Reducing the

Risk of Flashovers

in the Design of an Underground
Ammunition Storage & Processing Facility

ABSTRACT

Flashovers are hazards to ammunition and human safety in an ammunition storage area. Therefore, it is vital that such areas are designed with features that prevent flashovers initiated by electrical faults, external lightning events and electrostatic discharges. A comprehensive grounding and bonding scheme is essential to minimise such a hazard. This paper describes the flashover risks addressed in the design of an underground ammunition storage area, and the various engineering efforts adopted to implement the grounding, bonding and electrical systems within such a facility. The performance and maintenance of these safety features are addressed.

Chua Hian Koon
Teh Siaw Peng
Ho See Fong
Lim Jiunn Shyan

Reducing the Risk of Flashovers in the Design of an Underground Ammunition Storage & Processing Facility

INTRODUCTION

There are many benefits of storing ammunition underground. Besides providing good protection from adversarial attacks, such a facility could also reduce the land sterilisation area required to ensure safe land use around the area. Despite these benefits, there are new challenges in designing a safe environment for underground ammunition storage. 'Flashover' is a general term used to describe a disruptive discharge around or over the surface of a solid or liquid insulator. In the design of any ammunition storage and handling facility, it is important to consider the possible catastrophic events that can be initiated by the occurrence of a flashover. A flashover with a high energy content, and in the presence of a good mixture of explosive dust or flammable gas, is likely to cause an explosion. There are three classes of flashover hazards that need to be addressed:

The first class refers to lightning-induced flashover hazards. The safety of the ammunition stored underground from direct lightning strikes or from lightning-induced voltages must be considered.

The second class refers to electrical flashover hazards. In an underground facility, electrical power is essential for lighting, ventilation and pumping functions. Electrical flashover hazards can occur in the form of short circuit faults along the electrical network, over-voltages generated by the switching of electrical equipment or the aging of or damage in the insulation of electrical equipment.

The third class refers to flashovers induced by the accumulation of electrostatic charges. During the handling of sensitive explosive devices such as electric fuze primers, electrostatic charges accumulated on a human body or any charge storage device could accidentally discharge through the primer circuit and fire it off.

There is limited knowledge and experience in designing ammunition storage and processing facilities in an underground environment. There is also a lack of literature that addresses the flashover hazards peculiar to underground ammunition storage and processing. Much insight has been gained from studying the mining industries and underground tunnelling projects. This paper shall address the concerns of flashover hazards in building such a facility in Singapore and suggest some engineering measures that have been adopted to mitigate the occurrence of such hazards.

LIGHTNING FLASHOVER HAZARDS

Singapore has one of the highest rates of lightning activity in the world. Lying near the equator, Singapore has weather that is hot and humid almost all year round. Conditions are favourable for the development of lightning-producing thunderstorm clouds. An average of 171 thunderstorm days (days when thunder is heard) is recorded annually in Singapore, according to the National Environment Agency, Singapore (2002). Lightning in Singapore has an average ground flash density of 12.6 strokes per year per square kilometre. The occurrence will be higher along the coastal region, areas with water bodies and higher ground with vegetation. This awesome natural phenomenon, with the capacity to reach discharges of up to 200kA and create voltage potentials of up to millions of volts, can wreak havoc if not properly addressed.

Conventional above-ground ammunition storage facilities can be effectively protected against the effects of lightning by fitting the facilities with air termination networks, earth termination systems, appropriate surge protection and more importantly, leveraging the interconnected network of reinforcement bars usually inherent in the construction of such facilities. This concept of protecting the ammunition through potential equalisation, by creating a Faraday cage around the ammunition, has been tested to be effective (International Symposium on Defense Construction, 2002). By ensuring the placement of ammunition at practical distances from the walls of the facilities, lightning flashover hazards could be effectively mitigated.

There is limited knowledge, however, on the effects of lightning strikes on an underground environment. An ammunition storage facility built in granite rocks may appear to be well protected, yet the possibility of other lightning-induced flashover risks cannot be discounted. Technical literature from the international engineering community has revealed the possibilities of lightning propagation through the earth and the potential for igniting flammable gases in underground coal mines (Novak and Fisher, 2001). Studies have shown that a potential difference of up to 15.6kV could be generated at the base of a coal mine 600-feet deep under the surface.

In May 2007, a research team from Sandia National Laboratories published a news release suggesting that the explosion at the Sagao Mine, located near Buckhannon, West Virginia, US on January 2006, was likely to be caused by lightning. The research team cited two possible modes of transmission of lightning energy deep into the coal mine. The first mode is through a lightning strike on the earth's surface and the resulting propagation of lightning current through the overlying strata into the underground space. The second mode is through a direct lightning strike on metallic penetrations such as conveyers and power lines at the entrance of the mines and propagating deep within.

Therefore, it is important to consider the effects of lightning in an underground space, especially if the underground space is built within high-grade granite rocks. Granite rocks have a high resistivity of between 1000Ω-m to 3000Ω-m. The depth of penetration of lightning is proportional to the resistivity of the earth. This means that there is a possibility that significant electric fields generated by lightning strikes on the surface of high resistive granite rocks could propagate deep into the underground space. If the earth strata were uniform, the electric fields generated underground should be evenly distributed such that there would not be any build-up of significant potential difference. However, in reality, rock strata are usually not uniform, especially at the ceiling of the rock cavity.

