SUPERB

Preliminary feasibility study

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FOI-R--4062--SE
ISSN 1650-1942 February 2015

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Photo: SP

Titel	SUPERB - förstudie
Title	SUPERB - Preliminary feasibility study
Rapportnr/Report no	FOI-R—4062--SE
Månad/Month	February
Utgivningsår/Year	2015
Antal sidor/Pages	18 p
ISSN	1650-1942
Kund/Customer	FMV
Forskningsområde	11. Vapen, Skydd och säkerhet
FoT-område	Vapen och skydd
Projektnr/Project no	E34541
Godkänd av/Approved by	Lars Höstbeck
Ansvarig avdelning	Informations- och aerosystem

Sammanfattning

FOI och SP har på uppdrag av FMV genomfört en förstudie för att undersöka om vattendimma kan användas för att dämpa effekten av interna explosioner i fartyg. Studien omfattade:

- effekten av vattendimma på elektrisk och elektronisk utrustning i fartyget;
- tillgänglig förvarningstid före träff i fartyget;
- möjligheterna att avgöra var en inkommande robot kommer att träffa fartyget;
- nödvändig tid för att aktivera systemet och fylla ett utrymme med vattendimma samt nödvändig vattenmängd för att upprätthålla dimman under ett bekämpningsförlopp.

Studien visar att ett system baserat på vattendimma med avsevärd förmåga att dämpa explosioner har goda möjligheter att installeras på fartyg. Dämpningen av övertryck, kvasistatiskt tryck och impuls är alla i storleksordningen 30-50%.

Vidare visar studien att det sprinklersystem för brandsläckning som tagits fram i FIST-projektet också är lämpligt för att dämpa explosioner, ehuru med ett högre vattenflöde. Detta betyder att samma rör, sprinklers etc. går att använda till både brandsläckning och explosionsdämpning.

Sammanfattningsvis visar studien att ett system med vattendimma har goda möjligheter att installeras på fartyg och att systemet skulle kunna minska effekten av inre explosioner med 30-50%.

Nyckelord:

Vattendimma, brandsläckning, explosionsdämpning, verkan i fartyg

Summary

The Swedish Defence Agency (FOI) and the Technical Research Institute of Sweden (SP) have jointly carried out a project as contracted by the Swedish Materiel Administration (FMV). The project aimed to carry out a limited feasibility study of the concept to deploy water mist inside a ship to decrease the effect of detonating munitions. The feasibility study covered:

- the effects of water mist on electronics and electrical equipment inside the ship;
- the available warning before impact;
- the possibilities to predict where on the ship the incoming threat will impact;
- the required reaction time to fill a volume in the ship with water mist and the volumes required to maintain the mist during the engagement sequence.

The study clearly indicates that a system based on water mist effectively could be deployed on-board ships to decrease the effects generated by an internal blast. The reductions in generated over-pressure, quasi-static pressure and impulse are in the order of 30-50%.

Furthermore, the study shows that the fire-suppression in the FIST-project is suitable also as an explosion mitigation system, albeit with an increased flow. This means that the same nozzle configuration, piping etcetera can be used for both firefighting and explosion mitigation.

Overall, the study clearly indicates that a water mist system for explosion mitigation could be deployed to ships and that it would reduce the effects generated by internal blasts with 30-50%.

Keywords: Water mist, fire suppression, explosion suppression, ship survivability

Contents

1 Introduction

The Swedish Defence Agency (FOI) and the Technical Research Institute of Sweden (SP) have jointly carried out a project as contracted by the Swedish Materiel Administration (FMV). The project aimed to carry out a limited feasibility study of the concept to deploy water mist inside a ship to decrease the effect of detonating munitions.

SUPpression of Explosions and Reduction of Blast by Water Mist is a proposal for a trilateral project created in cooperation between Sweden, Canada and the Netherlands. Explosion mitigation with water mist was identified as a natural continuation of the FIST project [1] where new technologies for fire suppression on board naval crafts were studied.

The feasibility study covered the following topics:

- the effects of water mist on electronics and electrical equipment;
- the available warning before impact;
- the possibilities to predict where on the ship the incoming threat will impact;
- the required reaction time to fill a volume in the ship with water mist and the volumes required to maintain the mist during the engagement sequence.

