EXPERIMENTAL DETERMINATION OF PASSENGER BEHAVIOUR IN SHIP EVACUATIONS IN SUPPORT OF ADVANCED EVACUATION SIMULATION

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SUMMARY
Recent international efforts have been made to develop tools for the rational analysis of passenger ship evacuation to supersede prescriptive rules that focused on layout and arrangements. A number of models have been developed and are in various stages of validation.

A fundamental aspect of these models is the quality of the data that is used to identify the processes to be modelled, populate the algorithms in the model and validate the model results.

In response to a development contract from Transport Canada for a simulation program for ship evacuation, BMT Fleet Technology Limited constructed a custom facility to collect human performance data to support evacuation simulation. The Ship Evacuation Behaviour Assessment (SHEBA) facility has been in operation for two years, and has collected timing and behavioural data for personnel moving and performing shipboard activities under difficult circumstances.

Results from the initial series of tests on SHEBA are presented, and it is noted that these have been incorporated in the simulation program maritimeEXODUS. In general, angles up to 10 degrees of heel have little effect, male participants being less affected than females. The data is incorporated in the model as speed adjustment factors, modifying the mobility at zero angle of heel and applying to gender and age attributes.

Subsequent modifications to the SHEBA rig have been made to investigate naval ship configurations and this program is described.

A new European program, FIREEXIT, focused on integrating a ship evacuation model and a fire spread model and enhancing the capability of the simulation, includes further experimental work on SHEBA and in other facilities in Canada. For this project, SHEBA will be rendered gas tight and experiments with smoke and cyclic motions combined will be conducted.

AUTHORS BIOGRAPHY

Ian F. Glen graduated into the RCNC in 1967 and held a number of naval architecture positions in the UK MOD and the Canadian DND before joining Arctec Canada Limited in 1980. He has been President of the company – which recently joined the BMT group – for 20 years. Mr. Glen has headed the initiative to develop the SHEBA facility and, with his co-authors has contributed to the development of the ship evacuation simulation program.

Gareth Igloliorte is a graduate of the BASc Ocean Engineering and Naval Architecture program at Memorial University of Newfoundland, after which he joined BMT Fleet Technology Limited as a project engineer. Gareth has led many of the SHEBA upgrades and tests and is the principal engineer providing consultation services on evacuation using the maritimeEXODUS program.

Professor Edwin Galea is the CAA Professor of Mathematical Modelling and Director of the Fire Safety Engineering Group at the University of Greenwich. He has worked in the area of fire safety for 15 years, and has been the lead developer of the EXODUS evacuation simulation software suite as well as carrying out numerous full-scale evacuation trials.

present. Involved in marine R&D for the last 15 years, involved in the development of numerous projects related to simulators, ice navigation, diesel engine performance analysis, radars and Search and Rescue technology. Was the Government Scientific Authority for the initial phase of the Ship Evacuation Simulation project.

NOMENCLATURE

BMT British Maritime Technology
FSEG Fire Safety Engineering Group
IMO International Maritime Organisation
SHEBA Ship Evacuation Behaviour Assessment Facility

1. INTRODUCTION:

In the wake of major maritime disasters such as the Herald of Free Enterprise and the Estonia, and in light of the growth in the numbers of high density, high-speed ferries, large capacity cruise ships, and smaller passenger vessels such as cruise/tourist craft, issues concerned with the evacuation of passengers and crew at sea are receiving renewed interest. In evaluating evacuation arrangements on ships, emphasis to date has been on the physical arrangements with little consideration of the human behaviour and environmental factors associated with emergency evacuation. Research into evacuation from aircraft and buildings in the last ten years has led to a greater understanding of the human factors in such emergencies, and sophisticated evacuation simulation models have been developed [1, 2]. The International Maritime Organization, through its Fire Prevention working group, has developed guidelines for conducting more advanced analysis of evacuation – firstly in the form of a simplified calculation of traffic flow using analytic methods [3], and more recently for the use of advanced simulation programs that account the environment, human behaviour, etc., [4].