In the construction of an underground storage facility, it is a common practice for steel bolts to be drilled into the rock crevices as a safety measure to prevent loose rocks from falling. Additional bolts are also drilled into the rocks to support overhanging structures for the ventilation system, as shown in Figure 1. These

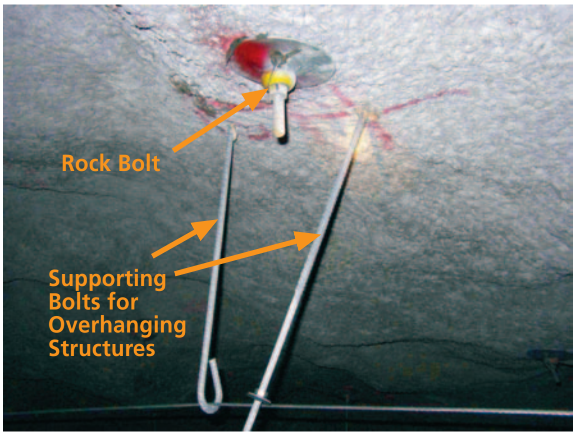

Figure 1. Rock bolts and supporting bolts commonly used in underground space

rock bolts and overhanging structures contribute to create a non-uniform electric field distribution along the ceiling surface, thus creating potential gradients.

Some forms of ammunition contain flammable liquid which, upon release into the atmosphere e.g. during accidental spillage, will easily vapourise and form flammable vapour clouds. In an underground space, ventilation is limited and any gaseous emission will potentially be contained in a confined space. If flammable vapour or explosive dust were to accumulate to an appropriate mixture at the top of the underground space, a lightning-induced potential difference might generate flashovers that could spark off the combustion of the vapour or dust. In the building of an underground ammunition facility, the question of whether a lightning strike would generate a potential difference between the underground rock bolts great enough to initiate a flashover has to be addressed. Figure 2 shows an illustration of this problem.

Assuming that the resistivity of the earth strata is uniform and that the current from a lightning strike on the surface of earth is discharged uniformly in a semi-hemispherical manner into the earth, the potential difference between two points in the ceiling of the underground space can be estimated by the following relationship:

$$V_{AB} = V_A - V_B = \frac{I_L \cdot \rho}{2\pi}\left(\frac{1}{r_A} - \frac{1}{r_B}\right) \quad \text{(Eq 1)}$$

Assuming that the lightning strikes directly above point A, where $r_A = D_E$, the induced potential difference between two points in the underground space can be expressed by the following relationship:

$$V_{AB} = \frac{I_L \cdot \rho}{2\pi}\left(\frac{1}{D_E} - \frac{1}{\sqrt{D_E^2 - D_S^2}}\right) \quad \text{(Eq 2)}$$

There are two possible strategies to prevent a build-up of potential difference. One strategy is to ensure that the potential gradient in the

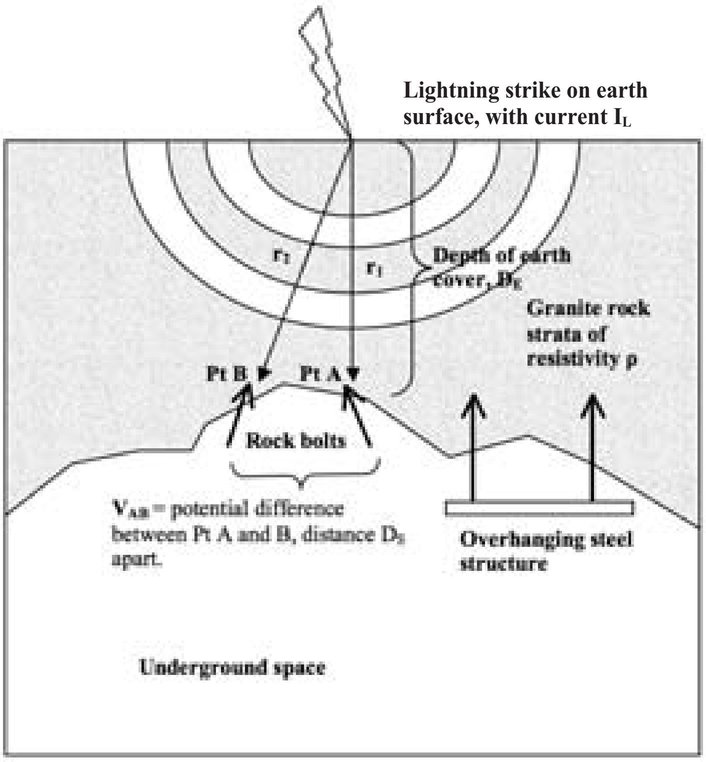

Figure 2. Illustration of lightning propagation into underground space

underground space does not exceed the minimum breakdown strength of air. The dielectric breakdown strength of air ranges from 1MV/m to 5MV/m, depending on the humidity and the atmospheric pressure. In the worst case scenario, if two adjacent rock bolts are separated by 0.5m, there needs to be a potential build-up of 500kV across the two bolts to initiate a flashover. This scenario can be avoided by ensuring that there is a minimum separation distance between adjacent rock bolts and metallic structures. In other words, the further the rock bolts are apart from one another, the greater is the potential difference required to generate a flashover.