These topics are covered in the following chapters.

2 Effects on electrical equipment

The effects of water mist on electrical equipment were tested by Huges Associates [2]. The purpose was to assess whether the equipment could function if it was protected by HI-FOG. An electrical circuit board and an external modem were placed in different protective encapsulations of varying NEMA Ratings and exposed to water mist. The leakage current between the lines in the circuit board was monitored and the functionality of the external modem was monitored during the exposure to the mist. Figure 1 presents how affected the equipment was with encapsulation of varying NEMA rating.

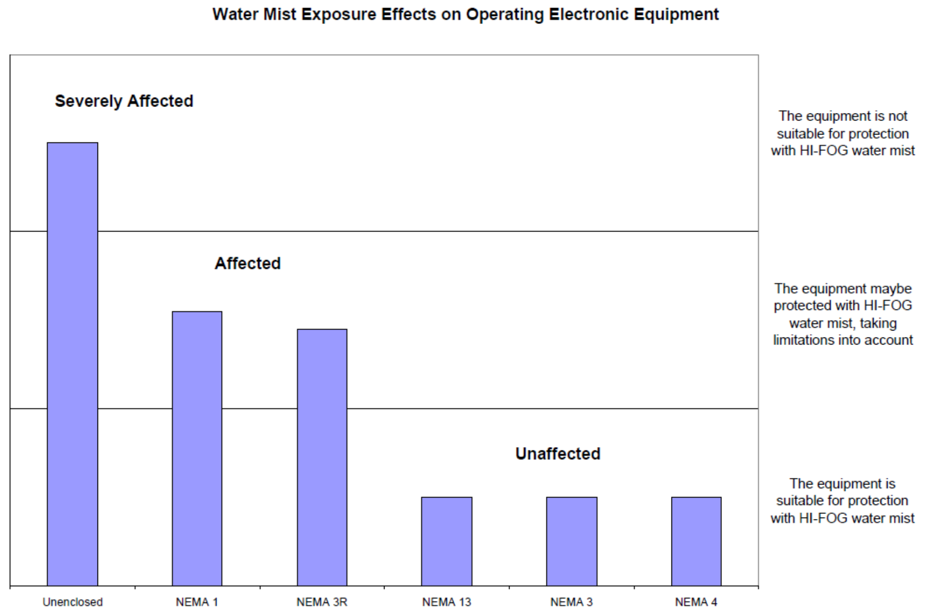

Figure 1. Effects of water mist exposure on operating electronic equipment

The mentioned tests used the American NEMA (National Electrical Manufacturers Association) rating for the protection level of electronics. However, Swedish defence systems use the international IEC IP (International Electrotechnical Commission Ingress Protection) rating. The two rating systems are not identical, but the IEC IP (Ingress Protection) rating can be approximated when the NEMA rating is known.

In Table 1the equivalent IEC IP ratings for the NEMA rated encapsulations are presented. Table 2 shows the IEC IP ratings used on different parts of the ship [3] and outlines the requirements as defined by the standard [4].

Table 1 – Tested NEMA Rating and equivalent IEC class.

Tested NEMA ratings	Equivalent IEC class
NEMA 1	IP20
NEMA 3R	IP24
NEMA 13	IP54
NEMA 3	IP55
NEMA 4	IP66

Table 2. IP ratings as used on ships.

Location	Standard	Ingress of objects	Ingress of water	Test design
CIC, Bridge	IP22	>12.5 mm Fingers or similar objects	Dripping water when tilted up to 15°	Test duration: 10 minutes Equivalent to 3 mm/min rainfall
Weapons deck, Electronics room	IP44	> 1 mm Wires, screws	Splashing of water	Test duration: 5 minutes Water volume: 10 l/min Pressure: 80-100 kPa

3 Possible threats and available warning

A ship can be attacked by a multitude of different weapons. However, this feasibility study only considers weapons with a warhead that detonates inside the ship. In particular, the study considers anti-ship missiles that can be launched from ships or aircraft at ranges from a few kilometres up to several hundred kilometres. Such missiles are equipped with seekers and are capable of hitting a ship with high accuracy. Important parameters for anti-ship missiles are summarised in Table 3.

