Functional Modelling, Scenario Development, and Options Analysis to Support Optimized Crewing for Damage Control

Phase 2: Scenario Development

Gerard Torenvliet and Greg Jamieson

CMC Electronics Inc.
415 Legget Drive
Box 13330
Ottawa, Ontario
K2K 2B2

Contract Number W7711-057972/A
CMC Document Number 1000-1370-2

On behalf of
DEPARTMENT OF NATIONAL DEFENCE

Defence R&D Canada – Toronto

Contract Report

DRDC Toronto CR 2007-061

31 March 2007

Author

Gerard Torenvliet

Author

Greg Jamieson

Approved by

Dr. Renée Chow, DND Scientific Authority

Approved for release by

Dave McKay, HFE Program Manager

This report is UNCLASSIFIED
CMC Electronics Inc., Human Factors Engineering

cmc electronics

Functional Modelling, Scenario Development, and Options Analysis to Support Optimized Crewing for Damage Control

Phase 2: Scenario Development

Gerard Torenvliet
Project Lead
(613) 592-7400 x 2613

Greg Jamieson
Cognitive Work Analysis Expert
(416) 946-8504

Dave McKay
HFE Program Manager
613-592-7400 x 2522

CMC Electronics Inc.
415 Legget Drive
Box 13330
Ottawa, Ontario
K2K 2B2

PWGSC Contract No.: W7711-057972/A
Report No.: CMC Document Number 1000-1370-2
DRDC Toronto CR 2007-061

On behalf of
DEPARTMENT OF NATIONAL DEFENCE

Defence R&D Canada – Toronto Scientific Authority
Dr. Renée Chow
Defence R&D Canada
1133 Sheppard Avenue West
Toronto, Ontario, M3M 3B9
(416) 635-2000 x 3015

Functional Modelling, Scenario Development, and Options Analysis to Support Optimized Crewing for Damage Control

Phase 2: Scenario Development

31 March 2007

PWGSC Contract No. W7711-057972/A

Prepared by

CMC Electronics Inc.

Military Aviation Electronics
Human Factors Engineering
415 Legget Drive
Ottawa, Ontario
K2K 2B2

cmc electronics

Functional Modelling, Scenario Development, and Options Analysis to Support Optimized Crewing for Damage Control

Phase 2: Scenario Development

31 March 2007

CMC Document Number 1000-1370-2
PWGSC Contract No. W7711-057972/A

Prepared by:

Gerard Torenvliet
Project Lead

Greg Jamieson
Cognitive Work Analysis
Expert

Approved and
Released by:

Dave McKay
HFE Program Manager

CMC Electronics Inc.
Military Aviation Electronics
415 Legget Drive
Ottawa, Ontario, Canada
K2K 2B2

ABSTRACT

The Canadian Navy hopes to achieve significant lifetime cost reductions by implementing optimized crew levels across its next-generation fleet. Defence Research and Development Canada has recognized that optimized crewing can only be achieved through a thorough Human-Systems Integration effort, and that this effort will require systems modelling techniques to help the Navy predict the effectiveness of technologies and work strategies that aim to reduce operator workload and improve mission success. This report describes the second phase a project undertaken to provide Defence Research and Development Canada with such a technique, and details the development of two damage control scenarios. One additional phase of analysis is planned, to identify three different sets of damage control equipment and the crew level required to operate that equipment under the damage scenarios that have been defined. The outputs from this project will be used as inputs for a follow-on project to develop a simulation of human and automated work in the damage control domain. The scenarios documented in this report coupled with the results of the first phase of work are a strong basis for the final phase of this project, and the follow-on simulation development effort.

RÉSUMÉ

La Marine canadienne souhaite réduire de façon significative les coûts du cycle de vie grâce à l'optimisation des équipages de sa flotte de prochaine génération. Recherche et développement pour la défense Canada a reconnu que l'optimisation de l'armement en équipage ne peut se réaliser que par l'intégration totale des systèmes humains et que cela exigera des techniques de modélisation de systèmes qui aideront la Marine à prédire l'efficacité des technologies et des stratégies de travail qui ont pour but de réduire la charge des opérateurs et d'améliorer les chances de succès de la mission. Ce rapport décrit la deuxième étape d'un projet qui procurera ces moyens à Recherche et développement pour la défense Canada et explique les détails de la mise au point de deux scénarios de contrôle des avaries. Une autre étape d'analyse est prévue : elle consiste à trouver trois équipements de contrôle des avaries et l'effectif nécessaire pour faire fonctionner ses équipements compte tenu des scénarios de contrôle des avaries définis. Les données de ce projet serviront de fondement à un projet de suivi visant à simuler le travail humain et automatisé dans le domaine du contrôle des avaries. Les scénarios documentés dans le présent rapport, conjugués aux résultats de le première étape de travail, constituent un solide point de départ pour l'étape finale de ce projet, de même que pour les travaux subséquents de développement de la simulation.

EXECUTIVE SUMMARY

In response to its recent strategic planning activity, the Canadian Navy is currently planning for a significant restructuring of their forces. Over the lifetime of a class of ships, personnel costs are much larger than procurement costs; accordingly, the Navy is hoping to develop a next-generation fleet that includes optimized crewing levels to reduce personnel costs. Defence Research and Development Canada has recognized that the Navy's objectives can only be met through a thorough Human Systems Integration effort, and that this effort will require systems modelling techniques that will help the Navy to predict the impact of various crewing level and technology combinations on operator workload and mission success.

Defence Research and Development Canada has recently initiated a project to provide the Navy with a systems modelling methodology that provides a workload simulation facility based on a functional model of the system of the interest. It is hoped that this methodology will allow for comparisons of the workload induced by various combinations of technology and crewing. Further, since it is expected that in the future crewing levels will be predicated on the crew requirements for damage control, damage control has been selected as the domain for the development of this new analysis suite.

This report describes the results of the second phase of this project, in which one medium and one high complexity damage control scenario were developed. Included in the report is a rationale for the methodology followed, reviews of existing damage control scenarios, reviews of real-world damage control incidents, details on the two scenarios that were developed, a task inventory to describe actor-independent elements of work that must be carried out for each scenario, and finally, a comprehensive set of measures of effectiveness.

SOMMAIRE

Dans la foulée de sa récente activité de planification stratégique, la Marine canadienne planifie actuellement une restructuration importante de ses effectifs. Pendant la durée de vie d'une classe de navires, les frais en personnel s'avèrent beaucoup plus élevés que les frais d'acquisition du navire; en conséquence, la Marine souhaite élaborer une flotte de la prochaine génération qui optimise l'armement en équipage de manière à réduire les frais en personnel. Recherche et développement pour la défense Canada a reconnu que les objectifs de la Marine ne peuvent être atteints que par l'intégration totale des systèmes humains et que cela exigera des techniques de modélisation de systèmes qui aideront la Marine à prédire les répercussions de l'utilisation de différents niveaux d'effectifs et de combinaisons technologiques sur la charge de travail des opérateurs et les chances de succès de la mission.

Recherche et développement pour la défense Canada vient de lancer un projet visant à doter la Marine d'une méthode de modélisation de systèmes permettant de simuler la charge de travail à partir d'un modèle fonctionnel du système auquel on s'intéresse. Cette méthode devrait permettre de comparer la charge de travail découlant de différentes combinaisons de technologies et d'effectifs. Par ailleurs, étant donné que l'on s'attend à ce que l'armement en équipage repose à l'avenir sur les besoins en effectifs chargés du contrôle des avaries, le contrôle des avaries a donc été retenu comme domaine devant servir à mettre au point ce nouveau programme d'analyse.

Ce rapport présente les résultats de la deuxième étape de ce projet au cours de laquelle deux scénarios de contrôle des avaries ont été élaborés. L'un de ces scénarios présente une situation de contrôle des avaries de complexité moyenne et l'autre de niveau élevé. Le présent rapport contient le fondement de la méthodologie utilisée, des études des scénarios actuels de contrôle des avaries, des études de comptes rendus d'incidents réels impliquant le contrôle des avaries, des détails sur les deux scénarios qui ont été mis au point, un inventaire des tâches décrivant certaines particularités qui font partie de chaque scénario (acteurs ou éléments indépendants). On y trouvera également un ensemble complet de mesures d'évaluation du rendement.

REVISION PAGE

REVISION	PAGES AFFECTED	DATE	APPROVAL

TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd)

SECTION **TITLE** **PAGE**

LIST OF ANNEXES

ANNEX **PAGE** **PAGE**

LIST OF FIGURES

FIGURE **TITLE** **PAGE**

LIST OF TABLES

TABLE **TITLE** **PAGE**

SECTION ONE – INTRODUCTION

1.1 GENERAL

In response to its recent strategic planning activity (2001), the Canadian Navy is currently in the early stages of planning for a significant restructuring of its forces (Canadian Department of National Defence, 2005). As the Navy's current fleet is retired, plans are underway to replace it with a next generation fleet. This fleet will be designed to meet two objectives. First, the Canadian Navy requires increased flexibility to allow it to respond to a broader range of threats and support missions that are expected to evolve over time. Second, the Navy also requires a fleet that will be more cost effective than the current fleet, and hopes to achieve this through reduced manning and increased commonality of equipment and training. Even though this new fleet is not expected to be operational until the mid 2020's, the long lead times involved in naval procurement (on the order of 10 to 15 years for the design and acquisition of a new warship) require that planning must begin now.

Defence Research and Development Canada – Toronto (**DRDC-T**) has recognized the important role that human performance will play in the accomplishment of the above objectives. To meet its objectives of expanding capabilities while reducing crew size, the Navy must find a way to amplify the capabilities of their crews. This will be achieved, in part, by equipping the fleet with new and advanced forms of automation that will permit the crew to better understand evolving situations and react promptly with optimal solutions. However, automation is not a panacea, and poorly conceived automation has the potential to actually increase operator workload (Bost, Mellis, & Dent, 1999) and make the joint human-automation system more susceptible to failures (Woods, 1996). Notwithstanding these 'ironies of automation' (Bainbridge, 1983; Wiener, 1989), automated systems have tremendous potential for success if their design and selection is based on a thorough human factors engineering (**HFE**) analysis.

In response to the Navy's strategic plan and their expected increase in reliance on automated systems, DRDC-T is seeking to develop expertise in both the selection of automation technology and the evaluation of human-machine systems that leverage automation. In terms of selection, they are seeking to develop systems modelling techniques that will help to generate guidance criteria for the selection of appropriate automation. In terms of evaluation, they are seeking to develop methods of workload modelling and analysis that can leverage the previous systems modelling effort and still provide valid and reliable results as to the impact of different crewing and automation options on human workload.

DRDC-T has identified the domain of damage control on board the Halifax class frigate as useful for the development of their expertise in these areas. While the damage control systems in the Halifax class frigate are not scheduled for a major upgrade, DRDC-T expects that any insights gained from an analysis of damage control on the Halifax class frigate will readily generalize to the proposed successor to the Halifax class frigate, the Single-Class Surface Combatant (**SCSC**). Thus the domain of damage control on the Halifax class frigate will provide useful insights both to address current concerns with respect to methodology development, and also to provide a sound basis for future analyses in support of the design and development of the SCSC.

1.2 PROJECT OBJECTIVES

The main objective of this project is to support DRDC-T in the development of a simulation environment that will enable them to assess the performance and effectiveness of a given level of crewing and automation by evaluating the impact of varying levels of crew and automation on damage control operations. The purpose of this project is not to develop the simulation itself, but rather to perform three phases of analysis to prepare for that work.

a. **Phase I: Development of a functional model of damage control.** The first phase of this work was intended to develop a means-ends functional model of damage control that is not based on specific scenarios, crewing levels, or automation technologies. Rather, this model reflected the full extent of Halifax class frigate damage control functions in a manner that will afford later 'what-if' analyses to be conducted based on different scenarios, crewing levels, and automation technologies. This phase of the project was completed in March 2006 (see Torenvliet, Jamieson, & Cournoyer, 2006).

b. **Phase II: Development of damage control scenarios.** The functional model developed in Phase I describes the work domain in which damage control is performed on the Halifax class frigate. The objective of Phase II is to develop two damage scenarios, one of medium complexity and the other of high complexity. As these scenarios will be used to test different crewing and automation options, it is important that they are posed in a way that will generalize to all three options. Task inventories will also be developed for each of the scenarios that describe the elements of work that could be assigned to either a human actor or to automation. Finally, Measures of Effectiveness (**MOEs**) and Measures of Performance (**MOPs**) will be developed that allow for comparison of different combinations of crew and automation in the network. The work in this phase will be an important input to the eventual simulation model that is the end-goal of the larger project. The deliverables from this phase will be structured for portability to a simulation effort. The work from this phase is the subject of this report, and was completed in March 2007.

c. **Phase III: Specification of crew-automation options.** In this final phase, the work of the first two phases will be supplemented by the identification of possibilities for the automation of damage control, the specification of three options for damage control automation (the status quo option that characterizes the automation currently in use in the Halifax class frigate; an intermediate option that uses currently available and tested automation technologies, and a full option that employs the full extent of the state-of-the-art in automation technologies), and the definition of the crewing levels required under the three automation approaches. As with Phase II, because this phase will produce inputs to the final simulation model, it is important that the crew-automation options be specified in ways that are readily tractable in a simulation environment. This work is planned to be completed in June 2007.

To ensure that results of all three phases accurately represent the reality of damage control operations on the Halifax class frigate, it is important that all work be performed in close consultation with relevant Subject Matter Experts (**SMEs**). This will ensure that the work

products accurately capture the subtleties of the damage control domain, and ultimately, that the final simulation model will be valid and reliable.

1.3 RATIONALE

1.3.1 General

While the first phase of this research was guided by an established methodology for the development of an Abstraction Hierarchy (**AH**) representation of a work domain, this second phase of scenario development was not predicated on any established methodology. As is discussed below, there is no theoretically-based formal treatment of scenario development in the Human Factors (**HF**) literature. In the absence of a formal methodology, the project team had to conscientiously define a suitable approach and methodology as the project unfolded. Our approach was based on three considerations: the nature of the scenarios required for this phase of the project, the complexity of understanding how the damage of a scenario would propagate through the Halifax class frigate, and the specific concerns of human performance with advanced automation that these scenarios should be sensitive to. These considerations are described below.

1.3.2 Scenarios and scenario development

While scenarios are commonly used in human-factors design (see, e.g., Beyer & Holtzblatt, 1998; Courage & Baxter, 2005; Go & Carroll, 2004; Rosson & Carroll, 2002) and are the starting point for a Human Engineering program structured according to MIL-HDBK-46855A (United States Department of Defence, 1999), there is little agreement in the HF literature about the types of information that scenarios should include. In the majority of cases, scenarios are stories that serve to add depth and flavour to an analysis effort. Rosson & Carroll (2002) advocate this view: “Scenarios have a plot; they include sequences of actions and events, things that actors do, things that happen to them, changes in the setting, and so forth. These actions and events may aid, obstruct, or be irrelevant to goal achievement (p. 18).”

This view of scenarios is actor-dependent, but scenarios that read like stories may not be appropriate for this project. As was argued in the report on the first phase of this project, since the actual damage control equipment and their associated crewing levels for analysis will not be defined until the third phase, as much as possible the work prior to this definition should be actor-independent (Torenvliet et al., 2006). For this phase of the project to produce scenarios that will readily generalize from the current equipment in the Halifax class frigate to two as-yet undefined sets of damage control equipment for the Halifax class frigate and their associated crewing levels, it would be helpful if the scenarios could be defined without reference to the damage control equipment or personnel they implicate.[1]

If a scenario is defined in an actor-independent way (that is, without reference to the damage control automation and personnel in the Halifax class frigate) one of the important variables determining how the scenario will play out over time – the actors – will be missing.

[1] While it would be beneficial to produce this sort of generalizable scenario, a valid alternative approach would be to produce a larger set of fully specified scenarios that include the initial damage situation, damage control equipment, and crewing level. However, in the long-run this approach is not likely to be as efficient as using more generalizable scenarios. Since one of the broader aims of this research program is to develop a technique that will be suitable for other contexts, it is prudent to make all efforts to ensure the technique is as efficient as possible.

Instead of being a story, this type of scenario will be a set of initial conditions, a *mise en scène*. The idea of treating a scenario in this way is not new. Kirwan (1987) used this type of scenario twenty years ago as a basis for a human reliability analysis. More recently, Kim Vicente and his colleagues have performed a large body of research about human adaptation in a process control micro-world that treats scenarios as a set of initial conditions along with subsequent faults. These scenarios serve as an input for a simulator of system dynamics (Vicente, 1997).

While the literature seems to reveal an inconsistent treatment of scenarios across different authors and their research, there is a less apparent consistency at work. This consistency is not at the level of the scope or form of scenarios, but at the level of their purpose. In all instances where scenarios are used, from full stories to brief *mises en scène*, their purpose is to specify fixed values for the as-yet unresolved items of a design problem. At the concept stage, when most elements of the system are unresolved, story-based scenarios are often a useful starting point for design and analysis. As more and more elements of the design are resolved, scenarios become increasingly constrained because the established elements of the design define the way in which the system will respond over time. Scenarios are still useful in the context of systems that have been fully designed, but in this case they can only address the way in which the environment impinges on the system. At this late stage, the most useful scenario is a *mise en scène* – the initial conditions and any perturbations that impinge on the system from the environment. But in all cases, the purpose of a scenario remains the same – to specify fixed values for the unresolved items of a design problem.

