshop: Phase II - Full Scale Offensive Fog Attack Tests," NRL Memorandum Rpt NRL/MR/6l 80-97-7944, Naval Research Laboratory, Washington, DC, April 24, 1997.

30. Haupt, T.A., Henley, G., Parker, B.S., Kirkland, R., Floyd, J., Scheffey, J.L., Tatem, PA. and Williams, F.W., "User Manual For Graphical User Interface Version 2.8 with Fire and Smoke Simulation Model (FSSIM) Version 1.2," NRL Memorandum Report NRL/MR/6180—08—9145 of October 10, 2008

ACKNOWLEDGMENTS

The IRM structure as described in this report was developed by T&E Solutions, LLC, Washington, DC. DCRSim development has been supported by LFT&E efforts. The readiness and proficiency testing program is sponsored by the Office of the Secretary of Defense's Director, Operational Test and Evaluation Office.