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Fire Management on Container Ships: New Strategies and Technologies

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ABSTRACT: Design and construction of container ships follow consolidated requirements, with standard consideration of fire management. Indeed, cargo fires can have important consequence on crewmembers and cargoes, as well as impacting coastal zone and marine environment. Innovative strategies include prevention of events and mitigation of consequences. Digital solutions, providing with situational pictures onboard and around the vessel are fundamental for new fire management solutions, seamless and integrated into the vessel IT infrastructure, according to IMO regulations and the recent EMSA CARGOSAFE Report. The assessment of these solutions requires theoretical evaluation, validation activities in simulated environment and demonstration activities in real environments, with use cases to prove feasibility and benefits. This paper, after a review of traditional preventing and mitigating solutions against fire and an analysis of container ships fires, proposes applicable innovative technologies and operational measures, emerging problems for their potential implementation and requirements for virtual and real tests design.

1 INTRODUCTION

The first fire protection requirements for international shipping were in 1914 SOLAS Convention, issued in response to the sinking of the Titanic in 1912. It contained basic fire safety requirements, later integrated into the 1929 and the 1948 SOLAS Conventions, including lessons learned by accidents (e.g. Morro Castle passenger ship fire, which caused 134 casualties in 1934) and advances in maritime technology during World War II. A greater emphasis on fire safety aboard ships, demonstrated by the development of three new parts (D, E and F) in Chapter II of the 1948 SOLAS Convention, exclusively dedicated to fire safety applied to both passenger and cargo ships. It established three methods of construction for passenger ships and basic fire protection requirements for cargo ships, later integrated by the 1960 SOLAS Convention, which exported to cargo ships a number of passenger ship's fire safety requirements. Despite the developed safety requirements, the fire is still a relevant factor generating accidents causing fatalities and material dam-ages, as demonstrated by data collected in Table 1, including almost 50% of fires onboard container ships. According to EMSA, fires and explosions are in the top five causes of accidents and erroneous human actions during shipboard operations are responsible for more than 70.1% of the total number of fires and more 76% of those on cargo ships [1] [2] [3]. Moreover, in terms of traffic and transport capacity:

- About 70% of international freight traffic is by ship (about 60,000 billion of tons-miles) and that about 9,000 billion of tons-miles is container traffic;
- The average container ship today in operation has a displacement of about 270,000 t and a payload of about 150,000 t (5300 TEU).

Table 1. Fires onboard commercial ships causing fatalities and material damages: period 2015-2020

Year	Text Fires onboard all commercial ships	Fires onboard container ships
2015	11	7
2016	12	7
2017	7	2
2018	4	2
2019	4	0
2020	2	1

Therefore, the relevance of the potential consequences on fires onboard this typology of ships is self-explaining, as well as the potential benefits achievable by effective technological solutions for prevention fires and mitigation of their effects.

All these concepts received reinforcement and validation by the very recent (March 2023) issue of the CARGOSAFE Report, commissioned by European Maritime Safety Agency (EMSA) [4], with the goal to identify cost-effective measures for reducing the risk of cargo fires on new-builds and existing containerships, which will represent a milestone for the future research activities in this field.

2 FIRE TYPOLOGIES AND CAUSES

There are many possible typologies and sources of shipboard fires. The investigations are normally able to identify with sufficient level of details the causes generating the fires and to consolidate progressively a knowledge on them. The classification of fires includes:

- Accidental: in which the proven cause does not involve any deliberate human act to ignite or spread the fire;
- Natural: events such as lightning, wind, etc., which do not involve any direct human intervention;
- Incendiary: deliberately set under circumstances in which the individuals know that the fire should not be set;
- Undetermined: when the proof of the cause is still missing.

