LIGHTNING SAFETY IN THE MINING INDUSTRY

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1. ABSTRACT.

Investigations at various mine locations worldwide disclose many power quality and safety issues traceable to ignoring lightning safety. Some examples are:

1.1 Mine-wide mobile radio communications fail following a lightning strike to a central radio tower. Surge protection was not adequate. (Canada)

1.2 Five maintenance workers are injured when lightning strikes a stationary vehicle. The lightning early warning system is low cost and old technology. (Peru)

1.3 A central computer system is damaged by a lightning strike. Important geological data is lost. Grounding methods are in violation of codes and standards. (USA)

1.4 More than $US one million is spent on some 350 unconventional-design lightning rods. The product is not approved by USA or international lightning protection codes and standards. Safety to all buildings is compromised. (Peru)

1.5 Miners are killed when lightning explodes methane gas inside a subsurface mine. A comprehensive approach to lightning safety is absent. (hundreds of deaths in mines in USA, Russia, & China.)

1.6 Four of eight gas turbine generators suffer lightning-induced failures. Production losses at the mine are $700,000/day. The power shortage lasts three months. (Papua New Guinea)

1.7 Lightning causes failure of a primary water pumping system. Underground flooding closes the mine for 45 days. (South Africa)

1.8 Smelter potline is "frozen" after lightning hits a substation. 164 pots have to be dug out by hand. Production is shut down for seven weeks. (USA)

1.9 Haul truck is struck by lightning with consequential tire explosion. Grenade-like fragments kill two workers. (Mexico)

1.10 Mine superintendent standing outside during a thunderstorm is killed by lightning. (Australia)

1.11 Radio operator inside a building is killed by lightning. Grounding is poor. (Indonesia)

1.12 Mine worker next to a tree is killed, one injured. (Dominican Republic)

1.13 Two workers killed, seven injured in two separate incidents in gold & copper mines. (Laos)

1.14 Lightning disables two substations near an underground mine. 275 workers are trapped 2 km below the surface. Production is suspended. (So. Africa)

1.15 Two exploration crew members struck by lightning are airlifted to hospital. Handheld detector fails to warn of threat in time for evasive action. (Peru)

1.16 Lightning is responsible for primary mill breakdown. (Norway)

1.17 Main freeze plant power transformer power supply is destroyed by lightning. 30 ft. thick ice wall shaft melts forcing mine closure. (Canada)

With such known cases it is difficult to support a position that lightning incidents are rare. This Paper suggests that lightning is responsible for significant economic and personal costs in the industry. How to defend against the lightning hazard at mining operations? We recommend adoption of a lightning hazard mitigation and safety planning process. This must be endorsed by senior mine management and Corporate-level engineering and safety management.

2. LIGHTNING BEHAVIOR & CHARACTERISTICS.

2.1. Physics of Lightning. Lightning's characteristics include current levels up to 400 kA with the 50% average being about 25kA, temperatures to 15,000 C, and voltages in the hundreds of millions. There are some ten cloud-to-cloud lightnings for each cloud-to-ground lightning flash. Globally, some 2000 on-going thunderstorms generate about 50-100 lightning strikes to earth per second worldwide. Lightning is the agency which maintains the earth's electrical balance. The phenomenology of lightning flashes to earth, as presently understood, follows an approximate behavior: the downward Leader (gas plasma channel) from a thundercloud pulses toward earth. Ground-based air terminators such as fences, trees, blades of grass, corners of buildings, people, lightning rods, power poles etc., etc. emit varying degrees of induced electric activity. They may respond at breakdown voltage by forming upward Streamers. In this intensified local field some Leader(s) likely will connect with some Streamer(s). Then, the "switch" is closed and the current flows. Lightning flashes to ground are the result. A series of return strokes follow.