2. EVACUATION SIMULATION PROGRAM – maritmeEXODUS

One such program is maritmeEXODUS, developed by the Fire Safety Engineering Group of the University of Greenwich, with the assistance of, among others, Transport Canada and BMT, from the rather successful EXODUS suite of building and aircraft evacuation simulation model [5]. maritmeEXODUS embodies not only well validated human behaviour rules, but also the effect of deck angle, ladders and doors as found on ships, tasking of occupants (e.g., collect lifejacket before going to muster station), crew assignments and recognition of familiarity differences between crew and passengers, effect of lifejackets on mobility, and a fully integrated module that addresses the various means of abandoning the ship via lifeboats, chutes, etc. maritmeEXODUS benefits from the validation work carried out on its non-marine predecessors, and subsequently, in recent applications to ship evacuation trials, has demonstrated a high level of accuracy.[6] Part of the success of maritmeEXODUS is the data set used to provide the empirical behaviour factors for the evacuating passengers, some of which has been collected in a unique, purpose-built facility.

2.1 THE SHEBA FACILITY

In order to collect the essential behavioural data for the shipboard environment, BMT Fleet Technology Limited designed and constructed a custom facility at its laboratory in Ottawa, Canada. The establishment of the facility was funded by BMT. The SHip Evacuation Behaviour Assessment facility (SHEBA) is the
largest facility of its kind, and consists of a muster room (3.65 m x 2.4 m) at one end of an 11 m long corridor at the other end of which there is a flight of stairs ascending 2 m to a platform and exit. The corridor and stair dimensions (and stair slope) are based on standard sizes found on passenger vessels. Handrails were also fitted in the corridor and along the stairs according to standard ship sizes. The corridor is 1.89 m wide (1.63 m between railings). The staircase is 1.53 m wide (1.30 m between railings). The staircase has a total of nine steps. The vertical distance between each step is 200 mm with a step run of 230 mm.

The entire rig is mounted on hydraulic rams that can heel the facility to 22°. The rig is outfitted with shipboard features such as marine lights and signage and has vinyl flooring.

The rig is constructed inside a gas-tight laboratory. In its original configuration, the rig had no solid roof, but rather a framework of structural members. This allowed the behaviour of test personnel to be monitored from the raised platform behind the rig. During tests the lights in the main building are dimmed to minimize the impact of the external environment on the subjects in the test rig, which is lit with its own marine lighting system – and emergency lighting system.

Data is recorded with optical sensors and video cameras as described below. The rig is fitted with a public address system and an alarm bell.

The length of the passageway permits accurate measurements of group behaviour, including the all-important contra-flow in which two groups meet in the passageway going in opposite directions. This is a full-scale rig and does not require corrections to data for acceleration, end effects, etc.
2.2 DATA COLLECTION SYSTEM

To measure the speed of individuals in the passageway and on the stairs, there are five optical sensors connected to a data acquisition computer. The corridor sensors are spaced 4.6 m apart and are approximately 1 m from the floor, below the level of the handrail (Figure 4). The first sensor is approximately one metre from the mustering room while the last sensor is about 1 m from the bottom of the stairs. This was done to eliminate the acceleration and deceleration phases of movement in the passageway. A custom program was used to calculate the time intervals between the sensors and return the speed.

The speed and behaviour of groups were analysed from video recordings taken from six cameras positioned overhead in the passageway and stairs (Figure 5). The locations for recording the times (and the locations of the optical sensors) were shown by black lines marked on the floor and walls of the facility. The black lines were easily visible in the video recordings even when a large number of people were in the passageway.

Each of the video cameras recorded to its own dedicated videocassette recorder, each with a synchronized digital timer that recorded onto the tape for measuring times of individuals and groups to \( \frac{1}{100} \) s.

Part of the initial study using the SHEBA facility was to determine the flow rate of people through a typical silled ship doorway. The open silled doorway is shown in Figure 6. In a later program in 2002 for a Naval client additional features were added as described later in the paper.