This interpretation of scenarios – that is, that they should specify the unresolved items in a design problem – defined the approach to scenario-building followed in this report. Even though these scenarios are being designed to support conceptual phase analyses, when the scenarios are finally used, the scope of the unresolved design items will be limited. The work already performed in the first phase of the project defined the work domain within which damage control operates. This work domain is the boundary for scenario development – all items inside the work domain are potentially resolvable design elements, and those in the environment beyond the boundary are necessarily unresolved. Work in the third phase will define three different sets of damage control equipment for the Halifax class frigate and the crew levels they require for effective operation. Accordingly, the scenario development of this phase should result in scenarios that specify the required unknowns outside of the work domain / environment boundary established in the first phase and that are actor-independent so that they will generalize to the three equipment and crew level options (design elements that are inside the work domain / environment boundary) of the third phase. In other words, the scenarios to be developed should be in the form of *mises en scène*.

1.3.3 Damage propagation

At the outset of this phase, the project team expected that the scenarios to be developed would include two types of information. First, they would begin with specific damage control incidents (or, ways in which the environment impinges on the work domain). Second, they would include details about the ways in which the damage caused by the incident could potentially propagate across the ship given different types of damage control interventions.

As the work for this phase unfolded, it became clear that these two types of information are quite different. To specify damage incidents, it is necessary to understand the complex and challenging ways in which the environment can affect the ship. It was clear that the

best source for this type of information is current SMEs in naval damage control, preferably Sea Training staff. These SMEs are experts in scenario-based training and frequently develop scenarios that are intended to tax even experienced damage control staff, so they are a natural source for this type of information.

While damage control SMEs also have a knowledge of the way in which damage propagates across the ship, their level of understanding is tailored to the objectives of containing and resolving damage before it propagates as opposed to precisely describing the way in which it propagates. In other words, their understanding of damage propagation is based on the requirements for developing and executing procedures to control damage, and not the actual physics describing fire, smoke, and flood propagation. For example, SMEs have heuristics to predict the rate at which a fire in a space will spread if no measures are taken to contain it (6 minutes for vertical spread, and 13 minutes for lateral spread). These heuristics work because they are conservative – if damage control efforts are coordinated based on their predictions, when resources are available to set a fire boundary, it will be planned for a space to which the fire has not yet spread. However, even though these heuristics are effective for coordinating a damage control response, they lack accuracy. The spread of fire is not simply a function of time, but also of the materials in the space. For example, a fire in a paint locker will spread at a different rate than a fire in a space that contains only a trashcan (indeed, the latter fire may not have enough fuel to spread at all). In addition, SMEs do not have heuristics to describe how smoke or floods spread. In terms of the damage control response required for these types of damage, it is sufficient only to understand that smoke and floods do spread, and quickly, so boundaries should be set to stem their spread as quickly as possible.

The level of understanding of the physics of damage propagation held by SMEs in damage control is appropriate for and well-suited to damage control operations. It also helped SMEs to give rich descriptions of the way in which the current Halifax class frigate crew and damage control equipment would respond to damage. It is not, however, the best basis for a study of the workload induced by various different types of damage control equipment and their associated crewing levels. If this research is to generate strong conclusions related to optimized crewing, it would be better served by a model of damage control with greater detail and physical accuracy.

The formulae required to accurately describe the propagation of damage are complex, and integrating them into a model of the Halifax class frigate in a way that would generate strong conclusions on human workload and system efficacy would be costly and difficult. Fortunately, a great deal of the work required has been done already by other navies around the world. Most significantly, the US Navy's Naval Research Lab (**NRL**) has spent over 10 years and US $35 million building a series of increasingly complex, accurate, and efficient models of damage propagation (F. Williams, personal communication, 27 February 2007). This work has focused on building predictive models of the propagation of smoke and fire, and has resulted in the Fire and Smoke Simulator (**FSSIM**), an accurate and computationally efficient model of fire and smoke propagation and suppression (Floyd, Hunt, Tatem, & Williams, 2004; Floyd, Hunt, Williams, & Tatem, 2004) that also includes a graphical user interface (Haupt et al., 2006). While FSSIM is not currently customized for the Halifax class frigate, it is able to generalize to any ship as defined in a set of configuration files. FSSIM does not include treatment of flooding and the ship stability problems that flooding induces, but this problem has been addressed in another NRL simulation program, the Illinois Damage Control simulator (Shou et al., 2000; Sniezek, Wilkins, Wadlington, & Baumann, 2002; Wilkins & Sniezek, 2000). The Illinois

Damage Control simulator has not progressed as far as FSSIM, but its solutions to flooding and flood control are well-documented (see the Bibliography included in Wilkins & Sniezek, 2000) and could potentially be integrated with FSSIM. The QinetiQ corporation has also developed a similar damage control simulator, called SURVIVE, in cooperation with the United Kingdom's Ministry of Defence (**MOD**) (Turner, Horstmann, & Bain, 2006).

While it is too early to recommend a specific simulator, the project team is of the opinion that this research project would be better served by adopting one of these simulators of damage propagation than by attempting to build a new one from scratch. As discussed above, even if the project team was able to collect more detail on the nature of damage propagation than heuristics, a simulation based on those insights would be inaccurate and any guidance for optimized crewing based on that simulation would be weak. On the other hand, if the final simulator is based on an accurate and validated model of damage propagation, it would be able to produce stronger, more defensible guidance for optimized crewing. Consequently, the scenarios presented in this report only include the ways in which the environment could impinge on the Halifax class frigate to cause damage, and do not include details of damage propagation beyond a high-level presentation of the extent of damage that could be caused by each scenario.

1.3.4 Human performance with advanced automation

A major aim of this research is to ensure that automation employed in future damage control systems capitalizes on human capabilities and respects human limitations. It is therefore important that the scenarios developed in this phase be sensitive to known human-automation interaction issues. Over the past two decades, a growing literature has drawn attention to the potential drawbacks of human automation interaction. Lee (2006) provides a structure for considering how these drawbacks might be manifested in damage control automation.

1.3.4.1 Out-of-the-loop unfamiliarity

Control engineers often think about automation in the context of feedback control loops. In that context, automation replaces control loops that include a human element with ones that do not. The effect of this is either to remove the human from the control model altogether, or more frequently to assign the human to supervisory control loops – away from the data, decision, and doing frontier. Once outside the inner control loops, human operators find it very difficult to remain in tune with what the automation is doing. Several aspects of automation design contribute to this problem. First, automation systems frequently fail to provide the human supervisor with adequate feedback (that is, information) about the behaviour of inner control loops. Second, the human operator is not well-suited to the passive monitoring task, even when provided with adequate feedback. Third, supervisory control encourages task switching and interruptions which further remove the operator from the inner control loops. Finally, since operators are out-of-the-loop, they tend to develop poor mental models of inner control loops and the processes that they control.

All four of these design factors are likely to contribute to human-automation challenges in damage control.[2] The first aspect, removal of the human from inner control loops,

[2] It is important to note that the assertions to follow are necessarily predictive – the damage control automation does not yet exist. It would be deceptively easy for any automation designer to dismiss these predictions. Engineers are, in fact, adept problem solvers and, once made aware of any specific issue, can posit viable solutions to them The key here is that the predictions are a projection of *persistent observations of difficulties encountered when humans*

is likely a necessary design decision if reduced workload (or reduced manning) is to be achieved. The design challenge is to provide access to inner control loops without overloading the operator – a very difficult balance to strike. The second and third aspects remind us that the operator is likely to have an incomplete awareness of the automation state and behaviour. The final aspect of automation design that contributes to out-of-the-loop unfamiliarity, poor mental models, can be viewed as a consequence of the above and a precursor to inappropriate reliance decisions (see Section 1.3.4.4, below).

1.3.4.2 Clumsy automation

Automation is frequently targeted at high-tempo phases of work with the aim of reducing operator workload (see Section 1.3.4.1, above). Ironically, if the human-automation interaction is not well anticipated, this can result in an increase in workload at times when the human is already busy. This phenomenon is called ‘clumsy automation’; clumsy automation can be further subdivided into non-routine or routine clumsiness. Non-routine clumsiness is associated with non-routine events in the domain. This could include maintenance evolutions or emergency operations. Routine clumsiness is manifested during routinely occurring high workload phases of operations, such as start-up or shutdown of major systems. For example, flight management systems are notorious for forcing pilots to perform data entry tasks during busy pre-flight evolutions.

Damage control seems highly susceptible to non-routine clumsy automation. The highly temporal nature of the domain suggests that the most critical automation tasks will be performed when the operator is extremely busy and under extraordinary duress. What might be anticipated as necessary and simple human inputs to the automation could quickly become overwhelming annoyances.

Damage control automation may also be susceptible to routine clumsiness, but to a much lesser extent compared to non-routine clumsiness. In the damage control domain, set-up may be necessary when a ship makes ready to sail or when maintenance activities cause temporary changes in the resources or constraints of the damage control system.

1.3.4.3 Automation-induced errors

Even well-design automation introduces new opportunities for humans to make errors, and the occurrence of those errors and their effects can be difficult to predict or detect. There are three types of errors that are commonly acknowledged to be induced by automation:

a. **Mode errors.** Mode errors occur when mode status or transitions are not effectively communicated to operators. Operator actions that are reasonable in one mode may have dramatically different effects in another mode.

b. **Brittle failures.** Brittle failures occur when simple data entry slips result in sudden and severe degradation in system performance. Opportunities for such failures are afforded by highly automated decision processes that are susceptible to poor quality data.

---

interact with advanced automation. It is the aim of this research to circumvent these design shortcomings through informed analysis and design.

c. **Configuration errors.** Configuration errors occur in the set-up phase of automation, particularly if data entries are not rigorously checked.

Of these three types of errors, mode errors are the most insidious and the most widely discussed in the human factors literature. Designers use modes to increase the context sensitivity of the automation. Although the approach is powerful and flexible, human operators engaged in supervisory control experience a great deal of difficulty keeping in sync with the automation modes, particularly when those modes are poorly enunciated or when transitions are induced by internal logic that is not well understood by the human.

Brittle failures and configuration errors, while important, appear to be more idiosyncratic. Both can be thwarted by rigorous input checking – an accepted practice in software engineering. It is not expected that these types of errors will be a large factor in the context of the present study.

1.3.4.4 Inappropriate trust

Trust is a complex attitude held by a person towards other agents (including automated ones) that may help or hinder achievement of the person's goals. Because this attitude develops implicitly and in response to a wide variety of influences, it is extremely difficult to model. However, there is substantial empirical evidence that trust affects reliance on automation. Inappropriate reliance behaviour can take the form of misuse (relying on automation that is incapable) or disuse (rejecting capable automation). Since people tend to rely on trusted automation and reject distrusted automation, it is easy to anticipate how trust plays a substantial role in reliance decisions and the appropriateness of those decisions.

1.3.4.5 Behavioural adaptation

Operators and organizations often adapt their behaviours in ways that nullify the safety or performance advantages of automation. This adaptation is usually implicit and may take one of two forms. First, operators sometimes respond to increases in safety with more risky behaviour; as if a risk set-point exists for the system as a whole. Second, organizations may suffer a 'diffusion of responsibility' amongst themselves. This can create situations in which no one is explicitly responsible for critiquing the decisions and actions of the automation.

These types of behavioural adaptation are not expected to be a major issue for damage control automation. The maladaptive behaviour of adopting more risky behaviour is most commonly encountered in familiar tasks that are aided by automation. For example, anti-lock braking systems do not improve driving safety because drivers adapt by traveling at higher speeds and braking more aggressively. Damage control automation is unlikely to replace tasks that are so highly practiced, so this maladaptive behaviour seems unlikely. Diffusion of responsibility also seems an unlikely problem for damage control automation because military organizations are highly practiced at role allocation and reinforcement. One would expect this organizational strength to carry over to mixed initiative damage control teams.

1.3.4.6 Skill loss and skill shift

Workers often suffer degradation in their manual task performance skills when those skills are not regularly practiced (as is the case when the skill-based tasks are automated). These tasks are often associated with physical control tasks, but degradation of cognitive tasks have

also been noted. In situations where automation assumes only a portion of the tasks associated with a job, it may have the effect of shifting emphasis to other skills. If these skills are less robust in the operator population, the joint human-automation system may suffer performance degradations from the introduction of automation.

1.3.4.7 Job satisfaction

Although automation is often envisaged by designers as relieving workers of some burden, it often has the unintended effect of reducing worker satisfaction with their job. This is often explained as a combined reduction in decision latitude and increase in work demands. While automation may reduce workload, it also reduces an operator's ability to affect the work system, resulting in a reduced sense of control. Meanwhile, the operator remains in charge of a more powerful and capable system; one that requires him to exercise less robust skills at a pace determined by a machine. The result can be highly demoralizing for the worker.

1.3.4.8 Implications

The implications of this review of human performance with advanced automation for this project are summarized in Table 1-1, below. While this review has identified a large number of issues that have important implications for this project, Table 1-1 shows that these implications will require more active consideration in Phase III of this project (when automated solutions are being considered) and during the development of the simulation of damage control (when the workload associated with the use of automation are being considered, and sensitivity conditions around the use of automation are being developed).

Even though these considerations are expected to be most important during Phase III, this work was also grounded in them as they were reviewed a number of times during the development of the scenarios, task inventories, and MOPs/MOEs detailed in this report.

Table 1-1. Summary of the implications of known issues in human performance with advanced automation for this project.

Issue	Implications	Priority
Out-of-the-loop unfamiliarity	If possible, the simulation should include sensitivity tests in which the human working with the automation makes a poor decision based on a lack of familiarity with the inner workings of the automation. (Note that this may be challenging to do in a convincing way.)	Moderate
Clumsy automation	Analysis of the candidate automated systems should focus on identifying the tasks that the operator must engage in only to manage the automation, and should identify the phases of operation in which the automation requires operator input. This information will be an important input to determining the human workload induced by the automation.	High; this is an important consideration for damage control.

Issue	Implications	Priority
Automation-induced errors	Analysis of the candidate automated systems should focus on identifying their various modes of operation and the criteria for auto-switching between modes. This should help to reveal the potential for mode errors, the effects of which can be added as sensitivity tests in which the human working with the automation makes an action that would be appropriate for one mode, but that is not appropriate in the current mode.	High; this is an important consideration for damage control.
Inappropriate trust	Sensitivity testing for simulations of the automated systems should include instances when the automation is not trusted (and so the operator relies on other methods to gather information, make conclusions, or effect actions) and is over-trusted (and so the operator relies on the conclusions and recommendations of the automation even when they are wrong).	High; this is an important consideration for damage control.
Behavioural adaptation	This is not likely to be a significant issue in a military context.	Low
Skill loss and skill shift	This is not likely to be a significant issue in the context of this project.	Low
Job satisfaction	Since damage control is only a small aspect of shipboard work, and one that – if its effectiveness is enhanced – will increase the safety of the crew, job satisfaction is not likely to be a significant issue.	Low

1.4 PURPOSE OF THIS REPORT

This report provides an account of the work performed for the second phase of the larger project described in Section 1.2, above.

1.5 REPORT OUTLINE

This report consists of the following sections:

a. Section One – Introduction

b. Section Two – Methodology

c. Section Three – Results

d. Section Four – Discussion, Conclusions, and Recommendations

e. Section Five – References

f. Annex A – Glossary of Terms and Acronyms

g. Annex B – Agenda for SME Data Collection Meeting

1.6 ACKNOWLEDGMENTS

The authors would like to acknowledge the continued assistance that was given by members of the Canadian Forces (**CF**) to this project. Lieutenant Commander (**LCdr**) Andrew Bellas (Sea Training Atlantic Maritime Systems Engineering (**MSE**) Officer) helped to

coordinate much of the data gathering for this phase of the project, and also participated with LCdrs Roger Heimpel (Canadian Forces Naval Engineering School (**CFNES**) Damage Control Division Commander) and Chris Howlett (Sea Training Atlantic Combat Systems Engineering (**CSE**) Officer) in a day-long scenario development effort. Chief Petty Officer (**CPO**) Gary White (Sea Training Atlantic Marine Electrical Engineering) participated in a half-day review of the scenarios that were developed and provided us with many helpful comments. In addition, the help of many other naval staff received in the previous phase of the project continued to bear fruit during this effort, as they directed us to a great deal of information that was used in this phase. Finally, the Scientific Authority (**SA**) for this project, Dr. Renee Chow, has offered a great deal of helpful direction and assistance to this effort. We are grateful for all of the assistance received; this phase of the project could not be completed without it.

SECTION TWO – METHODOLOGY

2.1 GENERAL

This section details the methodology followed to develop the medium and high complexity damage control scenarios, the task inventory, and MOEs and MOPs.

2.2 REVIEW OF OBJECTIVES

Since the work described in this report is a part of a larger research project, part of which has already been completed (Torenvliet et al., 2006), and part of which has not yet been fully defined (see Section 1.2), the project team began this phase of the work by reviewing the objectives of this larger research project and the specific objectives for this phase.