If certain rock bolts and metallic structures cannot be practically separated by the minimum distance, the second strategy is to bond them galvanically together to ensure that the potential difference across is not high enough to generate a flashover.

The presence of a steel-cased bore hole that extends from the earth's surface into the underground space will increase the magnitude of lightning-induced potential difference between the underground rock bolts (Fisher and Novak, 2001). Computational finite element methods can be employed to evaluate the electric field distribution in the underground space.

As mentioned earlier, the second mode of lightning propagation into an underground space is through a direct lightning strike on metallic elements at the entrance of the tunnel or shaft leading into an underground space. These metallic elements could be power cables, communication cables, metal pipes for drainage or fire-fighting applications, metallic ventilation ducts or metallic supporting structures. A direct lightning strike on these elements will cause a high discharge current to flow in them. As the lightning current flows along the path of the metallic element, it will generate points of potential difference between the element and its surrounding environment.

A transmission line model as illustrated in Figure 3 can be used to study the voltage and current transients that will propagate along the stretch of the metallic element leading into the underground space. The metallic element such as a stretch of structural steel overhanging support is modelled as a series of unit inductances: L_s and resistance R_s. Each unit section is earthed with a resistance R_e and has a capacitance to ground C_e. Circuit transient analysis software such as EMTAP or Pspice can be used to calculate the voltage transient on the metallic element at the end of the underground tunnel, for the worst cases of lightning strike.

The model can be used to determine the number of grounding points that is necessary to bring the conducted voltage transient at the end of the circuit to a safe and tolerable level. This will ensure that the potential rise will not be high enough to generate a flashover.

A flashover will be generated when there is a potential difference between two points built up beyond the electrical breakdown strength of air. To mitigate this mode of lightning effects, the metallic elements must be intentionally grounded at multiple sections to provide good current discharge paths as it stretches along the length of the tunnel from the entrance to the storage space. Equi-potential bonding should be applied to adjacent metallic elements on the wall and floor sections along the tunnel on ensure that the ground potential rise between these elements is minimised. The section on 'Grounding and Equi-potential Bonding' shall elaborate more on this aspect. For power-carrying conductors and communications conductors which cannot be grounded practically, surge suppression devices are installed at these service entry points to prevent the lightning-induced currents from propagating down these conductors.

Another possible mode of lightning propagation that warrants more study is how lightning will propagate through cracks in the

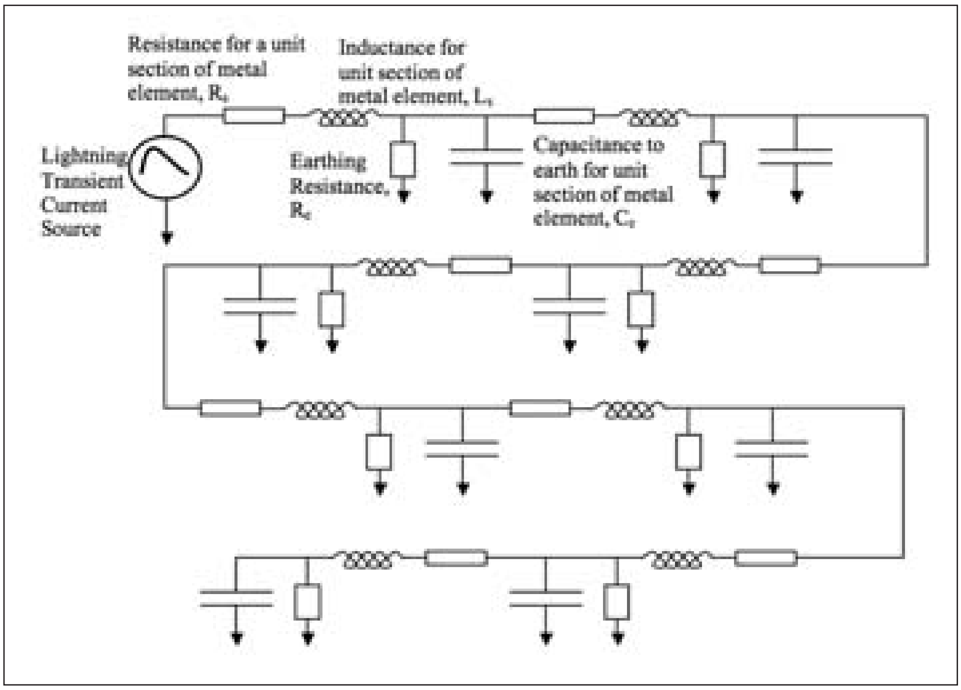

Figure 3. Circuit model of metallic element along the tunnel

rocks. It is common for rock formations to have cracks either naturally occurring or artificially made during blasting operations to create the underground space. Groundwater often flows through these cracks and may form a conductive discharge path for lightning currents to reach the underground space.