Approximately 60-70% of fires share a common scenario, based on the outflow of combustible liquid and contact with a hot surface, develops rapidly and reach temperatures of 700–1000°C [5]. According to a more systematic analysis, the source of ignition can be at or very near the point of origin of the fire. Nevertheless, such evidence may be missing due to heavy damages or destruction by the fire itself [6]. An effective source of ignition requires sufficient temperature, energy and contact time with the first fuel ignited to raise it to its ignition temperature. Therefore, the ignition process involves generation, transmission and heating and the investigations focuses on the identification of heat-producing device, substances or circumstances that could have resulted in ignition. Example are ships and cargoes materials, electrical items (e.g. circuits, equipment and fuses, light bulbs, fixtures), engine rooms (e.g. oil transfers), welding and burning, charging batteries, housekeeping, friction (e.g. during grinding), refrigeration (e.g. in compressors), smoking, flammable and liquids and gases (e.g. CNG and LPG), open flames and sparks, as well as low temperature ignition (e.g. with wood) and lightning.

These elements reflect themselves into the ship design phase, where the hazards evaluation based on the IMO Guidelines [7], which derive from the basic principles of IMO Convention SOLAS [8] and MARPOL [9].

In particular, the SOLAS Convention at Chapter II-2 deals with fire protection, fire detection and fire extinction, where the focus is on applicable requirements depending on ship type and, more interestingly for our purposes, it fixed fire safety objectives and functional requirements.

The established fire safety objectives are specifically the following:

1. Prevent the occurrence of fire and explosion;
2. Reduce the risk to life caused by fire;
3. Reduce the risk of damage caused by fire to the ship, its cargo and the environment;
4. Contain, control and suppress fire and explosion in the compartment of origin;
5. Provide adequate and readily accessible means of escape for passengers and crew.

Meanwhile the functional requirements for the construction of the ship are:

1. Division of the ship into main vertical and horizontal zones by thermal and structural boundaries;
2. Separation of accommodation spaces from the remainder of the ship by thermal and structural boundaries;
3. Restricted use of combustible materials;
4. Detection of any fire in the zone of origin;
5. Containment and extinction of any fire in the space of origin;
6. Protection of means of escape and access for fire-fighting;
7. Ready availability of fire-extinguishing appliances;
8. Minimization of possibility of ignition of flammable cargo vapours.

In this context, the Guidelines on alternative design and arrangements for fire safety outline the methodology for the engineering analysis required by SOLAS regulation II-2/17 Alter-native design and arrangements applying to specific fire safety systems, designs or arrangements requiring approval of technically justified deviations from the prescriptive requirements of SOLAS chapter II-2.

Additional recommendations for the prevention of fires are part of the International Convention for Safe Containers (CSC) [10] and for the mitigation of fire consequences are part of the Emergency Response Procedures for Ships Carrying Dangerous Goods (EMS Guide) [11].

In general, the following conditions and features are affecting the design requirements:

1. Pre-fire situation (ship, compartment, fuel load, environmental conditions);
2. Ignition sources (temperature, energy, time, area of contact with potential fuels);
3. Initial fuels (solid, liquid, gas, vapour or spray state, density, heat release power);
4. Secondary fuels (proximity to initial fuels, amount and distribution);
5. Extension potential (beyond compartment, structure, areas);

6. Target locations (items or areas associated with the performance parameters);
7. Critical factors (ventilation, environment, operational, time of day):
8. Relevant statistical data (past fire history, frequency and severity rates).

A systematic risk analysis for each hazard can allow at providing with quantitative comparative elements, such as in [12].

3 STANDARD FIRE SAFETY MEASURES ON CARGO SHIPS

A basic strategy, valid in all firefighting situations, involves four distinct aspects: locating, informing, containing and finally extinguishing a fire [13].

The location is mainly by detection devices in various ships' compartments, such as exemplified in [14], or simply by detection of odours or smoke by the crew. In some areas, the fire generation probability is higher; therefore, regular checks and visits should concentrate on them.

After the fire detection, the information must circulate quickly. It is essential the precise information of the bridge about location and extent of the fire. Moreover, the finder can also fight the detected fire, if in the initial phase, and attract attention using any potentially useful action, such as Shouting fire, banging on bulkheads, setting off nearby alarms equipment, etc..

Well-located fire resisting bulkheads and decks are normally able to contain the spread of the fire and firefighting personnel must check the secure of these barriers whilst fighting the fire. Ventilation should be possibly off, as well as exhaust fans. Fast and complete isolation of flammable materials is also a key measure to take. A fire is three-dimensional and its containment should be six-dimensional. Meanwhile the fighting strategy will vary according to the location of the fire.

