Annals of MIRCE Science

"MIRCE Science is a theory of the motion of working systems through MIRCE Space resulting from any functionability actions whatsoever, used for Management of In-service, Reliability, Cost & Effectiveness."
Dr J. Knezevic, Founder, 1999

MIRCE Science: Lightning as an Imposing Functionability Action

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Abstract

MIRCE Science is a theory of the motion of working systems through Mirce Space compelled by imposing functionability actions, which is used for predicting expected functionability performance for a working system type. For accurate predictions to be made it is essential a scientific understanding of the mechanisms that govern imposing functionability actions, the occurrences of negative functionability events before engineering, technological, business and economical decisions are made. Lightning strikes are not uncommon physical mechanisms that completed the motion of working systems through Mirce Space. For example, airliners in the worldwide fleet average at least one strike per year. Hence, the main objective of this paper is to understand physical mechanisms that generate the occurrences of lightening events and assesses their impacts on the work done by working systems in general and an aircraft in particular. The available methods for dealing with them in respect to the provision of safety by detection, protection and design are also addressed in the paper.

Key words: MIRCE Science, lightening strikes, discharge mechanism**,** impact of lightening on aviation

Citation: Knezevic, J., MIRCE Science: Lightning as an Imposing Functionability Action. Annals of MIRCE Science. MSA2024-7-29. MIRCE Science, Exeter, UK, 2024.

Published: 29 July 2024

MIRCE Science unique identifier: MSA2024-7-29

1. Introduction

Every day, an average, around 8 million lightning strikes discharge across the planet Earth, which is the equivalent of about 100 lightning strikes every second. For example, airliners in the worldwide fleet average at least one lightning strike per year. Although meteorologists may forecast the general conditions that cause lightning, but the exact location and time of future lightning strikes cannot be predicted. However, for successful management of in-service performance of working systems lightning detection and monitoring are very important as they have impact on the public safety, potential wildfires, protection of electrical supply and so forth.

The main objective of this paper is to address lightening as an imposing functionability action driven by a natural physical phenomenon and to assess its impact on the functionability performance of working systems types, in general with some specific examples related to commercial aviation, as well as to outline existing lightening protection methods and approaches.

2. Brief Overview of MIRCE Science

The philosophy of MIRCE Science is based on the premise that the purpose of the existence of any working system is to do work. The work is considered to be done when the expected measurable function is performed through time. MIRCE Science focuses on the scientific understanding and description of the physical phenomena and human rules that govern the motion of working systems through MIRCE Space[1]. A full understanding of the mechanisms that generate this motion is essential for the accurate predictions of the expected work done by a given working system type using the mathematical scheme of MIRCE Science. [1]

In accordance to MIRCE Science philosophy a working system type could be in one of the following two functionability states:

- Positive Functionability State (PFS), a generic name for a state in which a working system type is able to deliver a measurable function(s)
- Negative Functionability State (NFS), a generic name for a state in which a working system type is unable to deliver a measurable function(s), resulting from any reason whatsoever.

Being in one of these two functionability states is a physical manifestation of the motion of a working system type through in-service time.

The motion of a working system type through the functionability states, in the direction of in-service time, is caused by imposing functionability actions. MIRCE Science philosophy classifies all functionability actions whatsoever as following:

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1 MIRCE Space is a conceptual 3-dimensional coordinate system containing a sequential motion of a working system through quantised functionability states in time and probability of being in them. [1]

- Positive Functionability Action (PFA), a generic name for any natural process or human activity that compels a working system type to move to a PFS
- Negative Functionability Action (NFA), a generic name for any natural process or human activity that compels a working system type to move to a NFS.

The mechanisms, nature, frequency and complexity of functionability actions, positive and negative, is specific to each working system type, but the consequential movements to corresponding functionability state is common for all of them.

The motion of a working system type through the functionability states is manifested through the occurrences of functionability events, which in MIRCE Science philosophy are classified as following:

- Positive Functionability Event (PFE), a generic name for any physically observable occurrence in time that signifies the transition of a working system type from a NFS to a PFS
- Negative Functionability Event (NFE), a generic name for any physically observable occurrence in time that signifies the transition of a working system type from a PFS to a NFS.

In essence functionability events, positive and negative, are physically observable occurrences that are taking place during the in-service life of working systems. These events are measurable physically properties for each individual working system that contributes to the formations of the trajectory of the motion of the whole population type through in-service time.

