A systems engineering and strategic approach to holistic lightning safety and protection solutions

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***Abstract*—The importance of a systematic and structured approach to the engineering of lightning protection systems has previously been discussed [1]. Seen in a broader context, the engineering of lightning protection systems forms a subset (albeit an important one) of holistic lightning safety for living beings, structures and systems. It thus becomes necessary to consider such a structured and systematic approach in terms of this broader context. This paper builds on the concepts previously discussed and introduces and develops a systematic and strategic approach, and engineering and management framework, for the engineering and life-cycle management of holistic and coherent lightning safety and protection solutions.**

Keywords-Lightning safety, lightning protection, systems engineering, human factors, Lightning Safety Strategy, Lightning Safety Plan, Integrated Lightning Engineering Plan.

I. Introduction

Limitations in the current approach applied to lightning protection as observed in South Africa and elsewhere resulted in the formulation and recommendation of the Integrated Lightning Engineering Plan (ILEP) concept and methodology [1] as a core mechanism and engineering management framework to ensure a holistic and systematic approach to achieve effective lightning safety and protection at a facility.

It is pertinent to reiterate that the key objectives of lightning safety and protection are to ensure safety of living beings, and to protect infrastructure and systems against direct losses (such as, for example, actual damage to structures and equipment) and against indirect or consequential effects (such as, for example, downtime and loss of production, and loss of services), and that these objectives are interrelated [1, 2]. In the case of living beings, their safety and protection must be considered not only in respect of specific facilities, but also in a broader context such as within the communities wherein they live and pursue daily work and leisure activities.

In South Africa, for example, whilst there is very little published data on lightning morbidity, there are reportedly up to 100 lightning-related fatalities (and probably at least 4 to 5 times as many survivors presenting for clinical treatment) annually [3]. Published data [4] reports that the annual lightning deaths per million people for the first decade of the 21st century in South Africa varied between 1.5 (urban) and 8.8 (rural). Figures for other African countries, for example, were reportedly considerably higher. Although there has reportedly been little systematic collection of lightning death information in many global regions, and lightning fatality data reportedly continues to be missing for many parts of the world with high lightning density and large populations, it has been estimated that worldwide lightning annually claims about 24000 lives, with an estimated 240000 people suffering injury due to lightning [4].

In considering that lightning protection can be considered as a subset of the broader definition and requirements of lightning safety, it becomes necessary to apply and extend the engineering and management framework within the broader context of lightning safety and protection solutions.

This paper further argues that the discipline of systems engineering, and a systems engineering approach, is and remains applicable, coupled with a strategic approach and perspective, as the appropriate engineering and management approach to be adopted for holistic lightning safety and protection solutions.

This paper therefore *builds on* and *extends* the earlier definition and description of the Integrated Lightning Engineering Plan (ILEP) [1] to provide a *broader* and *more comprehensive* understanding of the recommended systematic and strategic engineering and management approach and framework to address these, and of the associated requirements, constraints and issues.

II. THE SYSTEMS ENGINEERING APPROACH

Whilst the systems engineering approach and methodology was born out of the requirements associated with complex engineering projects (such as those in the military and aerospace sectors), lightning safety and protection applications can and should also be considered as complex in nature.

Such complexity in applications and application environments is characterized by factors such as, for example,

- diversity and multiplicity in systems, technologies and interfaces, as well as in engineering, operational, and maintenance environments,

- consideration and integration of human factors, and
- in the resulting engineering, operational and general management challenges that arise.

A systematic, structured, coherent and holistic approach to the broader requirements and issues is therefore required in order to effectively address the inherent complexities.

Systems engineering has been defined by various authors, such as Blanchard and Fabrycky [5], and Kossiakoff et al [6]. Essentially it is a process whereby a structured and orderly process is followed in the evolution of a system or a solution, beginning with an understanding of needs and hence requirement definition, and ending with deployment, maintenance and operation of the system or solution in a sustainable manner. As a key part of this process the interrelationships (or interfaces) between aspects or components of the system or solution are defined and managed, including, for example, variations in definitions and other aspects which can impact on other components. This is obviously particularly pertinent *whatever* the nature of the aspects and components, whether physical, technical, or living beings, and whether static or mobile.

