Journal of Advanced Marine Engineering and Technology, Vol. 48, No. 4, pp. 235~251, 2024
J. Advanced Marine Engineering and Technology (JAMET)
https://doi.org/10.5916/jamet.2024.48.4.235

ISSN 2234-7925 (Print)
ISSN 2765-4796 (Online)
Original Paper

Lightning risks and mitigation solutions for vessels

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(Received June 5, 2024 ; Revised July 19, 2024 ; Accepted August 15, 2024)

Abstract: The risk of economic loss, loss of human life, and permanent and serious injuries due to lightning strikes is prevalent across all industries and market sectors. Recreational, commercial and defence vessels and their occupants are no different except that, in some cases, these vessels are in remote locations on the sea where failures and fires from lightning strikes can seriously compromise safety onboard or be catastrophic. This paper provides a unique quantitative analysis of the risks posed by lightning on vessels, vessel assets, and their personnel. The methodology used is based on the risk calculations described in lightning protection standards, adapted to the special features of vessels. The paper describes the physical damage that is known to occur when lightning strikes vessels directly or indirectly and then provides a comprehensive mitigation approach that can be used to minimise losses due to lightning. This four-step mitigation approach comprises direct-strike protection, surge protection, earthing and bonding, and personal protection (for situations where personnel are at risk). A generic and practical lightning protection solution is provided for all types of vessels using some of the outcomes of the latest international research on lightning protection and extensive experience over many years.

Keywords: Lightning risk, Lightning damage, Lightning protection, Vessels, Maritime safety

1. Introduction

Thousands of thunderstorms are in progress at any given time throughout the world, resulting in tens of millions of lightning strikes to Earth each year **[1]**. Climate change modelling shows that global lightning activity is predicted to increase by about 12% for every degree of rise in global average air temperature **[2]**, so the frequency and severity of thunderstorms is also increasing.

Whilst total lightning activity over bodies of water (oceans, lakes and rivers) is typically less than the activity over the same area of land, there are several aspects of thunderstorms over water that make lightning extremely dangerous. For example:

(a) Pre-strike electric fields are 4-5 times larger over water than over land **[3]**.

(b) Lightning strikes are more intense over oceans **[4]**.

(c) Isolated objects on water, such as ships, become the most likely strike point for lightning due to the lack of competing points that initiate upward leaders – a key element of the lightning attachment process that determines the strike point **[5]**.

(d) The isolation of being at sea means that equipment in vessels is "mission critical" and injuries to occupants is more "catastrophic".

(e) Lightning strike density in shipping lanes is higher than similar yet relatively unnavigated areas of the ocean **[6]**.

In point (a), the measure of "intensity" depends on the method of observation, e.g., optical vs radio sensors at ELF, VLF, and VHF. However, lightning flashes over oceans have larger currents, longer durations, and are brighter than flashes over land **[4]**. Also, Holzworth *et al.* **[7]** found "superbolts" with energies that are 3σ above the mean occur predominantly over oceans.

In point (b) and leading into point (c), unlike structures on land, any vessel on water presents as a very likely strike point in a thunderstorm due to its electric field enhancement with little "competition" from adjacent points. When lightning enters a vessel, it tries to find a low-impedance path to the water. Hence, it will damage whatever comes between it and the water.

Damage commonly seen in lightning strikes to vessels include:

- Electrical failures – electrical components such as the battery, refrigeration controls, air conditioning, instruments, sensors, and controls.
- Mast damage – particularly sailboats with non-metallic masts.
- Hull problems – particularly those made of fibreglass, but a hole in any hull is possible.

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- Catastrophic events – lightning is well-known to start fires on unprotected vessels.

Of course, personnel safety is also compromised because there is a risk of death or serious injury.

With regard to point (d), interactions between ships and atmospheric electricity have been observed and recorded for thousands of years. However, Thornton *et al.* **[6]** analysed 12 years of high-resolution global lightning stroke data from the Worldwide Lightning Location Network (WWLLN) and found that lightning strike density is enhanced by up to a factor of two directly over shipping lanes in the northeastern Indian Ocean and the South China Sea in comparison to adjacent areas with similar climatological characteristics. These authors hypothesised that the increase is due to emissions of aerosol particles.

In a recent study, Petersen **[8]** has expressed a contrasting hypothesis regarding the lightning enhancement found by Thornton *et al.* **[6]**, namely that tall objects in high electric field environments are known to initiate lightning. Hence, the alternate explanation for the lightning enhancement is that tall, well-grounded ships may be facilitating lightning production – particularly in storms that are near the tipping point between remaining "electrified shower clouds" and becoming thunderstorms.

Regardless of which hypothesis is more likely, the fact remains that lightning activity along shipping lanes is double what it would be for similar but relatively unnavigated waters. This fact implies that the risk of a lightning incident is double what it would normally be over water.

The main points and research addressed in the remainder of this paper are (i) the author's quantitative lightning risk analysis for vessels and their personnel, using a tailored approach that combines traditional methods presented in standards as well as newer methods, (ii) a review of the type and extent of damage that occurs on vessels as a result of lightning strikes, and (iii) a step-by-step outline of a systematic lightning protection strategy to mitigate the risks and losses due to lightning.

2. Lightning Risk Analysis

The aim of this section of the paper is to present some calculations of the risks posed by lightning when vessels encounter or operate in thunderstorms. Lightning is an external electrical hazard that adds to the common electrical accidents and incidents that can occur due to internal electrical faults on vessels. A simple event tree diagram of the hazards posed by lightning on vessels is shown in **Figure 1**. On this basis, the paper emphasises the need to assess and mitigate the risks associated with lightning strikes to ensure the safety of vessels and their occupants.

Much of the equipment in vessels at sea is critical. Damage to this equipment due to lightning strikes can lead to the loss of electrical power supply, propulsion, and navigation control. The paper underscores the severe risks posed by fire hazards resulting from arcing and sparking events on vessels, which can be triggered by lightning strikes. Navigation accidents can occur, since steering, navigation radar, fire pumps, and engine controls are highly critical equipment that are sensitive to electrical surges. Lightning is a common cause of such effects, hence the importance of dealing with it appropriately. Critical equipment onboard cannot usually be substituted, so once it catches fire, total loss of vessel control and an accident becomes inevitable.

Despite the importance of assessing lightning risks to vessels, there is limited availability of published literature on lightning risks specific to vessels. Hence, more research and analysis are needed in this area to better understand and address lightning risks in the maritime industry. However, Nicolopoulou *et al.* **[9]** have undertaken such a study. These authors calculated the expected number of lightning strikes on three ship models with comparative application of various lightning attachment models and stroke current distributions. They found that, in coastal areas, a ship is expected to be struck by lightning approximately every two years. These authors also proposed a new method for lightning protection of critical masts on ships that combines a shielding analysis procedure and a statistical lightning interception model. This aspect will be addressed in Section 4 of the paper.

The scarcity of literature on this topic emphasises the importance of assessing lightning risks to vessels due to the critical nature of onboard equipment and the potential catastrophic consequences of lightning-induced accidents. Proper assessment and mitigation of lightning risks are crucial for maintaining operational efficiency and ensuring the safety of personnel onboard vessels.