ELECTRICAL FLASHOVER HAZARDS

Electrical flashovers can be generated in many ways. The following are some known ways:

a. Damage to power cables along the tunnel due to rock fall
b. Arc initiation during the switching of circuit breakers
c. Flashover across power-carrying bus-bars due to insulation failures
d. Flashover across medium voltage transformer windings due to insulation failures or surface conduction across conductive dust
e. Flashover across electrical terminals due to human error, rodents or vermin
f. Loose connections in electrical wiring causing overheating and minor arcing between connections – this may extend over a period of time to cause air ionisation in an enclosure which could lead to a flashover to ground
g. Accidental energising of bus-bars when maintenance personnel are working on them, or when tools are left in the switch gear compartments
h. Accidental energising of bus-bars when the grounding switch of circuit breakers has not been opened
i. Overheating of motor control panels resulting in insulation failures that may progress to flashover

The incidences in the above list can take place in any installation, and the effects will be catastrophic if the flashover ignites flammable gas or explosive dust in an ammunition facility. The design of the protection systems and the method of installation for the electrical infrastructure have to be such that they prevent flashover hazards.

Fundamental in the design of the electrical network of an underground ammunition facility is the type of grounding system to adopt. The choice of grounding system is important as it affects not just the overall electrical safety but also the lightning safety of the facility.

A five-wire TN-S electrical grounding system can be used. It is suited to the distribution system in Singapore as it provides a protective earth conductor in each outgoing circuit, allowing the safe return of fault currents in the case of any phase-to-earth faults. This thus provides protection against direct and non-direct contacts. For such a TN-S electrical system, the low voltage network is solidly grounded at one point at the secondary winding of the transformer. At the low voltage level, overcurrent protection and ground fault protection devices should be installed to provide two levels of circuit protection from electrical faults. The protective earth conductor provides a continuous low impedance path for the earth current to flow through, thus permitting the positive action of the ground fault protection devices. However, this will inevitably also generate higher fault currents.

It is sometimes necessary for ammunition facilities to be sited deep underground to provide the necessary protection. In such situations, electrical networks may stretch several kilometres. It is thus not uncommon for medium voltage distribution of electricity to be used to overcome the problem of voltage drop. It is important to define zones within the underground space, such that medium voltage electrical substations, distribution rooms, equipment and control panels are located at safe distances away from the zones where ammunition is physically stored or processed. At the medium voltage level, pilot wire differential-relay protection should be incorporated to provide discrimination and trip circuit breakers during real cable faults.

Active ventilation, fire suppression and compartmentalisation systems should be specifically designed such that an electrical fire or flashover hazard at the equipment zones does not ignite any flammable compound or propagate into the ammunition storage or processing areas. Electrical switchgears or circuit breakers can be located in positive-pressurised plant rooms and housed in metal compartments that prevent the ingress of dust.

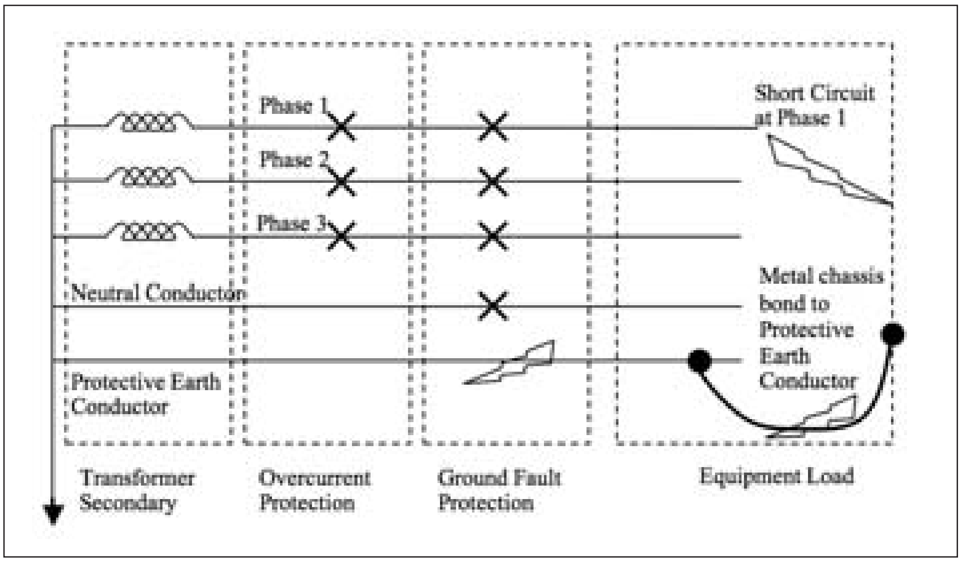

Figure 4. Illustration of a TN-S electrical earthing system

Gas-insulated switchgears are designed such that the bus-bars and the switching contacts are enclosed either in a vacuum or in SF6 gas pressurised tubes. They should be considered for application as they confine flashover arcs at the points of switching contacts within the pressurised tubes, thus providing additional safety compared to air circuit breakers.

ELECTROSTATIC FLASHOVER HAZARDS

Lessons in the history of ammunition handling have shown us the risks of electrostatic flashover or discharge on components of ammunition systems. During the 1950s, the US Naval Ordnance Laboratory investigated the accidental firing of a Mk112 type electric primer and concluded that some electric fuze type primers are extremely susceptible to initiation by electrostatic discharges due to the charges accumulated during the handling procedures (Kabik and Ayres, 1951). As modern ammunition systems are increasingly integrated with miniaturised electronic firing and control features, they may not be much safer under similar exposure to electrostatic discharge.