2.3 SCENARIO REVIEW

The first step in developing a set of damage control scenarios was to acquire and review a comprehensive set of existing damage control scenarios. Three different types of scenarios were reviewed:

a. **Damage control training scenarios.** Training scenarios are those used to train CF personnel, and have been developed by the CFNES for training conducted at the Damage Control Training Facility (**DCTF**) or by Sea Training for training conducted on ships, either during ship Workups (**WUPS**) or while at sea. The project team was able to acquire a set of 80 DCTF scenarios (each packaged as a Microsoft Word file) and 16 Sea Training scenarios with evaluations for 3 different crews on each scenario (packaged as 3 Microsoft Excel files, each with information on the 16 scenarios as applied to a single ship). These scenarios were reviewed to understand their basic form, elements that might be candidates for re-use, and domain-specific language that should be considered in the development of the scenarios for this project.

b. **Actual naval damage control incidents.** Over the past few years, there have been a number of high-profile naval damage control incidents involving craft similar to the Halifax class frigate. The project team identified the following incidents to review: (1) The HMS Nottingham, which in 2002 ran aground off the coast of Australia; (2) The USS Cole, which in 2000 was the subject of a terrorist bombing; (3) The USS Princeton, which in 1991 was damaged by an Iraqi sea-mine; (4) The USS Samuel B. Roberts, which in 1988 was damaged by an Iranian sea-mine; and (5) The USS Stark, which in 1987 was hit by two Iraqi Exocet missiles. These incidents were chosen due to their recency (all have occurred in the past 20 years) but they also include a wide range of damage control concerns. They were reviewed to understand the ways in which documented damage control incidents differ from (or are similar to) training scenarios, and to gain familiarity with the complexities of these incidents. The reviews were brief, focusing on materials readily available on the internet, as opposed to in-depth forensic reviews.

c. **Scenarios for testing advanced automation.** The US Navy's Naval Research Laboratory has been exploring the application of advanced automation to damage control in the Damage Control Automation for Reducing Manning (**DC-ARM**) project (Williams et al., 2003). The five different peacetime scenarios and one comprehensive wartime scenario that were composed for the DC-ARM project were reviewed.

In addition, since the scenarios developed in this research will ultimately be used to investigate the efficacy of advanced automation in reducing the size of the damage control team required for operational effectiveness, the project team also hoped to be able to review vendor scenarios designed specifically for testing advanced automation. Inquiries were made about such scenarios with one large vendor of damage control automation, L-3 MAPPS, but this vendor does not currently have scenarios specifically for this purpose. Instead of focusing on the human performance concerns of automation, this vendor's human factors test strategy has a much broader, system-oriented focus (R. St-Pierre, personal communication, 13 February 2007). While it is unfortunate that the project team was not able to locate vendor scenarios for testing automation, the DC-ARM scenarios helped to provide some insight into the way automation should be tested, and the human performance concerns related to automation have also been an important consideration throughout this research (see, for example, Section 1.3.4).

2.4 SCENARIO DEVELOPMENT

2.4.1 SME data collection meeting

After a basic understanding of damage scenarios was gained through the scenario review, the work of developing the medium and high complexity scenarios commenced. This work began with a trip to Sea Training Atlantic at Canadian Forces Base (**CFB**) Halifax. There, the project team held a one-day scenario development data collection meeting. The following CF personnel were in attendance:

a. LCdr Andrew Bellas, the Sea Training Atlantic MSE Officer;

b. LCdr Chris Howlett, the Sea Training Atlantic CSE Officer; and

c. LCdr Roger Heimpel, CFNES Damage Control Division Commander.

The following project team personnel were also in attendance:

a. Dr. Renée Chow, the project SA;

b. Commander (**Cdr**) (Retired) Michael Churcher, who has experience in MSE on a number of CF platforms.

c. Mr. Gerard Torenvliet, the project lead.

The purpose of this meeting was to develop preliminary outlines for one medium and one high complexity damage scenario. As can be seen from the meeting agenda (included in Annex B), this was accomplished in a meeting with five distinct parts:

a. **Common ground / project overview.** The purpose of the first part of the meeting was to discuss the project objectives in general and the requirements for the

scenarios in particular. This included a discussion of scenario complexity and scenario scope, as well as a discussion of what would be the eventual MOEs and MOPs for the damage control effort performed in response to these scenarios. The discussion of scenario scope focused on defining the stopping rules for the scenarios, that is, criteria defining when damage can be considered as solved, or out of control.

b. **Scenario identification.** The purpose of the second part of the meeting was to identify the medium and high complexity incidents from which to develop the damage scenarios. Staff members from both Sea Training and DCTF were present, and they were encouraged to work from the scenarios they were familiar with to generate these initial ideas. The discussion of scenario complexity that took place in the first part of the meeting was frequently referenced to ensure that the scenarios chosen would involve qualitatively different amounts of damage.

c. **Scenario development – medium complexity scenario.** The next step was to take the idea for the medium complexity scenario and to work out in detail the way the damage from that scenario would evolve on the Halifax class frigate. A timeline was established and then details were fleshed out along that timeline.

d. **Scenario development – high complexity scenario.** After participants completed a first pass on the medium complexity scenario, the high complexity scenario was worked out in detail in the same way, along with its timeline.

e. **Scenario refinement.** During the last portion of the meeting, we revisited both the medium and high complexity scenarios to fill in any missing information, and also to develop a number of preliminary measures of effectiveness and measures of performance.

An attempt was also made to gather data about the generic properties of damage spread from the CF personnel present at the meeting; it was hoped that this data would help in developing rules for predicting the spread of damage across the Halifax class frigate. Unfortunately, SMEs' rules for predicting damage spread (see Section 1.3.3), while effective at ensuring that damage control resources are deployed in the right locations, do not generalize well outside of the current procedures for controlling damage in the Halifax class frigate. As is detailed in Section 1.3.3, on the basis of this finding the overall approach to this project was changed to rely on more accurate predictions of damage spread available through damage control simulators such as FFSIM, Illinois, or SURVIVE.

2.4.2 Scenario development

The data collected during the SME data collection meeting was then refined into preliminary versions of the medium and high complexity scenarios. The first step in this process was to write a set of notes from the SME data collection meeting and then to refine those notes in a series of project team meetings to ensure that they included all of the data from the SME meeting. As a part of this refinement, we paid particular attention to the criteria for scenario complexity and stopping rules that were established with input from SMEs.

The records from the data collection meeting showed a strong focus on the procedures currently in use in the Halifax class frigate. While these procedure-based notes have

been kept for reference in the next phase of this project, to make the scenarios actor-independent it was necessary to abstract them away from procedure-based descriptions to some actor-independent core. Consequently, instead of developing the scenarios as a full time evolution based on current Halifax class frigate procedures, it was decided to develop them instead as a set of initial conditions along with high-level predictions on the way damage would propagate if there were no damage control response. In this framework, each scenario has three important phases:

a. **Initial damage.** This phase describes the parts of the ship affected by the initial onset of damage. For fires, this was typically the specific space in the ship where ignition occurred; for floods, this was the source of the flood (either the location of a hull rupture or a fire-main break); and finally, for structural integrity problems, this was the location of the bulkhead, deck, or wall breach.

b. **Primary propagation.** This phase describes the parts of the ship that would be affected by the first-level propagation of damage. For fires, propagation was from the initial damage to the entire zone or, for zone fires, to adjacent zones. For floods, the initial (and only) propagation was flooding to the waterline of affected spaces, or flooding as per hatch configurations for fire-main ruptures. Propagation of structural damage was not anticipated because ships are typically very well-built and structural damage does not propagate (see the results of the review of actual damage control incidents in Section 3.2.3) and, if structural damage were to propagate, the project team did not have the knowledge to predict the conditions under which and the ways in which it would propagate.

c. **Secondary propagation.** Under this framework, fires are the only type of damage to have a secondary propagation, and this propagation is from all affected zones to all adjacent zones (up, down, fore, and aft).

Since the results of the SME data collection meeting indicated that any capable damage control system must stop damage prior to its tertiary propagation, damage propagation was not modelled beyond secondary propagation.

The scenarios were recorded in two ways. First, a chart was prepared for each scenario that included the initial conditions (e.g., “Peacetime cruising, Damage Condition Y”), a brief framing story, and a hierarchy showing the initial damage and primary and secondary levels of propagation. Second, the initial damage points and the primary and secondary levels of propagation were illustrated on a diagram of the Halifax class frigate.

2.4.3 SME review

Initial versions of the scenarios were distributed to a Sea Training SME, CPO Gary White. A teleconference was held with CPO Gary White (Sea Training Atlantic Marine Electrical Engineering) on 20 February 2007 where they were reviewed. All comments from this review were integrated into the final version of the scenarios, which are presented in Sections 3.3.4 and 3.3.5.

2.5 TASK INVENTORIES

After the scenarios were complete, the project team developed a task inventory that catalogued the minimum, but sufficient number of task types that are required to cope with each damage scenario. As with much of the work already completed for this project, the tasks in the task inventory were specified in an actor-independent way so they will generalize to the third phase of this project (where specific sets of damage control equipment and their associated crewing levels will be defined) and the eventual simulation that is to be developed as a result of this project. To do this, the project team used the first steps of a Hierarchical Task Analysis (Annett, 2003, 2004), a functional, actor-independent form of task analysis, to develop the task inventories.

Although the project team originally intended to develop two task inventories, one corresponding to each scenario, the degree of overlap between the two inventories was so substantial that they were merged into a single inventory. In the final analysis, there were no tasks that we could rule out for either scenario because, in an actor-independent context, it is impossible to know how far or in what ways the damage would propagate over time. In addition, the project team also hoped to be able explicitly to map each task back to the AH of damage control. While each task was assessed to ensure that it fell within the bounds of the AH, the original proposal to perform this mapping was naïve. Even high-level, actor-independent tasks can be driven by concerns of multiple nodes at multiple levels within an AH, and similarly, can affect multiple nodes at multiple levels within the AH. As it turned out, the process of ensuring that all of the concerns of each task could be accounted for within the existing AH uncovered one issue that had not been considered before.

The results of this analysis are documented in Section 3.4.

2.6 MEASURES OF EFFECTIVENESS AND MEASURE OF PERFORMANCE

2.6.1 Background

A brief search of the literature reveals that there are many different definitions of the terms MOE and MOP. These terms are used widely, and often casually. For this project, however, it is important to make a clear distinction between MOEs and MOPs, because they are subtly but importantly different from one another.

The most precise definition that the project team could find of MOEs was the following:

> Measures of effectiveness: Metrics used to *measure results achieved* in the overall mission and execution of assigned tasks. (Chairman of the Joint Chiefs of Staff, 2003, pp. GL-9, emphasis added)

In a slightly different context, the US Department of Defence's Modelling & Simulation Glossary defines MOPs as follows:

> Measure of Performance. Measure of how the system/individual performs its functions in a given environment (e.g., number of targets detected, reaction time, number of targets nominated, susceptibility of deception, task completion time). It is closely related to inherent parameters (physical and

> structural) but *measures attributes of system behavior*. (United States Department of Defence, 1998, p. 136, emphasis added)

The emphasized words in each definition show the clear distinction between MOEs and MOPs: MOEs *measure results achieved* while MOPs *measure attributes of system behaviour*. For example, in the context of damage control, an MOE might be the amount of fire spread, and the criterion for effectiveness might be that the fire may not spread beyond the zone where it started. An MOP related to this MOE could be the time required to set a boundary around a fire, and the criterion for performance might be that boundaries must be set above in six minutes, and fore and aft in 13 minutes.

This distinction relates back to the theme of actor-independence already introduced in this report. Whereas MOEs should be defined already in early stages of system design, to help set criteria on what the system must be able to achieve, MOPs can only be defined in later stages of design when the specific equipment, actors, and processes put in place to achieve the MOEs are being established. At this stage, MOPs measure items related to the achievement of the MOEs that are specific to the equipment, actors, and processes that have been specified. Still, even when the MOPs have been defined, the MOEs remain to define the *sine qua non* of the system.

Since MOPs cannot be defined until the equipment, actors, and processes required to meet the MOEs have been established, it is currently too early to define MOPs; this must wait until the next phase of the project. At present the three different sets of damage control equipment, actors, and processes have not yet been defined, so this is an appropriate time to define MOEs. As will be seen, the AH of damage control is a useful basis for doing this. (It should be noted, however, that once the equipment, actors, and processes for damage control have been defined that it may become clear that some MOEs would be better considered as MOPs.)

2.6.2 Method

The method followed to establish MOEs was to consider each of the nodes of the AH model of damage control, to determine if there are any quantitative measures for the constraints of each node that can be considered as MOEs. This was done bottom up, beginning at the Physical Function level of the model and proceeding up to the Functional Purpose level. The bottom up strategy was chosen because it was deemed likely that nodes at higher levels of the model might have MOEs that are aggregations of those for nodes at lower levels. In addition, since the task inventory includes many items that can easily be used to define MOEs, items from the task inventory were used as the basis for MOEs as much as was possible.

Specific nodes at the Physical Form level (that is, specific compartments or tanks) were not explicitly considered in this work. It is likely that in an actual design effort, specific instantiations of the MOEs would be put in place for specific compartments (e.g., fires in magazines must be extinguished before munitions in the magazine explode; fires in the Operations Room must be extinguished in less than three minutes, etc.), but it is expected that these compartment-specific MOEs will be tailored versions of more general MOEs corresponding to nodes in higher levels of the AH.

The MOEs that were developed are documented in Section 3.5.

SECTION THREE – RESULTS

3.1 GENERAL

This section presents the four major results for Phase II of this project – a review of damage control scenarios and incidents (Section 3.2), the development of two scenarios of damage control (Section 3.3), the development of task inventories related to each scenario (Section 3.4), and the development of measures of effectiveness and performance (Section 3.5).

3.2 SCENARIO REVIEW

3.2.1 General

This section of the report details the results of the scenario review described in Section 2.3.

3.2.2 Review of damage control training scenarios

As discussed in Section 2.3, the project team reviewed a set of 80 DCTF damage control scenarios, and 16 Sea Training Scenarios. This section describes the results of this review.

3.2.2.1 DCTF scenarios

The DCTF at the CFNES is intended to teach ship's crews the skills and procedures of damage control in a realistic environment. It provides initial and refresher training to all Halifax class frigate crews, as well as team training to crew members assigned to any of the damage control section bases. The heart of the DCTF is a network of typical ship compartments surrounded by a damage control training infrastructure. Each compartment includes special equipment to allow instructors to create and control fires, smoke, and floods. The DCTF allows for the relatively realistic emulations of fires and floods in a safe, controlled, and stable environment. While this has many benefits for training, the experience is still not the same as real battle damage. DCTF trainees can learn to expect the ways in which damage can manifest itself in each compartment, and because damage is controlled by instructors, the experience can feel safe and predictable. To increase the reality and psychological pressure of DCTF training exercises, training is typically based on damage scenarios. These scenarios are each a specific *mise en scène*, and include a framing story to situate trainees, the times at which instructors should initiate the various types of damage the DCTF can emulate, and the ways in which damage can spread if trainees are not properly following the normative procedures. The scenarios also include miscellaneous directions for the instructors, and some include specific instructional aims. The scenarios do not, however, include specific MOEs (as can be found in the Sea Training scenarios; see Section 3.2.2.2, below). It is likely that MOEs are communicated to instructors by some other method.

The typical contents of a DCTF scenario are as follows:

a. **Aim** (optional). Some of the scenarios begin with a brief statement of instructional aims (e.g., "*to re-affirm the abilities of the attack team*").

b. **Scenario**. The main opening feature of all scenarios is a statement of the incident driving the scenario (e.g., "*The threat is Multi. Two attacks, 1 each from both the Port and Stbd. Sides. One missile from each attack. DCTF engages and splashes both. However, fragments from the downed missiles cause's fires / a Firemain break / various equipment failures and casualties throughout the ship. Ship's Helo is air borne.*"). Some scenarios also include details of the ship's damage control state (e.g., "*Peacetime cruising*").

c. **Sequence of events.** The broad story driving the scenario is always followed by a statement of the precise timing of the incidents that make up each scenario. Typically, the timing begins at -6 minutes so that the crew's ability to 'close up' to action stations by a scenario time of 0 minutes can be tested.[3] Damage incidents can arise any time after scenario time -6. These incidents are described with a scenario time, story-based details to explain the damage, specific instructions for DCTF to emulate that damage, and details of the broader impact of the damage and the ways to emulate that (e.g., "*SPLASHED MISSILE IMPACT #2 – PORTSIDE. Causing major fires on the PORTSIDE of Sections 1F and Major flood in section 2E. Fragment damage causes a Firemain BREAK at Frame 42, 1 Deck. Fire Pump # 2 is rendered unavailable and is lost. **NOTE: Isolation of the Firemain break at frame 42, should cause a complete failure of the Firemain aft of frame 40. This will affect any fire attack teams aft. There must be co-ordination between the Engine Rm. Staff, Control Rm. and the Passageway staff.*") The sequence of events also includes the way in which damage will spread if crews are not responding appropriately (e.g., "*T+10: Fire spread to SMI-E and/or 1 Mess if poor response to ships office and with no boundary established fwd of blkd 32.*").

d. **Explanatory notes.** Many scenarios also include a set of explanatory notes that can include additional details on how to emulate the damage (e.g., "*On initiate primary fires start, Low, Door open is Key for High Fire where required.*"), how the training should be monitored (e.g., "*For each fire incident, the standard lead instructor and safety numbers will be employed.*"), any specific procedural benchmarks that must be respected (e.g., "*Fleet standard for boundaries is T+10.*"), and other assorted training directives (e.g., "*Free play will be tolerated. Timings are to be strictly adhered to.*").

e. **Monitoring positions and incident coordinators.** All scenarios also include these sections, which give guidance for how the DCTF staff should be deployed throughout the facility during the scenario.

f. **Additional details**. Scenarios close with an extended discussion of each of the events in the scenario. These discussions include more specific information about the way in which damage should be emulated within a compartment, the correct procedural responses for trainees to demonstrate, the correct fire boundaries to set, and the criteria (if any) for declaring trainees who do not perform the proper

[3] In damage control terms, 'closing up' is the process by which the ship transitions from any state to a state where the various damage control stations are manned and all personnel assigned to damage control are either responding to damage or are able to do so.

damage control responses or precautions as casualties (e.g., "*The Fwd Engine Room is "LOST TO SEA" in the second attack. Any Boundary that is established in the Fwd. ER will be a casualty as a result"* or "*Power isolation to the space must be considered before anyone steps into the water. Make casualty of first person who steps into the water if power is not isolated.*").

g. **Signs.** Finally, some scenarios close with a number of signs printed in large text. These signs (e.g., "*GUN POWER SUPPLY DAMAGED BEYOND REPAIR*") can be printed out and posted around the DCTF to give trainees information about scenario items that cannot be emulated by DCTF equipment.