Research studies conducted at MIRCE Akademy[2] by staff and students had shown that any serious studies of the functionability mechanisms have to be based between the following two boundaries [1]:

- the "bottom end" of the physical world, which is at the level of the atoms and molecules that exists in the region of 10^{-10} of a metre.

- the "top end" of the physical world, which is at the level of the solar system that stretches in the physical scale around 10^{+10} of a metre.

This range is the minimum sufficient "physical scale" which enables scientific understanding of relationships between physical phenomena that take place in the natural environment and the physical mechanisms that govern functionability events during the life of working systems.

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[2] for more information follow the link: http://www.mirceakademy.com/news/2/15/MIRCE-Functionability-Actions/

2. Lightening as Functionability Action

Lightning is an atmospheric discharge of electricity. Being the most visible form of electricity and a widely recognised natural phenomenon, lightning remains relatively poorly understood. Even the most basic questions of how lightning is initiated inside thunderclouds and how it then propagates for many tens of kilometers have only begun to be addressed. In the past, progress was hampered by the unpredictable and transient nature of lightning and the difficulties in making direct measurements inside thunderstorms. However, the advances in technology enable creation of remote sensing methods, instrumentation and rocket-triggered lightning experiments that are now providing new insights into the mechanisms of lightning.

Proper understanding of lightning phenomena involves the synthesis of many branches of physics, from atmospheric physics to plasma physics to quantum electrodynamics, and provides a plethora of challenging unsolved problems. However, in this paper only an elementary review of the scientific understanding of lightning as an imposing functionability action is provided.

Generally speaking lightning is the dissipation of static energy stored in cloud clusters. Scientists believe that the static energy stored in clouds comes from the relative motion of precipitation within the clouds that generate free electrons resulting in stored charges collected within the cloud. Positive charge in the cloud will seek negative charges on the Earths' surface. While in the same manner, negative charges in the cloud will seek positive charges on the ground. Lightning begins to move away from the cloud filled with static energy through what is known as leaders. Leaders are electrical energy moving out to seek ground or an object of opposite charge. Leaders stem from what is called a lightning channel. Lightning energy moves from the lightning channel in leader streams. If the leaders do not find anywhere of an opposite charge or "ground" to transfer the energy in an opposite charge or "ground" the leader, the leader is pull back into the channel and the channel stores the leader charge which increases the energy in the leader channel. This process continues as leader stream away from the lightning channel seeking an opposite charge, constantly growing energy in the lightning channel until a leader finds an oppositely charged object, which could be cloud or ground[3], creating an electrical circuit and quickly discharges the energy built up in the channel. This transfer of channel energy can be dramatic since the stored plasma often reaches levels of electrical power beyond a million volts and reach temperatures of over 25,000°C! When lightening flashes, it finds the faster path down to Earth and then it follows the same route back up to the cloud again. A downward flash of lightening leader travels at up to 1,600 km/s, while the return speed is up to 140,000 km/s. [3]

The research performed has shown that lightening makes the air inside a cloud nearly 6 times hotter than the surface of the Sun! The hot air inside a thundercloud expands and vibrates which makes the loud rumbling crash that is commonly called a thunder. Thunder and lightening happen at the same time but there is always a gap between the flash of light and the crash of a thunderclap. That is because light travels many times faster than sound[4].

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[3] In a given geographic area, there can be as many as 10 times more cloud-to-cloud as cloud-to-ground strikes. Furthermore, discharges can also occur within individual clouds.

[4] The speed of light is 299,792,458 ms^{-1} whereas the speed of sound in air is between 331 ms^{-1} at 0ºC and 360

Rough rule of thumb says if the number of seconds between the flash of lightening and the bang of thunder are counted and divided by 3, the results obtain would represent the approximate distance of the storm in kilometres. [3]

Thunderstorms are most common near the equator. This is because it's hotter, so there is more hot air (energy) to rise and create more thunderclouds and lighting. Hence, geographical areas like South America, Central Africa and Indonesia have on average 100-200 thunderstorms a year. [3]

The main types of lightening observed are listed below:

- Ball lengthening that is manifested as a slow moving ball of the fire that can sometimes appear inside structures[5]
- Zig-zag lightening that is a giant spark that "zig-zags" its way to the ground
- Forked lightening that looks like the letter Y upside down
- Sheet lightening that makes a white light that fills a wide area of the sky
- St Elmo's fire that is a faint flickering glow around trees, buildings or ships masts.