The environment in the underground space is usually warm and humid, with the relative humidity level in some areas reaching as high as 99%. This benefits electrostatic discharge (ESD) control as static charges are easily discharged from a body through the moist air. However, it is still important in the design of the underground facility that ESD control measures are adopted. It is uneconomical to enforce ESD control measures throughout the entire span of the facility, thus specific zones would need to be identified for the handling, unpacking and processing of ammunition. ESD control measures can thus be limited to these zones.

The explosive safety code of the UK Department of Defence suggests a list of comprehensive ESD control measures for a typical above-ground facility and can be suitably applied in an underground ammunition processing environment.

Safety features should be installed to facilitate the discharge or 'bleeding' of body static charges. In zones for ammunition storage, air-conditioning equipment installed should maintain the relative humidity level above 60% so as to prevent the build-up of electrostatic charges. Personnel static discharge bars should be located at accessible locations e.g. the entrance of storage areas and ammunition processing areas.

In zones of ammunition processing, anti-static or conductive flooring can be installed as a means of personnel discharge. Anti-static flooring helps to discharge any charged body slowly to earth via a resistive layer. The use of anti-static flooring for zones processing ammunition with ignition energy between 1mJ and 156mJ and the use of conductive flooring for ammunition with ignition energy less than 1mJ are recommended (Joint Service Publication, 2006). The UK ESTC code recommends that anti-static flooring have a surface-to-earth resistance between 50kΩ to 2MΩ, whereas the conductive flooring is to have a surface-to-earth resistance of less than 50kΩ.

GROUNDING AND EQUI-POTENTIAL BONDING

Due to the poor conductivity of the rocks in an underground rock cavern, it will be difficult to obtain low resistance grounding throughout the whole facility. The choice of the grounding system adopted will affect the electrical and lightning safety of the underground space. The mining industry in the US is required by regulations to install safety grounds in mines that are electrically isolated from the grounds of the mine substations. This is to ensure that the safety grounds are maintained at absolute potential and not energised to a dangerous level during a lightning strike on incoming power lines or during ground faults. One of the reasons is due to the fact that most mines extend far away from the substations. It is impractical to ensure that the mine walls and floors are well bonded to the power system ground when there are no large metallic structures, steel beams or embedded reinforced concrete that span the length of the mine tunnels. However, electrical mining equipment in these areas have ground conductors that extend to the grounds of the substations. Mineworkers are thus prone to shock hazards as they come between two elements tied to different isolated grounding systems. Maintaining two separate ground systems ensures that the potentials of both the equipment ground and mines' floor are kept independently at a safe absolute potential.

However, such a separation of grounding systems does have its problems as discussed in Cooley and Hill (1986 & 1988). An underground ammunition facility, unlike a mine, is a long-term fixed installation. Multiple large metallic structures are usually installed along the length of the tunnel to provide for ventilation, smoke control and other fire-fighting features. In practice, it is difficult to ensure that the two grounds are not coupled, especially when these large metallic structures extend along the length of an underground tunnel. Having two separate grounding systems in close proximity but not interconnected will inevitably result in ground to ground potential differences. This may lead to a shock hazard, which could be lethal in the event of an electrical fault or a lightning strike.

The type of method used to ground an underground electrical system should be carefully considered. There are four possible options: (1) ungrounded, (2) solidly grounded, (3) low resistance grounded or (4) high resistance grounded. Each type of grounding system offers its advantages and disadvantages.

An ungrounded electrical system will result in severe transient over-voltages as high as six times the nominal system voltages. There is also difficulty in locating and removing ground faults in such a system as there is no direct return for ground fault currents.

Solidly grounded electrical systems potentially generate high fault currents, typically in the order of 1,000A for low-voltage systems. Although such high fault currents have high-energy content that is sufficient to generate arc-flash hazards, they will also trip over-current protection devices more easily. Solidly grounded systems do not generate high over-voltages and allow the quick location of faults. They are more suited for a TN-S five-wire electrical system as they are intended for fault currents to flow through a low earth loop impedance to trip the ground fault protection devices. Solidly grounded systems ensure that the transformer secondary windings are Wye-grounded to the substation ground and will complement the low impedance grounding for lightning protection.

It has been a popular practice since the 1970s to adopt high resistance grounding in mines and petrol-chemical industries to reduce the magnitude of short circuit currents. High resistance grounding reduces the magnitude of fault currents to low levels (typically 5A to 25A), thus preventing the destructive effects of ground fault currents and reducing the risk of arc flash hazards. Since fault currents are limited to such low levels, process plants can continue to operate without interruption. Therefore, high resistance grounded systems offer service continuity. A high resistance grounding system is applied to three-phase three-wire loads where phase-to-neutral loads are not served, and thus it is not practical to be used for a TN-S five-wire electrical network. Another concern is the conflict with lightning safety-grounding practices. Lightning safety codes prefer a low impedance grounding and bonding system to ensure that the potential rise between two points is kept to a minimum. In the case of lightning-induced equipment potential rise, there may be a risk that high potential differences may be built up across the equipment chassis and phase conductors. A higher insulation level will hence be required on equipment connected to the electrical system (as commented by Dr Abdul Mousa, 2008).