The structure presented above was used consistently across all of the 80 DCTF scenarios analyzed. In addition to following this structure, there were many scenarios that were exact duplicates of one other. Even for scenarios that have different initiating incidents and timing, they all tended to make use of similar types of damage. This is because the DCTF only has a limited number of compartments, each of which are designed to emulate specific types of damage. For example, many of the scenarios include fires in the mess and galley, floods in the after engine room, and a requirement for a casualty power run from frame 40 to 20.

While DCTF staff are able to use different scenario stories in conjunction with a relatively small number of possible types of damage (when compared with an entire ship) to create challenging training exercises, those scenarios have limited value for the definition of scenarios for this project. In the context of this project, their main value was to help the project team to understand the flavour of a typical damage control scenario. Since DCTF scenarios are so specific to the compartments of the DCTF, the project team did not anticipate to be able to re-use any of the elements of these scenarios. Finally, in its review of these scenarios, the project team did not identify any domain-specific language or terminology that it was not already familiar with.

3.2.2.2 Review of Sea Training scenarios

The two Sea Training organizations of the Canadian Navy, Sea Training Atlantic and Sea Training Pacific, have as their primary function to conduct operational training. As a part of this primary function, they create training materials and evaluate operational capabilities in preparation for employing ships in a variety of tasks. The strength of Sea Training when compared to the DCTF is that they can train using the whole ship; the obvious weakness is that training on the ship can involve only lightly simulated damage. Consequently, the training delivered by Sea Training cannot add the same realism to teaching the skills of damage control as the DCTF, but can be stronger than the DCTF in terms of training in procedures, ship navigation, and crew coordination.

Even though their environments are different, there are many similarities between DCTF and Sea Training scenarios: both include a listing of damage incidents over time, as well as details for how training staff should deploy to support the conduct and evaluation of the scenario. There are two significant differences. First, although Sea Training scenarios may be labelled with an indication of a framing story (e.g., "*Bomb Threat #3 – The Big Boom*"), quite often a framing story is missing. Many scenarios only have functional labels, like "*DC Problem #1*". Second, the scenarios also include specific directions as to how performance should be evaluated. Framing details are not included because Sea Training scenarios are typically used

during ship WUPS, when the ship is already operating within a larger scenario. Sea Training scenarios complement the broader ship scenario and so they do not require framing details of their own.

Sea training scenarios follow a more rigid template than DCTF scenarios. The typical contents of a Sea Training scenario are as follows:

a. **Header – origin, date, ship class and/or name, type of training, and title.** Every scenario includes a standard header to communicate the origin of the scenario (Sea Training Atlantic or Pacific), the date the scenario was run, the class of ship it was designed for, the type of training (e.g., "*WUPS*"), and the title (e.g., the descriptive "*Bomb Threat #3 – The Big Boom*" or the functional "*DC Problem #1*"). These headers are more formal than those for the DCTF scenarios, presumably because Sea Training scenarios and the evaluation become a part of the ship's record.

b. **Scenario.** Just as with DCTF scenarios, the main opening feature of Sea Training scenarios is a statement of the scenario. For Sea Training scenarios, however, the incident is described at the granular level of individual damage points; these points are generally not tied together by a framing story. For example, "*T – Bomb explodes – NBCD filtration #2. Major fires NBDC Filt #2, Switchboard #1, WardRoom. Firemain rupture FS 24. T+10 – Fire AC Plant #2 if no boundary set.*"

c. **Detailed scenario breakdown.** The remaining portions of a Sea Training scenario present the scenario in detail. The main features here are a breakdown of the Sea Training staff assigned to monitor the various ship staff, details of how the damage for the individual damage incidents is to be simulated, and criteria about how simulated damage should spread. These scenarios can also include CSE considerations, such as specifications of the equipment that is lost as a result of damage, and details of the casualties that will be sustained at various points during the scenario.

d. **Scenario critique.** Sea Training scenarios also include a critique of the performance of a ship's crew in addressing the scenario. This critique begins by commenting on the performance of the ship's crew in following the appropriate damage control procedures, with a focus on the performance of the damage discoverer, the attack teams, and the damage boundaries. Each of these parties is given a rating of satisfactory or unsatisfactory, which is then rolled up into a satisfactory / unsatisfactory rating for the overall incident. The evaluation is rounded out with a focus on each of the groups contributing to the damage control effort: Command, Damage Control Headquarters (**HQ1**), Ops, Forward Section Base (**FSB**), Aft Section Base (**ASB**), Section Base 3 (**SB3**), the manning pool, the Emergency Response Team (**ERT**), and Casualty Clearing. The time required for each of these groups to close up is measured, comments are made on their overall performance, and they are given a satisfactory / unsatisfactory rating. The critique closes out with a set of general comments and an overall satisfactory / unsatisfactory rating. Overall, these critiques are a good indication of the most useful MOPs for training damage control.

The structure described above was used in all of the scenarios. Despite the strict format, the Sea Training scenarios exhibited a much greater range of damage locations than the DCTF scenarios, indicative of the fact that the scenario authors had a larger canvas for scenario design available to them (the whole ship).

The value of the Sea Training scenarios in terms of this project is that they help to emphasize the wide range of damage that can happen to a ship. They also help to clarify that in terms of the current Halifax class frigate damage control system, which largely requires manual fire-fighting, there are two ways to add complexity to a scenario – increasing the number of damage incidents and decreasing the amount of resources available for damage control. Additionally, in the context of a manned response, additional complexity can be added if damage is in spaces that are difficult to access, either because the entry is down a ladder (directly into the path of the heat coming from the fire) or because the most efficient advance path has been blocked. Since these scenarios seem to have been designed with the aim of varying levels of complexity, the general form of these scenarios informed the discussions that were conducted with SMEs to establish the two scenarios for this project.

3.2.3 Review of actual naval damage control incidents

While the review of damage control training scenarios helped the project team to understand the ways in which typical damage control scenarios can be constructed, damage control training scenarios only represent the types of damage that SMEs can readily anticipate. While these types of damage control problems do occur while ships are at sea (for instance, one SME told us of a fire he experienced early in his career that started in a trash can containing some oily rags), the complex damage control problems that occur in practice are often much more complex than even the most difficult Sea Training scenarios. To get a broader view of the types of damage possible, five prominent damage control incidents were reviewed to better understand the complexities of real-life damage control work.

3.2.3.1 HMS Nottingham – Major flooding incident

On 7 July 2002, the HMS Nottingham, a UK Type 42 destroyer, ran aground on a submerged, but well-charted rock 200 miles off the coast of Australia. The collision with the rock ripped a 50m long gash in the hull of the ship, from the bow to the bridge, which induced major flooding in five separate compartments (including the large Forward Engine Room), nearly causing the ship to sink. Damage control efforts were able to save the ship, but not without help from external agencies. Once the crew of the ship had the flooding under control, members of the New Zealand navy came aboard to continue the effort. In the end, the ship was saved only because the crew performed a major shoring effort to reinforce the bow and plug some of the hull breaches. Even with this effort, the ship could not be sailed back to the UK on its own, but was instead sea-lifted on a semi-submersible heavy-lift ship.

Figure 3-1. The damaged HMS Nottingham being sea-lifted back to the UK.

The project team was not able to find a great deal of detail on this incident in the public domain. Nonetheless, the details that are available demonstrate some important characteristics of a major flood-related damage control incident. First, it is very difficult to sink a modern warship. The Nottingham had a large gash along one third of its length, and yet survived. Second, for a flood to be a major damage control incident on its own, it has to be very large. Third, flooding incidents have long time constants. Fires can spread quickly and so introduce a great deal of time pressure into an incident, but flooding generally spreads much more slowly. When a damage control organization is confronted with floods and fires, floods can typically be ignored until the fires have been contained.

Sources: Wikipedia.org (http://en.wikipedia.org/wiki/HMS_Nottingham_%28D91%29); PSi Daily Shipping News for 14 July 2002 (http://www.ibiblio.org/maritime/Scheepvaartnieuws/Pdf/scheepvaartnieuws/2002/juli/013-15-07-2002.PDF). Sources were last accessed on 28 February 2007.

3.2.3.2 USS Cole

On 12 October 2000, while refuelling in Yemen, the USS Cole was hit by a large explosive device brought alongside the ship on a small boat. The resulting explosion blasted a 35-foot diameter hole in the side of the ship, killed 17 sailors and injured 39 others, and caused major flooding in the ship's engineering spaces and major fires in the ship's galley. Although few details can be found on the damage control effort, the damage on the Cole seems to have been difficult to contain. Casualty clearing confused the initial response to the fires induced by the explosion, and due to the size of the hole in the ship, flooding was a major long-term concern. The attack occurred at midday, and damage is reported to have been under control by

evening. Just as with the HMS Nottingham, the USS Cole was crippled and had to be sea-lifted home on a heavy-lift ship.

Figure 3-2. A close-up of the damage inflicted on the USS Cole. For scale purposes, note the size of the sailors in the foreground.

Again, the project team was not able to find many details on the damage control response to the damage inflicted on the USS Cole. The details that are available, however, demonstrate especially that casualties can add significant confusion to a damage control effort. In addition, in instances where casualty clearing is required, the casualties can also imply resource shortages that will affect a ship's ability to combat damage quickly. Even though the US Navy has surely learned many important damage control lessons from the USS Cole, this incident again demonstrates that modern warcraft are very resilient to damage – even a 35 ft diameter hole was not able to sink the USS Cole.

Sources: Wikipedia.org (http://en.wikipedia.org/wiki/USS_Cole_bombing); Surface Warfare Magazine (http://www.dcfp.navy.mil/mc/museum/COLE/Cole1.htm); NavSource Online (http://www.navsource.org/archives/05/01067.htm); DoD USS Cole Commission Report (http://www.defenselink.mil/pubs/cole20010109.html). Sources were last accessed on 28 February 2007.

3.2.3.3 USS Princeton

On 18 February 1991, the USS Princeton was operating in a known mine-field in the Persian Gulf when it struck a large acoustic mine. The initial explosion lifted the fantail of the ship nearly out of the water, and the subsequent shock waves (worsened by the sympathetic detonation of another mine 300 yards away) heaved the ship with horizontal and vertical deflections of four to six feet on a cycle of six to seven seconds. Although the mine did not blast a hole in the hull, the structural damage from the shock waves was severe: forty feet from the stern, 8 inch by 10 inch I-beams snapped; the fantail was nearly severed from the ship; a six-inch crack opened on the ship's superstructure, and more than ten percent of the superstructure was separated from the deck; there was also major hull buckling over the length of the ship; and finally, there were many instances of flooding through various fractures, burst welds, and split seals. At the time of the explosion, the Princeton was also turning hard to starboard. The blast jammed the port rudder in its position, so the ship could not be steered. In terms of the AH presented in the first phase of this project, the three main functional purposes of the ship were severely compromised:

a. **Stability.** It is estimated that 80% of the ship's structural integrity had been compromised, and 90 minutes after the incident, the ship's captain was still trying to figure out if the ship was going to sink.

b. **Manoeuvrability.** The ship was in the middle of hostile waters, but was not able steer. Due to the structural damage it had sustained, the vibrations from running the gas turbines could have sunk the ship.

c. **Mission effectiveness.** The ship's weapons systems were incapacitated, and basic defences were not restored for 105 minutes.

Remarkably, even though most of the crew were hurled off of their feet by the force of the blast, no crewmembers were killed in this incident and only three were injured.

Figure 3-3. One of the cracks in the USS Princeton's hull as a result of the mine it hit.

The case of the USS Princeton demonstrates that the constraints in the ship's work domain are very important considerations in a damage control incident. Published reports show the captain actively considering how close the ship was to sinking, how much structural integrity remained in the hull, how to get moving as quickly as possible, and how to restore the ship's ability to fight. It also demonstrates that a ship can have a very major damage event without experiencing a single fire. Finally, it again demonstrates that there are some types of damage for which the best damage control system is a well designed and strong ship. Even with the best flood control techniques, the USS Princeton would not have survived if it did not have such a strong hull and good ship design.

Sources: Wikipedia.org (http://en.wikipedia.org/wiki/USS_Princeton_%28CG-59%29); Surface Warfare Magazine, May/June 1999 (http://www.navsea.navy.mil/swmagazine/summarytmp.aspx?iContentID=84&iDataPrimeID=1849); Princeton's Mine Encounter (http://www.warships1.com/US/BB61stats/index-BB2-pst17.htm). Sources were last accessed on 28 February 2007.

3.2.3.4 USS Samuel B. Roberts

On 14 April 1988, the USS Samuel B. Roberts was operating in the Persian Gulf during the Iran-Iraq war, when it hit a mine. The force of the blast of this mine on the USS Samuel B. Roberts was just as impressive as was the force of the blast on the USS Princeton, and just as devastating: the hull sustained a 15-foot diameter breach, the bow numbers of the ship went almost completely under water, and the ship was essentially cut in two across its mid-section, leaving the main deck as the essential structural component holding the front and back of the ship together. The Samuel B. Roberts also experienced significant fires as a result of the blast, with initial blast fires reaching higher than the mast of the ship, and flames coming out of the intake louvers to a height of 100 to 150 feet. The ship was at action stations when it hit the

mine, and it only sustained ten injuries as a result. Additionally, all of the combat systems survived the explosion, and were available after only 15 minutes of downtime when the ship's power was restored.

The flooding problems on the ship were immediately obvious. The captain brought as many pumps as possible on-line, and was educting over 5000 gallons of water per minute, but found that the ship was still sinking at a rate of one foot every fifteen minutes. The flooding was such a problem that at one point it was possible to put your hands in the water from a kneeling position at the stern of the ship. The fires were also a significant problem, and fighting them was adding to the flooding problem. These fires were fuelled by up to three feet of fuel resting on top of the water in the flooded engine room, so they had enough fuel to burn for a long time. Eventually, the commander decided to stop fighting the fires, and to concentrate fully on solving the flooding problem; it is likely that this is the decision that saved the ship. The ship also carried 400% of its allowance of Aqueous Film Forming Foam (**AFFF**), and used three-quarters of that to finally put out the fires.

The case of the Samuel B. Roberts adds to the other incidents already presented because it shows how damage control efforts – specifically flood control and fire fighting – can be defeated by one another. In such a situation where a ship could be lost, difficult decisions need to be made that few would want to trust to automated systems.

Sources: Wikipedia.org (http://en.wikipedia.org/wiki/USS_Samuel_B._Roberts_%28FFG-58%29); Surface Warfare Magazine, May/June 1999 (http://www.navsea.navy.mil/swmagazine/summarytmp.aspx?iContentID=84&iDataPrimeID=1849); Surface Warfare Magazine, March/April 1990 (http://www.dcfp.navy.mil/mc/museum/ROBERTS/Roberts1.htm). Sources were last accessed on 28 February 2007.

3.2.3.5 USS Stark

On 17 May 1987, the USS Stark was on routine patrol in the Persian Gulf during peacetime operations when it was hit without warning by two Exocet missiles from an Iraqi F-1 Mirage fighter. The first missile entered the ship and did not detonate, but disintegrated, causing major damage. The second missile entered at almost the same point as the first and exploded. The impact from the two missiles and the explosion of the second caused severe structural damage, compromised the ship's watertight integrity, and severed a fire-main. The combination of the explosion from the second missile and the unused propellant from both missiles caused an intense fire that quickly engulfed the berths where it hit. 37 crew members were killed, many in the berths, and 21 were injured.

In addition to the damage to the ship's structure and the fires, all of the ship's communications were lost, and crewmembers had to communicate with other ships using radios from aircrew survival vests. The significant number of casualties meant that there was a tremendous shortage of resources to use to combat the damage, and there was plenty of damage to combat. Fires were raging where the missiles hit, and the ship was taking on a significant amount of water (both from hull breaches and from the severed fire-main) so that it eventually listed to an angle of 16 degrees. The crew fought the damage long and hard, but because their

numbers were depleted, were quickly exhausted. The damage was not contained until assistance was received from the USS Waddell and Conyngham.

Figure 3-4. The USS Stark, severely listing to port as a result of flooding.

Figure 3-5. External view of the damage caused to the USS Stark by two Iraqi Exocet missiles.

The incident on the USS Stark demonstrates the challenge that can be posed when major damage is sustained along with major casualties. Although the crew of the Stark was able to perform the initial response to its damage, the long-term solution was to bring in resources from another ship to finish the job. In addition, this scenario demonstrates the complexity involved in missile damage. Missiles pose a triple-threat to ships: their initial impact can breach a ship's hull; the explosion from a warhead can cause severe structural damage and fires; and finally, the unused propellant from a missile can cause extremely hot fires that are difficult to put out, and that spread quickly.