Lightning doesn't strike the ocean as much as land, but when it does; it spreads out over the water, which acts as a conductor. In existing literature, various different estimates have been given for the distance over which it would dissipate, to the point where it would no longer be a harmful to a person. Fish, which usually move around at greater depths, are safer than human swimmers. Protruding heads or even entire bodies, such as those presented by surfers or paddle boarders, could put people in greater danger. Boats can be fitted with lightning conductors, which direct the charge into the sea, while avoiding their most vulnerable parts, such as passenger areas or equipment rooms.

Lightening also hits deserts and sandy beaches that are high in silica or quartz. As the temperature in the affected areas reaches more than 1800° C, the lighting can fuse the sand into silica glass. The blast of a billion Joules of energy radiates through the ground making fulgurites[6].

3. Lightening Strike as Functionability Event

Lightning strike is not only spectacular functionability event; it is a rather dangerous natural phenomenon. Each year around 2,000 people are killed worldwide by lightning [2]. Although hundreds more survive strikes, they suffer from a variety of lasting symptoms, including memory loss, dizziness, weakness, numbness, and other life-altering ailments. Strikes can cause cardiac arrest and severe burns, but 9 of every 10 people survive. The average USA citizen has about a 1 in 5,000 chance of being struck by lightning during a lifetime. [3]

Many houses are grounded by rods and other protection that conduct a lightning bolt's

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ms^{-1} at 50 ºC

[5] In 1984, Russian airline passengers were surprised to see a blob of ball lightening floating over their heads inside the plane. No one was hurt however the plane's radar was damaged.

[6] **F**ulgurites, from the Latin fulgur, meaning "lightning", are natural tubes, clumps, or masses of sintered, vitrified, and/or fused soil, sand, rock, organic debris and other sediments that can form when lightning discharges into ground.

electricity harmlessly to the ground. Homes may also be inadvertently grounded by plumbing, gutters, or other materials. Grounded buildings offer protection, but occupants who touch running water or use a landline phone may receive a shock by conducted electricity.

Lightning may also occur in Volcanic Ash clouds formed in the immediate vicinity of eruptions because the vertical movement and collision between solid particles within the cloud generates static charges.

In June 2006 a total of 17,000 lightening strikes hit Alaska, starting hundreds of fires, which by the end of June destroyed an area twice of the size of London. [3]

It is worth pointing out that flashes of lightening have been observed on Venus and Jupiter. Lightening on Jupiter is thought to be more powerful than on Earth, but happens less frequently.

4. The Impact of Lightening on Aviation

Through history of aviation there have been cases of aircraft being brought down by lightning strikes that started electrical fires or arced into unprotected fuel tanks, significant damage to aircraft today is a rare functionability event. However, in the early years of jet transport, the in-flight breakup of a Pan American World Airways Boeing 707-121 over Elkton, Maryland, in 1963 while on approach to Philadelphia, killed 81 people on board. The incident was attributed to lightning and became a watershed event in advancing aircraft protection. It was later determined that the breakup resulted from an explosion in a fuel tank due to a lightning strike. Subsequently, in USA the nascent Federal Aviation Administration (FAA) required that lightning safety devices be installed on all commercial aircraft, including the now familiar static “wicks” or dissipaters on the trailing edges of wings and control surfaces.

A few examples of accidents and incidents that have been reported with lightning being attributed as a principal contributing factor:

- In 1969 the US Apollo 12 spacecraft was hit by lightening as it took off for the Moon. It survived. However, in 1987, a rocket launched from Florida crashed after lightening damaged its on-board computer. US shuttle launches were postponed when lightening was around.

- On February 8, 1988 a flight from Hanover to Düsseldorf, Germany, a Fairchild Metro III commuter turboprop crashed on approach to Dusseldorf after a lightning strike resulting in “disconnection of all batteries and generators from the aircraft's electrical system” including the termination of the cockpit voice recorder record". Twenty-one people died (19 passengers and 2 crew).