2.2 Lightning Effects . Thermal stress of materials around the attachment point is determined by: a) heat conduction from arc root; b) heat radiation from arc channel; and, c) Joule heating. The radial acoustic shock wave (thunder) can cause mechanical damage. Magnetic pressures – up to 6000 atmospheres for a 200 kA flash - are proportional to the square of the current and inversely proportional to the square of the diameter of struck objects. Voltage sparking is a result of dielectric breakdown. Thermal sparking is caused is caused when melted materials are thrown out from hot spots. Exploding high current arcs, due to the rapid heating of air in enclosed spaces, have been observed to fracture massive objects (i.e. concrete and rocks). Voltage transfers from an intended lightning conductor into electrical circuits can occur due to capacitive coupling, inductive coupling, and/or resistance (i.e. insulation breakdown) coupling. Transfer impedance, due to loss of skin effect attenuation or shielding, can radiate interference and noise into power and signal lines. Transfer inductance (mutual coupling) can induce voltages into a loop which can cause current flows in other coupled circuits.

2.3 Stochastic Nature of Lightning. Absolute protection from lightning may exist in a thick-walled and fully enclosed Faraday Cage, however this is impractical in most cases. Lightning "prevention" exists only as a vendor-inspired marketing tool. Important new information about lightning may affect sensitive facilities. First, the average distance between successive cloud-to-ground flashes is greater than previously thought. The old recommended safe distance from the previous flash was 1-3 miles. New information suggests that a safe distance should be 6-8 miles (*Lopez & Holle, National Severe Storm Center, 1998*). Second, some 40% of cloud-to-ground lightnings are forked, with two or more attachment points to the earth. This means there is more lightning to earth than previously measured (*Krider, Intl. Conf. Atmospheric Electricity, 1998*). Third, radial horizontal arcing in excess of 20 m from the base of the lightning flash extends the hazardous environment (*Sandia Labs, 1997*). Lightning is a capricious, random, irregular and unpredictable event. At the macro-level, much about lightning is understood. At the micro-level, much has yet to be learned. Scientists have forecast a significant increase in lightning in future years due to climate change/global warming (*Uman, 1991*).
When lightning strikes an asset, facility or structure (AFS) return-stroke current will divide up among all parallel conductive paths between attachment point and earth. Division of current will be inversely proportional to the AFS path impedance, Z (Z = R + XL, resistance plus inductive

reactance). The resistance term will be low assuming effectively bonded metallic conductors. The inductance, and related inductive reactance, presented to the total return stroke current will be determined by the combination of all the individual inductive paths in parallel. Essentially lightning is a current source. A given stroke will contain a given amount of charge (coulombs = amp/seconds) that must be neutralized during the discharge process. If the return stroke current is 50kA – that is the magnitude of the current that will flow, whether it flows through one ohm or 1000 ohms. Therefore, achieving the lowest possible impedance serves to minimize the transient voltage developed across the AFS path through which the current is flowing [e(t) = I (t)R + L di/dt)].

3.0 <u>LIGHTNING PROTECTION DESIGNS & DEFENSES FOR MINING OPERATIONS.</u>

Power & Productivity Losses at: Processing Control Areas? Electric Power Substations? Security? IT/Computers? Radio Communications & Dispatch? Administration? Fuel Farm? Explosives Storage? Mitigating a lightning shutdown of critical areas can be achieved by the use of a detailed protective approach*,* described below in general terms.

3.1 <u>Air Terminals</u>. Since Franklin's day lightning rods have been installed upon ordinary structures as sacrificial attachment points, intending to conduct direct flashes to earth. This *integral air terminal design* does not provide protection for electronics, explosives, or people inside modern structures. Inductive and capacitive coupling (transfer impedance) from lightning-energized conductors can result in significant voltages and currents on interior power, signal and other conductors. Overhead shield wires and mast systems located above or next to the structure are preferred to lightning rods in many circumstances. These are termed *indirect air terminal designs*. Such methods attempt to collect lightning above or away from the sensitive structure, thus avoiding or reducing flashover attachment of unwanted currents and voltages to the facility and equipments. These designs have been in use by the electric power industry for over 100 years. Investigation into applicability of dielectric shielding may provide additional protection where upward leader suppression may influence breakdown voltages (*Sandia Laboratories, 1997*). Faraday-like interior shielding, either via rebar or inner-wall screening, is under investigation for critical applications (*US Army Tacom-Ardec*).
Unconventional air terminal designs which claim the elimination, screening or redirecting of lightning (DAS/CTS - Charge Dissipators) or lightning preferential capture (Early Streamer Emitter – ESE/CVM - Dynasphere) deserve a very skeptical reception. Their claimed effective protection radius is exaggerated and has been criticized by the scientific community. See in Google "unconventional air terminal designs" for authoritative discussions. Unconventional designs are not recognized by major Codes, including IEC 62305-3 section 5.2; AS/NZS 1768 (2007) sections 1.1 and 4.3.2 (d) and NFPA-780 (2011) section 1.1.3. *Caveat Emptor !*