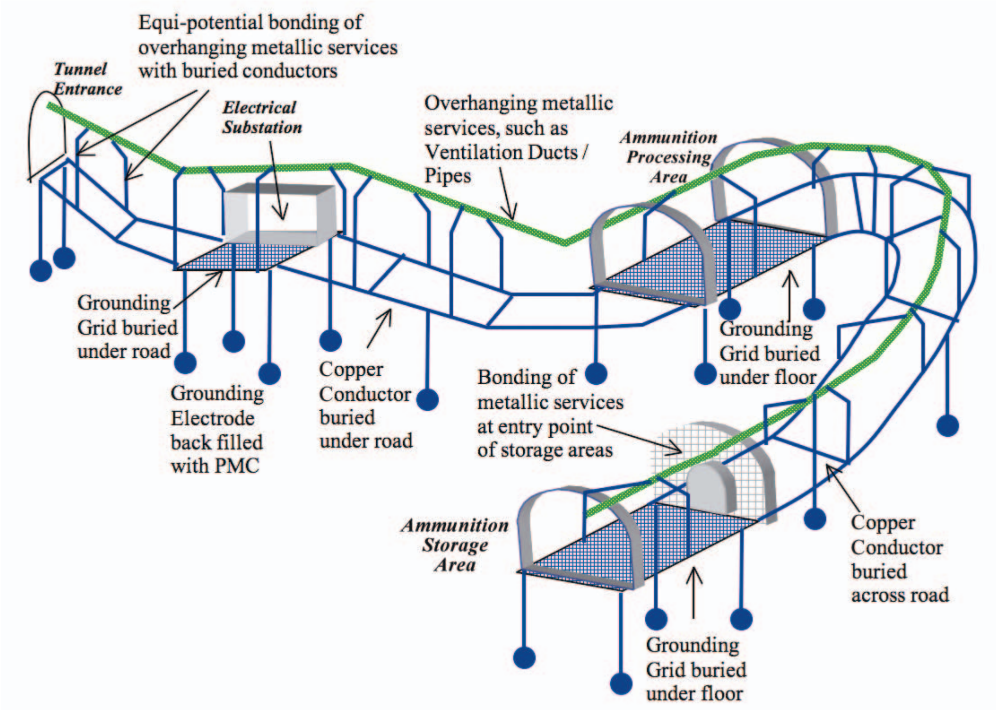

Figure 5. Illustration of grounding system for an underground ammunition facility

It is thus more practical to install a common grounding system and achieve as low a resistance to the ground as possible.

An extensive grounding system should be designed for an ammunition facility in the rocks in order to prevent both lightning and electrical flashover hazards due to uneven ground potential rise. Figure 5 gives an illustration of an underground common grounding system. The grounding system consists of metallic grid networks embedded under the concrete floors of the electrical substation as well as zones where ammunition is stored or processed. The grounding grids below electrical substations prevent hazardous ground potential rise in the event of a phase-to-ground fault. In zones where ammunition is to be processed or stored, the grounding grids prevent ground potential rise when lightning strikes propagate into the underground space. Along the stretch of the tunnel, bare copper conductors are embedded under the road surface. At various intervals of the tunnel, bonding conductors provide equi-potential bonding between the buried copper conductors and the overhanging metallic services. For storage areas, a Faraday Cage concept is adopted. Metallic services are equi-potential bonded to entry points of the storage areas to further ensure that any lightning-induced currents flowing through would not cause ground potential rise at the storage areas. Figure 6 shows an illustration of such an installation. Ammunition safety is further

Figure 6. Equi-potential bonding of metallic services at entry points before concrete walls are cast

enhanced by storing ammunition in metal containers that will act as a second layer of an equi-potential Faraday Cage.

There are various ground enhancement materials that can be used to achieve low impedance grounding amidst high resistivity rocks. These include coke, bentonite clay and conductive concrete. Expected high rate of corrosion and groundwater wash-off must be considered in the choice of the ground electrode installation adopted. In the tropics, the weathering effects on rocks make the selection of aluminum unsuitable as an electrode material. Coke powder or chemical enhancement materials are also unsuitable in underground environments, as groundwater can wash off such materials over time, and they may eventually exhibit unstable resistivity (Switzer, 1998).

The impedance of a ground electrode installation to remote earth can be imagined to be similar to conductive onion-like layers of equal thickness (Paschal, 2000). If the conductivity of the materials immediately surrounding the metal electrode is improved, the overall earth impedance of the ground electrode would be significantly reduced. This is more effective than extending the length or diameter of the electrode.

Low impedance grounding can thus be achieved in the high-resistive rocks by drilling deep bore holes at various sections of the tunnel. Each of these bore holes should have a copper electrode planted within and filled with conductive concrete materials. The copper electrode is further bonded at the top to the total grounding grid network. Figure 7 shows an illustration of such a ground electrode installation. Bonding several grounding electrodes in parallel to the grounding grid network can further reduce the impedance to remote earth.