2.1 Study Assumptions

The lightning risk study needs to encompass a practical range of vessel sizes (and heights) and allow for the wide range of lightning activity encountered around the world.

Table 1 shows the range of vessel dimensions included in the lightning risk study. Separate risk calculations will be made for each vessel category in **Table 1**.

Lightning activity is typically expressed as a "ground flash density" (GFD), in units of ground flashes per square km per year. GFD over land ranges from about 0.5 to more than 30 flashes/

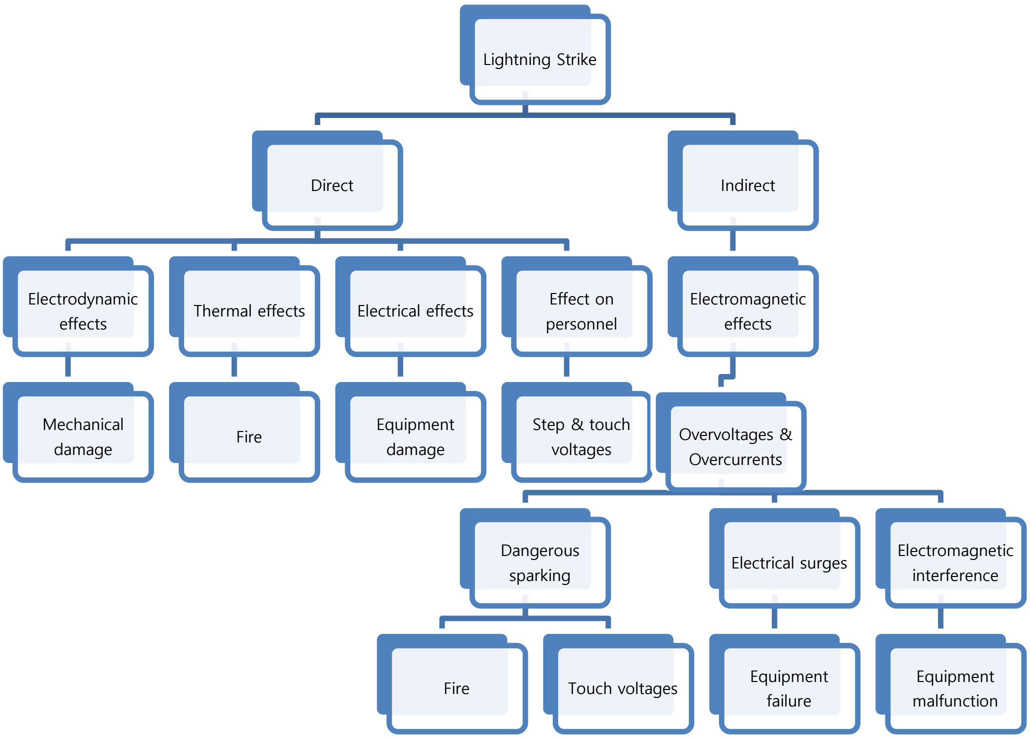

Figure 1: Generic event tree diagram for lightning hazards on vessels. This diagram assumes personnel are not so exposed that they would be struck directly, the consequence of which may be death

km^2/yr. A NASA map of world lightning activity is shown in **Figure 2**.

Table 1: Range of vessel types and sizes assumed for the lightning risk calculations. The parameters L, W and H are the vessel's overall length, beam width and height above the waterline ("freeboard") *to the highest point*, respectively. The latter (H) is a key parameter for estimating lightning strike risk

Vessel Type	L (m)	W (m)	H (m)
Small recreational boat	10	3	3
Sailing yacht (maxi)	30	5	45
Superyacht	50	10	20
Navy / Coastguard Patrol Boat	60	10	25
Navy Frigate	120	15	35
Navy Destroyer	150	20	55
Navy Amphibious Assault Ship	230	30	65
Small Cruise Ship	80	15	15
Cargo (Handymax)	150	30	30
Cargo (Bulk Carrier / Tanker) & Large Cruise Ship	300	40	60

Mackerras *et al.* **[1]** estimated that the ratio of the mean global land-to-ocean total flash density is about 3.4. Hence, a reasonable range of GFD for lightning over bodies of water or oceans is 0.1 to 10 flashes/km^2/yr. This range will be used for the lightning risk analysis. Note that lightning activity in littoral (shoreline / coastal) areas is likely to be somewhere between the land and ocean values.

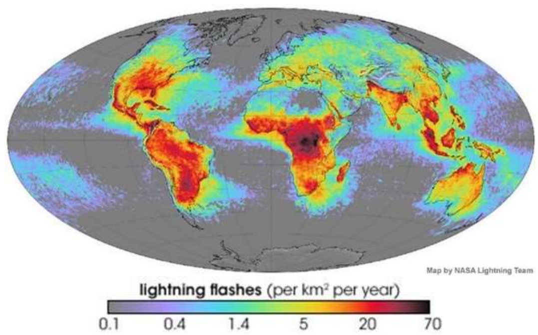

Figure 2: World Lightning Map produced by NASA's Lightning Imaging Sensor on the Tropical Rainfall Measuring Mission satellite between 1995 and 2002. The map shows the average ground flash density in units of lightning flashes to Earth per square kilometre per year.

2.2 Lightning Collection Area

A "first-principles analysis" can be used to estimate the lightning "collection area" (A_e) of the vessels listed in **Table 1**. The simple principles outlined in lightning protection standards **[10][11]** can be used for this purpose. However, additional methods will also be used for comparison purposes.

In simple terms, the risk estimate can utilise the "3H rule" per the above standards if the "structure" can be approximated by known dimensions with an equivalent height. For an isolated, "equivalent rectangular structure" of length L, width W, and height H (in metres) on flat ground (but in the present study, "on the water"), the lightning collection area is given by:

$$A_e = L\,W + 6\,H\,(L + W) + 9\,\pi\,H^2 \tag{1}$$

For a ground flash density (GFD), the number of cloud-to-ground lightning flashes per year (N_D) in a given collection area is given by:

$$N_D = GFD\,.\,A_e \tag{2}$$

Note that this:

- Formula is geared towards providing an average value to be expected over a long period of time. Since lightning has a highly random nature, over shorter periods of time there may be more or less flashes than the number estimated with this formula.
- Calculation must be performed for the GFD range established in Section 2.1, i.e., 0.1 to 10 flashes/km^2/yr.

A more fundamental way in which to determine exposure area is via the use of the "striking distance" (d_s) or "attractive radius" (R_a) of the vessel. Hence, additional calculations will also be performed using this concept and the results compared with the 3H rule.

The rolling sphere method (RSM) described in standards **[10][11]** can be used to obtain the striking distance, which comes from an empirical formula describing the simple "electrogeometric model" (EGM), namely:

$$d_s = 10\,I_p^{0.65} \tag{3}$$

where I_p is the prospective lightning stroke current (which, in turn, is related to the charge on the downward leader).