Sources: Wikipedia.org (http://en.wikipedia.org/wiki/Uss_stark); NAVSEA DC Museum (http://www.dcfp.navy.mil/mc/museum/STARK/Stark3.htm). Sources were last accessed on 28 February 2007.

3.2.3.6 Discussion

Overall, these real-life damage control incidents show the extreme difficulty posed by a major damage control incident. In each of the incidents reviewed, the survivability of the ship was a major concern, and all ships could have been lost had different decisions been made. It is

also important to note that even though there are similarities across these five incidents, there are also perverse differences that would have been difficult to anticipate. The size of the hull breach on the HMS Nottingham was of a scale that would be difficult to predict; at the time of the USS Cole incident, the idea of a marine-borne suicide bomb was novel; the USS Princeton suffered from not one, but two mine blasts; the damage inflicted on the USS Samuel B. Roberts resulted in a complex interaction between the two different damage control responses; and finally, the USS Stark suffered from intense fires and difficult stability problems. Given these complexities and the very real risk that in each case the ship would have been lost, these incidents define the extreme end of the scale of damage control complexity.

These incidents also provide a commentary on the challenges faced by advanced automation in the face of complex damage control incidents. Each of the incidents discussed involved novel approaches to damage control tailored to the individual circumstances at hand; just as it would be difficult to predict the particular circumstances encountered in the design of an automated solution, it would also be difficult to design automated solutions to address much of the damage.

Finally, these incidents emphasize that converting the constraint-based representation of the work domain in the AH model into a display for shipboard damage control could have helped crews to manage some of the complex interactions at play in these scenarios. For example, if ships had an accurate way to gather information about the constraints of the Stability functional purpose, it could be clear when efforts to fight fires were also sinking the ship.

3.2.4 Review of DC-ARM Scenarios

Researchers in the DC-ARM project created peacetime and wartime scenarios for testing the advanced automation for damage control they developed. Two different types of scenarios were developed to test the advanced automation from two perspectives – the peacetime scenarios were designed to investigate the effects of the advanced automation on the situation awareness of the Damage Control Officer, and the wartime scenarios were designed to investigate the capability of the automation to contain damage to what is called the Primary Damage Area, or the area initially affected by the damage incident. Both types of scenarios are *mises en scène*.

These two types of scenarios are described below.

3.2.4.1 Peacetime Scenarios

The peacetime scenarios seem to have been designed to include incidents that might confuse the DC-ARM early-warning fire detection system. For example, the incidents included trash can fires, smouldering electric cables, and smouldering bedding as incidents that the automation should classify as fires, and toasting Pop-Tarts, diesel engine exhaust, and welding as incidents the automation should not classify as fires. These scenarios were designed to be conducted in situations similar to Peacetime Cruising under Damage Control Condition ‘Y’ on the Halifax class frigate.

3.2.4.2 Wartime Scenarios

The wartime scenarios were designed to simulate the effects of being hit by a medium anti-ship missile, and involved assumptions about the bulkheads that would be ruptured, the fires

and floods that would be caused, and the number of casualties that would occur. The types of damage that are specified are quite specific to characteristics of the ex-USS Shadwell as a damage simulator (for example, the use of a large heptane spray fire combined with a wood crib fire in the Communications Centre / Crew Living Space). These scenarios were designed to be conducted in conditions similar to Action Stations under Damage Condition 'Z' on the Halifax class frigate.

3.2.4.3 Discussion

Especially the peacetime DC-ARM scenarios are relevant from the point of view of testing automation, as they deal specifically with the potential for false positive or false negative alarms, and concerns related to inappropriate trust in automation (Section 1.3.4.4). Depending on the types of sensors chosen during Phase III of this project, it may be useful to test the robustness of human-machine system in the face of such nuisance incidents. The wartime scenarios also involve the interesting automation challenge that actual operational priorities need be considered instead of just saving the ship.

3.3 SCENARIO DEVELOPMENT

3.3.1 Overview

This section presents the medium- and high-complexity scenarios that were developed.

3.3.2 Complexity definition

To develop medium and high complexity damage scenarios, it was important to first define 'complexity' with respect to a damage scenario. In other words, what is the baseline level of complexity for a medium complexity damage scenario, and what is the difference between a medium-complexity scenario and a high-complexity scenario? When damage control SMEs were consulted for their views on these topics, their opinion was that complexity is best measured by the amount of damage control work induced by the scenario, that a medium complexity scenario should be challenging but routine, and that a high complexity scenario should be difficult, and close to the limit of what a crew should be expected to cope with. Since this definition of complexity and the interpretations of medium and high complexity resounded well with the SMEs being consulted, they were used as the basis for the initial development of the damage scenarios.

While these ideas were useful for brainstorming about scenarios with damage control SMEs, as the scenarios were refined, so too these ideas needed refinement. Especially this initial definition of complexity had a significant problem in the context of this project: it is a process definition (that is, it is about *how* things get done) and as such, it defines complexity in an actor-dependent way. While the scenarios that were generated may be complex given the current configuration of the Halifax class frigate, if the same process definition of complexity were applied to those scenarios in the context of a different damage control system and crewing level in the Halifax class frigate, it is possible that the scenarios would not be at all complex, or that they would be prohibitively complex. To continue with the strong actor-independent flavour of this research, it was important to replace this process-oriented definition of complexity with a

product definition, that is, a definition either about what is damaged or about what actor-independent processes need to be invoked to control the damage.

The project team was able to identify two different candidate measures of complexity:

a. **Scales of incident.** Brooks and Baller (2006) have proposed a measure of incident criticality for scenario development called 'Scales of incident' that is actor independent. It is based on the type of event, the time required to contain the damage, the effect on ship systems, and the expected type of resolution. While the precise details of this measure cannot be included in this report (the original report was provided to the project team under restrictions), it is still possible to evaluate the proposed scenarios against this measure and report the degree to which this measure indicates that the scenarios differ in their complexity.

b. **AH coverage.** The AH produced in the first phase of this project is also a useful tool for assessing the complexity of the scenarios. Under the assumption that a scenario that involves a large number of the constraints in the AH is more complex than one that involves only a small number of constraints, a method was developed for assessing AH coverage. This method involves assessing the scenario against each level of the AH, as follows:

   - **Physical Form, Physical Function and Generalized Function levels.** For these levels, for each AH node, the number of sections or tanks of the ship in which the constraints of the AH node are broken or threatened are counted (where a section is any space on any deck bounded fore and aft by a watertight bulkhead[4]).

   - **Abstract Function and Functional Purpose levels.** For these levels, the number of AH nodes whose constraints are threatened or broken by the damage are counted. In addition, if a constraint is threatened, the severity of the threat to or breakage of the constraint is classified as high or low. [5]

   Comparing these counts at each level across scenarios should at least corroborate the results of the scales of incident measure (above).

[4] The AH Physical Form level treated the ship from the point of view of compartments, but for the purposes of this measure of complexity, a count of individual compartments is not diagnostic of the extent of damage present. While sections themselves vary in size, the number of compartments within a section varies much more. If individual compartments were counted, damage that occurred in a section of the ship with many compartments would appear more severe than damage that appeared in another section of the ship with fewer compartments. Of course, even counting sections is not a fully valid measure of complexity, but it should be adequate for the purposes of this project.

[5] An alternate approach could have been to base the differences in counting technique on the levels of decomposition, and so counting items at the system and subsystem levels of decomposition (the Functional Purpose, Abstract Function, and Generalized Function levels of abstraction) using the method described above for the abstract function and functional purpose levels, and items at the component level of decomposition (the Physical Function and Physical Form levels of abstraction) using the method described above for the Physical Form, Physical Function, and Generalized Function levels of abstraction. While there is merit in this approach, the only method the project team found for evaluating severity at that Generalized Function level was by counting and comparing the number of sections affected, the approach that was finally followed.

The results of applying these measures to the medium and high complexity scenarios are presented in Section 3.3.6, below.

3.3.3 Stopping rules

In addition to characterizing scenario complexity, it was also necessary to determine the scenario stopping rules, the criteria that must be met for the damage incurred by a scenario to be considered resolved or out of control. These criteria are as follows:

a. **Resolved damage.** The criteria for damage resolution differ for the three main types of damage. Fire damage is considered to be resolved when all fires have been extinguished *and* the risk of re-ignition has been eliminated.[6] Flood damage is considered to be resolved when either the ship is not taking on any additional water or when the net amount of inflow to the ship is equal to or less than the net amount of outflow. Structural damage is considered to be resolved once any shoring required to prevent the spread of the structural damage has been put into place. Note that these resolution criteria were determined based on the traditional responsibilities of a ship's damage control organization, and are all met prior to any repair that might be performed by CSEs or at a dockyard.

b. Out-of-control damage. The criteria to determine if damage is out-of-control also differ for the three main types of damage. Fires are considered to be out-of-control if they propagate past the secondary propagation zones; floods are considered to be out of control if the ship is sunk; and structural damage is considered to be out of control if the ship no longer has structural integrity (i.e., it breaks into two or more pieces). No damage control system can be considered capable if it allows any of these criteria to be met.[7]

These stopping rules helped to determine the extent to which the damage control scenarios were expanded, and also were the basis for some of the MOEs presented in Section 3.5.

3.3.4 Medium complexity damage scenario

3.3.4.1 Overview

The medium complexity damage scenario that was developed is presented in Figure 3-6. This scenario is based on the typical damage problems that crews would face midway through ship WUPS, and involves non-critical flooding in a number of tanks and the Command and Control Equipment Room #4 (**CCER 4**), a potentially large fire in the Galley, and a secondary fire in the Refrigeration Machinery Space (**RMS**).

[6] On the Halifax class frigate, reducing the risk of re-ignition is done by a process called 'overhauling'. For class A fires this involves searching every compartment affected by fire to verify that no smouldering materials remain; for class B fires it involves spraying a layer of AFFF in compartment affected by fire; and for class C fires it involves isolating the power supply to the equipment on fire. Currently this is a conservative procedure (e.g., for class A fires *every* locker and drawer is emptied and wet down).

[7] The criteria for determining if flooding and structural integrity problems are out of control may be weak. The work-domain constraints related to these criteria were not taxed in either of the scenarios that were developed and so these criteria were not analyzed as rigorously as the criterion for fire.

3.3.4.2 Initial conditions

The initial conditions for this scenario are a ship involved in peacetime cruising, in Damage condition 'Y'. The condition of peacetime cruising means that crew would not be at actions stations, but rather would be serving their regular watches. Damage condition 'Y' means that all doors and hatches below the waterline separating watertight compartments from one another (called 'Y' openings) would be closed.

An unfortunate implication of this choice is that peacetime cruising implies that ships have a 'safe-at-sea' priority. This means that in the event of damage, the damage control priority is not to maintain some mission capability, but rather to keep the ship and her crew as safe as possible. As a result, there will be much less difficulty in managing the damage control response because one set of constraints (those of the Functional Purpose of Mission Effectiveness) are out of play. If possible, it would be beneficial to design the simulator to be developed after Phase III of this project to be able to run scenarios under different initial conditions so that both peacetime and wartime contexts could be tested.

It should also be noted that not having the crew at action stations biases these scenarios in favour of automated damage control systems. Automated systems do not suffer from fatigue in the same way as humans, and so can always be at an enhanced level of readiness to combat damage. Fortunately, even though this bias exists, it is realistic. Ships do not typically keep their crew at action stations because it cannot be sustained for long periods of time, and is typically unnecessary.

3.3.4.3 Framing story

The framing story for the medium complexity damage scenario is as follows: while sailing on a foggy day, the ship hits an ISO container[8] that has fallen from a container ship and is floating free in the ocean. The impact causes a gash across a number of the ship's tanks and a puncture in the hull at the CCER 4. The shock from the impact induces fires in both the Galley and the RMS.

This framing story for this scenario will likely resonate with naval SMEs. There are many floating hazards in the ocean, and hitting a large one could cause significant damage.

3.3.4.4 Notable features

Under the current Halifax class frigate damage control system, this is a relatively straightforward damage scenario. It poses two interesting challenges that will be useful test-cases for more modern damage control systems:

a. **Two fires in close proximity to one another.** The fires in the Galley and the RMS are in close proximity to one another. Since there are typically personnel in the Galley, the alarms indicating a fire in the Galley would quickly be corroborated by an eyewitness account. The RMS, on the other hand, is not a manned space. Since it is so close to the galley, it is possible that any smoke alarms from that space would be considered as a secondary indication of the

[8] Readers unfamiliar with ISO containers can refer to the Wikipedia article on container shipping (http://en.wikipedia.org/wiki/Containerization).

galley fire (due to smoke spread) and not a primary indicator of a different fire in this space. It is expected that advanced automation will ensure that the presence of two separate fires will be diagnosed more quickly than with the current system.

b. **Toxic fumes.** Toxic fumes may be released as a result of the fire in the RMS. This would be a consideration in providing any manned response to the fire in this space.

c. **Access and planning.** Since it is likely that with the current Halifax class frigate damage control system the initial diagnosis of the damage situation would be a single fire in the Galley, this fire would likely be assigned to the FSB. On attacking the Galley fire, the FSB team would feel that the floor under their feet was heating up, and a communication loop would have to be engaged to re-plan the fire boundaries and to allow the FSB to attack the fire in the RMS. While the FSB is attacking the fire in the RMS, HQ1 would have to task another attack team to attack the galley fire (this team could come from the FSB, ASB, or the manning pool). Again, it is likely that the effects of this complication would be mitigated by advanced automation.

The flooding concerns involved in this scenario are not significant, and the flooding here is more of a nuisance than a threat. However, with different initial conditions (e.g., wartime) the effect of this flooding could be quite significant, as the Command and Control Equipment Room includes much of the primary command and control data processing equipment.

Medium Complexity Damage Scenario

Initial Ship Condition: Peacetime Cruising - Damage Control Condition Y

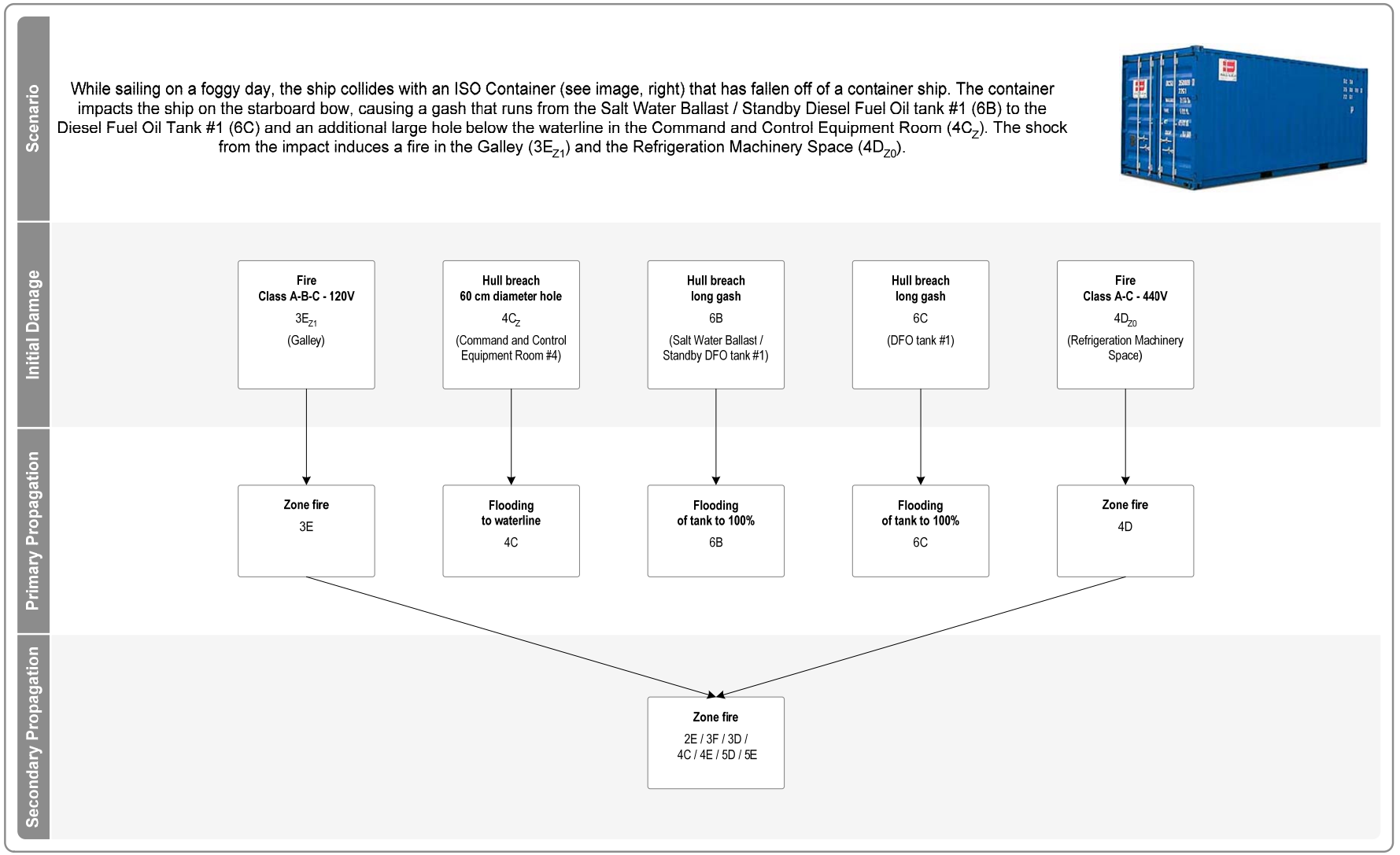

Figure 3-6. Medium complexity damage scenario showing initial conditions, framing story, and damage propagation