The presence of groundwater that washes off minerals and salts from the topsoil will contribute to the weathering effects on rocks. A higher rate of metal corrosion may be

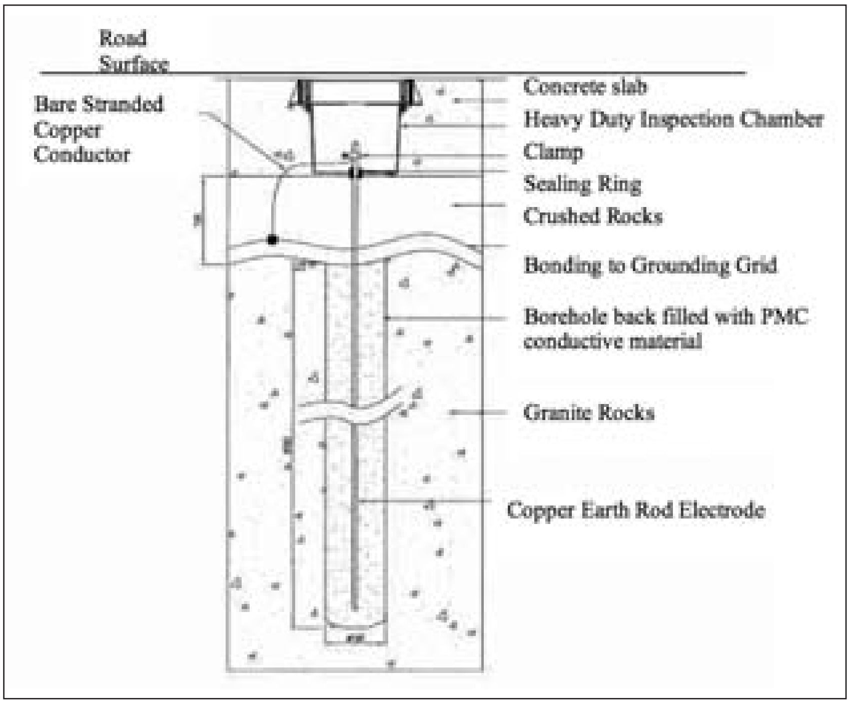

Figure 7. Illustration of a ground electrode installation in high-resistive rocks

experienced in underground space. It is thus important to conduct regular checks on the condition of the grounding and bonding conductors as part of the maintenance plan.

ZONING

As with the masterplanning of any major facility, the zoning of functional areas within the ammunition facility and the subsequent hazardous area classification are important parts of the design consideration. Area classification provides a methodology for analysing and classifying an environment where flammable vapour, mist or dust may occur with the expected operations of the area. This zoning template will help designers in the proper selection and installation of apparatus to be used safely in the environment.

JSP 482 and ATEX ('Atmosphères Explosibles') Directive (94/9/EC) on safety requirements for electrical installations and standards of protection for equipment give a good guide in defining zones of hazardous areas. JSP 482 recommends classification of areas based on the type of explosive substance present and the frequency of the presence of such explosive gases, vapour or dust. It also further defines the type of protection for different Equipment Zones. Areas deemed to have a potential for the release of explosive gas or vapour will be classified as Category A. Category B facilities refer to areas where there is a risk of explosive dust present in the atmosphere. Category C comprises all explosive buildings in which explosives do not give rise to flammable vapour or explosive dust at normal storage temperature.

Further zone classification is assigned to Category A and B areas in recognition of the differing degrees with which explosive concentrations of gases, vapours or dust may arise in terms of both frequency of occurrence and probable duration of existence on each occasion. Zone 0 is assigned to places where explosives gases and/or vapour will be present continuously or for long periods. Electrical equipment should not be installed unless it is absolutely essential and must comply with ATEX Equipment Category 1. Locations where explosives gas and/or vapour atmosphere will be likely to occur in normal operation will be classified as Zone 1 and the electrical equipment installed shall be certified to meet ATEX Equipment Category 2 standard. Zone 2 will cover areas where a flammable atmosphere is not likely to occur in normal operation but will exist for only a short time if it does occur. Electrical equipment will be certified to meet ATEX Equipment Category 3 standard.

JSP 482 provides further reference to specific types of protection appropriate for different zones (e.g. intrinsic safety types for Category A Zone 0 and flameproof types for Category A Zone 1) as well as maximum surface temperature requirements for the electrical equipment in explosive storage. Special consideration should also be given to allow for the possibility of change in use of the area which may require a different classification and involve a different set of site compatibility issues related to operational and maintenance activities.

As discussed, areas within the facility can be divided into Equipment Zones according to the nature of the explosives that are stored or handled as well as the processes to be undertaken. Electrical installations and equipment are then afforded the same Equipment Category as the areas in which they are installed or used. Equipment that meets the high safety and explosion-proof standards for Category A and B zones is often more costly. The use of this zoning concept helps to ensure that the appropriate equipment is used for the different zones instead of the entire facility. This will effectively reduce hazards from electrical flashover and also ensure the economical usage of the equipment.

CONCLUSION

Lightning, electrical and electrostatic flashover hazards could occur in ammunition storage facilities and those built underground are no exception. Safety measures such as potential equalisation and sound grounding could be implemented to mitigate these risks. The challenge is always in the application of these measures to the actual facility, especially when it is underground and houses complex services and systems. Prior planning to classify the facility into different functional zones would provide a focused approach to meet the requirements of each area. Finally, good design and implementation would need to be consistently complemented with sound operation and maintenance practices to keep the hazards at bay and ensure that the ammunition facility remains safe for storage, operations and other related activities.