On the other hand, the more analytical and rigorous studies of researchers, e.g., **[12]-[16]**, readily provide estimates of the attractive radius. The Rizk **[14]-[16]** formula for a structure height *H* is given by:

$$R_a = 25.9\,H^{0.48} \tag{4}$$

In the analysis that follows, the simple EGM and the Rizk formulae will be used to estimate collection area.

In general, formulae such as those above require the lightning stroke current. The use of a median stroke current (around 30 kA) is not representative of the complete log-normal distribution of stroke current amplitudes. Hence, a representative value of the stroke current must be based on the integral of the probability density function for the current amplitudes to give the probability-weighted average collection area. Such an analysis was carried out in **[17]**. It was found that the mean (weighted) stroke current is approximately 40 kA. Consequently, 40 kA will be used in the EGM calculation. Note that the Rizk formula already considers the probability density function of stroke currents, so this parameter is not needed for direct input into **Equation (4)**.

2.3 Lightning Incidence Calculations

Tables 2 and **3** present the results of the lightning incidence calculations made for the different vessels listed in Table 1, using the simple 3H, EGM and Rizk methods. As can be seen, different methods give different results, with no clear trend to choose just one method. Given these variations, the mean value of all three methods was used to progress to the probability calculations.

Table 3 shows the mean time between flashes to the range of vessel categories included in the risk analysis. Generally speaking, direct strikes to vessels can be expected once every year to few years in higher lightning areas, and once every hundred to several years for low lightning areas.

2.4 Probability Calculations

The previous section quantified the likelihood of lightning flashes to vessels. Attention now turns to the consequences of those strikes. Broadly speaking, lightning can cause equipment / operational / economic damage and can even start fires, particularly but not limited to vessels carrying flammable or explosive materials. These aspects are addressed in Section 3 of the paper. In this and the next sub-section of the paper, the focus will be on *personnel hazards* due to lightning strikes.

The probability of occurrence of a potentially hazardous lightning incident involving a person on a vessel is given by:

$$P_{incident} = P_{strike} \times P_{exposure} \tag{5}$$

where $P_{incident}$ is the probability of an incident that may involve a person during a thunderstorm, P_{strike} is the probability of a direct lightning flash to the vessel and $P_{exposure}$ is the probability that someone will be in an exposed or dangerous position at the instant of a lightning flash to the area.

Table 2: Lightning incidence calculations for the vessels listed in Table 1, using the "simple 3H", "electrogeometric model" and Rizk analytical formulae. These calculations assume the exposure time is 365 days per year. The range of the results corresponds to the assumed GFD range, i.e., 0.1 – 10 flashes/km^2/yr

Vessel Type	Lightning Incidence Range (flashes/yr)		
	3H Rule	EGM	Rizk
Small recreational boat	0.0001 – 0.0052	0.0038 – 0.3800	0.0006 – 0.0605
Sailing yacht (maxi)	0.0067 – 0.6686	0.0038 – 0.3800	0.0081 – 0.8144
Superyacht	0.0019 – 0.1901	0.0038 – 0.3800	0.0037 – 0.3739
Navy / Coastguard Patrol Boat	0.0029 – 0.2877	0.0038 – 0.3800	0.0046 – 0.4632
Navy Frigate	0.0065 – 0.6479	0.0038 – 0.3800	0.0064 – 0.6398
Navy Destroyer	0.0145 – 1.4463	0.0038 – 0.3800	0.0099 – 0.9874
Navy Amphibious Assault Ship	0.0228 – 2.2776	0.0038 – 0.3800	0.0116 – 1.1592
Small Cruise Ship	0.0016 – 0.1611	0.0038 – 0.3800	0.0028 – 0.2837
Cargo (Handymax)	0.0062 – 0.6235	0.0038 – 0.3800	0.0055 – 0.5518
Cargo (Bulk Carrier / Tanker) & Large Cruise Ship	0.0236 – 2.3619	0.0038 – 0.3800	0.0107 – 1.0734

Table 3: Mean time interval between lightning flashes (MTBF) to the vessels, using the mean lightning incidence from the three methods investigated. Once again, the range of the results corresponds to the assumed GFD range, i.e., 0.1 – 10 flashes/km^2/yr, to which each vessel may be exposed.

Vessel Type	MTBF Range (yrs)
Small recreational boat	673 – 6.7
Sailing yacht (maxi)	161 – 1.6
Superyacht	318 – 3.2
Navy / Coastguard Patrol Boat	265 – 2.7
Navy Frigate	180 – 1.8
Navy Destroyer	107 – 1.1
Navy Amphibious Assault Ship	79 – 0.8
Small Cruise Ship	364 – 3.6
Cargo (Handymax)	193 – 1.9
Cargo (Bulk Carrier / Tanker) & Large Cruise Ship	79 – 0.8

The values for P_{strike} for the vessel have already been obtained (see **Table 2**). These values are based on 24 hours-per-day, 365 days-per-year collective exposure to lightning.

The values for $P_{exposure}$ are based on behavioural patterns that may vary during a 24-hour period or from day to day. The worst-case scenario would be personnel exposure on a vessel for 24 hours-per-day, 365 days-per-year, but this extreme may not be realistic. Hence, 50% of this exposure time is assumed for the probability calculations.

The probability calculations are shown in **Table 4**.

Table 4: Estimated probability of a personnel incident occurring on a vessel under the assumptions stated and for the assumed GFD range of 0.1 – 10 flashes/km^2/yr.

Vessel Type	P_{strike} (yr^{-1})	$P_{exposure}$	$P_{incident}$ (yr^{-1})
Small recreational boat	0.0015 – 0.1486	0.5000	0.0007 – 0.0743
Sailing yacht (maxi)	0.0062 – 0.6210	0.5000	0.0031 – 0.3105
Superyacht	0.0031 – 0.3147	0.5000	0.0016 – 0.1573
Navy / Coastguard Patrol Boat	0.0038 – 0.3770	0.5000	0.0019 – 0.1885
Navy Frigate	0.0056 – 0.5559	0.5000	0.0028 – 0.2780
Navy Destroyer	0.0094 – 0.9379	0.5000	0.0047 – 0.4690
Navy Amphibious Assault Ship	0.0127 – 1.2723	0.5000	0.0064 – 0.6361
Small Cruise Ship	0.0027 – 0.2749	0.5000	0.0014 – 0.1375
Cargo (Handymax)	0.0052 – 0.5184	0.5000	0.0026 – 0.2592
Cargo (Bulk Carrier / Tanker) & Large Cruise Ship	0.0127 – 1.2718	0.5000	0.0064 – 0.6359

2.5 Personnel Risks on Vessels

According to IEC 62305-2 [10], the risk component related to injury of human beings, R_A, is given by:

$$R_A = N_D \times P_A \times L_A \qquad (6)$$

where:

- N_D is the flash incidence given by **Equation (2)**,
- P_A is the probability that the lightning flash will cause an injury to human beings via one of the mechanisms outlined in the literature, e.g., Cooper *et al.* **[18]**, typically some form of electric shock, or a trauma incident

such as acoustic shock wave, e.g., Gluncic *et al.* **[19]**, and

- L_A is the "consequent loss" (of human life) or serious injury, which depends on the proportion of people present and at risk, and the amount of exposure time.