The importance and relevance of *human factors* in the effectiveness and performance related to the design, implementation, operation and maintenance of systems is recognized, and adds to the complexity of systems. This is particularly pertinent to lightning safety and protection applications, where the human factor is particularly relevant. This relevance can and must be considered in terms of the objectives both of lightning safety and lightning protection, as well as the methods used to design and implement appropriate measure and solutions.

III. ISSUES AROUND HUMAN FACTORS

The duality of the objectives around lightning safety and lightning protection has been noted above.

In considering the safety and protection of living beings, such as persons, the broader context such as the nature and extent of the communities within which they live and work must be considered as mentioned above. For example, people are generally not static, and move around their place of work or other place of activity (whether an industrial plant or agricultural facility) including outdoor areas. Similarly, their indoor or sheltered areas may offer inadequate inherent protection from direct and indirect effects of lightning.

Similarly the *behaviour* of persons, under normal conditions and otherwise, must be carefully considered. This includes taking into account the need to appropriately direct human behaviour before, during and after thunderstorm activity. Whilst this may appear at face value to be simplistic, to do this appropriately is actually a complex matter involving various issues beyond the development of simple procedures, including training, awareness and change management. The latter can be particularly challenging and complex, for one example in the case of addressing deeply-help myths and beliefs [7] and countering them with solutions based on scientific reality and in a way that will encourage acceptance. A particular human factor challenge also arises, for example, in dealing with "legacy" installations, policies and techniques related to the protection of structures and systems.

Safety in many industries and applications, including electrical, mining and other industrial applications, has long been formalised through, for example, occupational health and safety legislation, regulations and programmes, and has seen growing significance and importance over the years. This is evidenced, for example, through "zero-tolerance" type paradigms, and the associated procedures, strategies, plans, oversight and competency requirements.

In the case of lightning safety, a lack of appreciation of risks (including the "it won't happen to me" mindset), coupled with human and other factors such as inappropriate individual behaviour (and appropriate guidelines), an inadequate holistic approach, inadequate procedures and systems, cost-cutting and a "short-cut" "grudge purchase" mindset, and management and individuals not "buying in" to the risks and hence the need to adopt appropriate solutions, can lead to a situation where the "holes in the cheese" line up as per Reason's "Swiss Cheese Model" [8] applied to accident and incident causation (in particular related to complex systems and applications).

Inadequate consideration and management of human factors related to the engineering and management of lightning protection solutions (including throughout the lifecycle of the solution), and of other systemic organisational and related issues and challenges, can lead to the failure or under-performance of the solution measures. Examples of such pertinent systemic issues and challenges include engineering and engineering coordination across complex organisational structures (including organisational "silos") and change management. The *human factor* is a significant element in these issues and challenges.

This further motivates the need in practice to rethink and to adopt a different approach to lightning safety and protection.

In particular, this implies that a lightning safety and lightning protection solution must be developed within the appropriate human context (as well as the context of other living beings), in addition to the infrastructural and other engineering aspects of safety and protection solutions, such as detection systems and protection components and facilities. It therefore also implies a requirement for an integrating tool, to integrate the various aspects of a safety and protection solution. It also implies a need to create an enabling environment (or framework) and strategy (including for the human factors associated with that).

Consideration of methodologies such as the "Swiss Cheese Model", and of the further development of these to consider systemic organisational issues (including human factors) and their impact on accidents and incidents [9], is considered by the authors to be particularly pertinent in the context of lightning safety and protection and in the development of appropriate mitigation strategies. This applies particularly, but not only, in the context of "complex applications".

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IV. TOWARDS A STRATEGIC APPROACH TO LIGHTNING SAFETY AND PROTECTION

In considering lightning safety, many techniques, methods and recommendations have been advocated.

These include "rules of thumb" such as the well-known "30/30 rule" [10] and slogans such as "when thunder roars, go indoors" [11]. Whilst the former may indeed have wide application, the latter has limitations, particularly in countries and areas that are less developed and where "substantial structures" may not be readily accessible or available.

Similarly, numerous recommendations and methods or techniques have been advocated, such as where and how to seek shelter, places and things to avoid, and what to do when caught out in the open in an exposed situation.

The use of detection systems, in their various guises, as an early warning tool is increasing being adopted.

Various issues, constraints and challenges in respect of lightning protection solutions and their engineering approach have also previously been discussed [1].