3.2 <u>Downconductors</u>. Downconductor pathways should be installed outside of the structure. Rigid strap is preferred to flexible cable due to inductance advantages. Conductors should not be painted, since this will increase impedance. Gradual bends always should be employed to avoid flashover problems. Building structural steel also may be used in place of downconductors where practical as a beneficial subsystem to emulate the Faraday Cage concept.

3.3 <u>Bonding</u> assures that unrelated conductive objects are at the same electrical potential. Without proper bonding, lightning protection systems will not work. All metallic conductors entering structures (ex. AC power lines, gas and water pipes, data and signal lines, HVAC ducting, conduits and piping, railroad tracks, overhead bridge cranes, roll up doors, personnel metal door frames, hand railings, etc.) should be electrically referenced to the same ground potential. Connector bonding should be exothermal and not mechanical wherever possible, especially in below-grade locations. Mechanical bonds are subject to corrosion and physical damage. HVAC vents that penetrate one structure from another should not be ignored as they may become troublesome electrical pathways. Frequent inspection and cross-joint measuring (maximum 10 milliohms) of connectors to assure continuity is recommended.

3.4 Grounding. The grounding system must address low earth impedance as well as low resistance. A spectral study of lightning's typical impulse reveals both a high and a low frequency content. The grounding system appears to the lightning impulse as a transmission line where wave propagation theory applies. A considerable part of lightning's current responds horizontally when striking the ground: it is estimated that less than 15% of it penetrates the earth. As a result, low resistance values (25 ohms per National Electrical Code) are less important that volumetric efficiencies.
Equipotential grounding is achieved when all equipments within the structure(s) are referenced to a master bus bar which in turn is bonded to the external grounding system. Earth loops and consequential differential rise times must be avoided. The grounding system should be designed to reduce AC impedance and DC resistance. The use of buried linear or radial techniques can lower impedance as they allow lightning energy to diverge as each buried conductor shares voltage gradients. Ground rings connected around structures are useful. Proper use of concrete footing and foundations (Ufer grounds) increases volume. Where high resistance soils or poor moisture content or absence of salts or freezing temperatures are present, treatment of soils with carbon, Coke Breeze, conductive cements, natural salts or other low resistance additives may be useful. These should be deployed on a case-by-case basis where lowering grounding impedances are difficult and/or expensive by traditional means.

3.5 Corrosion and cathodic reactance issues should be considered during the site analysis phase. Where incompatible materials are joined, suitable bi-metallic connectors should be adopted. Joining of aluminum down conductors together with copper ground wires is a typical situation promising future troubles.