- On 25 September 2001, an Embraer 145 in descent to Manchester (UK) sustained a low power lightning strike which was followed, within a few seconds, by the left engine stopping without indicating a failure. A successful single engine landing followed. The Investigation concluded that the cause of failure of the FADEC-controlled AE3007 engine (which has no surge recovery logic) was the aero-thermal effects of the strike to which all aircraft with relatively small diameter fuselages and close mounted engines are vulnerable. It was considered that there was a risk of simultaneous double engine flameout in such circumstances which was impossible to quantify.

- On 4 December 2007, while approaching Bodø (Norway) the crew of a Dornier 228-200 (LN-HTA) lost control of their aircraft resulting from a powerful lightning strike, which temporarily blinded both pilots and damaged the aircraft such that they lost elevator control. After regaining partial pitch control using pitch trim, a second attempt at a landing resulted in a semi-controlled crash that seriously injured both pilots and damaged the aircraft beyond repair. The Investigation concluded that the energy in the lightning had probably exceeded certification resilience requirements and that up to 30% of the bonding wiring in the tail may have been defective before lightning struck.[7]

- An Airbus A330-200 was struck by lightning just after arriving to Perth WA Australia, on 26 November 2014. It was allocated a stand following a one hour post-landing delay after suspension of ramp operations due to an overhead thunderstorm. Adjacent ground services operatives were subject to electrical discharge from the strike and one who was connected to the aircraft flight deck intercom was rendered unconscious. The investigation found that the equipment and procedures for mitigation of risk from lightning strikes were not wholly effective and also that perceived operational pressure had contributed to a resumption of ground operations which hindsight indicated had been premature.

5. Mechanics of the Motion of Lightning through the Aircraft Structure

An aircraft flying in an electrically charged area may also complete the circuit and receive a strike that will continue from the aircraft to the ground or another cloud. These strikes on aircraft commonly occur within 1,500 m of the freezing level[8].

A lightning strike is accompanied by a brilliant flash of light and often by the smell of burning, as well as noise, which can be very distressing to passengers and crew. However, significant physical damage to an aircraft is rare nowadays and the safety of an aircraft in flight is not usually affected. Damage is usually confined to aerials, compasses, avionics, and the burning of small holes in the fuselage. Of greater concern is the potential for the transient airflow disturbance associated with lightning to cause engine shutdown on both: a FADEC[9] control and non-FADEC engines with close-spaced engine pairs.

A strike at the aircraft's radome will travel along the outer skin and exit at an extremity like a wingtip, the tail or a control surface. The entry point will vary from pitting to a small hole; at

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[7] https://www.skybrary.aero/index.php/D228,_vicinity_Bod%C3%B8_Norway,_2003

[8] The freezing level, or 0 °C (zero-degree) isotherm, represents the altitude in which the temperature is at 0 °C (the freezing point of water) in a free atmosphere.

[9] FADEC: full authority digital engine (or electronics) control a system consisting of a digital computer, called an "electronic engine controller" (EEC) or "engine control unit" (ECU), and its related accessories that control all aspects of aircraft engine performance.

the exit point however, the charge may burn a larger hole. Meanwhile, the path of the charge along the airframe can produce scorching, often at rivets as the charge arcs across the miniscule gaps between rivet heads and adjacent skin.

If the charge exits from a control surface, hinge bushings and bearings may be spalled and require replacement. Strikes can also affect avionics, antennae and, especially, compasses. In any case, after a lightning strike, the airframe will require a thorough inspection and any serious damage repaired, meaning that the most tangible negative result of the lightning encounter will probably be downtime and repair, as necessary. Reportedly, airlines spend millions of dollars annually returning struck aircraft to service.

6. Lightning Compelled Flameouts

FADECs programmed with surge-protection logic can respond to flow disruption temperature spikes by automatically shutting down the engines. This aircraft configuration has proven to be vulnerable to engine flameouts as a lightning strike charge travels longitudinally down the sides of the fuselage seeking an exit point. In the case of closely spaced fuselage-mounted engines, the strike's "aero-thermal effects" can disrupt intake flows of both powerplants. FADECs programmed with surge-protection logic can respond to such disruption temperature spikes by automatically shutting down the engines. On the other hand, hydro-mechanically controlled engines, as an indirect result of lightning strikes, will tend to experience transient over-temperature conditions while continuing to operate, as shutdown protocols are manually controlled by the flight crew.