Table 3. Selected missile data (open data from Wikipedia).

Missile	**Weight**	**Speed**	**Warhead weight**	**Terminal trajectory**
Sea Skua	145 kg	270 m/s	30 kg (9 kg RDX)	Sea skimming
Harpoon	526 kg	240 m/s	221 kg	Sea skimming 3 m eller dykning ~ 1°
Exocet	670 kg	310 m/s	165 kg	Sea skimming 3 m
SS-N-22	4500 kg	1000 m/s	320 kg	Dykning ~ 1°
Hsiung Feng III	1500 kg	630 m/s	225 kg (EFP nedåt)	Sea skimming 3 m
BrahMos	2500 kg	900 m/s	200-300 kg	Sea skimming 4 m
Naval Strike Missile	410 kg	300 m/s	125 kg	Sea skimming 2 m

The available warning time before impact can vary significantly depending on the circumstances. History shows several examples of surprise resulting in almost no advance warning, such as in the USS Stark incident in 1987. However, a reasonable assumption is that the ship will be able to detect the incoming missile using its own sensors, i.e. its surveillance radar and its electronic warfare sensors. This means that detection of a sea-skimming missile will happen at a distance of about 15-20 kilometres. Sea skimming missiles are usually subsonic, which means that the available warning will be given around a minute before impact.

A supersonic missile will approach on a higher altitude, which results in a greater distance at detection. However, the higher speed means that the available warning can be given as little as 30 seconds before impact.

4 Possibilities to predict point of impact

Where on the ship an incoming missile impacts depends both on the missile and on the actions of the ship. The missile uses its on-board seeker to select an aimpoint. For a radar-guided missile, the aimpoint will usually be the point that gives the highest radar cross section, which often is at a central part of the ship or in the area of the bridge. An IR-guided missile can aim for a pre-selected point at the ship, which presumably would be somewhere in the centre.

Most anti-ship missiles are sea-skimming, which means that they will impact 2-5 metres above the waterline. After impact, the warhead is designed to penetrate the hull and to detonate inside the ship. However, history tells that some missiles overall fail to detonate, while others detonate on impact, so it is not possible to say at which point the warhead will detonate.

This discussion means that a default assumption is that the missile will hit the central regions of the ship at 2-5 metres above the waterline.

However, the actions of the ship have a strong effect on where the missile will impact. When the ship has identified that it is attacked, it will employ various countermeasures. Electronic countermeasures such as chaff and jammers will be employed to pull off the missile and these actions will be combined with manoeuvres to present the missile with a small radar cross section coming from the ship and to facilitate the pull-off.

A meaningful prediction of the point of impact based on observations of the missile trajectory can only be made in the very final phase of the trajectory. Many incoming anti-ship missiles will perform evasive manoeuvres during the last kilometres to avoid being shot down by the ship's defences. These manoeuvres might only stop during the last kilometre. This means that an accurate prediction of the point of impact only can be made during the very last seconds before impact.

However, while predicting the impact point is rather difficult, a prediction of the time-to-go remaining to impact can be made with high accuracy, better than 10% of the actual time-to-go, starting from shortly after the first detection of the incoming missile, i.e. normally at 30-60 seconds before impact.

To conclude, the ability to measure the trajectory of the incoming missile to make an accurate prediction of the point of impact is highly limited. A more reasonable approach is to assume that the missile will impact within a few metres of the centre of gravity of the radar cross section given the aspect angle the ship presents to the missile and that the impact will be 2-5 metres above the waterline.

5 Expected performance

Several tests have been performed at TNO in the Netherlands [5] and at the Naval Research Laboratory in the United States [6] showing a good potential for explosion mitigation using water mist. These tests were performed in blast proof bunkers and the water mist system was activated before the explosive charge was detonated. Some key results are presented in Table 4.

Table 4. Pressure reductions at varying charges and volume discharge densities.