It therefore becomes necessary, in order to achieve an effective and integrated lightning safety and protection solution, to "take a step back" and to consolidate all of the individual or "isolated" concepts, methods, techniques and recommendations into a *holistic* and *coherent* safety and protection strategy within a *structured* and *systematic* approach.

Any safety and protection strategy must obviously begin with an understanding of the pertinent risks and issues. These include:

- Lightning exposure and other risks that impact on the particular situation and potential solutions.
- Consequences and effects to be mitigated.
- Constraints and challenges that impact on risks and solutions.

From this understanding, such a safety strategy must therefore, in a coherent and holistic manner, comprehensively address, *inter alia*:

- Realistic and achievable objectives/goals.
- Measures required prior to, during and after lightning events.
- Mitigation of risks and issues.
- Practical implementation of the strategy, including aspects such as resources (in a broad sense), change management and sustainability.
- Relevant human factors.

The effective addressing of human factors across the application spectrum of lightning safety and protection is considered by the authors to be a key element in the successful design, implementation, operation and management of effective solutions. The range of human factors to be addressed covers a wide range, including for example human factors pertinent to personal safety measures to those pertinent to the management of protection solutions and the life-cycle engineering of solutions and processes.

V. INTRODUCING A LIGHTNING SAFETY AND PROTECTION STRATEGY FRAMEWORK

This paper proposes the concept of a Lightning Safety Strategy (LSS), to achieve an effective and integrated lightning safety and protection solution for a particular scenario and application. Such a LSS encapsulates a strategic and structured approach on at least two primary levels (a layered approach), these being

- a macro-level and
- a micro-level,

and which approach takes account of the requirements, risks (in a broad context), issues, challenges and constraints at each level in an integrated, holistic and coherent manner. This layered approach is diagrammatically illustrated in Figure 1.

The macro-level would be characterised by a broader perspective ("big picture"). This includes elements or aspects such as:

- Understanding and characterisation of the application environment, including human factors, and of the current situation(s).
- Objectives and goals.
- Overall planning and coordination.
- Training and awareness.
- Monitoring and ongoing management.
- Resource management (including financial, skills and operational).
- General and conceptual strategic direction, methodology and planning, including for example, macro facilities such as a detection network and associated warning systems, funding and various enabling frameworks and constraints (such as, for example, political, regulatory, and ethical).

The macro-level strategy element therefore establishes the *broad framework* within which the micro level strategy is enabled and coordinated.

The micro-level strategy is then characterised by particular circumstances and risks, and associated mitigation and management. It would typically be addressed, enabled and coordinated (including implementation aspects) through one or more *Lightning Safety Plans (LSPs)*, and would typically focus on particular applications, such as facilities and communities.

Such a Lightning Safety Plan, focussed on a particular application, and enabled through the macro strategy

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framework, is then a comprehensive plan (within a risk-based approach) that addresses, *inter alia*:

- Pertinent risks and issues, on a broad-based risk basis, for that application.
- Risk mitigation, including:
  - What to do (and not to do).
  - When, how and where to do it.
  - Provides for appropriate facilities and measures (for example warning systems, protection areas/facilities and particular protection measures).
- How it will be supported, including for example the details pertaining to:
  - Training and awareness programmes.
  - Incorporation of lightning safety plan and strategy into the overall health and safety strategy and plans for a facility or community.
  - Other elements and measures within the macro-strategy.
  - Engineering coordination planning, within a life-cycle approach

