THE "WIRELESS REVOLUTION" AND THE SAFE TRANSPORT, STORAGE AND HANDLING OF EXPLOSIVES AND EXPLOSIVE DEVICES.

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Abstract: There was a time, not long ago, when people used wires to send a message or to make a phone call. Imagine being without our smartphones and tablets with data connectivity now so readily available. Technologies such as cellular, 3G and 4G, Wi-Fi, WiMax, ZigBee, Bluetooth and satellite communication are behind current wireless connectivity. New services, based on new ways of using low-power wireless technologies, are now growing rapidly. Familiar wireless services are, for example, wide-area and local-area networks, GPS tracking, RFID and video security - all important for the smooth and controlled running of business today.

In the explosives manufacturing, storage and distribution chain people may hesitate to adopt new wireless technologies, despite the benefits, as the safety implications are not always clear. Part of this difficulty may lie in conservative regulation, but the key is to appreciate the issues behind wireless safety for this industry.

This paper covers the electromagnetic susceptibly of electric detonators, explosives, and electronic systems for management, communications, control and security. Assuring safety of any explosives operation involving wireless communication lies in understanding the physical interactions, performing an effective risk assessment and implementing the risk treatment measures indicated.

1. INTRODUCTION

(Note: A glossary of terminology used in this paper is provided in Clause 8).

There are many new, low-power wireless technologies, typically operating at an effective radiated power (ERP) of 2 W or less and typically below 100 mW. For these systems manufacturers, regulators and users may, however, be uninformed on safe practices applicable to the explosives manufacturing and distribution industry.

Electromagnetic Compatibility or EMC standards and tests exist to ensure that electronic and electrical systems may operate together in harmony in an electromagnetic (EM) environment.

Using EMC principles, this paper considers the effects of electromagnetic radiation on the safe storage, transport and handling of:

- Packaged electric detonators.
- Packaged electronic detonators.
- Low sensitivity explosives.
- Electronic equipment in the storage and delivery chain.

The importance of risk assessment and risk treatment of explosives operations and products in an EM environment is underlined and risk identification is described.

2. ELECTRIC DETONATORS

For storage, transport and handling, the primary risk of initiation is EM radiation coupling into the leading wires of the packaged detonators.

British Standards Institution (BSI) Publication

A detailed document on the safety of electric detonators in EM fields is PD CLC/TR 50426:2004 - Assessment of inadvertent initiation of bridge wire electro-explosive devices by radio-frequency radiation. Guide.

European electric detonators are classified into seven sensitivities in this document[1]:

Table 1: Parameters of electric detonators	Type I	Type II	Type III	Type IV	Type V	Type VI	Type VII
No-fire current in mA	180	300	450	450	1 200	4 000	200
Bridge wire DC resistance* in Ω	1	0,9	0.45	0,5	0,15	0,05	1
Value of safety resistance	0	0	0	0	0	0	50
* Note: For analysis, the leading-wire resistance is added to the bridge wire resistance.							

Whilst the BSI document is primarily a blast site risk assessment resource, useful information for storage and transport of electric detonators is provided:

- Electric detonators with folded and overwrapped leading wires[2], as in Figure 1, are relatively insensitive to electromagnetic interference (EMI). (Author's note: authorities require the ends of the leading wires to be shunted to further minimize stray current susceptibility).

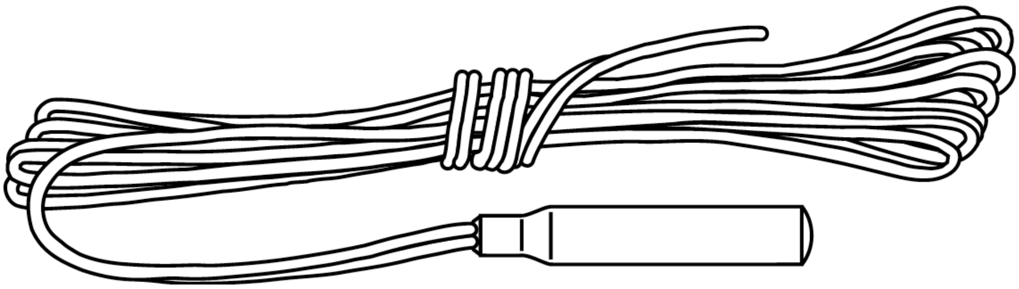

Figure 1: Commercial electric detonator showing winding and overwrapping of lead wires