REFERENCES

I. Kabik and J.N. Ayres. (1951). The initiation of Electric Fuze Primers by Electrostatic Discharge, US Naval Ordnance Laboratory, Report 1762, pp 1-11.

John Paschal (September 2000). Not all Ground Roads are Created Equal. Published by Electrical Construction & Maintenance (EC&M) magazine. Retrieved on June 2008 from http://ecmweb.com/images/archive/0900groundrods.pdf

Keith Switzer, Erico Inc. (October 1998). Achieving an Acceptable Ground in Poor Soil. Published by Electrical Construction & Maintenance (EC&M) magazine. Retrieved on June 2008 from http://ecmweb/grounding/electric_achieving_acceptable_ground/

Lightning Activity in Singapore, National Environment Agency Singapore. Retrieved on June 2008 from http://app.nea.gov.sg/cms/htdocs/article.asp?pid=1203

Marvin E. Morris, Cliff A., Chua H.K. and Teh S.P. (2002). Using the Faraday Cage Concept for Substantially Improved Lightning Protection of Critical Facilities: Measurement of the Lightning Response of Explosives Storage Structure 7919 Using the Transfer Impedance Measurement Instrumentation System. International Symposium on Defense Construction, 2002.

Novak T. and Fisher T. (2001). Lightning Propagation through the Earth and its potential for Methane Ignition in Abandoned Areas of Underground Coal Mines. IEEE Transactions on Industry Applications, Vol 37, No.6, November/December 2001, pp 1555-1562.

Sandia National Laboratories (2007). Sandia research indicates that lightning was the likely cause of Sago Mine explosion. Retrieved on June 2008 from http://www.sandia.gov/news/resources/releases/2007/sago.html

UK, Joint Service Publication (JSP) 482. (2006). Safety Standards for Electrical Installations and Equipment in Explosive Facilities. Vol 1. Edition 2, Change 3, Chapter 8.

Wils L. Cooley, Herman W. Hill, Jr. (1986). Coupling of Mine Grounds to Surface Grounds. IEEE Transactions on Industry Applications, Vol 22. No. 2, March/April 1986, pp 360-364.

Wils L. Cooley, Herman W. Hill, Jr. (1988). Mine Power System Grounding Research. IEEE Transactions on Industry Applications, Vol 24. No. 5, September/October 1988, pp 846-852.

ENDNOTES

Comment made by Dr Abdul Mousa, Ph.D., P. Eng., Fellow IEEE, Lightning protection consultant, Vancouver, Canada, Co-moderator of Lightning Safety & Power Quality Issues Interest Group.

This paper was first presented at the 2008 US Department of Defense Explosives Safety Board Seminar on 12 - 14 August 2008 in Palm Springs, CA and has been adapted for publication in DSTA Horizons.

BIOGRAPHY

Chua Hian Koon is Assistant Director (Mechanical and Electrical – Protective Infrastructure) and oversees the strategic development and implementation of mechanical and electrical engineering and operational masterplans for defence infrastructures. He is the Deputy Chairman of the Technical Review Committee for Code of Practice for Lightning Protection, Singapore. Hian Koon was part of the team that was awarded the Defence Technology Prize (DTP) 2006 Team Award for their work in protective technology research. A Public Service Commission scholar, Hian Koon received Dip D'Ingenieur in Electrical Engineering (First Class Honours and Master) from the Ecole Nationale Superieure D'Ingenieurs Electriciens de Grenoble in 1988, and also holds a joint Master in Engineering Science from the Ecole Centrale de Lyon.

Teh Siaw Peng is a Programme Manager (Mechanical and Electrical – Protective Infrastructure) and oversees the engineering masterplanning, design and implementation of essential electrical systems for the Ministry of Defence (MINDEF) and the Singapore Armed Forces. He is a member of the Technical Review Committee for Code of Practice for Lightning Protection as well as a registered Professional Engineer (Electrical) with the Professional Engineers' Board. Siaw Peng received his Bachelor degree in Electrical Engineering from Nanyang Technological University.

Ho See Fong is a Senior Engineer (Mechanical and Electrical – Protective Infrastructure). He is involved in the development and project management of electrical networks in MINDEF facilities and advises on the lightning safety. He has also been involved in projects exploring new technologies in Energy and Power using fuel cells. He received his Bachelor degree in Electrical and Electronic Engineering from the Imperial College, London, United Kingdom, before furthering his training to attain a Master of Science in Electric Power Engineering from the Royal Institute of Technology, Sweden.

Lim Jiunn Shyan is a Senior Engineer (Mechanical and Electrical – Protective Infrastructure). He is involved in the planning, design and implementation of protective electrical systems and building management systems in MINDEF facilities. Jiunn Shyan also contributes to the study and implementation of lightning protection systems for MINDEF facilities, as well as the development of lightning protection for some of the equipment onboard air and land platforms. He was part of the team that was awarded the DTP 2007 Team Award for their work on the Underground Ammunition Facility. He received his Bachelor degree in Electrical and Computer Engineering (Honours) from the National University of Singapore in 2005.