3.6 Transients and Surges. Electronic and electrical protection approaches are well-described in IEEE STD 1100 and the NLSI website. Ordinary fuses and circuit breakers are not capable of dealing with lightning-induced transients. Surge protection devices (SPD aka TVSS) may shunt current, block energy from traveling down the wire, filter certain frequencies, clamp voltage levels, or perform a combination of these tasks. Voltage clamping devices capable of handling extremely high amperages of the surge, as well as reducing the extremely fast rising edge (dv/dt and di/dt) of the transient are recommended.
Protecting the AC power main panel; protecting all relevant secondary distribution panels; and protecting all valuable plug-in devices such as process control instrumentation, computers, printers, fire alarms, data recording & SCADA equipment, etc. are suggested. Protecting incoming and outgoing data and signal lines (modem, LAN, etc.) is essential. All electrical devices which serve the primary asset such as well heads, remote security alarms, CCTV cameras, high mast lighting, etc. should be included.
Transient limiters should be installed with short lead lengths to their respective panels. Under fast rise time conditions, cable inductance becomes important and high transient voltages can be developed across long leads. SPDs with removable internal modules are suggested.
In all instances the use high quality, high speed, self-diagnosing SPD components is suggested. Transient limiting devices may use spark gap, diverters, metal oxide varistors, gas tube arrestors, silicon avalanche diodes, or other technologies. Hybrid devices, using a combination of these techniques, are preferred. SPDs conforming to the International CE mark are tested to a 10 X 350 us waveform, while those tested to IEEE and UL standards only meet a 8 X 20 us waveform. It is suggested that user SPD requirements and specifications conform to the CE mark, as well as ISO

9000-9001 series quality control standards. Beware of many unreliable products in the marketplace. Who are the reputable vendors?
Uninterrupted Power Supplies (UPSs) provide battery backup in cases of power quality anomalies…brownouts, capacitor bank switching, outages, lightning, etc. UPSs are employed as back-up or temporary power supplies. They should not be used in place of dedicated SPD devices. Correct Category A (wall outlet) installation configuration is: AC wall outlet to SPD to UPS to equipment.

3.7 Detection. The best detector is human recognition equating thunder with lightning: hearing thunder indicates the lightning is within one's hearing range. That is very close. It is time NOW to seek shelter. The marketplace provides good/not good/poor products for lightning detection. They are available at differing costs and technologies and may be useful to provide early warnings. They acquire lightning signals such as RF, MF, EF, or light from Cloud-to-Cloud or Cloud-to-Ground or atmospheric gradients. Users should beware of over-confidence in detection equipment. They are not perfect and do not always acquire all lightning all the time. Detectors cannot "predict" lightning. Detectors cannot help with first strike "Bolt From The Blue" events. Some detectors should only be used for hobby purposes: not for life safety. The list of reputable detection equipment is short. We recommend redundancy of (where possible) a network system, a professional grade detector, and a reliable handheld (most are no more than 60% efficient) detector. A notification system of radios, loudspeakers, strobe lights, remote sirens, telephone, cell phone and/or other communication means should be employed with the detectors. See the NLSI website page www.lightningsafety.com/nlsi_lhm/detectors.html for a more detailed treatment of detectors. We can recommend and supervise installation of one or more types of detectors based upon local conditions.

3.8 Inspection, Maintenance & Testing. Modern diagnostic testing is available to "verify" the performance of lightning conducting devices as well as to indicate the general route of lightning through structures. With such techniques, lightning pathways can be inferred reliably. Sensors which register lightning current attachments can be fastened to downconductors. Regular physical inspections and testing should be a part of an established preventive maintenance program. Failure to maintain any lightning protection system may render it ineffective.

4. PERSONNEL SAFETY ISSUES.

4.1 Education is the essential tool for outdoor employee and contractor safety. It should be a part of the initial induction training process and a topic for regular toolbox safety briefings. NLSI provides various safety instruction media (videos/booklets/instruction materials) for this purpose. They should be installed on the mine's IT server system for access by all persons.

4.2 Lightning safety should be understood and practiced by all personnel during thunderstorms. If thunder is heard, the accompanying lightning is within one's hearing range: evacuation to a safe location should be immediate. Measuring lightning's distance with professional-grade detection equipment is an estimate with varying accuracies. Detector selection is site-specific and cannot be summarized here. We generally recommend suspending all outdoor activities when lightning crosses a ten mile radius. With compliance to a NLSI Field Audit, it may be possible to reduce this radius to 5-8 miles. Activities should not be resumed until 20-30 minutes has expired from the last observed thunder or lightning. This is a conservative approach -- perhaps it is not practical in all circumstances. Safety is the prevailing directive. Generally for outdoor workers, we suggest an action protocol according to recommendations in NFPA-780, Annex M:

Yellow Alert – Lightning is 20 to 40 miles (30-60 km) distant. Be cautious.
Orange Alert - Lightning is 11-19 miles (16-30 km) distant. Be aware.
Red Alert - Lightning is 0-10 miles (0-16 km). Suspend activities. Go to shelter.