The accommodation areas construction is normally almost exclusively by Class A material to face by water or soda-acid type extinguishers after having isolated the electrical circuits. Ventilation and exhaust fans can stop and fire can close. Moreover, a water spray would help achieving the maximum cooling effect.

The machinery spaces fires involve mainly Class B material requiring the use of foam type extinguishers. Only for the smallest fires, hand extinguishers are suitable. The alarm and the bridge information should be quick. Isolation of oil tanks and keeping cool them will be a primary measure.

In cargo spaces, with smoke detection and carbon dioxide flooding system the procedure requires to ensure the closure before flooding of air entry and exit points by fire dampers. A fire could also generate a high probability of explosion, as well as an independent explosion could generate a fire. The rapid use of foam and any cooling procedure of the nearby areas is strongly recommendable.

A fire outbreak requires ignition, presence of combustible material and abundance of oxygen, available in large quantities almost everywhere. Any source of air, natural or by ventilation should be possibly off.

The systems used for cargo ships have independently powered pumps, used for general service and ballast water management too, which supply engine room hydrants and the deck through the an isolating valve, always accessible from outside the machinery space to prevent loss of water from pipes in the engine room. A sea water supply system to fire hydrants fits to every ship. Several pumps in the engine room supply the system, with number and capacity dictated by legislation and technical rules..

Finally gaseous-based systems, working with stored or locally produced gases (e.g. CO_2, inert gases, halon, etc.) displaces the oxygen in the concerned spaces and thus extinguish the fires.

4 FIRES ON CARGO SHIPS: A SYSTEMATIC ANALYSIS

Despite the proven effectiveness of many measures for preventing the fire events and mitigating their effects, important fires are still a reality, also in recent years, as highlight-ed in Table 1. Therefore, a systematic analysis of the most relevant fires on cargo ships carried out with reference to the period 2008-2022, helped to identify areas of potential improvements, both in prevention and mitigation.

A worldwide systematic ad homogeneous approach to fires onboard cargo ships is not yet a reality, despite the efforts of the International Maritime Organization (IMO) and the European Maritime Safety Agency (EMSA), both actively working in this direction. Therefore, the research work referred in this paper is not result of a full systematic analysis, though identifies some good practices, such as those made available by the Japan Transport Safety Board, Marine Accident and Incident Reports [15], and Transport Malta, Marine Safety Investigation Unit [16].

Table 2 summarizes the analysed fires and explosions, having [15] [16] as main, but not exclusive, sources.The systematic analysis of the events, the identification of causes, the estimation of consequences and the highlighted recommendations pave the way to learn lessons and to identify systems able to act in the direction of risks prevention and mitigation.

5 NEW STRATEGIES AND TECHNOLOGIES FOR FIREFIGHTING

Basing on the systematic analysis of literature concerning fire accidents onboard cargo ships, the study identified some promising technologies to integrate into strategies for early detection of fires and mitigation of their effects.

Table 2. Selection of fires and explosions on cargo ships

Year	Ship	Location	Description	Consequences
2008	Pyxis (Ro-Ro)	Pacific Ocean (Japan)	Fire from cars decks	1 death
2008	Und Adriyatik (Ro-Ro)	Atlantic Ocean (Portugal)	Fire and explosion from container holds	1 death and 4 seriously injured
2012	MSC Flaminia (Container)	Atlantic Ocean (Portugal)	Fire and explosion from container holds	1 death and 4 seriously injured
2013	Taigan (Tanker)	Wakkanay port (Japan)	Fire from crew cabins	6 deaths and 3 seriously injured
2016	Eiwa Maru 3 (Tanker)	Wakayama Bay (Japan)	Explosion and fire from tanks during cleaning	1 death and 2 seriously injured
2017	Manhattan Bridge (Container)	Felixstowe port (UK)	Auxiliary boiler explosion and fire	1 seriously injured
2017	Tai Yuan (Solid bulk carrier)	Hakata port (Japan)	Fire from metals	Total loss of ship and cargoes
2020	MV Croatia (Container)	South Chinese Sea (Malaysia)	Explosion	Minor damages to cargoes
2022	Felicity Ace (Ro-Ro)	Atlantic Ocean (Portugal)	Fire from cargo holds	Major damages to ship and cargoes