Charge	**Lab.**	**M_{H2O} [kg/m^3]**	**Peak Pressure reduction**	**QSP reduction**	**Impulse reduction**
3.2 kg TNT	NRL	0.09	44%	43%	31%
22.7 kg TNT	NRL	0.07	40%	36%	35%
22.7 kg TNT	NRL	0.06	26%	16%	28%
22.7 kg TNT-equiv Destex	NRL	0.07	43%	25%	33%
22.7 kg TNT- equiv PBXN-109	NRL	0.07	49%	39%	41%
22.7 kg TNT- equiv PBXN-109	NRL	0.03	9%	16%	20%
23.5 kg Semtex	TNO	0.44	40%	50%	30%
23.5 kg Semtex	TNO	0.36	7%	20%	9%

It can be seen that a significant pressure reduction is possible. Peak pressure, quasi static pressure and the pressure impulse were reduced by up to 50%.

The results seem to be sensitive to the water concentration in the volume and the values presented by TNO and NRL vary significantly. NRL and TNO had two different approaches to estimate the amount of water dispersed in the air at the time of detonation. TNO measured the total amount of discharged water and estimated the amount dispersed in the air, while NRL used a droplet size analyzer to estimate the water concentration in the air.

The method of visually estimating the water concentration is obviously uncertain. However, the data presented by NRL can also be questioned. The nominal surface discharge density of the system that was said to result in a water concentration of 0.07 kg/m^3 is approximately 8.4 mm/min. If the concentration is correct the average falling speed of the water is approximately 2 m/s. This seems unreasonably high since a water droplet with a diameter of 54 µm (measured Sauter mean diameter, D32 in NRL´s tests) has an expected terminal falling velocity of approximately 0.1 m/s [7].

In this pre-study it is assumed that a water concentration of about 0.4 kg/m^3 is required to achieve the best mitigating effects shown in Table 4, but the uncertainties on the measured/estimated water concentrations are substantial and it is not known whether the optimal water concentration has been covered in the performed tests.

6 Activation time and water consumption

To estimate required pre-activation time and total water consumption for an explosion mitigation system a few relevant system alternatives with spray characteristics known from earlier performed research or literature was studied. The characteristics of the spray from Ultrafog 202-2, 09-O are known from the FIST-project [8] and the characteristics of the spray from Protectospray D3 were found in literature [9].

In addition, a nozzle studied for fire suppression/extinguishment in the FIST project, the BETE TF8-170, has been included in this study. The droplet characteristics when using this nozzle are not known and best estimate values are used in this study.

Based on the system pressure, the initial droplet velocity at the nozzle is calculated [10] and the retardation and terminal velocity can be calculated for a known droplet diameter [7]. Knowing this, the travelling time for a droplet from nozzle to floor and the mass of airborne water below one nozzle is calculated for a nozzle height of 2.4 m. The results from these calculations and input data are presented in Table 5.

Table 5. Input data and calculation results for studied nozzles at relevant system pressures

Nozzle/system	**k-factor [l/min*bar$^{1/2}$]**	**Droplet diam.[1] [mm]**	**Time to floor [s]**	**Water in air per nozzle [kg]**
Ultrafog 202-2,09-O	2.07	0.15	11	3.83
Tyco D3 @ 7 bar	17.3	0.5	2.6	1.98
Tyco D3 @1.4 bar	17.3	1.0	1.3	0.44
TF8-170 @ 10 bar	5.93	0.3[2]	4.7	1.47
TF8-170 @20 bar	5.93	0.25[3]	7.6	3.35

Based on the data in Table 5 the concentration of water in the air and the surface discharge density can be calculated for different nozzle spacings. The results from these calculations are, together with the conditions in TNO´s tests, plotted in Figure 2. It can be seen that a nozzle spacing of less than 1 m is required to get the proper water concentration with D3 nozzles at ≤ 7 bar and with TF8-170 at 10 bar, a spacing of just under 2 m is required with the Ultrafog nozzle and with TF8-170 at 20 bar.