If an ALARP risk approach is taken, then the maximum probability for P_A must be used, i.e., 1.0. On the other hand, lower values can be used if justified, e.g., where extensive lightning protection measures are provided. In this analysis, it will be assumed that no lightning protection measures are in place.

With regard to N_D and L_A, the probability calculations in **Table 4** have already taken into account the former and part of the latter (via the exposure time). However, L_A is more rigorously defined as follows:

$$L_A = r_t \times L_T \times (t_z / 8760) \quad (7)$$

where r_t is a "loss reduction factor" that depends on the type of soil or flooring, L_T is the is the typical mean percentage of persons injured by a lightning flash, and t_z is the time in hours per year for which the persons are present in the area of interest.

Standards **[10][11]** suggest a value of 0.01 for L_T *if the person is in some form of structure or shelter* when the incident occurs. For people on the deck of a vessel, this scenario is not applicable. Such people may also be adjacent to a structural element of the vessel and hence at risk of a side-flash. The exact value to use in this case is difficult to estimate as the international literature, obviously, tends to focus on deaths and injuries rather than, for example, "near misses" with no injuries. However, according to Ritenour *et al.* **[20]**, up to 80% of people involved in a lightning incident receive some form of injury. Hence, a conservative value of 0.8 will be used.

With regard to r_t, **Table C.3** from IEC 62305-2 **[10]** is used, where the value of r_t ranges from 10^{-2} for the most conductive surfaces to 10^{-5} for materials with a high voltage withstand. As personnel on vessels will often be standing on metallic surfaces, a value of 10^{-2} must be used.

Individual (single person) risks were computed using the guidelines above. These risks are shown in **Table 5**, noting that they are all "per person" risks. Hence, for *N* people exposed to lightning, the risks in **Table 5** should be multiplied by *N*.

Standards **[10][11]** typically nominate 1.0×10^{-5} yr^{-1} as a "tolerable" lightning risk for loss of human life or serious injury. Comparing this value with the calculations summarised in **Table 5**, the ***personnel risk is seen to be intolerable for the majority of vessel types across the range of typical lightning activity encountered over bodies of water***.

Table 5: Outcome of lightning risk calculations (annualised) that are applicable to persons aboard vessels. The values shown are applicable to a **single person at risk**, i.e., they are "per person" risks. As before, these risks were calculated for an assumed GFD range of 0.1 – 10 flashes/km^2/yr

Vessel Type	**Risk Range for Individuals (yr^{-1})**
Small recreational boat	5.94×10^{-6} – 5.94×10^{-4}
Sailing yacht (maxi)	2.48×10^{-5} – 2.48×10^{-3}
Superyacht	1.26×10^{-5} – 1.26×10^{-3}
Navy / Coastguard Patrol Boat	1.51×10^{-5} – 1.51×10^{-3}
Navy Frigate	2.22×10^{-5} – 2.22×10^{-3}
Navy Destroyer	3.75×10^{-5} – 3.75×10^{-3}
Navy Amphibious Assault Ship	5.09×10^{-5} – 5.09×10^{-3}
Small Cruise Ship	1.10×10^{-5} – 1.10×10^{-3}
Cargo (Handymax)	2.07×10^{-5} – 2.07×10^{-3}
Cargo (Bulk Carrier / Tanker) & Large Cruise Ship	5.09×10^{-5} – 5.09×10^{-3}

3. Physical Damage

3.1 Background

Apart from the personnel risks on vessels due to lightning as calculated in Section 2, structural elements of vessels and sensitive and/or critical equipment onboard can be damaged in lightning storms. Such incidents can pose serious consequences for operational integrity and safety at sea. Furthermore, the magnitude of charge or current delivered by a lightning strike can lead to fires onboard, especially if explosive or flammable materials are being transported. Such fires can be uncontrollable out at sea, e.g., if fire-fighting equipment is out of service after the strike.

Aside from structural damage to prominent items such as masts, towers, bridges, antennas, tanks, and hulls, typical items of critical equipment on vessels that can be damaged by direct (full or partial) lightning currents and induced surges from the extreme electromagnetic field of the return stroke(s) of a nearby lightning flash include:

- Navigation systems,
- Control systems, instruments and sensors,
- Communication systems,
- Power supply and its backup,
- Motors, and
- HVACR.

Such equipment operates at relatively low voltages and hence any surge or "overvoltage" in the electrical lines connecting to them can cause severe damage. Even if there is no damage, surges can result in errors in communication signals that subsequently cause operational problems or pose risks to navigation safety.

3.2 Marine Insurance Statistics

Perhaps unsurprisingly, there is very little published (public) information available on insurance claims and statistics around lightning damage to vessels. According to BoatUS*, an analysis of 10 years of marine insurance claims on smaller vessels has revealed which ones are most at risk. They found that more lightning damage occurred to taller vessels than lower ones, e.g., sailboats have significantly more lightning claims than powerboats (ranging from 0.1 to 6.9 damage claims out of every in 1000 boats). Also, larger boats have more lightning claims than smaller ones (6 per 1000 boats in the 12-20 m class). Importantly, almost all of the insurance claims included damaged electronics. This aspect is discussed further in Section 3.3.

In terms of the losses in the smaller vessel category addressed above, Salway **[21]** states that lightning has a big impact on modern watercraft. Losses that used to be around US$250,000 are now approaching US$1 million due to the sophisticated electronics and equipment aboard. This author states that "as an industry, we are experiencing strikes in regions where we haven't seen them before".

Analysis of insurance industry loss data by Allianz Global Corporate & Specialty **[22]** uncovered 1269 claims from lightning strikes in the marine and aviation† transportation sector over a 5-year period. The cost of damage claims was around €110 million.

3.3 Surges from Direct and Indirect Lightning Strikes

As stated by Nicolopoulou *et al.* **[23]**, even though metallic vessels have been deemed to be somewhat "self-protecting" due to the conductive nature of the hull, electrical equipment within the vessel is subjected to extremely high values of electromagnetic radiated field and to portions of the injected lightning current. Hence, the "surge immunity" of naval equipment is essential for the reliable operation, e.g., of vital communication and navigation systems. For vessels with non-metallic hulls, the electromagnetic environment is even more harsh when lightning strikes the vessel.

In both cases above, lightning does not have to strike the vessel directly to impose large surges (or "lightning induced overvoltages") on the conductive lines connecting equipment within the vessel. The frequency of these "indirect strikes", i.e., those striking the water nearby or a land object when the vessel is docked, is much higher than direct strikes. Hence, the probability of damage to vulnerable equipment is even higher than the risks to personnel that were calculated in Section 2.5.

Nicolopoulou *et al.* **[23]** carried out a computational study on a full-scale, metal-hulled bulk carrier struck by lightning. They simulated the direct strike with a standardised, first negative lightning stroke of 100 kA with a waveshape of 1/200 μs and allowed computation of the electromagnetic field of the lightning channel with a "perfect electric conductor" model. These authors modelled a realistic electric network within the vessel, including loads such as lighting, navigation and control equipment, communications, propulsion, etc.