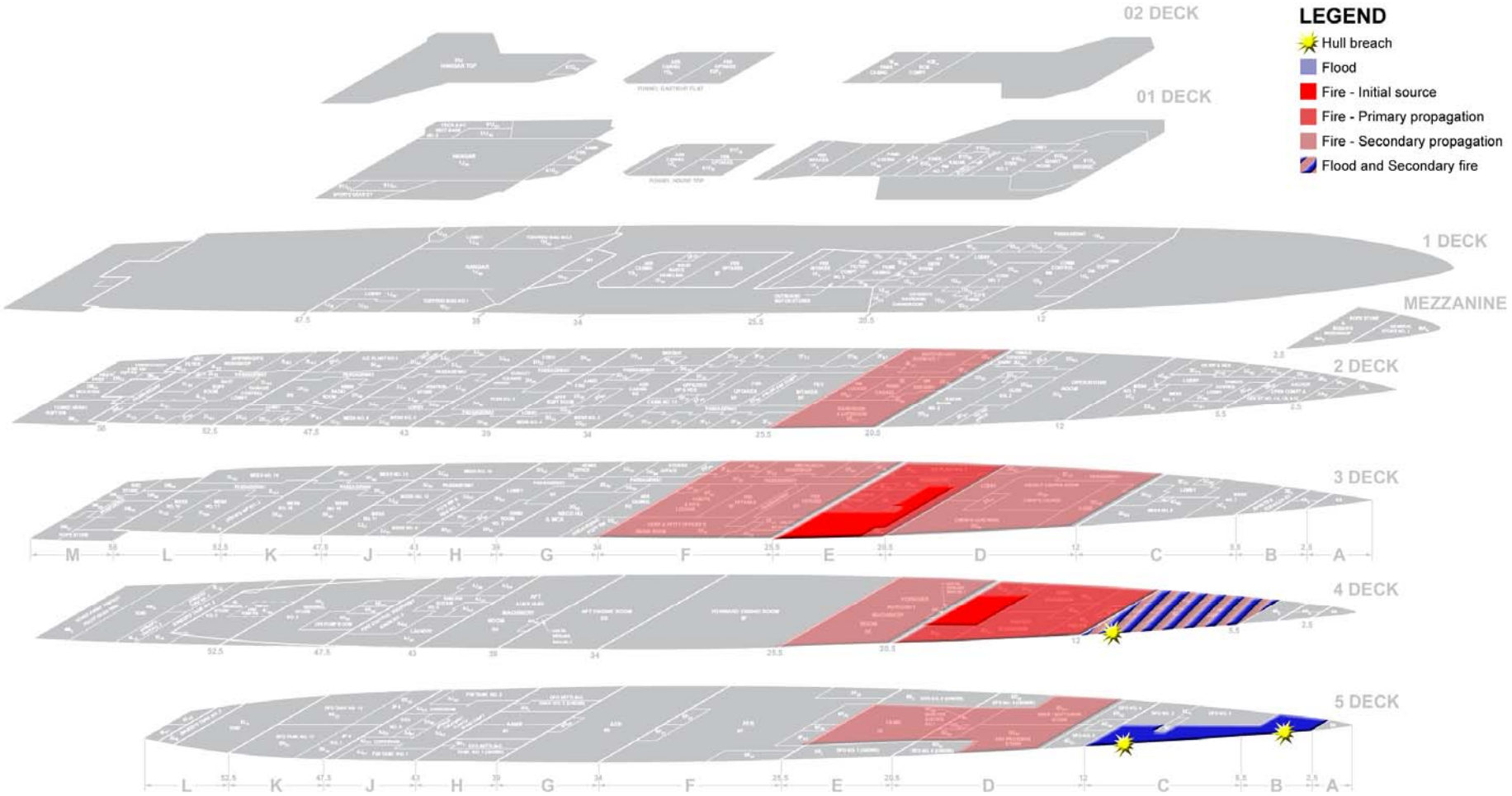

Figure 3-7. An exploded view of the Halifax class frigate showing the initial damage and primary and secondary propagations for the medium complexity damage scenario

3.3.5 High complexity damage scenario

3.3.5.1 Overview

The high complexity damage scenario that was developed is presented in Figure 3-8. This scenario is reminiscent of the most difficult damage scenarios that Sea Training presents to crews close to the end of ship WUPS. It involves a large explosion in the aft of the ship that inflicts heavy casualties in nearby messes (about 30 junior engineering staff) and induces a large multi-zone fire. A few minutes later, this initial damage is added to by a collision with a fishing boat that causes moderate flooding and two additional fires amidships. The casualties inflicted by the initial explosion induce a severe manning shortage for damage control, because the messes affected by the explosion house many of the ranks that normally make up the damage control attack teams. Further, the explosion also incapacitates the ASB; even if the ASB would be able to relocate, it would be without its fire-fighting gear.

3.3.5.2 Initial conditions

The initial conditions for the high complexity scenario are the same as those for the medium complexity scenario, and involve the same benefits and drawbacks. The reader is referred to Section 3.3.4.2 for more details.

3.3.5.3 Framing story

The framing story for the high complexity damage scenario is as follows: While on a fisheries patrol, the oxygen and acetylene tanks in the Shipwright's Workshop explode, causing devastating damage in sections 2L and 3L, a great deal of damage in the surrounding sections, and heavy casualties (about 30 junior engineering staff) in the messes in section 3L. The explosion also severs the ship's steering cables, causing a loss of ship's steering, and severs a fire-main, causing flooding until the break can be addressed.

With the ship's steering disabled, four minutes later it is unable to avoid a collision with a steel-hulled fishing boat. This collision occurs amidships, in the area of the Forward Auxiliary Machinery Room (**FAMR**), and causes flooding in FAMR and fires in the Forward Switchboard and the Forward A/C Plant.

While the framing story for this scenario is somewhat contrived, the types of damage incurred are representative of some of the actual damage control incidents reviewed in Section 3.2.3. The USS Stark sustained damage in the area of its crew messes, and 37 crewmembers were lost, and the USS Cole sustained damage in the area of its engineering spaces (similar to the FAMR) which caused major flooding of the same. While the combination of these two types of damage may be unlikely, difficult damage control cases are often difficult precisely because they are unexpected.

3.3.5.4 Notable features

Under the current Halifax class frigate damage control system, this is a very complex damage scenario. There are many challenges and features of this scenario that would be useful test-cases for more modern damage control systems:

a. **Stress and uncertainty.** The initial explosion would likely cause a great deal of stress for those responsible for coordinating the damage control effort, and the extent of the damage (and the casualties) would likely be difficult to ascertain quickly with current systems. This would make planning difficult, and increases the likelihood that crews will fixate on certain courses of action too early. This feature represents an opportunity for advanced automation, but in combination with (c), below, also represents a challenge. Poorly designed automation, especially clumsy automation, could exacerbate this situation.

b. **Resource shortages and decision making.** Since the explosion at the beginning of the scenario inflicts casualties on so many of the crew, and since these crew (junior engineering staff) are typically relied upon for the manned part of a damage control response, even with reliable information about the extent of the casualties, it will be a challenge to deploy personnel effectively to control the damage in the most efficient way. Since great flexibility and intuitive decision making (Klein, 1998) are likely to be great assets in confronting these resource shortages – especially in the context of incomplete or uncertain information – this feature will likely be better handled by manned rather than automated solutions to damage control.

c. **System failures.** It is likely that a large explosion would cause any elements of a damage control system that were distributed across a ship (e.g., sensors and actuators) to fail. Recommendations from an automated system could be based on incomplete information, and operators may be prone to trust these recommendations inappropriately. In addition, any fitted fire systems would likely be compromised. Again, this feature favours a manned solution to damage control.

d. **Potential for fire spread.** Resource shortages will increase the amount of time required to muster a manned response to any of the damage, and so the likelihood that the damage will spread increases. This feature favours an automated system that could quickly address the fires resulting from the collision with the fishing boat, so that resources could be freed to deal with the larger fires to the aft of the ship before they spread.

Under a set of initial conditions that would place the ship in a conflict, features (a) and (b) would be exacerbated as the task of damage control coordination would also involve managing the ship's current priorities to keep all critical ship systems up and running. This is an especially important consideration with the fire in the Forward Switchboard. Under peacetime operations, shutting down this switchboard to allow for fire-fighting would be a quick and easy decision, but during a conflict, this switchboard would likely not be shut down as easily.

High Complexity Damage Scenario

Initial Ship Condition: Peacetime Cruising - Damage Control Condition Y

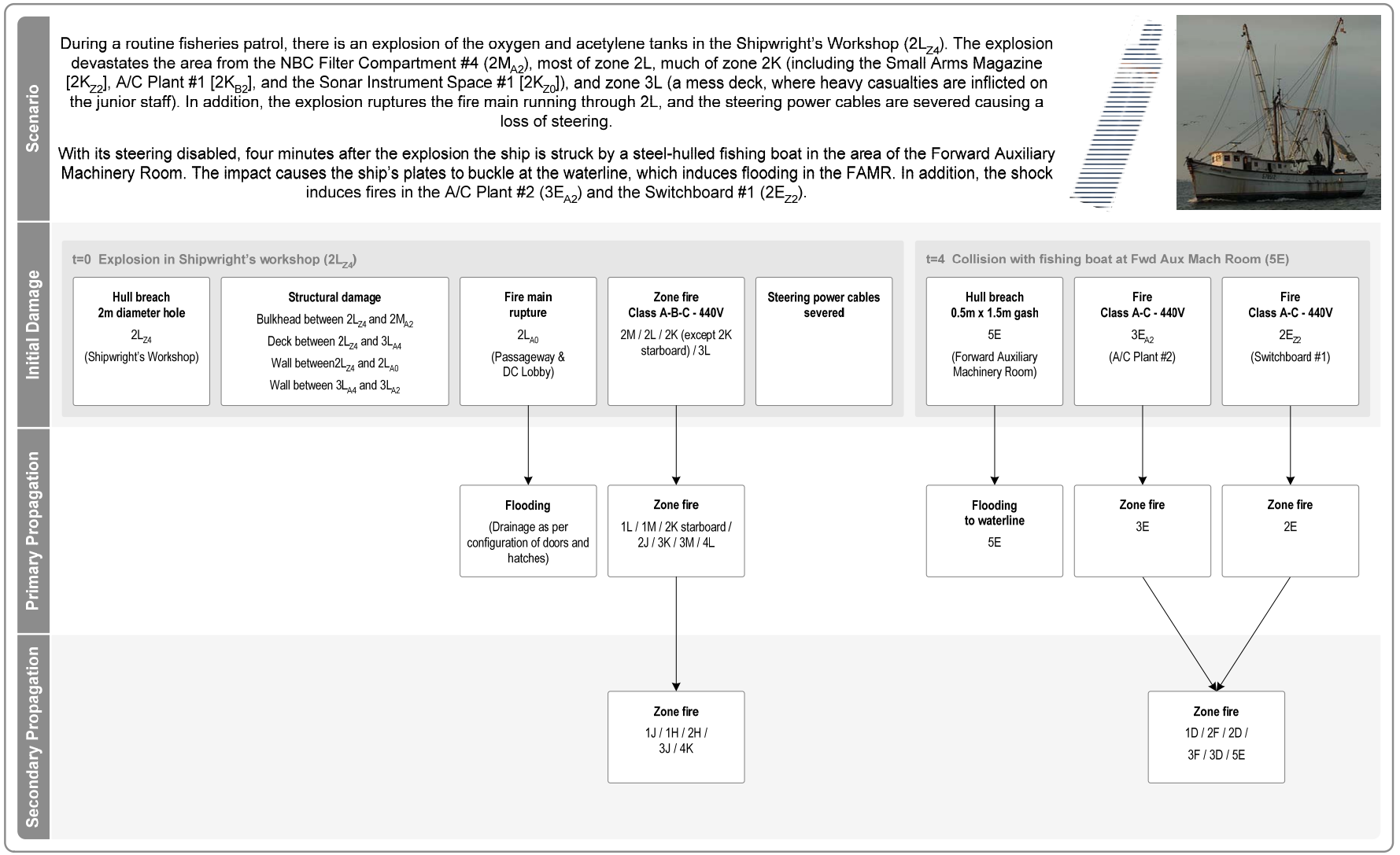

Figure 3-8. High complexity damage scenario showing initial conditions, framing story, and damage propagation

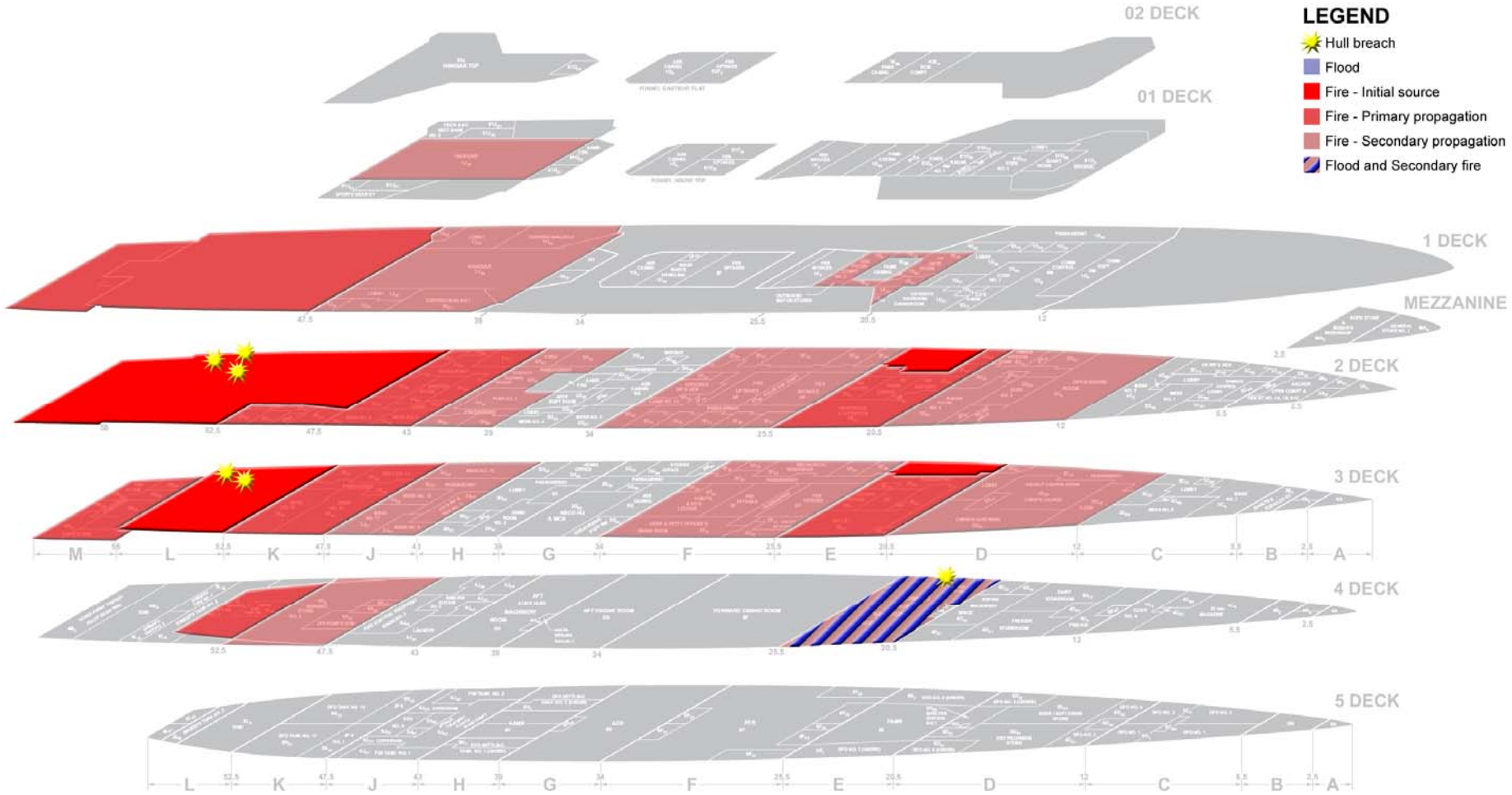

Figure 3-9. An exploded view of the Halifax class frigate showing the initial damage and primary and secondary propagations for the high complexity damage scenario

3.3.6 Analysis of scenario complexity

The complexity of the medium and high complexity scenarios was analysed based on the measures of complexity presented in Section 3.3.2. The results of this analysis are presented below.

3.3.6.1 Scales of incident

Using the scales of incident measure (Brooks & Baller, 2006), the medium complexity can be characterized as a single *significant incident* from which a frigate should be able to easily recover. The high complexity incident involves one *critical incident* coupled with a *significant incident*. In terms of ship recoverability, the results of this measure indicate that a frigate the size of the Halifax class frigate should easily be able to recover from the medium-complexity scenario, and that the high complexity scenario is within, but at the edge of, the boundary of the damage the Halifax class frigate should be able to recover from. This result is a clear indication that there is an important difference in the complexity of the two scenarios, with the high complexity scenario being more complex. In addition, the basic level of complexity of both scenarios is reasonable and useful for further phases of this project.