In 2001, an Embraer ERJ 145 regional airliner received a lightning strike while descending for an approach to Manchester International Airport in England, followed by the left Rolls-Royce AE3007 turbofan flaming out without any fault indication or audible warning in the cockpit. The crew was on top of the situation and immediately transitioned to a successful single-engine landing. A post-incident investigation concluded that the failure of the FADEC-equipped engine was due to the aero-thermal effects of the strike characteristic of aircraft with small-diameter fuselages and aft-mounted engines. It further considered that a risk existed for loss of both engines, but investigators were unable to quantify that.

As a precautionary measure when entering areas of electrical activity in aircraft with FADEC-equipped engines, experts recommend that, if within operating limits, flight crews fire up the APUs[10] so that, in the event of a double engine failure, electrical power and hydraulics will be maintained while emergency relights of the engines can be attempted. It is worth saying that it is possible that APUs can be affected by lightning strikes, too. It's also recommended that flight crews review memory items for a dual engine relight before venturing into areas of known lightning activity.

[10] APU: Auxiliary Power Unit is a device on a vehicle that provides energy for functions other than propulsion. They are commonly found on large aircraft and naval ships as well as some large land vehicles.

7. Lightning Protected Aircraft Structures

To survive multiple lightning strikes an aircraft has to be designed as “Faraday cage.” Back in the 18th century electricity pioneer Michael Faraday created a metal-lattice contraption that conducted high-voltage electricity harmlessly around a hapless volunteer encaged within it. The device is often still used in magic acts and static electricity demonstrations. In the aircraft, the aluminium skin subs for the lattice, carrying the charge along the outside of the airframe to an exit point.

However, ensuring the aircraft’s occupants, systems, avionics and fuel are protected, means there must be no gaps in the conductive path, thus keeping the electrical charge on the outside of the aircraft. So, part of what is known as the “hardening” process against lightning damage involves, among other things, metal strapping across any gaps in the skin to maintain that uninterrupted conductive path.

While aluminium is an excellent conductor, composite media, (graphite-epoxy or “carbon fibre”), are less so. That’s why a mesh of copper wire or other conductive material is included in the lay-ups of composite aircraft to provide conductivity. Because a radar antenna cannot be contained in a conductive enclosure, radomes are fabricated of composite media, so to protect them, lightning diverter strips consisting of solid metal bars or closely spaced conductive disks are bonded on the outer surface of the dome to carry the charge into the airframe.

Lightning strike hazards include the potential to affect the variety of computers on-board modern aircraft, such as the flight management system (FMS), navigation systems; electronic engine controls and even fly-by-wire systems, due to power surges.

Newton [4] cites an airline incident where a lightning strike “caused the autothrottle to go to idle, the autopilot and yaw damper to disengage, over half the fault lights to illuminate, the captain’s flight director and navigation display to fail, and an erroneous indication of an engine failure to occur.” These anomalies can happen because, as the lightning charge passes over the exterior of the airframe, induction from the electricity can cause “transients” in wiring inside the aircraft termed “lightning indirect effects.” To address this threat, airframe and avionics designers apply a number of hardening techniques and devices to their equipment including simple grounding, various types of shielding and surge-suppression devices to meet aircraft certification requirements imposed by the FAA and other international civil aviation authorities. As everything essential for flight safety must be protected to the maximum extent possible, the risk of lightning being the direct cause of a crash has been greatly reduced during last 50 years.

In designing aircraft today, particular attention is devoted to protection of the fuel system and tanks to ensure that lightning charges cannot produce sparks that could ignite fuel or vapours. Accordingly, the aircraft wings, carry-through structures and other elements involving the fuel system must be sufficiently thick to prevent burn-through, and all brackets, fasteners, structural joints, filler ports, vents, electrical pumps and fuel lines must be designed and insulated to prevent ignition.

The same design philosophy also applies to the engines and their mechanical or electronic controllers. Even further, over the years, petro-chemical refiners have formulated jet fuels with less-explosive vapours.

8. Lightening Events Detection and Avoidance

Knowing the whereabouts of lightning actions is key to avoiding it, and flight crews now have more resources available than ever to do so. These include a network of ground-based detection tools, as well as airborne systems to complement weather radar, to assist in flight planning and, once airborne, chart paths safely around or through active areas.