It was found that the induced overvoltages at the bridge equipment exceed the withstand voltage of the equipment, i.e., equipment would likely be damaged without protection. Whilst some shielding of the electromagnetic field was seen below deck, conducted overvoltages were found to be transferred into the interior of the hull in some locations.

In summary, equipment at positions close to openings, such as the bridge control room, is severely exposed to the lightning electromagnetic field and to the highest values of overvoltages across the interior of the hull structure. Furthermore, cases of external cable routes such as coaxial cables of antenna masts and cable shields bonded to the hull are subject to direct conduction of the lightning current that results in the withstand voltage of the equipment being exceeded. Nicolopoulou *et al.* **[23]** conclude that the use of shielded cables and the proper installation of surge protection devices (SPDs) are the most efficient methods to prevent the consequences of a lightning strike within the electric network of a vessel.

4. Mitigation Solutions

Earlier sections of the paper have described the risks posed by lightning to personnel and marine vessels. In most cases, the

* BoatUS, 2014, online article at: https://www.boatus.com/expert-advice/expert-advice-archive/2015/january/striking-lightning-facts.

† The aviation sector had 339 claims out of the 1269 claims.

lightning risks are intolerable, so mitigation measures need to be put into place.

This section of the paper briefly describes the historical developments behind the protection of marine vessels, provides a generic, comprehensive, four-step approach to lightning protection, and then focuses on the specific lightning protection measures needed on marine vessels to mitigate the risks to tolerable levels.

4.1 Historical Approaches

Benjamin Franklin is recognised as the inventor of the lightning rod in 1752. According to Bernstein & Reynolds **[24]**, soon after Franklin's invention, a lightning protection system was devised for ships of the Royal Navy which used a chain conductor draped into the sea from the top of the mast. This system had only limited success because the chain, raised only when lightning was expected, often was not in place when lightning struck, it interfered with personnel manning the rigging, and was not capable of conducting some lightning strokes without damage to itself or the ship.

In Great Britain, around 220 Royal Navy ships were lost or damaged by lightning strikes during the Napoleonic wars of 1803 to 1815. In 1820, Harris **[25]** invented a system of fixed lightning conductor plates which were routed along the aft side of the mast down through the hull to the copper sheathing on the bottom of the ship. He spent the next two decades trying to persuade the British Admiralty to test his system and require its installation. Harris faced old prejudices, notions of economy, and bureaucratic suspicions of technological innovation. It took a successful trial installation on eleven ships, an extensive campaign by Harris to publicise the extent of lightning damage to the navy, the favourable recommendations of two study committees, and administrative changes in the Admiralty before the Royal Navy finally adopted his approach in 1842. In contracts, by this time, the Imperial Russian Navy had already adopted the proposed lightning protection system.

However, to put everything into perspective, very little progress was made in understanding the properties of lightning until the late 19th century, which is when photography and spectroscopic tools became available as diagnostic tools in lightning research [26]. The work of Wilson in England in 1916, and Schonland et al in South Africa in the 1930s, kicked off the 20th century international research on lightning. Since that time, a lot more has been learnt about the characteristics and effects of lightning and how to mitigate it. These studies are still continuing today.

4.2 Comprehensive Approach to Lightning Mitigation

This section of the paper describes proven measures to reduce asset and personnel risks due to lightning strikes. Note that it is not possible to completely eliminate the risk of loss due to lightning and this is why there are internationally accepted "tolerable risk" values. However, a large reduction in the risk can be achieved via a systematic and comprehensive approach to lightning protection that considers the major damage mechanisms and potential losses due to lightning.

At an overview level, the conceptual graphic shown in **Figure 3** summarises the comprehensive approach that needs to be taken to minimise losses due to lightning. This approach is comprised of four key steps:

I. Protect critical assets against direct lightning strikes.
II. Protect electrical and electronic equipment against surges and transients.
III. Provide a low impedance reference earth / ground and bond all conductive elements to minimise voltage differences.
IV. Protect people.

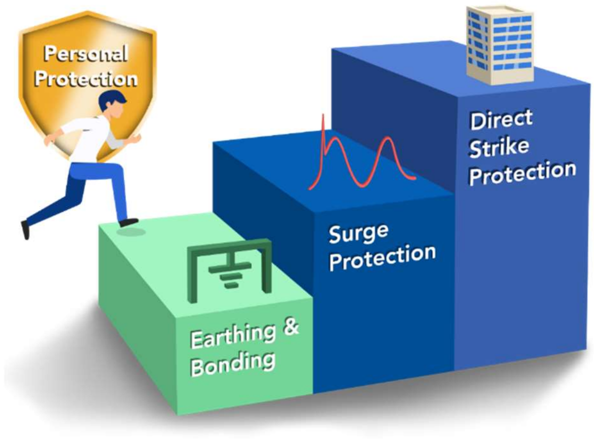

Figure 3: Conceptual graphic summarising the four key steps that need to be implemented to reduce the risk of losses due to lightning to tolerable levels (reprinted with permission from Lightning Protection International Pty Ltd).

This approach is applicable across all industry sectors, e.g., agriculture, aviation, marine, commercial, industrial, and recreational buildings and facilities, cultural, defence, mining, petrochemical / oil & gas, power & renewables, communications, transportation and utilities. It is applicable to any system, structure (including vessels), site or facility in which maintaining operational efficiency, minimising losses, and keeping personnel safe is necessary or important.

The remainder of this section provides more details on each step as it applies to vessels.

4.2.1 Step I – Protection Against Direct Strikes

Step I involves the capture of lightning strikes with “air terminals” (sometimes called “lightning rods” or “air terminations”). Air terminals must be strategically positioned at high-risk points to minimise the possibility of lightning bypass, a process sometimes called “shielding”. Some of the key points in Step I include:

- Effective shielding depends on the protection area provided by each air terminal and the positioning of the air terminal(s) to achieve the desired “interception efficiency” or “lightning protection level” (LPL).
- Both of these aspects must be taken into account by the “lightning protection design method” that is used. In general, the tallest and most exposed points on a vessel are the most vulnerable to a direct strike, so the correct installation of air terminals near or on these vulnerable points is a key element of Step I.
- The lightning current must then be carried down to ground in a safe manner with “downconductors”, away from sensitive equipment and personnel. Hence, the prevention of dangerous sparking between the downconductors and internal conductive components (conduits, pipes, equipment chassis, incoming and outgoing conductors, etc.) is essential. Dangerous sparking between different parts can be avoided by means of “equipotential bonding” or electrical insulation between the parts.
- Hence, there are generally two application methods and, consequently, two types of downconductors used, namely:
  - (i) Protection by “equipotential bonding”, utilising bare downconductors or the “natural components” of the vessel, and
  - (ii) Protection by “isolation”, either utilising insulating materials (as in the case of insulated downconductors) or a suitable air gap or “separation distance”. **Equation (8)** is a simple way of calculating the separation distance, s in metres **[10][11]**:

$$s = \frac{k_i k_c}{k_m} l \tag{8}$$

where l = longest length of the downconductor path to ground with no equipotential bonding point in metres, k_i is 0.08, 0.06 or 0.04 for LPL I, II or III/IV respectively, k_c is 1.0, 0.66 and 0.44 for 1, 2, and ≥ 3 downconductors, and k_m is 1.0 or 0.5 for air or concrete / bricks / wood respectively.