[1] Sauter mean diameter, D_{32} values are used.
[2] Based on best estimates.
[3] Based on best estimates

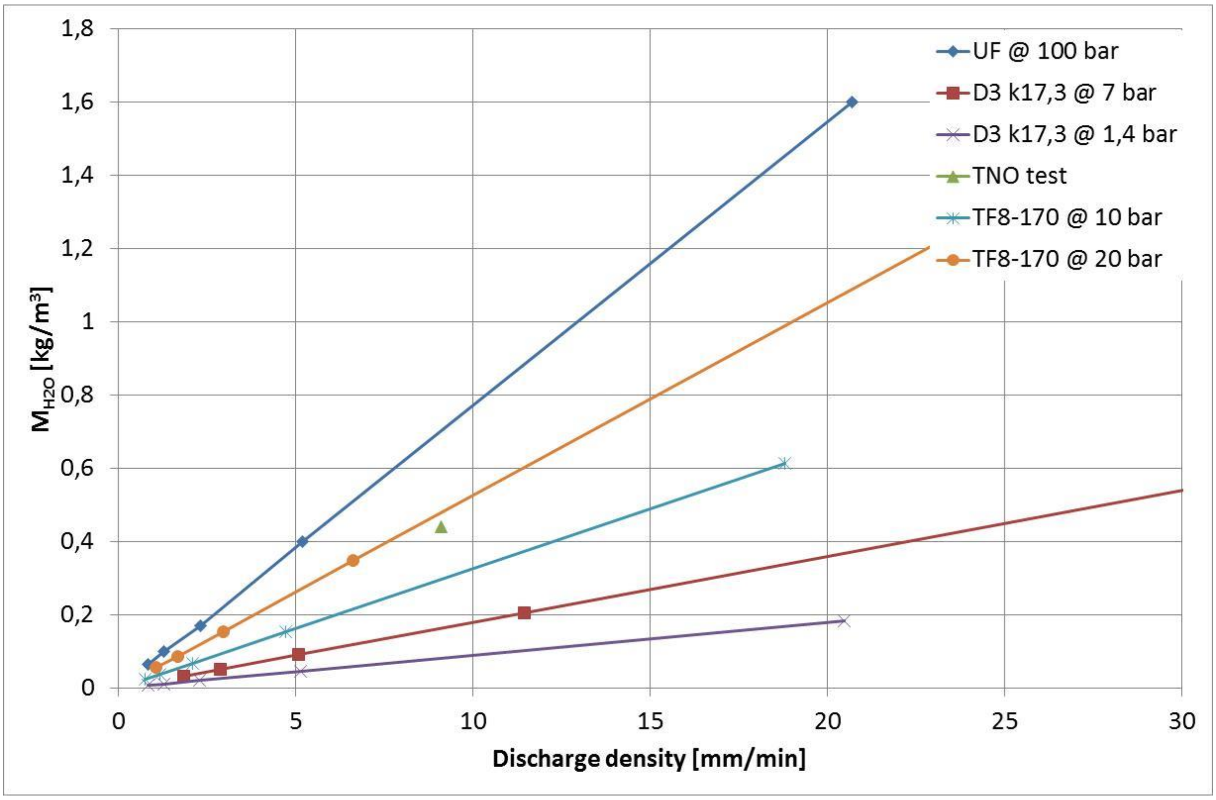

Figure 2. Water concentration [kg/m^3] and surface discharge density [mm/min] at varying nozzle spacing. The data points represent 5, 4, 3, 2 and 1 m spacing.

Since BETE TF8-170 with a spacing of 1.75 m at a system pressure of 10 bar was found to be an efficient and robust fire suppression system in the FIST-project it seems like an interesting candidate for an explosion mitigation system as well. The big advantage of such a system is that the same nozzle configuration, piping etcetera is used for both firefighting and explosion mitigation.

7 Application to ships of Visby size

To get an appreciation of total water consumption, maximum flow rates, pump requirements etc. a Visby class ship is studied as an application example for a firefighting/explosion mitigation system consisting of BETE TF8-170 with a spacing of 1.75 m.

The pre-activation time for such a system is based on the droplet travel time from nozzle to the floor in Table 5 and it is assumed that the system will keep all volumes with the correct water concentrations for 5 seconds to give sufficient margins for errors when calculating the time to explosion. This means that the system will discharge water for about 12.6 seconds (7.6 s “filling time” and 5 s “holding time”).

With a nominal surface discharge density of 8.7 mm/min and an estimated total of 2,000 m^2 protected deck surface the total amount of discharged water will be about 3,600 litres. Today, a Visby class ship has firefighting water tanks containing 5,000 litres.