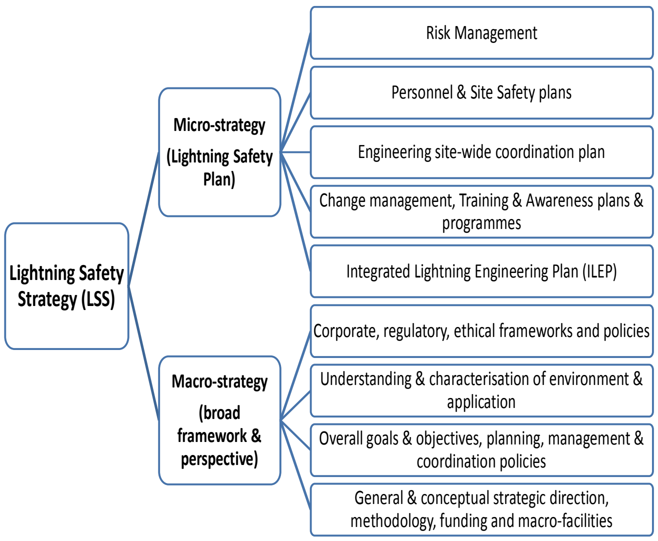

Figure 1: LSS layered structure, with examples of key elements and aspects

Figure 1 diagrammatically illustrates the layered breakdown of the Lightning Safety Strategy (LSS) into the macro- and micro- strategic arms, with examples of key elements and aspects pertaining to each.

The Lightning Safety Plan therefore enables and encapsulates the *engineering* of an effective lightning safety and protection solution. This engineering solution, within the *particular context* of the Lightning Safety Plan, is described in an *Integrated Lightning Engineering Plan (ILEP).*

The Lightning Safety Plan(s) hence also devolve ultimately into "personal plans of action", which process is facilitated, *inter alia*, through effective change management, including training and awareness programmes and activities.

Through this strategic and structured approach, the holistic lightning safety and protection solution therefore becomes a coherent and holistic solution, integrated at a specific application level through the lightning safety plan(s) as the manifestation of the micro-level strategy, and enabled and managed through the macro-level strategy and framework.

It is also important that this approach be seen and emphasised to not be a static strategy and solution, but to be appropriately dynamic within a dynamic application environment as previously discussed [1]. A life-cycle approach is therefore critical.

Typical functional "building blocks" or elements of such a Lightning Safety Plan (LSP) are shown in Figure 2 below. The importance of an integrated and coordinated approach, and of the management of human factors, the engineering planning, and of a life-cycle approach, is emphasised.

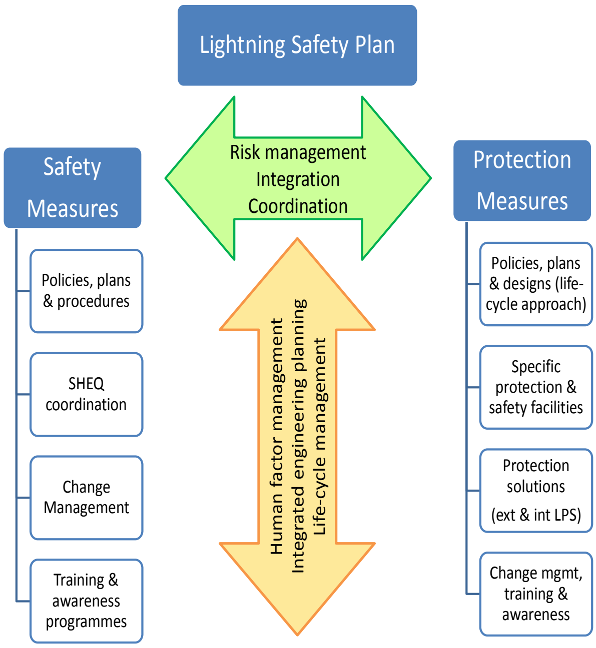

Figure 2: Lightning Safety Plan (LSP) - typical functional "building blocks" or elements

Such a strategic and structured approach therefore also provides a substantive qualitative and quantitative tool to

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enable improved management visibility of the nature and extent of the risks associated with lightning safety and protection, and hence of the required nature and extent of the required solution. This is critical in facilitating the implementation and "enforcement" of adequate and appropriate lightning safety and protection solutions.

VI. THE LIGHTNING SAFETY STRATEGY (LSS)

The Lightning Safety Strategy (LSS) as described can also be illustrated by the diagram below (Figure 3). This diagram illustrates the layered strategic framework, as well as the life-cycle approach.