- Maximum safe field strengths for packaged Type II electric detonators[3]:

Below 10 MHz	-	2 000 V/m RMS (10 000 W/m^2 mean).
10 MHz - 100 MHz	-	700 V/m RMS (1 300 W/m^2 mean).
100 MHz - 1 GHz	-	100 V/m RMS (26 W/m^2 mean).
Above 1 GHz	-	300 V/m RMS (240 W/m^2 mean).

  (Author's note: Type II is the standard electric detonator sensitivity in the United Kingdom. The Institute of Makers of Explosives publication SLP-20[4] uses 1 Ω, 40 mW sensitivity devices, similar to the Type I in Table 1. In this case the field strength immunity for packaged devices will be about half of the above figures).

The most susceptible range of 100 MHz to 1 GHz requires scrutiny as many relevant communication systems operate in this region.

EMI immunity requirements for electric detonators in transport

Various military and civil EMC requirements follow:

- The UK Ministry of Defence explosives regulations (JSP 482)[5] require electric detonators and systems containing electric detonators to be assessed as safe for sea and air transportation at field strengths of at least 200 V/m.
- US MIL STD-461F[6] Table VII stipulates field strength susceptibility of up to 200 V/m for aircraft and above deck on ships and 50 V/m for ground transport.
- Cenelec report CLC(SG)819 covering electromagnetic compatibility for civil aircraft[7] requires, for system certification, average field strengths up to 10 V/m from 100 MHz to 1 GHz and up to 200 V/m at frequencies above 1 GHz.

These standards infer that:

- From MIL-STD-461 there should be no issue with ground transport of packaged Type I and Type II electric detonators.
- Above-deck sea transport of Type II electric detonators should be possible as high intensity radiation from radar systems is above 1 GHz where the packaged electric detonator immunity is 300 V/m.
- On civilian aircraft Type II electric detonators, suitably packaged to meet UN transport of dangerous goods requirements, should be adequately EMI resistant.

Examples for radio exclusion distance from packaged electric detonators

IEC 61000-4-3[8] gives the relationship between power, distance and field strength from a transmitter as:

$$E = k\sqrt{P}/d \qquad \textit{Equation 1}$$

Where:
E is the field strength (V/m).
k = 7 for free-space propagation.
P is the effective radiated power (ERP) (W).
d is the distance from the antenna (m).

Example 1: For a terrestrial FM transmitter operating at 100 MHz with an ERP of 100 kW the critical distance for 100 V/m is 22 m. With the radiating antennae on a high tower, there should be no problem with maintaining this exclusion distance.

Example 2: Taking a 25 W vehicle-mounted two-way radio operating at 150 MHz (2 m wavelength) the critical distance for 100 V/m is only 350 mm. Unfortunately equation 1 does not hold for distances below about one wavelength, and a different analysis technique for such "near-field" conditions is called for.

Analysis for electric detonators in the "near-field"

In example 2 and for many lower-power transmitting devices, the critical field strengths for packaged electric detonators are reached at distances below one wavelength.

Messrs Poynting Antennas (Pty) Ltd[9] were contracted by Messrs AEL Mining Services Ltd[10] to study near-field coupling into electric detonators for low-power devices in the 100 MHz to 3 GHz frequency range, the area of interest in this paper. (Extracts of this study are reproduced by courtesy of Messrs AEL Mining Services).

The Poynting study sought to remove the variability of close range antenna coupling and determined the minimum transmitter radiated power required to meet the "no fire" power levels of AELMS electric detonators, which are equivalent to the Type II and Type V electric detonators in Table 1, above.