4.2.2 Step II – Protection Against Surges and Transients

Step II is required to mitigate overvoltages, surges and transients due to lightning, as discussed in Section 3.3. Such overvoltages can damage or destroy primary and secondary electrical / electronic equipment within a vessel. This so-called “surge protection” is achieved via the use of “surge protection devices” (SPDs).

There are many aspects to consider with the application of SPDs. A brief summary of the main aspects of this vast topic includes the following key points:

- The aim is to limit residual voltages to within the immunity level (or withstand voltage) of the internal equipment.
- Surge protection technologies can generally be classified into two categories, namely “shunt SPDs” and “surge filters”, which are parallel and series protection devices respectively.
- Electrical line being protected – power vs signal / data / communications will determine the type of SPD required.
- Primary (or “point-of entry”) vs secondary protection – the former needs to be more robust to deal with larger overvoltages and the latter needs to cater for sensitive equipment “down the line”.
- Some of the parameters that need to be considered when selecting SPDs include:
  - Maximum Continuous Operating Voltage (MCOV) – a major safety consideration, e.g., prevention of fires.
  - Clamping voltage – to protect the downstream equipment.
  - Surge rating or line current – ability of the SPD to handle surge current (typically given in kA).
  - Protection modes – Line-Neutral (L-N), Line-Earth (L-E), Neutral-Earth (N-E), Line-Line (L-L).
  - Indication and life – older SPDs use indicator LEDs, whereas “smart SPDs” based on Bluetooth and other wireless technologies are now revolutionising this aspect of SPD maintenance and service **[27]**.

- Transients induced onto data, communication and signal lines can easily damage and destroy sensitive terminal equipment and hence lead to down-time. Protection of communications equipment requires the same concepts as those noted above, such as:
    - SPDs for sensitive equipment are typically multi-stage or series-connected devices with much lower operating currents and voltages. These SPDs are installed at the point of entry to the structure or at the equipment termination itself.
    - Internal wiring that extends more than 10-15 m should also be protected. Twisting or shielding of cables provides some protection. However, this practice should not be regarded as sufficient for the sensitive interfaces that characterise modern communication devices.

4.2.3 Step III – Provision of Good Earthing and Bonding

Step III is fundamental to the overall lightning protection scheme as it minimises "earth potential rise" (EPR) effects and hence helps to prevent fires and other damage due to sparking. However, this step is where vessels differ greatly from most other applications. Underneath the vessel exists a body of water (fresh or saline) that can act as a very good "earthing system" without the huge variation seen in ground- or soil-based earthing outcomes as a result of the large variation in soil resistivity.

Therefore, the key to good earthing on vessels is to ensure that all lightning downconductor paths are directly bonded to metallic items in contact with the water at all times. This task is relatively easy to achieve in vessels with metallic hulls, whereas vessels with non-metallic hulls require the installation of one or more dedicated "earth plates" under the hull‡.

Rigorous equipotential bonding is also necessary, particularly for a non-isolated lightning protection system where the vessel is electrified by the lightning strike. Bonding is primarily a voltage consideration and is accomplished successfully by connecting all conductive elements together to a single point of reference in a "star network" arrangement. Bonding should be carried out using suitable conductor sizes (typically 35 – 50 mm^2) and connections. The bonding path must be kept as short as possible so that a damaging voltage differential does not exist between the end of the bonding conductor and other conductive components within the vessel.

4.2.4 Step IV – Personal Protection

Step IV is the important task of protecting people (crew, passengers, etc. hereafter called "personnel") against lightning strikes. Much has been written about the effects of lightning on human beings, e.g., **[18][28]**. There are four main electrical mechanisms associated with lightning strikes that make cause injury or death to human beings, namely a:

- Direct strike to the person.
- Side flash from an adjacent structure, e.g., while sheltering beneath or near a (tall) tree.
- Touch voltage, i.e., contact with a conductor that has risen to a dangerous voltage that drives a dangerous or fatal current through the person's body to ground.
- Step voltage, i.e., an indirect cloud-to-ground strike that causes a large voltage in the soil or, in some cases, surface arcing along the ground which can create a voltage difference across the human body via the feet and legs.

The effects of these electrical mechanisms include burns to the skin, damage to various bodily organs and systems, unconsciousness, and death.

The lightning effects outlined above can be reduced dramatically via the installation of a properly designed lightning protection system by following the four steps in this paper. However, *it is very difficult to protect personnel from all lightning hazards*. Hence, ideally, no personnel should be out on deck / in the open during a thunderstorm, i.e., administrative / procedural controls should be used. According to AS 1768 **[11]**, to the extent consistent with safe handling and navigation of the vessel during a lightning storm, personnel should:

- Remain inside a closed vessel and avoid contact with metallic items.
- Stay as far as practicable from any items forming part of a downconductor path for the lightning current.
- Not be in the water, or dangle arms or legs in the water.

Even with a lightning protection system in place, avoiding contact with metallic items is very important. As shown by Nicolopoulou *et al.* **[29]** with electromagnetic simulations of lightning strikes to a ship, touch voltages as high as 19 kV were found in the bridge area of the ship. These authors explained that the dissipation of the lightning current on the ship's surface causes voltage rise of the hull which acts as the ground reference

‡ These earth plates are often made of stainless steel (316 marine grade), pending galvanic corrosion considerations.

level for the ship's electric grid and development of dangerous step and touch voltages.

There are also three main non-electrical mechanisms that can cause serious human injuries, namely:

- Acoustic pressure wave(s) from nearby thunder causing acoustic injuries, e.g., ruptured ear membranes or tinnitus.
- Radiation from the lightning channel causing eye damage, e.g., temporary blindness, vision damage, cataracts, etc.
- Flying or falling debris from structures struck by lightning.

Once again, these hazards are avoided by remaining inside the closed vessel, although appropriate PPE can also lower the risks.

In the next section, some practical solutions are presented for addressing the risks and hazards outlined in the four steps above.

4.3 Practical Solutions

In summary, the comprehensive, four-step lightning protection plan recommended in this paper requires consideration and implementation of (i) direct-strike protection, (iii) surge protection, and (iii) earthing and bonding, with (iv) personal protection as an additional factor in any situations where personnel are at risk.

Within Step (i), there are two aspects to capturing lightning strikes reliably, namely (a) the methodology used for positioning air terminals, and (b) the air terminal "hardware" used. Both aspects require further explanation before a practical solution can be presented for direct-strike protection – see Subsections 4.3.1 and 4.3.2. Finally, Subsection 4.3.3 presents a proven, effective solution for protecting vessels against lightning strikes.

4.3.1 Methodology

The "rolling sphere method" (RSM) is commonly used for positioning air terminals on structures **[10][11]**. It implements the simple "electrogeometric model" (EGM). To apply the RSM to vessels, an imaginary sphere with a radius equal to the striking distance calculated from the EGM, typically 45 metres, is rolled over the vessel in 3D. All surface contact points are deemed to require protection, whilst the unaffected surfaces and volumes are deemed to be protected.