4.3 When lightning threatens, standard safety measures should include: avoid water and all metal objects; get off the higher elevations including rooftops; avoid solitary trees; stay off the telephone. A fully enclosed metal vehicle – van, car or truck – is a mostly safe place because of the quasi-Faraday Cage effect. (See: YouTube "Faraday Cage" for a demonstration.) A large permanent building also can be considered a safe place. *(Disclosure. We design and we certify lightning shelters according to International Standards. Contact us for details.)*

Every organization should consider adopting and promulgating a Lightning Safety Plan specific to its operations. An all-encompassing General Rule should be: "If you can hear it (thunder), clear it (evacuate); if you can see it (lightning), flee it." For open pit mining operations, including processing, we suggest all workers should be within a 3-4 minute walk when Red Alerts are announced.

5. CODES AND STANDARDS.

In the USA there is no single lightning safety code or standard providing comprehensive assistance for mining activities. NFPA-780 is a general installation guideline for lightning protection systems. US Government lightning protection documents should be consulted. The Federal Aviation Administration FAA-STD-019d and the US Air Force AFI 32-1065 are valuable. The IEEE 142 and IEEE 1100 Recommended Practices are suggested. Other recommended federal codes include military documents MIL HDBK 419A, Army PAM 385-64, NAVSEA OP 5, AFI 32-1065, NASA STD E0012E, MIL STD 188-124B, MIL STD 1542B, MIL STD 5087B, and UFC 3-570-01. The International Electrotechnical Commission IEC 62305 and IEC 61643 series for lightning protection are comprehensive, excellent reference documents for the lightning protection engineer. Adopted by many countries, IEC 62305/61643 are science-based documents applicable to many design situations. Spanish speaking mining operations should consult the Mexican lightning protection code NMX-J-549-ANCE. The AS/NZS-1768 (2007), the SANS-62305 (2007) and the Singapore 62305 are excellent documents. Beware the French NF C17-102 and the Spanish UNE-21186 codes which are produced by enthusiastic salesmen promoting unconventional designs, not by objective engineers and scientists.

6. CONCLUSION.

6.1 Natural hazards such as lightning are low probability/high consequences events. Risk management of the lightning hazard requires an in-depth assessment.
Lightning has its own agenda and may cause damage despite application of best efforts. Any comprehensive approach for protection should be site-specific to attain maximum efficiencies. In order to mitigate the hazard, systematic attention to details of grounding, bonding, shielding, air terminals, surge protection devices, lightning detection, personnel notification, safe shelters, personnel education, and adoption of risk management principles are recommended.

6.2 Areas of vulnerability at typical mines include: Security; Communications & Radio Towers; IT Operations; Gated Entrances; Conveyors & Crushers; Processing; Explosives Storage; Drilling; Loading; Hauling; Maintenance Buildings; Administrative Buildings; Laboratory Buildings; Cafeterias; Weigh Stations; Fuel Tanks Storage Areas; Compressor and Pumping Stations; Cranes; Guard Crossings; Exploration Crew Activities; Diesel Generator Stations; Electric Power Sub Stations…(this is not a complete listing…) and other high asset locations specific to particular mine activities.

6.3 Should a site-wide lightning hazard and risk assessment be conducted? Should a walk down evaluation of critical electrical and electronic equipments be conducted to identify defenses? Are mine personnel informed about lightning safety measures?

6.4 The NLSI consultancy at your mine properties can provide:

A. Comprehensive worker safety training.
B. Site-focused Policies and Procedures.
C. Comprehensive inspections of electrical/electronic vulnerabilities with recommended defenses.

We have on-the-ground experience at large scale mining operations in Ghana, Tanzania, Peru, Dominican Republic, Cuba, Mexico, Papua New Guinea, Australia, and the USA. Contact us for a mine site audit/assessment. Thank you for your attention to this Technical Report.

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