During the last four decades, considerable research throughout the world has been devoted to understanding the nature of lightning, predicting and detecting it over large areas, and delivering these data to pilots, ATC[11] facilities and airport operators in near real time. Today, in the United States, much of this research has been conducted under the auspices of the National Oceanic and Atmospheric Administration's (NOAA) National Severe Storms Laboratory (NSSL).

Ground-based lightning detection networks (LDNs) have been established in many countries to monitor thunderstorm development, intensity and movement over wide areas. Some are owned and operated by governments, while others function in the private sector, often under contract to users. Data from these arrays are monitored by a variety of agencies for issuing warnings, forecasting and, in severe cases, deployment of rescue/response teams. Lightning strike data from these networks are also archived for research purposes, post-accident investigations and even insurance risk calculations.

The U.S. component in this array is the National Lightning Detection Network (NLDN) developed by the New Mexico Institute of Mining and Technology and operated by Vaisala Inc.[12], out of Tucson, Arizona. It has been in existence in one form or another for 30 years. Its origins derive from research conducted under contract for the Electric Power Research Institute by the State University of New York at Albany, principally to determine how to get lightning detection to users in near real time. Eventually, this research was commercialised by Global Atmospherics.

With more than 100 lightning strike sensors installed throughout North America, the NDLN is considered a precision detection network able to see and record both cloud-to-cloud and cloud-to-ground lightning. The sensors are all ground-based, with more being added every year. They detect electrical discharges in the atmosphere, and their raw data are then transmitted via a satellite communications link to Vaisala's Network Control Center at Tucson for processing.

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11 ATC: Air traffic Control

12 It is a Finish company with headquartered in Helsinki, established more than 80 years ago. It markets meteorological data packages and a broad product line of weather gauging and instrumentation equipment such as wind direction indicators, barometric and temperature measuring devices, and automated weather advisory station (AWAS) equipment. It got into the lightning detection business when it acquired the former Global Atmospherics Inc., in 2002.

Literally within seconds, Vaisala's software calculates location, time, polarity and amplitude of each strike, which subsequently appears on a digital map or is sent to customers as text data. [4]

In addition to the NLDN, Vaisala operates a global lightning detection network based on a proprietary set of long-range sensors installed in other countries and sells a lightning data package, the GLD360, for it, too. [3] The company also markets its own display software called Thunderstorm Manager that enables users to set up rings around an airport, or any other entity sensitive to lightning, like a powerplant, on a video display at various distances and observe where strikes are occurring. Among Vaisala's U.S. customers for near-real-time lightning data are the FAA and National Weather Service (NWS). All data collected, a trove currently representing more than 160 million "flashes," have been archived since 1989 for research purposes. [4]

Among users of archived data are the NSSL, which manipulates the information to loft 3-D lightning maps to study lightning development and propagation. While it is possible today for meteorologists to forecast the likelihood of lightning activity, being able to predict individual strikes is still beyond reach. So, one of the goals of this work is to construct experimental forecasting models that can accurately forecast the maximum lightning threat every hour. As a related development, the next generation of U.S. weather satellites will contain the Geostationary Lightning Mapper, an instrument that will continuously map both in-cloud and cloud-to-cloud lightning activity over the Americas and adjacent oceanic regions to provide early indication of storm intensification and severe weather events. [4]

9. Conclusions

The objective of this paper was introducing a lightning strike as an imposing functionability action that causes a motion of working systems type through MIRCE Space.

The paper provides an overview of the current scientific understandings of physical mechanism that generate the occurrences of lightening events and assesses their impacts on the functionability performance of working systems types, with a several examples specifically related to the aviation industry.

Finally, the paper provides a brief overview of methods available for dealing with lightening strikes in respect to the provision of safety by detection, protection and design.

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Filename: MSA2024-7-29
Directory: D:\2024\JK-Lightening as a MIRCE Mechanism
Template: C:\Users\Mirce\AppData\Roaming\Microsoft\Templates\Normal.dot
Title:
Subject:
Author: Dr Jezdimir Knezevic
Keywords:
Comments:
Creation Date: 04/06/2024 21:45:00
Change Number: 18
Last Saved On: 29/07/2024 12:23:00
Last Saved By: Mirce
Total Editing Time: 49 Minutes
Last Printed On: 29/07/2024 12:23:00
As of Last Complete Printing
Number of Pages: 12
Number of Words: 4,960 (approx.)
Number of Characters: 28,276 (approx.)