The advantage of the RSM is that it is conceptually simple, even for application to vessels with complicated shapes. However, since it is a simplification of the physical process of lightning attachment to a vessel, it has some limitations. The main limitation is that it assigns an equal upward leader initiation and lightning attachment probability to all contact points on the vessel, i.e., no account is taken of the role of electric field enhancement in upward leader initiation. Furthermore, when the RSM is applied to a vessel of height greater than the selected sphere radius, the sphere touches all parts of the vertical sides of the vessel structures above a height equal to the sphere radius.

The limitations of the RSM have led many researchers to develop improved lightning attachment models for air terminal placement, e.g.,

- "Leader progression model" of Dellera & Garbagnati **[30]**,
- "Collection volume method" of Eriksson **[12][13]**, later expanded to extended structures as described in D'Alessandro *et al.* **[31][32]**,
- "Simplified leader inception model" of Becerra & Cooray **[33][34]**, and
- "Leader inception theory" of Rizk **[35]-[37]**.

All of these models have "leader propagation" at their heart, i.e., allow for the propagation of upward and downward leaders.

Referring specifically to vessels, Cvjetković *et al.* **[38]** state that most vessels are "non-conventional" structures, particularly under the dynamic conditions of rolling, pitching and swinging. They assert that existing "standardised methods are insufficient and do not provide the required level of safety". These authors also proposed the use of a lightning strike warning system on board the vessel, where the crew could be alerted in real time. This suggestion fits in well with mitigation of the personnel risks discussed in Section 2 of this paper.

Hossam-Eldin & Omran **[39]** presented a technique to use the Collection Volume Method (CVM) for the placement of conventional or non-conventional lightning protection systems on vessels. These authors made calculations that included the vessel height and dimensions, radius of curvature, location, risk factors, and lightning parameters. They applied the method to a range of vessels, i.e., medium-sized war, cargo, destroyer, and aircraft carrier. They showed the method to be a very efficient means for lightning protection of vessels.

Hossam-Eldin & Abdalla **[40]** also published a new concept for lightning protection of vessels, using a "leader potential concept". This method is based on a publication by Mazur & Ruhnke **[41]** that suggested striking distance can be estimated from the potential of the downward lightning leader. This transfer of concept in **[40]** resulted in lightning protection systems that were the least conservative (or most efficient) when compared to the RSM and CVM when applied to a warship, frigate, destroyer, aircraft carrier and cargo vessel. However, their analysis did not consider upward leaders. Out of the three methods they compared, only CVM takes the upward leader into account.

Fortunately, the work of Rizk **[35]-[37]** solves the above deficiency. Rizk's "leader inception theory" (LIT) uses the concept of space potential and considers both the downward and upward leaders in the lightning attachment process. The LIT is universally applicable, i.e., can deal with lightning protection problems in power systems, ordinary buildings, vessels, etc.

In summary, improved lightning attachment models have been applied successfully to direct-strike protection of vessels. Hence, there is no need to rely solely upon the RSM.

4.3.2 Hardware

During a thunderstorm, the electric field between the thundercloud and the vessel (and surrounding water) is at highly elevated levels. Under such conditions, "corona discharge" emanates from many points on a vessel, as well as from any air terminals installed for lightning protection, during the so-called "pre-strike phase of the storm. Historically, this effect was seen commonly on sailing ships and was called "St Elmo's Fire" **[42]**.

In terms of lightning protection, corona discharge results in the development of a space charge "volume" or "cloud" above the object(s) **[43]**. Sharp-tipped air terminals are well known to produce substantially more corona space charge than blunt-tipped air terminals **[44][45]**. There is now significant theoretical and experimental evidence that space charge accumulation around the top of an air terminal has a detrimental effect on its ability to initiate and sustain an upward leader **[46]-[49][36][50]-[56]**. The outcome of this space charge effect is that lightning capture is much less reliable because it affects the ability of the air terminal to launch the continuous, uninhibited upward leader that is needed for reliable interception of the downward lightning leader.

Hence, the most basic fact about lightning protection is that is far better to install optimised air terminals at the most likely strike point(s) on the vessel. The correct placement of air terminals is achieved with a suitable lightning attachment model as described in Subsection 4.3.1, preferably a modern leader propagation model that can account for the variables and parameters involved in the lightning attachment process e.g., D'Alessandro *et al.* **[31]-[32][45]**, Rizk **[35]-[37]**.

The most important optimised parameter is the *geometry* of the air terminal. This aspect was first studied systematically by Moore **[46]** and more recently by other researchers **[55][56]**. The optimum air terminal is one that is *corona minimising* during the pre-strike phase of a thunderstorm but, upon the initial descent of the downward leader, commences the corona-streamer-leader process in a dynamic response that leads to a continuously propagating upward leader and ultimate interception of the downward leader. Calculations of corona onset for given air terminal shapes rely on basic gas discharge physics **[57]** and calculations of the optimum air terminal geometry for practical installations are also achievable **[58][59]**.

All of the above concepts and research are described in more detail in D'Alessandro **[60]**.

4.3.3 Proven Lightning Protection Approach

A comprehensive lightning protection approach for vessels can be formulated from all the principles outlined in earlier sections of this paper. The generic concept for this approach is illustrated in **Figure 4**.

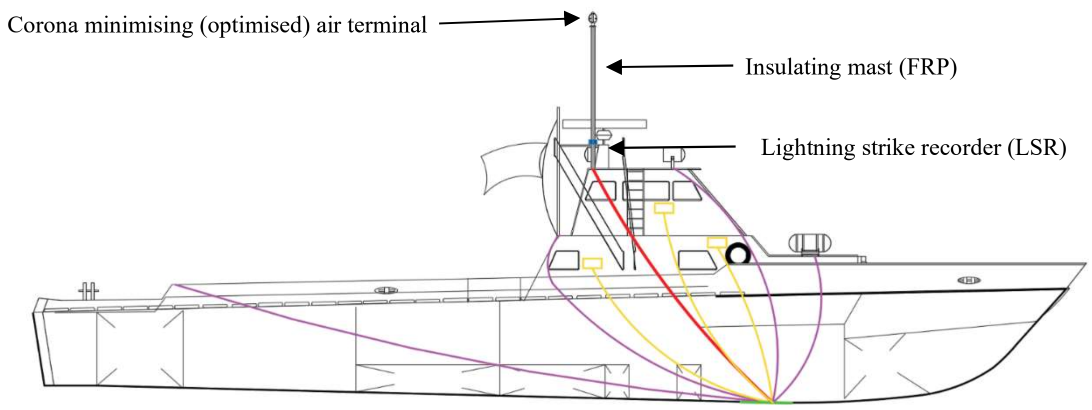

Figure 4: Conceptual drawing showing the proven, generic approach to protecting vessels against lightning strikes. Key: —— HVSC Plus insulated lightning downconductor cable, ☐ Surge protection devices (SPDs) on equipment, —— Surge protection bonds to earth, —— Bonding of vessel conductive elements to earth, —— Vessel earthing.