2.3 TESTING PROCEDURES

The initial tests on SHEBA were carried out in support of the development of the initial version of \textit{maritimeEXODUS} in 2001 and were funded by Transport Canada.
2.4 OBTAINING TEST PERSONNEL

Volunteers from the general public were used in the tests, generally in groups of about 15. These personnel were chosen covering a full range of ages and abilities – from 8-year old children to 80-year old persons, and there was even a special series of tests carried out with a person in a wheelchair. Careful attention was paid to ensuring that a good mix of the population distribution was achieved in each test group, and steps were taken to avoid a situation where, for example, an entire group was comprised of students.

Volunteers were sought via advertisements in local newspapers and exposure that was achieved in local television and radio stations. The BMT FTL website allowed volunteers to “sign up” directly. Volunteers were not paid, but generally the group enjoyed a barbecue supper and received commemorative gifts for their efforts over the three-hour testing period.
A breakthrough came in obtaining volunteers when it was decided to offer charitable donations to any organized group who volunteered, with the donation being proportional to the number in the group. This generated groups who were raising money for charities, rugby clubs, etc., and was a great success.

2.5 TEST PROCEDURES

All personnel attending were briefed, answered a medical questionnaire and signed waivers. The briefing informed the test subjects on the overall objective and the importance of the research, as well as safety issues and expectations for performance in the rig. This latter is always a concern as we tried to provoke motions that reflected a sense of urgency without causing danger to test personnel.

The test subjects were first asked to don lifejackets and the time to put these on was recorded for use in the software. Subsequently test subjects donned hard hats and gloves for personal protection. Life vests and hats were identified with numbers that were subsequently used and allowed us to match the subjects and their recorded physical attributes.

Individuals passed through the rig in both the up direction and the down direction, one at a time, to log their fast walk speed. Other than being briefed on what might be deemed a fast walking speed, there was no assistance given, and subjects were left to choose their approach – taking the high or low side of the passageway, etc.

The individual runs were repeated for all persons at zero degrees and at one or two other static angles in increments of 5 degrees. While initially the plan was to capture performance at 0, 5, 10, 15, and 20 degrees of heel, it became clear that there was no significant difference between 0 and 5 degrees and, in order to remain within the budget and schedule of the contract and to obtain a statistically meaningful result, tests eventually focused on 0, 10 and 20 degrees.

Measures were taken to prevent test subjects from adapting in advance by preventing test subjects watching prior tests or talking to other testers about strategy for dealing with the angle.

When individual runs were completed, group runs were conducted to assess the group behaviour and these tests were also conducted up and down the corridor/stairs. For the group tests, the group was “close packed” at the starting line to simulate an exiting crowd and then allowed to move as quickly as they wished. This led to overtaking and close packing on the stairs.

While the total speed of the group was noted, these tests were to answer questions concerning behaviour issues. For example, at zero tilt angle the passageway accommodated three persons across the width allowing a high flow volume. At higher heel angles there was no one occupying the centre of the passageway as test subjects held onto the rails on either side – thus reducing the flow rate along the passageway.

Figure 7 shows test personnel in the SHEBA rig at an angle.

In all cases where the group was involved, they were first assembled in the “muster cabin” prior to the rig being tilted, to reduce the likelihood of developing a “strategy” for the evacuation. When the rig had reached the target angle the group was given the command to evacuate. In these cases, every attempt was made to instil a sense of urgency with announcements to abandon ship, and the use of alarms and bells.

![Figure 7: Test Group in SHEBA at 20° Angle](image-url)

The group activity also included contra-flow where two groups of seven or eight people were set off from either end of the rig to pass in mid corridor. For these, we studied the passing behaviour as well as the net effect on the group speed of the passing effect.
3. RESULTS

The results were used to develop speed-modifying factors for the simulation program as a function of gender, angle, etc. They are also being used to modify behaviour models where such is needed.

Donning Lifejackets: This simple task is an important element in the total evacuation time, and is often incorporated in some nominal “delay” time between the alarm sounding and persons taking action. All test persons were given a demonstration of donning the lifejacket as they might in a real ship situation, and they were informed that they would be timed from touching the lifejacket as they reached for it to completing tying the main ribbons – but not the neck ties.