3.3.6.2 AH coverage

The result of applying the AH coverage measure of complexity to the scenarios is shown in Table 3-1, below.

Table 3-1. Results of applying the AH coverage measure of complexity to the medium and high complexity damage scenarios

	AH Coverage	
Level of Abstraction	**Medium Complexity**	**High Complexity**
Functional Purpose	**High severity – 0**	**High severity – 3:** ▪ Manoeuvrability ▪ Mission effectiveness ▪ Personnel safety ▪
	Low severity - 6: ▪ Stability ▪ Manoeuvrability ▪ Mission effectiveness ▪ Personnel safety ▪ Economic stewardship ▪ Environmental protection	**Low severity – 3:** ▪ Stability ▪ Economic stewardship ▪ Environmental protection
Abstract Function	**High severity – 0**	**High severity – 4:** ▪ Reserve buoyancy ▪ Structural integrity ▪ Ability to maintain desired course ▪ Minimize casualties
	Low severity – 11:	**Low severity – 8:**

	▪ Reserve buoyancy ▪ Structural integrity ▪ Positive righting arm ▪ List and trim ▪ Ability to maintain operational speed ▪ Ability to navigate ▪ Ability to sense environment ▪ Ability to affect environment ▪ Minimize casualties ▪ Minimize resource damages ▪ Minimize environmental impact	▪ Positive righting arm ▪ List and trim ▪ Ability to communicate ▪ Ability to navigate ▪ Ability to sense environment ▪ Minimize resource damages ▪ Minimize environmental impact
Generalized Function	**AH nodes x sections affected – 18:** ▪ Freeboard – 1 ▪ Watertight integrity – 3 ▪ Load and balance – 3 ▪ External communications – 3 ▪ Power generation & distribution – 1 ▪ Targeting sensors – 1 ▪ Effectors – 1 ▪ Protective measures – 2 ▪ Prompt response – 2 ▪ Spill prevention / containment - 1	**AH nodes x sections affected – 24:** ▪ Freeboard – 1 ▪ Watertight integrity – 1 ▪ Structural strength – 2 ▪ Load and balance – 2 ▪ Propulsion – 1 ▪ Power generation & distribution – 1 ▪ Helicopter support – 1 ▪ Protective measures – 6 ▪ Prompt response – 6 ▪ Prevention measures – 1 ▪ Spill prevention / containment – 1 ▪ Responsible resource allocation - 1
Physical Function	**AH nodes x sections affected – 10:** ▪ Flood control – 3 ▪ Fire suppression – 2 ▪ Fire containment – 2 ▪ Ventilation – 2 ▪ Power isolation – 1	**AH nodes x sections affected – 23:** ▪ Flood control – 2 ▪ Fire suppression – 6 ▪ Fire containment – 6 ▪ Ventilation – 6 ▪ Power isolation – 3
Physical Form	**AH nodes x sections affected - 5**	**AH nodes x sections affected - 7**

The differences in the severity of damage can be seen in a number of comparisons up the AH. First, even though the amount of damage at the Physical Form level is similar for the medium and high complexity scenarios (5 versus 7 nodes x sections affected), the small difference is magnified up the levels of abstraction. At the Physical Function level, there is a difference of 13 nodes x sections affected; and at the Generalized Function level, there is a difference of 6 nodes x sections affected. Even though the scope of threatened or broken constraints at the Abstract Function and Functional Purpose levels of abstraction are similar, the medium complexity scenario has no threatened or broken constraints of high severity, while for the high complexity scenario, 7 of 18 of the threatened or broken constraints are high severity.

These results show that there is an important difference in the levels of complexity of the two scenarios, with the high complexity scenario being more complex.

3.4 TASK INVENTORIES

The task inventory that was developed is shown in the table below. In general, the individual items are self-explanatory; where some amplification is useful, a note has been added to the item *in italics*. Note that the numbering of these items is meant to imply a plausible ordering. If the dynamics of a real damage control situation were to be observed, many loops and shunts would certainly be observed, some tasks would be performed in parallel, and others might be performed in a very different order than presented here.

Table 3-2. Task inventory for the medium and high complexity damage scenarios.

---

1 Monitor ship state. *A high-level control function that includes all of the ship properties that need to be monitored to detect damage and control it effectively.*

1.1 Monitor ship spaces[9]

1.1.1 Monitor ship spaces for presence of fire

1.1.2 Monitor ship spaces for presence of smoke

1.1.3 Monitor ship spaces for presence of water / floods

1.2 Monitor ship structure

1.2.1 Monitor hull for breaches

1.2.2 Monitor decks and bulkheads for structural integrity

1.3 Monitor ship ventilation

1.3.1 Monitor state of ventilation system

1.3.2 Monitor state of hatches and doors

1.3.3 Monitor state of ventilation valves

1.4 Monitor ship load and balance

1.4.1 Monitor ship's reserve buoyancy

1.4.2 Monitor ship's list and trim

1.4.3 Monitor ship's righting arm

1.5 Monitor ship mission requirements

1.5.1 Monitor command priorities

1.5.2 Monitor current damage control state

1.6 Monitor ship personnel

1.6.1 Monitor location of ship personnel

1.6.2 Monitor health of ship personnel

1.7 Monitor state of ship systems. *The damage control effort can be helped by information about the state of all systems that could cause, exacerbate, or prevent a damage control event (e.g., if the anti-missile defence systems are not functioning while the ship is in an area with missile threats, this knowledge can assist damage control in predicting the types of damage that could occur).*

1.8 Monitor state of damage control systems

[9] Although the Halifax class frigate currently includes heat sensors, the detection of heat is only a means to the detection of fire.

2 Coordinate damage control response. *A high-level control function concerned with detecting damage (if any), assessing its impact, and addressing that damage in the most efficient way given the ship's current priorities and resource constraints.*

2.1 Detect damage

2.1.1 Detect fire

2.1.1.1 Detect fire location

2.1.1.2 Detect fire type

2.1.1.3 Detect fire intensity

2.1.2 Detect flood

2.1.2.1 Detect flood location

2.1.2.2 Detect flood source

2.1.2.3 Detect flood volume

2.1.2.4 Detect flood rate

2.1.3 Detect structural problems

2.1.3.1 Detect hull breaches

2.1.3.2 Detect bulkhead and wall problems

2.1.4 Detect load and balance problems

2.2 Assess impact of damage

2.2.1 Assess impact of detected fire

2.2.1.1 Assess impact of fire on ship's functional purposes

2.2.1.2 Assess impact of fire on accessibility to ship spaces and equipment.

2.2.1.3 Assess potential for fire to spread to adjacent spaces

2.2.1.4 Assess impact of fire spread to adjacent spaces using criteria in 2.2.1.1 - 2.2.1.3

2.2.2 Assess impact of detected flood

2.2.2.1 Assess impact of flood on ship's functional purposes

2.2.2.2 Assess impact of flood on accessibility to ship spaces and equipment

2.2.2.3 Assess potential for free surface effect problems to arise

2.2.2.4 Assess potential for free communication effect problems to arise

2.2.2.5 Assess potential for flood to spread to adjacent spaces

2.2.2.6 Assess impact of flood spread to adjacent spaces using criteria in 2.2.2.1 - 2.2.2.5

2.2.3 Assess impact of detected structural problems

2.2.3.1 Assess impact of structural problems on ship's functional purposes

2.2.3.2 Assess impact of structural problems on accessibility to ship spaces and equipment

2.2.3.3 Assess potential for structural problems to compound

2.2.3.4 Assess impact of problem compounding using criteria in 2.2.3.1 - 2.2.3.4

2.2.4 Assess impact of detected load and balance problems

2.2.4.1 Assess impact of load and balance problems on ship's functional purposes

2.2.4.2 Assess impact of load and balance problems on accessibility to ship spaces and equipment

2.2.4.3 Assess potential for load and balance problems to compound

2.2.4.4 Assess impact of problem compounding using criteria in 2.2.4.1 - 2.2.4.4

2.3 Determine resource constraints

2.4 Determine damage control strategy

2.5 Allocate (or re-allocate) resources to resolve damage

2.6 Resolve damage

3 Control fire. *A high-level control function concerned with controlling fire damage based on the damage control response maintained by function 2. Note that smoke clearance is not included in this task, as it is a concern that typically falls outside of the purview of damage control.*

3.1 Contain fire

3.1.1 Shut down ventilation system to affected section

3.1.2 Close bulkhead isolation valves

3.1.3 Close all relevant doors and hatches

3.2 Bound fire

3.2.1 Set and maintain boundary above fire (if possible)

3.2.2 Set and maintain boundary aft of fire (if possible)

3.2.3 Set and maintain boundary forward of fire (if possible)

3.2.4 Set and maintain boundary below fire (if possible)

3.2.5 Set and maintain boundary port of fire (if possible)

3.2.6 Set and maintain boundary starboard of fire (if possible)

3.3 Prepare to control fire

3.3.1 Choose strategy to control fire

3.3.2 Ensure availability of fire control resources

3.3.3 Coordinate personnel safety for chosen strategy. *If a fire is to be fought by humans, this would include power isolation.*

3.4 Extinguish fire

3.5 Confirm fire extinguished

4 Control flood. *A high-level control function concerned with controlling flood damage based on the damage control response maintained by function 2.*

4.1 Contain flood

4.1.1 Close all relevant doors and hatches

4.1.2 Close all relevant ventilation valves (M openings, on vertical ventilation trunking)

4.1.3 Shore up bulkheads, decks, and hatches as necessary

4.2 Remove / manage source of flood

4.3 Remove flood water

4.3.1.1 Remove water from affected space to bilge

4.3.1.2 Remove water from affected space to sea

4.4 Remove bilge water

4.4.1.1 Separate oils from water

4.4.1.2 Remove water from bilge to sea

5 Control structural problems. *A high-level control function concerned with controlling structural damage based on the damage control response maintained by function 2.*

5.1 Shore up bulkheads, decks, and hatches as necessary

6 Control load and balance problems. *A high-level control function concerned with controlling load and balance problems based on the damage control response maintained by function 2.*

6.1 Redistribute loads across the ship

6.1.1 Drain water to lower decks

6.1.2 Move equipment, supplies, and fittings

6.1.3 Transfer equipment, supplies, and fittings to another platform

6.1.4 Jettison equipment, supplies, and fittings

6.2 Remove bilge water

6.2.1 Separate oils from water

6.2.2 Void water from bilge to sea

In the process of cross-checking the full concerns of each of these tasks against the AH of damage control, the project team discovered that in its treatment of the Generalized Function of Load and Balance, the existing AH does not include concerns related to ice accumulation on the superstructure of the ship. While ice accumulation is not a damage control concern, current levels of ice accumulation or the potential for ice accumulation to arise could be an important input to the overall load and balance of the ship. No other items of concern were identified.

3.5 MEASURES OF EFFECTIVENESS

The MOEs that were developed are presented in Table 3-3, below. This table presents the MOEs organized by node of the AH to which they are related. Many of the MOEs also correspond to specific tasks from the task inventory; where this is the case, the reference to the task inventory item is included in brackets.[10]

For many of the AH nodes at the Functional Purpose and Abstract Function levels of abstraction, there are no specific MOEs. This is because the concepts at these levels are at such a high level that no single measure expresses them adequately; rather, MOEs for these nodes are best expressed as an aggregate of the MOEs identified for the nodes they are connected to by ‘means’ (downwards) links.

In addition, specific target levels for each of the MOEs have not been established. It is expected that the good performance on most of the MOEs will be represented by simple minimum or maximum functions, or integrations of these functions over time. For example, all other things being equal, a damage control system that can ensure a positive righting arm and maximize the righting arm over time is to be preferred. Again, all other things being equal, a damage control system that can ensure a minimum amount of list and trim over time is to be preferred.

Finally, although it is likely that some MOEs are more important than others, they have not been prioritized. For example, the US Naval Research Lab is currently placing a high priority on developing damage control systems that will extinguish fires before they spread, which implies that the MOE *Number of compartments affected by fire spread* may have a higher

[10] All of the tasks in the task inventory, with the exception of all tasks under **1 Monitor Ship State** and the management tasks under **2 Coordinate damage control response** (specifically, **2.3 Determine resource constraints**, **2.4 Determine damage control strategy**, and **2.5 Allocate (or re-allocate) resources to resolve damage**) were converted into MOEs.

priority in the selection of an acceptable damage control system than the MOE *Time to assess impact of fire*.

Table 3-3. Measures of effectiveness.

AH Node		MOE
FUNCTIONAL PURPOSE		
1.01	Stability	Ability for personnel to stay on ship Period of ship roll
1.02	Manoeuvrability	Ability to move under own power
1.03	Mission effectiveness	Ability to remain on station
1.04	Personnel safety	Number of casualties
1.05	Economic stewardship	Overall monetary impact of damage
1.06	Environmental protection	Impact of ship on environment (potentially qualitative)
ABSTRACT FUNCTION		
2.01	Reserve Buoyancy	Volume of the watertight portion of the ship above the waterline
2.02	Structural integrity	Amount of designed structural integrity remaining
2.03	Positive righting arm	Righting arm Righting moment
2.04	List and trim	Amount of list Amount of trim
2.05	Ability to maintain operational speed	Difference between maximum speed possible and operational speed
2.06	Ability to maintain desired course	Available turning rate Available turning radius
2.07	Ability to communicate	Time required to communicate and receive feedback on an internal message Time required to communicate and receive feedback on an external message
2.08	Ability to navigate	Time required to obtain current position Accuracy of position reckoning
2.09	Ability to sense environment	Range of available sensors Time required to obtain position, course, and speed for a contact Accuracy of position, course, and speed reckoning Accuracy of friend/foe determination
2.10	Ability to affect environment	Range of required effectors Capability of required effectors
2.11	Minimize casualties	Number of casualties
2.12	Minimize resource damages	Monetary value of damaged resources
2.13	Minimize resource expenditures	Monetary value of resources expended
2.14	Minimize environmental impact	Impact of ship on environment (potentially qualitative)
GENERALIZED FUNCTION		

AH Node		MOE
3.01	Freeboard	Distance between waterline and the top of the watertight structure of the ship
3.02	Watertight integrity	Total influx of water Amount of shoring or repairs in use to maintain watertight integrity
3.03	Structural strength	Safety margin afforded by overall remaining structural strength
3.04	Load and balance	Weight/volume of water taken on by flooding Time to detect load and balance problems (Task 2.1.4) Accuracy of detection of load and balance problems (Task 2.1.4) Time to assess impact of load and balance problems (Task 2.2.4) Accuracy of assessment of impact of load and balance problems (Task 2.2.4) Time to redistribute loads across the ship (Task 6.1) Time to remove bilge water (Task 6.2)
3.05	Propulsion	Number of propulsion sources available Amount of time each propulsion source is unavailable due to the effects of damage
3.06	Steering	Availability of steering systems Amount of time steering systems are unavailable
3.07	Internal comms	Availability of internal communications systems Amount of time internal communications systems are unavailable
3.08	External comms	Availability of external communications systems Amount of time external communications systems are unavailable
3.09	Navigation sensors	Availability of navigation sensors Amount of time navigation sensors are unavailable
3.10	Power generation and distribution	Amount of power available Integrity of power network
3.11	Targeting sensors	Availability of targeting sensors Amount of time targeting sensors are unavailable
3.12	Effectors	Availability of effectors Amount of time effectors are unavailable
3.13	Helicopter support	Availability of helicopter support Amount of time helicopter support is unavailable
3.14	Protective measures	(*None*)
3.15	Prompt response	Total time from onset of damage to containment
3.16	Prevention measures	(*None*)
3.17	Spill prevention / containment	Volume of bilge-water expelled from ship
3.18	Resource allocation	(*None*)
PHYSICAL FUNCTION		

AH Node		MOE
4.01	Flood control	Time to detect flood (Task 2.1.2) Accuracy of flood detection (Task 2.1.2) Time to assess impact of flood (Task 2.2.2) Accuracy of assessed impact of floods (Task 2.2.2) Time to contain flood (Task 4.1) Time to remove / manage source of flood (Task 4.2) Time to remove flood water (Task 4.3) Number of compartments lost to sea due to primary damage Number of compartments lost to sea outside of primary damage zone (or, secondary flooding)
4.02	Structural reinforcement	Time to detect structural problems (Task 2.1.3) Accuracy of structural problem detection (Task 2.1.3) Time to assess impact of structural problems (Task 2.2.3) Accuracy of assessed impact of structural problems (Task 2.2.3) Time to enact shoring (Task 5.1)
4.03	Fire suppression	Time to detect fire (Task 2.1.1) Accuracy of fire detection (Task 2.1.1) Time to assess impact of fire (Task 2.2.1) Accuracy of assessed impact of fire (Task 2.2.1) Number of compartments affected by fire spread[†] Energy release rate for fire[†] Time to prepare to control fire (Task 3.3) Time to extinguish fire (Task 3.4) Time to confirm fire extinguished (Task 3.5)
4.04	Fire containment	*First six MOEs from Fire Suppression plus…* Time to contain fire (Task 3.1) Time to bound fire (Task 3.2)
4.05	Ventilation	Time to shut down ventilation to affected section (Task 3.1.1) Number of compartments (besides those with fire) affected by smoke
4.06	Power isolation	Time to isolate power for personnel safety (Task 3.3.3) Number of ship systems affected by power isolation

[†]Measures sourced from Williams, et al. (2003).