One challenge is to design a system capable of discharging 3600 litres of water at 20 bar in less than 13 seconds (~17 m^3/min). A pump with this capacity will be unreasonably big. A more realistic option is to use compressed gas instead of a pump to pressurize the system for explosion mitigation. The redundancy philosophy developed in FIST states that two redundant pump stations feeds two ring lines. These ring lines feed half of the nozzles in each compartment of the ship.

The working principle of a system for both firefighting and explosion mitigation is described in Figure 3.

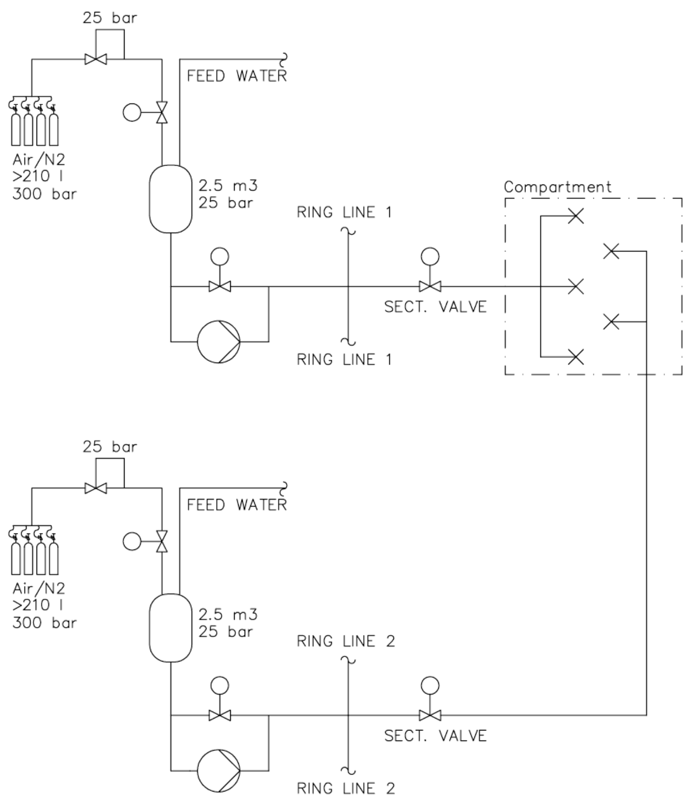

Figure 3. Flow chart diagram for a system designed for both firefighting and explosion mitigation.

8 Conclusions

This preliminary feasibility study clearly indicates that a system based on water mist effectively could be deployed on-board ships to decrease the effects generated by an internal blast. The reductions in generated over-pressure, quasi-static pressure and impulse are in the order of 30-50%.

Furthermore, the study shows that the fire-suppression in the FIST-project [1] is suitable also as an explosion mitigation system, albeit with an increased flow. This means that the same nozzle configuration, piping etcetera can be used for both firefighting and explosion mitigation.

The study also shows that the reaction time from activating the system to having enough water in the air is in the order of 5 seconds, which is a reasonable time for the deployment of a last-ditch protective system. Furthermore, the water consumption is also reasonable as the available tanks of firefighting water on a Visby class ship would be sufficient to fill all volumes of the ship with mist and to maintain the mist for about 5 seconds.

Overall, the study clearly indicates that a water mist system for explosion mitigation could be deployed to ships and that it would reduce the effects generated by internal blasts with 30-50%.

9 Proposed further work

The preliminary feasibility study has shown that a water mist system could be an effective means of decreasing the effect of an internal blast in a ship. This merits further studies, including tests, to be conducted on a national basis in Sweden as well as part of the international collaboration.

9.1 Nationally

A follow-on project to further explore the system concept proposed in this preliminary feasibility study should include:

- Literature survey focusing on conducted tests, but to an extent also covering theory and modelling;
- Further development of the system concept and how it could be integrated in the air defence system;
- Experimental investigation of drop size distribution and water concentration for relevant systems;
- Tests with the performance of water mist to suppress explosions, conducted in blast proof bunkers. The tests should include variations in drop size.

9.2 Internationally

An international collaboration project could include:

- Literature survey focusing on theory and modelling;
- CFD analysis of realistic ship-like structures and compartments;
- Tests in using more ship-like geometries and structures;
- Studies of additives to the water in the mist;
- Adaption of commercial water mist systems for explosion suppression;
- Development of guidelines for system integration on ships.

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