Figure 8 shows the distribution of times to don a standard, over-the-head “keyhole” lifejacket and tie the main ribbons for a total population of 74 persons. The final data set was over 250 persons. As expected, there were some persons who were not able to complete tying the laces in a reasonable time frame as they got them tangled or applied the lifejacket incorrectly. It is safe to assume that a person escaping would not stand around to complete this if they got into trouble but would either be assisted, given the time to correct the situation, at the muster point or simply organize their lifejacket as they evacuated. Consequently, the distribution of Figure 8 can be interpreted as shown with a mean time of 17 seconds and a distribution between 8 and 26 seconds.

Individually speed in the passageway: Figures 9 to 11 are examples of the data set for the full range of males tested in the data set. These show the size of the initial data set after spurious data were removed (such as those running), as well as the degree of scatter in the data. For non-zero angles, data for both directions is shown, providing an indication of any bias towards left or right heel angle. Analysis indicates little variation in most cases. Figure 12, taken from this data set, shows that as far as males are concerned, the heel angle has little affect on the mean speed of movement.

The data is used in the *maritimeEXODUS* simulation in the form of mobility reduction factors – modifying the appropriate speed for the age and gender for zero heel angle. Figure 13 shows these factors for males and females as a function of angle, and indicate that while males tended to move slightly faster, on average, under the adverse case of heel angle, such was not the case with females.
Figure 11: Speed of Males in Corridor at 20° Angle

Figure 12: Mean Speed of Males as a Function of Angle

Figure 13: Gender Influence on speed in Corridors

Figure 14 shows how this data appeared as a function of three age groups.

Figure 15 indicates the influence of wearing life vests in the passageway. What this figure shows is that while the speed of persons wearing lifejackets is lower than those without at zero angle, it is about the same at 10° and indeed faster at 20°. This phenomenon was also noted when the flow through doors was measured, (Figure 16) where it appears that the comforting effect of wearing the padded vest results in more aggressive behaviour at higher angles. These results are for different subjects and do not reflect a “learning” factor.

Note from Figure 15 that while the speed even when descending the stairs is somewhat increased when wearing a life vest, the life vest caused significant hesitation at the top of the stairs with many subjects at higher angles of heel, as subjects looked down to establish their footing. This information is also vital to an accurate simulation.

Figure 15: Influence of Wearing a Life Vest on Speed
4. NAVAL CONFIGURATION

In 2002, the SHEBA rig was used to provide data in support of a naval version of the evacuation software. For this, the facility was modified to include vertical ladders, watertight doors and hatches and steep stairways, features typical of naval ships but not generally experienced by occupants in large passenger ships.

A comprehensive set of tests was completed with the heavy watertight door hinged on the high and low side of the heel angle and the door athwartships and longitudinally and the hatch hinge opening in various positions relative to the angle and the vertical ladder. The steep stair was tested both in heel angle up to 20 degrees and in trim angle up to 10 degrees. The basic configuration is shown in Figure 17.

4.1 THE WATERTIGHT DOOR

The watertight door was an 8-clip door, operated by a single wheel in the middle of the door. The dimensions of the clear door opening were 760 mm by 1.67 m (30” by 66”), and there was a 30 mm (12”) sill. The door weighs approximately 140 Kg.

There were four positions of the door. With the door in a transverse bulkhead in the corridor, tests were conducted with the hinge on the “high” side and with the hinge on the low side. The door was also positioned at right angles to this by affixing it to a bulkhead in the cabin area. The door then opened “up” the slope or “down” the slope.

Stepping through the opening and closing the door behind was considered too dangerous at high heel angles and some of these tests were restricted.

4.2 THE WATERTIGHT HATCH

The watertight hatch was a 6-clip hatch, operated by a single wheel in the middle. The hatch was rectangular with rounded corners and the dimensions of the clear hatch opening were 762 mm by 838 mm (30” by 33”), with the hinge being on the longer side. There was a 150 mm (6”) sill around the top. The hatch had a single, spring-loaded hinge.