SECTION FOUR: DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

4.1 GENERAL

This section provides some final conclusions of the scenario development effort and recommendations for Phase III of this project as well as the follow-on simulation effort.

4.2 DISCUSSION – THE CONTINUING USEFULNESS OF THE AH

While much of the discussion of the results of this project has already occurred in the presentation of the results, there is one notable result which still requires a brief discussion. Throughout the conduct of this work, the project team was pleasantly surprised at ongoing usefulness of the AH representation of damage control developed in Phase I of this project. In Phase I, the development of that model was critical to gaining the in-depth knowledge of damage control required to be able to develop, document, and substantiate the scenarios presented in this report. In this phase of the project, the AH model was a useful touchstone at many points along the way. The rigour with which a work-domain analysis enforces an actor-independent view of a work-domain was instrumental in developing the methodology followed in this work (see, for example, the discussion on the nature of scenarios at Section 1.3.2 or the discussion on damage propagation in Section 1.3.3). The AH also paid back dividends in the development of MOEs. First, the idea that the project is still at an actor-independent stage helped in clarifying that only MOEs (and not MOPs) are germane at this phase of analysis, and second, the AH provided a useful structure for generating a comprehensive set of MOPs.

4.3 CONCLUSIONS

This report has presented the development of a medium complexity and a high complexity scenario for damage control. These scenarios are based on insights from current CF naval damage control training scenarios, research on recent real-world damage control incidents, interviews with naval damage control SMEs, and an understanding of the human performance issues introduced by advanced automation. Consideration has been made to ensure that these scenarios will be useful in the context of the simulation effort for which this work is laying a foundation, especially in that these scenarios have been developed to be actor-independent, and so should readily generalize across any combinations of damage control equipment and crewing that could be installed in (a simulation of) the Halifax class frigate. These scenarios have been analysed against two different measures of damage control complexity to demonstrate that their levels of complexity are useful and sufficiently different from one another. Finally, an actor-independent task inventory of all of the work required to combat the damage of these scenarios, as well as MOEs to compare different evolutions of damage control work have been provided. All of which is to say, the project team is confident that the methodology and results presented in this volume meet the objectives for which they were requested, and are a good basis for the future phases of work.

4.4 RECOMMENDATIONS

The following recommendations arise from the work presented in this volume:

a. **Recommend continuing with Phase III of this project.** The work on Phases I and II of this project have been productive and successful, and the project team is confident that the work completed to date is a strong basis for the final phase of this project.

b. **Recommend researching potential damage control simulators.** The results presented in Section 1.3.3 argue strongly that this project would be well-served by adopting some existing damage control simulator instead of building one from scratch. A proposed first step in this research would be to conduct a visit with Dr. Fred Williams of the NRL to discuss his experiences with such simulators.

c. **Recommend researching the application of Ecological Interface Design to damage control.** Seeing that the AH of damage control has been so useful in this project to date, it would be useful to investigate if the AH would also translate well into an interface designed according to the principles of Ecological Interface Design (Burns & Hajdukiewicz, 2004; Vicente & Rasmussen, 1992). This would also be helpful in understanding how the concept of object worlds developed in Phase I of this project can extend from analysis into design.

d. **Investigate ways to enable a simulation to run under both peacetime and wartime conditions.** The decision to base both of the scenarios in this volume on peacetime cruising conditions has limitations; to mitigate those limitations, it would be useful if the simulation that is hoped to be a follow-on to this work will be flexible enough to allow for peacetime and wartime conditions (and the different mission priorities introduced by the latter).

e. **Investigate ways to add automation complications to the simulation of the scenarios.** Table 1-1 in Section 1.3.4.8 summarizes the implications of the various characteristics of human performance with advanced automation on the development of automation for damage control. These implications should be reviewed prior to developing a simulator to investigate ways in which the simulator could be made flexible enough to include these conditions in sensitivity analyses.

f. **Promote the scenarios developed in this phase of the project, as well as the rationale behind them, to developers and/or vendors of damage control systems.** It is possible that the scenarios developed in this phase of the project and their rationale would be of benefit for Canadian industry. If there are any possibilities to promote this report to Canadian industry as a starting point for including automation considerations in scenario development, these should be pursued.

SECTION FIVE – REFERENCES

Annett, J. (2003). Hierarchical Task Analysis. In E. Hollnagel (Ed.), *Handbook of Cognitive Task Design*. Mahwah, New Jersey: Lawrence Erlbaum Associates.

Annett, J. (2004). Hierarchical Task Analysis. In D. Diaper & N. A. Stanton (Eds.), *The Handbook of Task Analysis for Human-Computer Interaction* (pp. 67-82). Mahwah, NJ: Lawrence Erlbaum Associates.

Bainbridge, L. (1983). Ironies of automation. *Automatica, 19*, 775-779.

Beyer, H., & Holtzblatt, K. (1998). *Contextual design: Defining customer-centered systems*. San Francisco, CA: Morgan Kaufmann.

Bost, J. R., Mellis, J. G., & Dent, P. A. (1999). Is the Navy serious about reducing manning on its ships? SC-21/ONR S&T Manning Affordability Initiative.

Brooks, R., & Baller, R. (2006). *RN Platforms - Recoverability*. Gosport, UK: QinetiQ Maritime Platforms & Equipment.

Burns, C. M., & Hajdukiewicz, J. R. (2004). *Ecological Interface Design*. Boca Raton, FL: CRC.

Canadian Department of National Defence. (2001). *Leadmark: The Navy's Strategy for 2020*. Retrieved 9 February 2007. from http://www.navy.dnd.ca/leadmark/doc/index_e.asp.

Canadian Department of National Defence. (2005). *Securing Canada's ocean frontier: Charting the course from Leadmark*. Retrieved 9 February 2007. from http://www.navy.forces.gc.ca/mspa_video-media/Securing_Canada_E.pdf.

Chairman of the Joint Chiefs of Staff. (2003). *Chairman of the Joint Chiefs of Staff Instruction: Joint capabilities integration and development system*. Retrieved 7 March 2007. from http://www.army.mil/thewayahead/acpdownloads/3170_01c.pdf.

Courage, C., & Baxter, K. (2005). *Understanding your users: A practical guide to user requirements, methods, tools, and techniques*. San Francisco, CA: Morgan Kaufmann.

Floyd, J. E., Hunt, S. P., Tatem, P. A., & Williams, F. W. (2004). *Fire and Smoke Simulator (FSSIM) Version 1 - User's Guide*. Washington, D.C.: Naval Research Laboratory.

Floyd, J. E., Hunt, S. P., Williams, F. W., & Tatem, P. A. (2004). *Fire and Smoke Simulator (FSSIM) Version 1 - Theory Manual*. Washington, D.C.: Naval Research Laboratory.

Go, K., & Carroll, J. M. (2004). Scenario-based task analysis. In D. Diaper & N. A. Stanton (Eds.), *The handbook of task analysis for human-computer interaction*. Mahwah, NJ: Lawrence Erlbaum Associates.

Haupt, T. A., Henley, G., Sura, B., Kirkland, R., Floyd, J. E., Scheffey, J., et al. (2006). *User Manual for Graphical User Interface Version 2.4 with Fire and Smoke Simulation Model (FSSIM) Version 1.2*. Washington, D.C.: Naval Research Laboratory.

Kirwan, B. (1987). Human reliability analysis of an offshore emergency blowdown system. *Applied Ergonomics, 18*(1), 23-33.

Klein, G. (1998). *Sources of power: How people make decisions*. Cambridge, MA: MIT Press.

Lee, J. D. (2006). Human Factors and Ergonomics in Automation Design. In G. Salvendy (Ed.), *Handbook of Human Factors and Ergonomics (3rd edition)*. New York: John Wiley.

Rosson, M. B., & Carroll, J. M. (2002). *Usability engineering: Scenario-based development of Human-Computer Interaction*. San Francisco, CA: Morgan Kaufmann.

Shou, G., Wilkins, D. C., Hoemmen, M., Mueller, C., Williams, F. W., & Tatem, P. A. (2000). *The DC-SCS Supervisory Control System for Ship Damage Control: Volume 2 - Scenario Generation and Physical Ship Simulation of Fire, Smoke, Flooding, and Rupture*. Urbana, IL: Knowledge-Based Systems Group, Beckman Institute, University of Illinois at Urbana-Champaign.

Sniezek, J. A., Wilkins, D. C., Wadlington, P. L., & Baumann, M. R. (2002). Training for crisis decision-making: Psychological issues and computer-based solutions. *Journal of Management Information Systems, 18*(4), 147-168.

Torenvliet, G. L., Jamieson, G. A., & Cournoyer, L. (2006). *Functional Modelling, Scenario Development, and Options Analysis to Support Optimized Crewing for Damage Control - Phase 1: Functional Modelling* (Contract Report No. CMC Document 1000-1370-1 / DRDC Toronto CR 2006-090). Ottawa, Ontario: CMC Electronics.

Turner, S. D., Horstmann, P., & Bain, G. (2006). *Warship Survivability*. Paper presented at the WARSHIP 2006: Future Surface Ships.

United States Department of Defence. (1998). *DoD Modeling and Simulation (M&S) Glossary*. Retrieved March 7, 2007. from http://www.dtic.mil/whs/directives/corres/html/500059m.htm.

United States Department of Defence. (1999). *Department of Defence Handbook: Human Engineering Program Process and Procedures* (No. MIL-HDBK-46855A).

Vicente, K. J. (1997). Operator adaptation in process control: A three-year research program. *Control Engineering Practice, 5*(3), 407-416.

Vicente, K. J., & Rasmussen, J. (1992). Ecological interface design: Theoretical foundations. *IEEE Transactions on Systems, Man, and Cybernetics, 22*, 589-606.

Wiener, E. L. (1989). *Human factors of advanced technology ("glass cockpit") transport aircraft*. Moffett Field, CA: NASA Ames Research Center.

Wilkins, D. C., & Sniezek, J. A. (2000). *The DC-SCS Supervisory Control System for Ship Damage Control: Volume 1 - Design Overview* (Technical Report). Urbana, IL: Knowledge-Based Systems Group, Beckman Institute, University of Illinois at Urbana-Champaign.

Williams, F. W., Farley, J. P., Tatem, P. A., Durkin, A., Nguyen, X., Luers, A. C., et al. (2003). *DC-ARM Final Demonstration Report* (No. NRL/FR/6180--03-10,056). Washington, DC: Naval Research Laboratory.

Woods, D. D. (1996). Decomposing automation: Apparent simplicity, real complexity. In R. Parasuraman & M. Mouloua (Eds.), *Automation and human performance: Theory and applications* (pp. 1-16). Mahwah, NJ: Lawrence Erlbaum Associates.

ANNEX A
GLOSSARY OF TERMS AND ACRONYMS

ANNEX A: GLOSSARY OF TERMS AND ACRONYMS

AFFF	Aqueous Film Forming Foam
AH	Abstraction Hierarchy
ASB	Aft Section Base
CCER 4	Command and Control Equipment Room #4
Cdr	Commander
CF	Canadian Forces
CFB	Canadian Forces Base
CFNES	Canadian Forces Naval Engineering School
CPO	Chief Petty Officer
CSE	Combat Systems Engineering
DC-ARM	Damage Control Automation for Reduced Manning
DCTF	Damage Control Training Facility
DRDC-T	Defence Research and Development Canada – Toronto
ERT	Emergency Response Team
FAMR	Forward Auxiliary Machinery Room
FSB	Forward Section Base
FSSIM	Fire and Smoke Simulator
HF	Human Factors
HFE	Human Factors Engineering
HQ1	Damage Control Headquarters
LCdr	Lieutenant Commander
MOD	Ministry of Defence
MOE	Measure of Effectiveness
MOP	Measure of Performance
MSE	Maritime Systems Engineering
NRL	(US Navy) Naval Research Lab
RMS	Refrigeration Machinery Space
SA	Scientific Authority
SB3	Section Base 3
SCSC	Single-Class Surface Combatant
SME	Subject Matter Expert
WUPS	Workups

ANNEX B
AGENDA FOR SME DATA COLLECTION MEETING

ANNEX B: AGENDA FOR SME DATA COLLECTION MEETING

Reproduced below is the agenda for the SME meeting that was held on November 2, 2006, for the purpose of developing the initial ideas for the scenarios for this project.

Scenario Development to Support a Simulation of Shipboard Damage Control
SME Data Collection
Held at Sea Training, Halifax, November 2, 2006

PROVISIONAL AGENDA

1. Welcome (8:00 – 8:15)

2. Rules of Engagement (8:15 – 8:30)

3. Introduction (8:30 – 9:15)

    a. Project Overview
    b. Data Collection Objectives
    c. Scenario Requirements
        i. Complexity
        ii. Scope
        iii. Other characteristics
    d. Measures of Effectiveness / Performance

4. Scenario Identification (9:15 – 10:15)

5. Break (10:15 – 10:30)

6. Develop Medium Complexity Scenario (10:30 – 12:00)

7. Lunch (12:00 – 13:00)

8. Develop High Complexity Scenario (13:00 – 14:30)

9. Break (14:30 – 14:45)

10. Revisit / Refine Scenarios (14:45 – 15:45)

11. Wrap-up & Adjournment (15:45 – 16:00)

DOCUMENT CONTROL DATA
(Security classification of the title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (The name and address of the organization preparing the document, Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's document, or tasking agency, are entered in section 8.)

Publishing: DRDC Toronto

Performing: CMC Electronics, Inc., 415 Legget Dr., Ottawa, ON K2K 2B2

Monitoring:

Contracting:

2. SECURITY CLASSIFICATION (Overall security classification of the document including special warning terms if applicable.)

UNCLASSIFIED

3. TITLE (The complete document title as indicated on the title page. Its classification is indicated by the appropriate abbreviation (S, C, R, or U) in parenthesis at the end of the title)

Functional Modelling, Scenario Development, and Options Analysis to Support Optimized Crewing for Damage Control: Phase 2 − Scenario Development (U) (U)

4. AUTHORS (First name, middle initial and last name. If military, show rank, e.g. Maj. John E. Doe.)

Gerard Torenvliet; Greg Jamieson

5. DATE OF PUBLICATION (Month and year of publication of document.)

March 2007

6a NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.)

70

6b. NO. OF REFS (Total cited in document.)

31

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of document, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Contract Report

8. SPONSORING ACTIVITY (The names of the department project office or laboratory sponsoring the research and development − include address.)

Sponsoring:

Tasking:

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant under which the document was written. Please specify whether project or grant.)

11gr

9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)

W7711−057972/A

10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document)

DRDC Toronto CR 2007−061

10b. OTHER DOCUMENT NO(s). (Any other numbers under which may be assigned this document either by the originator or by the sponsor.)

CMC Document Number 1000−1370−2

11. DOCUMENT AVAILABILITY (Any limitations on the dissemination of the document, other than those imposed by security classification.)

Unlimited distribution

12. DOCUMENT ANNOUNCEMENT (Any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11), However, when further distribution (beyond the audience specified in (11) is possible, a wider announcement audience may be selected.))

Unlimited announcement

DOCUMENT CONTROL DATA
(Security classification of the title, body of abstract and indexing annotation must be entered when the overall document is classified)

13. ABSTRACT (A brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual.)

(U) The Canadian Navy hopes to achieve significant lifetime cost reductions by implementing optimized crew levels across its next−generation fleet. Defence Research and Development Canada has recognized that optimized crewing can only be achieved through a thorough Human−Systems Integration effort, and that this effort will require systems modelling techniques to help the Navy predict the effectiveness of technologies and work strategies that aim to reduce operator workload and improve mission success. This report describes the second phase a project undertaken to provide Defence Research and Development Canada with such a technique, and details the development of two damage control scenarios. One additional phase of analysis is planned, to identify three different sets of damage control equipment and the crew level required to operate that equipment under the damage scenarios that have been defined. The outputs from this project will be used as inputs for a follow−on project to develop a simulation of human and automated work in the damage control domain. The scenarios documented in this report coupled with the results of the first phase of work are a strong basis for the final phase of this project, and the follow−on simulation development effort.

(U) La Marine canadienne souhaite réduire de façon significative les coûts du cycle de vie grâce à l'optimisation des équipages de sa flotte de prochaine génération. Recherche et développement pour la défense Canada a reconnu que l'optimisation de l'armement en équipage ne peut se réaliser que par l'intégration totale des systèmes humains et que cela exigera des techniques de modélisation de systèmes qui aideront la Marine à prédire l'efficacité des technologies et des stratégies de travail qui ont pour but de réduire la charge des opérateurs et d’améliorer les chances de succès de la mission. Ce rapport décrit la deuxième étape d'un projet qui procurera ces moyens à Recherche et développement pour la défense Canada et explique les détails de la mise au point de deux scénarios de contrôle des avaries. Une autre étape d'analyse est prévue : elle consiste à trouver trois équipements de contrôle des avaries et l’effectif nécessaire pour faire fonctionner ses équipements compte tenu des scénarios de contrôle des avaries définis. Les données de ce projet serviront de fondement à un projet de suivi visant à simuler le travail humain et automatisé dans le domaine du contrôle des avaries. Les scénarios documentés dans le présent rapport, conjugués aux résultats de le première étape de travail, constituent un solide point de départ pour l’étape finale de ce projet, de même que pour les travaux subséquents de développement de la simulation.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

(U) damage control, scenario, optimized crewing, work domain analysis