The first identified solution for early detection of fires onboard ships is the fiber optic linear heat detection, an optic-mechanical linear heat detection system [17]. For a single detection system, consisting of an optical fiber and a detector unit, the cable may be many km long. The detector emits a light pulse into the optical fiber and detects reflected light returning through the cable, whose intensity, wavelength and time between emission and reflection provides information about the temperature along the cable and monitor continuously temperature distribution along the entire cable and to follow temperature variations during fire. The most common techniques for distributed temperature sensing are Raman scattering, Brillouin scattering and Fiber Bragg Gratings (FBG). Both Raman and Brillouin scattering use the temperature dependence of light scattering due to molecular vibrations within the glass core of the optical fiber. FBG are modifications of the fiber (grating), which enable reflection of a temperature depending specific wavelength from the grating itself. The gratings (temperature sensing points) can space along the cable according to the detection needs. Fiber optic heat detection has a wide range of applications, including tunnels, conveyer belts, pipelines, wildlands, aircrafts and hazardous or Electro-Magnetic Interference (EMI) in intense environments (Figure 1).

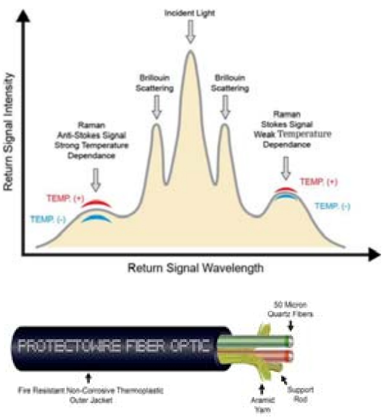

Figure 1. Typical fiber optic signals and cable

The second identified solution, promising for early detection of fire onboard cargo ships, is the thermal video camera detection, which employs camera and post-processing software. The camera can provide visual or thermal images. The detection of flames or smoke is achievable by analysing the images by motion, shape, colours, transparency, flicker and energy or boundary disorder information in the video or a combination by different spectral analysis [18] and interpreting algorithms [19]. Flame video detection is easier and more mature in terms of used technology than smoke detection, which is more appropriate for the detection of slow growing and smouldering fires. Fire detection algorithms may integrate the software normally employed for CCTV systems (Figure 2).

Figure 2. Typical view from a thermal CCTV camera

The third identified solution, promising for mitigation of effects of fires onboard cargo ships, is the use of unmanned aircrafts (drones), formally Unmanned Aerial Vehicles (UAVs). They are flying robots, remotely controlled or flying autonomously using soft-ware-controlled flight plans in its embedded systems integrated with onboard sensors and a Global Positioning System (GPS). The major reasons to use a drone are that it can reach heights that a human cannot reach, can direct properly where the target is and solve the problem, can save time and be easily handled, can be much more cost efficient than using a firefighting helicopter.

For the specific firefighting use, it should be able to carry heavy weights. At present, the multirotor drone typology SKYF looks good to carry heavy loads, such as fire extinguishers or retardants. It can carry up to a 180 kg of payload and fly for up to 8 hours. The SKYF uses the power and endurance of gasoline engines for lift and the instant torque of electric motors for control and stabilization, resulting in a heavy-lift, affordable multirotor (Figure 3) [20].

Figure 3. SKYF drone

6 IMPLEMENTATION OF FIBER OPTIC LINEAR DETECTION SYSTEM

The system is able to detect accurately the place where the fire starts and the temperature increase. In a Ro-Ro ship, the fiber optic cables position could be all over the floor of the vehicle deck according to a geometrical scheme corresponding to the parking slots (Figure 4).