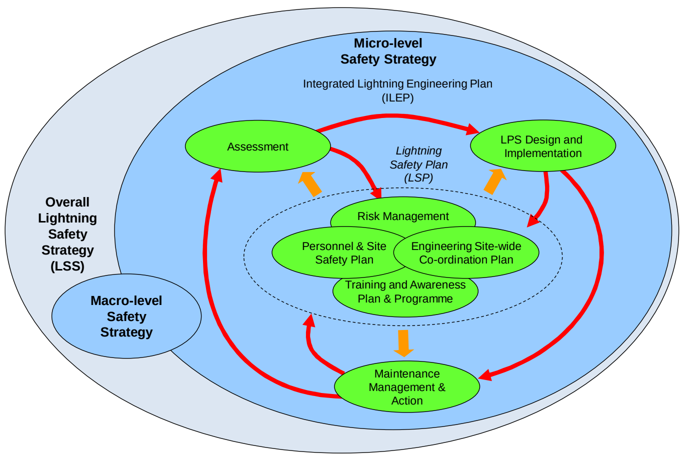

Figure 3: The Lightning Safety Strategy (LSS), indicating a layered and life-cycle approach

A life-cycle approach to the LSS is critical to ensure, *inter alia*, that throughout the dynamic life cycle of the lightning safety and protection solution:

- The application, its environment and the associated complexities are understood
- Associated constraints and risks (including financial, operational, technical, and organisational including capabilities) are identified and managed.
- Opportunities (including technical and operational coordination) are identified and exploited as appropriate.
- Solutions are engineered for life-cycle effectiveness.

The LSS model also illustrates that engineering, maintenance, technical and management coordination across an application (eg facility) and between operational and organisational functions (a "cross-cutting" approach) is critical throughout the solution lifecycle.

VII. THE INTEGRATED LIGHTNING ENGINEERING PLAN (ILEP)

The Integrated Lightning Engineering Plan (ILEP), as previously introduced and described [1], is now contextualised and refined within this broader and layered strategic framework (the LSS).

The ILEP therefore provides for a structured and systematic engineering approach within an overarching strategic framework as represented by the LSS.

Such a structured and systematic engineering approach takes account of a dynamic and complex application environment with interrelated factors and issues. It acknowledges that effective lightning safety and protection solutions cannot be designed, implemented, maintained and effectively utilised in isolation. It further emphasises that effective lightning safety and protection solutions are not achieved through a simplistic "cookbook" approach, using technical standards as "recipe books", but are achieved through a structured and systematic engineering approach where these standards play an important technical role but are applied through and within a structured, systematic and integrated strategic and engineering framework.

The ILEP is also compatible with a phased or staged approach or programme (typical of project implementation) within the life-cycle solution paradigm. Such a typical phased approach is illustrated in Figure 4 below.

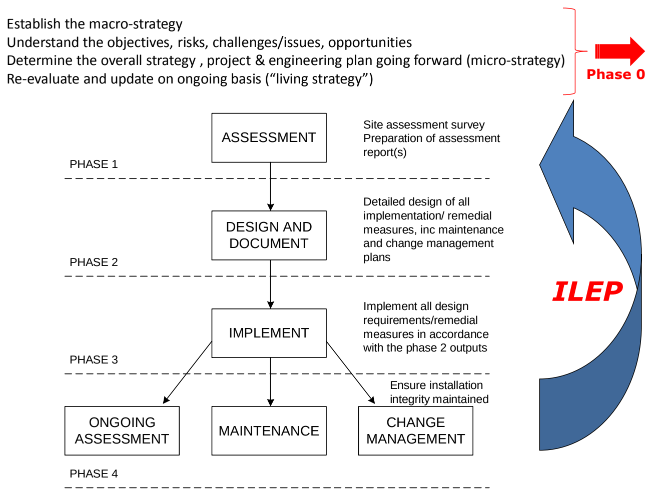

Figure 4: Typical phased engineering approach

VIII. CONCLUSIONS

It is clear that the current approach to management and engineering of lightning safety and protection requires a fresh approach. This is particularly pertinent to industrial and other high-risk scenarios.

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Effective lightning safety and protection solutions require an integrated, structured, systematic, coherent, holistic approach and strategy.

The requirements of such an approach include:

- An effective strategy at macro and micro levels.
- A considered understanding of the risks, consequences, objectives/goals, challenges and constraints.
- Lightning safety plan(s), incorporating appropriate engineering plans (as represented by the ILEP), for particular applications and communities (devolved ultimately into personal plans of action), and taking due cognisance of relevant human factors.
- Effective monitoring, management and revision on an ongoing basis.
- Coherence through an integrated and holistic approach.
- Adequate and appropriate resources
- Change management, including effective and tailored training and awareness programmes.
- An emphasis on the relevance and importance of human factors.

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