4.3 VERTICAL LADDER

The vertical ladder comprised 9, 25mm (1”) diameter rungs spaced 230mm(9”) apart vertically on a width of 400mm(16”). The top rung was 230mm(9”) below the upper deck, but because of the hatch sill, required a 380mm(15”) clearing step.

The ladder was affixed in the rig in the middle of the passageway width, in the “fore and aft” position – that is such that it would heel to the left.

4.4 STEEP STAIRS (60° LADDER)

Three sets of steep stairs were manufactured, two in aluminium and one in steel – the latter was made in-house in order to allow us to conduct ladder trim and ladder heel tests concurrently. Each ladder comprised 11 steps, spaced at 200 mm (7.8”), and each tread was 685 mm wide by 160 mm deep (27” by 6.3”). The stair was 2.3 m (7.5ft) high and has an angle of 60°. The stair was fitted with handrails on each side offset 230 mm (9”) from the stair treads as per current naval practice.

One set of aluminium stairs was mounted inside the rig under the hatch with a minimum clearance of 1100 mm that agreed with the installations in the Canadian Patrol Frigate. This stair was used for “heeled” tests.

In order to pursue “trim” tests in parallel, and to study the speed on stairs without a hatch, a separate rig was constructed with two stairs back to back, and a platform at the top. This whole rig was constructed outside SHEBA, and could be tilted up to 10° “fore and aft”.

![Figure 16: Flow Rate through Door with Life Vests](image-url)
In this case, we sought active naval personnel for our tests, but few were forthcoming and so we settled for some experienced shipboard personnel (former Navy, Coast Guard and merchant personnel) and fit members of the public generally between the ages of 18 and 45. For these tests, lifejackets were not worn, but the test sequence was largely the same with individual performance through the various opening and closing sequences of the door and hatch as well as group activity.

Figure 18 shows the results for people ascending and descending the vertical ladder at angles up to 20° divided into experienced versus inexperienced persons.

5. FIREXIT – THE EUROPEAN-CANADIAN INITIATIVE

A project has recently been started under the European Community Framework 5 Program to develop a fully integrated ship evacuation simulation model with an incorporated smoke/fire spread model and accounting for behaviour in smoke and under heel and motions. FIREXIT is being undertaken by seven European agencies under the management of BMT, and includes participation by three Canadian agencies funded separately by a program in Canada known as Precarn.

Details of the entire FIREXIT program are available at [7].
The Canadian contribution is principally to provide full-scale experimental data on evacuation behaviour and on entering and launching and leaving the ship by various marine escape systems. The latter work is being carried out at the Offshore Safety and Survival Centre of the Marine Institute of Memorial University in St. John’s, Newfoundland. The SHEBA rig is also playing a major role.

SHEBA is currently being modified to render it gas tight and to allow cyclic motions and will be used to measure the performance of test personnel in the corridor and on the stairs with the corridor filled with smoke and moving cyclic about a heel or trim angle.

Modifications are extensive and testing will take place over the summer of 2003 through to the summer of 2004.

6. CONCLUSIONS

An experimental facility has been constructed that allows full-scale ship evacuation behaviour to be assessed under reasonably economic and controlled conditions. The SHEBA facility has been used to provide data on the effect on mobility of heel angle for incorporation in an advanced evacuation simulation program. This facility has allowed a more accurate assessment of performance of crowds, contra flow and the behaviour on stairs, ladders and through doors.

Work is continuing with the facility to incorporate smoke and motions as part of a European/Canadian project to develop an intelligent and fully integrated ship evacuation simulator.

The SHEBA facility is open for business and is available to researchers in this area for work.

7. ACKNOWLEDGEMENTS

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8. REFERENCES


3  IMO MSC Circular 909 June 1999

4  IMO MSC Circular 1033 May 2002


7  FIREEXIT
HTTP://www.bmtprojectnet/fireexit/