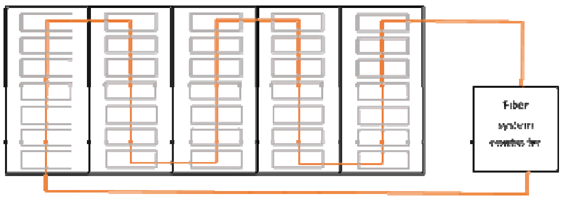

Figure 4. Scheme of the fiber optic cables layout on a deck

Wherever a parking slot would be the origin of fire, it would have an increase in temperature capable to make the signal that passes in the optic cable get variation reflected into the fiber system controller.

In general, the installation of fiber optic cables for fire detection would depend on the specific needs and requirements of the ship. In some cases, fiber optic cables could be in the cargo hold to detect fires in the cargo itself. Differently they could be on decks to detect fires that may occur in other parts of the ship, such as the engine room or living quarters. Installing fiber optic cables in multiple locations throughout the ship could provide comprehensive fire detection coverage and increase the chances of early detection and mitigation. Nevertheless, as the implementation cost is quite high, it is essential a thorough risk assessment and cost-benefit analysis to determine the optimal placement of fiber optic cables on a case-by-case basis. Moreover, the implementation of this system onboard the ships will require approval tests for the fulfillment of performances and reliability requirements. In view of the certification and validation process, a specific study allowed at identifying a preliminary sequence of tests that will include:

1. Sudden cause of smoke in a particular point due to excess of heat from a substance;
2. Overheat and fire on the deck, to ensure withstand of cable to temperature;
3. Difference of temperature in the fire origin location to identify clearance limit areas to set an appropriate system preventing undue alarms;
4. Difference between detected and manually measured temperatures;
5. Gradient of temperature over time to ensure appropriate sensibility to prevent excessive time between start of fire and detection.

The developed analysis highlighted the following advantages of fiber optic linear heat detection systems:

– Cover of a large area (up to various km) by a single detector;
– Activation time shorter than for any other heat detection technology;
– Robustness against electro-magnetic induction, dirt and dust as well as humidity;
– Uninterrupted monitoring of temperature during fire;
– High reliability thanks to rarity of false alarm for heat detection;
– Easy service thanks to the single detector;
– Manageability of high temperatures with appropriate coatings and type of fiber;
– Easy redundancy implementation: loop of fiber optic cable or second detector unit.

In parallel, the emerging potential problems are the following:

– Slow detection in comparison with other technologies: convective heat transport from fire to detector is necessary and potentially affected by existing airflows;
– Difficulties to detect smouldering fires with low heat;
– Dependence on time (some seconds delay between light pulses), quite negligible in comparison with expected detection time;
– High cost in comparison with other systems for heat detection.

7 IMPLEMENTATION OF THERMAL CAMERAS BASED DETECTION SYSTEM

For the assessment of the potential implementation of thermal cameras for early detection of fires onboard container ships, the choice was to develop a simulation of its use on an existing container ship, namely the Manhattan Bridge (Figure 5), with a capacity of 3032 TEU, involved in an important fire in 2017.

Figure 5. Manhattan bridge ship

The simulation included the virtual positioning of cameras on various decks by comparing the visibility ensured by different positions at angles of each deck (Figure 6). The best positioning demonstrated the possibility to monitor up to 608 containers (about 20% of the total load).

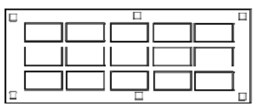

Figure 6. Schematic representation of thermal cameras on a container ship deck

As for fiber optic cable, also for thermal cameras the implementation of the system onboard the ships will require approval tests in view of certification and validation. According to the results of our research work, a preliminary set of required tests should include:

1. Geometric visibility from cameras' viewpoints to ensure the detection of the temperature or, at least the heat differential vs. the external environment;
2. Optical visibility of the camera in case of fog and smoke;
3. Increasing evolution of the temperature vs. alarm and clearance thresholds.

The developed analysis highlighted the following advantages of thermal cameras based detection systems

- Possibility to detect both smoke and flames;
- Possibility to combine with video-surveillance;
- Large area coverage by a single detector;
- Fast detection;
- Easy location and monitoring of alarmed events;
- Possible detection of hydrocarbons and H2.