(a) Direct strike Protection

Capture of lightning strikes at a prominent location (determined by the design methodology) is with one or more corona minimising air terminals, e.g., "Guardian CAT" or "Guardian Plus" **[45]**. The reasons for utilising this technology were explained in Section 4.3.2. The remainder of the direct-strike system implements "protection by isolation". This approach is a very effective for protecting vessels, i.e., discharge the lightning current into the water without electrification of any parts of the vessel.

The use of at least 2 metres of FRP mast together with an insulated lightning downconductor cable with an impulse withstand voltage of at least 500 kV **[61]** provides the necessary insulation and prevention of electrification of the vessel. This "HVSC Plus" cable minimises the risk of side flashes, a common problem with downconductors carrying fast rising lightning currents. Such incidents must be prevented on vessels because the arc flash can lead to a fire or blast in the nearby area, causing fatalities and losses.

A "lightning strike recorder" (LSR) may also be installed if information about the lightning strikes captured by the system is required. This information may include parameters such as date and time, size of strike (peak current), etc. and may be accessible remotely for convenience and keeping maintenance costs to a minimum.

Figure 5 is a photo of a typical direct-strike installation on a vessel.

(b) Surge Protection

Surge protection must be applied to all valuable and critical equipment on vessels. Such equipment has an incoming power line as well as data / signal / control lines, depending on their function. All of these lines may carry surges into the equipment and damage or destroy it, hence they all need appropriately selected surge protection devices (SPDs). For power lines, the choices depend on single- vs three-phase SPDs, shunt vs series, type of electrical system, etc.

Hence, the surge protection requirements of every vessel are different. They depend upon the size, function and nature of the vessel. A common example of power line protection is the DIN Rail-mounted 3DR100KA-385-NE100 surge protection setup. The same components are also available in a compact "power protection module", e.g., 3PPM100kA-385-NE100-AIMCB, allowing easier installation in many cases.

"Smart SPDs" are now available that allow monitoring of key physical parameters and provide easier indication methods for when SPDs need to be replaced. Further details on surge protection generally, and smart SPDs particularly, can be found in D'Alessandro **[27]**.

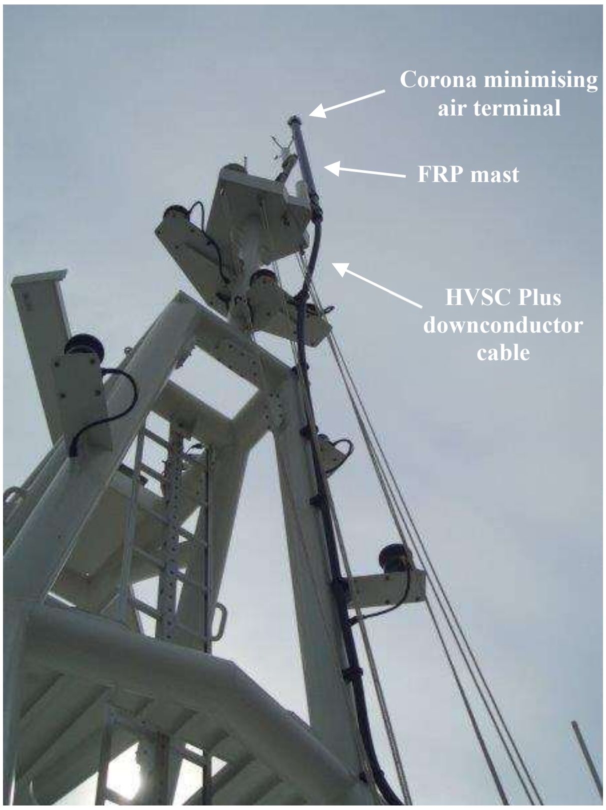

Figure 5: Typical direct-strike installation on a vessel that uses a "protection by isolation" approach

Figure 6: Typical surge protection installation for power lines

Figure 6 is a photo of a typical surge protection installation for power lines.

(c) Earthing and Bonding

The earthing and bonding arrangements of a vessel will also vary per the size, function, and nature of the vessel. Earthing is the final point of contact where the lightning strike safely dissipates into the water, whilst bonding conductors and connections ensure that lightning currents are controlled and dissipated into the water. Bonding conductors should have sufficient crosssection areas to ensure the full or partial lightning currents can be carried safely. The cross-sectional area typically varies from around 16 mm^2 to 50 mm^2 **[11][62]**.

Figure 4 shows an earth plate (in green) under a vessel as a standard method of earthing for vessels with non-metallic vessel hulls. For vessels with metallic hulls, the hull provides a very good earth plane. It is important to ensure direct bonding arrangements for all equipment, SPDs and conductive elements occur to a common point on the hull.

(d) Personal Protection

In Section 2.5, it was concluded that personnel risk is seen to be intolerable for the majority of vessel types across the range of typical lightning activity encountered over bodies of water. The best risk reduction measure is elimination, i.e., personnel on vessels are not outside in thunderstorms.

The problem with elimination is the decision-making around when shelter should be sought. This decision is best made with a "lightning warning system" (LWS), as also pointed out by Cvjetković *et al.* **[38]**. A LWS that detects all phases of a thunderstorm and provides a warning based on the magnitude of the atmospheric electric field is highly recommended.

It is recognised that elimination of risk may not always be possible. If this is the case, personnel should be wearing full PPE, which includes:

(i) Eye wear that is close-fitting with a wrap-around design and that blocks at least 99% of the UV radiation spectrum.

(ii) Ear plugs or earmuffs that provide a noise reduction of at least 30 dB, but preferably up to 120 dB.

(iii) Safety boots with soles that have a good withstand voltage, nominally at least 5 kV when wet and preferably up to 20 kV under a dry test.

Furthermore, contact with any conductive elements of the vessel must be avoided.

5. Conclusions

This paper has investigated the risk of asset and operational losses, as well as loss of human life, on vessels due to lightning storms. Such losses have even more serious consequences than land-based losses due to the remote locations of vessels, compromising safety onboard.

A detailed quantitative analysis of the risks posed by lightning to vessels and their personnel was carried out. It was found that the mean time between flashes to the range of vessel categories investigated is once every year to few years in higher lightning areas, and once every hundred to several years for low lightning areas. Hence, the risk of a lightning strike to a vessel cannot be ignored. Furthermore, the risk to personnel was to be intolerable for the majority of vessel types across the range of typical lightning activity encountered over bodies of water.

The paper then described the physical damage that is known to occur when lightning strikes vessels directly or indirectly and a comprehensive lightning mitigation approach was presented. This four-step approach is comprised of direct-strike protection, surge protection, earthing and bonding, and personal protection.

A generic and practical lightning protection solution was provided for vessels using some of the outcomes of the latest international research on lightning protection. This solution is applicable to all types of vessels, i.e., it has no dependence on the material of the hull, size of the vessel, type of electrical systems on board, etc. However, the specific details and material requirements will depend on the above variables.

With the increasing sensitivity of equipment and the importance of human life, lightning protection of vessels is essential. With appropriate measures in place, safer and more efficient vessel operations can be ensured.

Author Contributions

F. D'Alessandro: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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