Despite these advantages, emerging potential problems are:

- Uncertainties due to low level of maturity of the technology;
- Not negligible frequency of false alarm, e.g. due to heat reflections;
- Slow detection of flames, faster for smoke due to image processing needs;
- Possible accidental obstructions of viewing field;
- Hard detection of smoke in poor light conditions;
- Potential effects of weather conditions on flames detection;
- Sensibility to contamination of detector lens or window.

8 IMPLEMENTATION OF DRONES FOR FIRE EXTINCTION

The most feasible implementation of drones as a firefighting system was in two potential operational configurations:

- Installing a fire extinguisher onboard the drone;
- Connecting a long tube from a fire retardant tank (Figure 7), if compatible with the surrounding temperature that could damage the tube.

The use of drones for firefighting purposes is not completely new, as drafted in [21] and recently developed in [22], nevertheless, for the specific applications onboard container ships the key test required to ensure the performances of the methodology will focus on the determination of:

1. Maximum wind force and speed compatible with its flight;
2. Highest temperature compatible with the full operation by batteries or fuels.

The most relevant advantages identified for this solution are:

- Acquisition of information not available from other sources (e.g. from the top of the fire);
- Better visibility thanks to the possibility to bypass critical angles;
- Acquisition of real time situational data;
- Safety of pilots that can operate from a remote location.

Meanwhile, potential negative aspects are:

- High operational cost;
- Need of regular calibration of remote control systems, even if not used;
- Need of training for the pilots.

Figure 7. Drone connected with a pipe used for firefighting on a building

9 CONCLUSIONS AND NEXT RESEARCH DEVELOPMENTS

The identified methodologies demonstrated potential ability to detect and fight the fire thanks to consolidated technologies applied to the specific context of cargo ships. With reference to fires and explosions listed in Table 2, a systematic analysis identified that the systems based on fiber optic cables and thermal cameras would have played an important role for earlier detection of fire in the large majority of them, as summarized in Table 3.

Table 3. Potential role for early detection of fire by fiber optic cables and thermal cameras in re-cent fires onboard cargo ships

Year	Ship	Description	Potentially useful innovative detection systems
2008	Pyxis (Ro-Ro)	Fire from cars decks	Fiber optic cables
2008	Und Adriyatik (Ro-Ro)	Fire and explosion from container holds	Fiber optic cables
2012	MSC Flaminia (Container)	Fire and explosion from container holds	Thermal cameras
2013	Taigan (Tanker))	Fire from crew cabins	Thermal cameras
2016	Eiwa Maru 3 (Tanker)	Explosion and fire from tanks during cleaning	No
2017	Manhattan Bridge (Container)	Auxiliary boiler explosion and fire	Thermal cameras
2017	Tai Yuan (Solid bulk carrier)	Fire from metals	Thermal cameras
2020	MV Croatia (Container)	Explosion	Thermal cameras
2022	Felicity Ace (Ro-Ro)	Fire from cargo holds	Fiber optic cables

Therefore, these technologies seems to be ready for the integration into technical normative and the crewmembers training programmes for fire safety onboard cargo ships.

In particular, as anticipated for each introduced technological solution, the present study:

1. Verified the applicability and the potential effectiveness of the solutions for detecting and mitigating fires on cargo ships, by identifying the happened accidents where they could have played a key role;
2. Identified the further tests required to fulfil the requirements in terms of Reliability, Availability and Maintainability (RAM) to proceed towards recognized acceptance and certification;
3. Identified the main potential advantages and problems in a full-scale commercial implementation, which are the basis of deeper cost-benefit analyses finalized to identify the recommended most appropriate application fields for each solution at lifecycle level.

Moreover, next research developments should focus on:

– The integration of these systems, as also discussed in [23], into the increasingly diffused systems storing information on containers and ships before and during their trips. It would help to select the most appropriate firefighting systems after the first detection of a fire taking into account, among others, ship architecture, navigation and meteo conditions as well as typology of trans-ported goods;
– The comparison of the most appropriate suitable solutions basing on cost-efficiency evaluation, taking into account methodologies and assumptions setup by EMSA CARGOSAFE Report [4].

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