Worst-case safe power levels vs frequency are shown in the red lines in Figures 2 and 3, below:

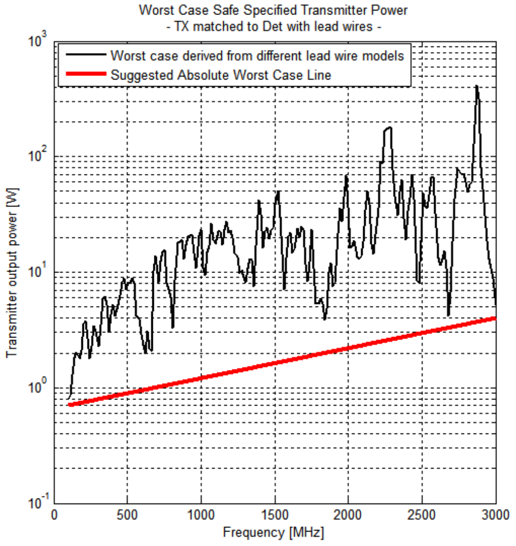

Figure 2: Safe power level vs frequency for Type II electric detonators.

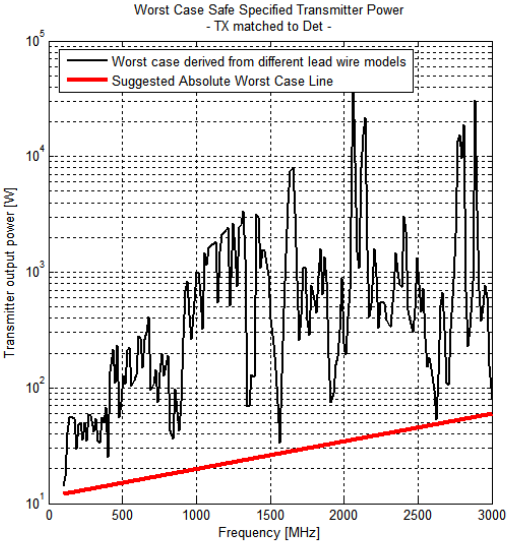

Figure 3: Safe power level vs frequency for Type V electric detonators.

For folded leading wires and for radios in very close proximity to the devices:

- Type II electric detonators will have a very small probability of initiation for powers of up to 700 mW at 100 MHz, rising to 4 W at 3 GHz.
- Type V electric detonators have a very small probability of initiation for powers of up to 11 W at 100 MHz, rising to 60 W at 3 GHz.

Other radio exclusion requirements to be observed

Explosives transportation near blast sites: United States Department of Labor regulations[11] require signs 1000 ft from blasting zones requiring radios to be turned off, and that mobile transmitters that are less than 100 ft away from electric blasting caps in other than original containers be de-energized and effectively locked.

Other authorities may have similar regulations.

Cautionary notes:

Metal containers for transport of electric detonators, either as part of a vehicle or as a standalone carry box, do not guarantee EMI immunity as sneak entry paths are easily found. A "Faraday Cage:" is required where all metal panels are strapped electrically and lids or doors need to be fitted with appropriate EMI seals. No relaxation of radio exclusion requirements should be contemplated.

Folded electric detonator leading wires, as in Figure 1, or as supplied in the manufacturers original packaging are essential in the above analysis. Once the wires have been unwound or separated, electric detonators become **considerably** more sensitive to EMI.

Transport of electric detonators with unfolded and separated wires demands radio exclusion or risk assessment!

Table of radio exclusion distances for packaged electric detonators

Data for Table 2 comes from the BSI guide for critical field strength of 100 V/m in far-field conditions together with the Poynting criteria for near-field cases under about one wavelength (Λ).

For values in this table, where the critical distance, d_{crit}, calculated using equation 1, is less than Λ, the Poynting criteria are used, and where the power allowed here is exceeded, then an exclusion distance of one wavelength is recommended. For fusehead types other than II and V, interpolation was used based on the initiation power, RI^2, where, in Table 1, R is the bridge wire resistance and I is the no-fire current.

Table 2: Radio exclusion distance for different electric detonator sensitivities and various transmitting devices

Transmitter Details					Minimum recommended exclusion distance from packaged detonators						
Type	ERP (W)	Freq. (Mhz)	Λ (m)	d_{crit} (m)	Type I (m)	Type II (m)	Type III (m)	Type IV (m)	Type V (m)	Type VI (m)	Type VII (m)
Fixed communication	25	150	2	0,35	2	2	2	2	2	0	0
Mobile communication	5	150	2	0,15	2	2	2	2	0	0	0
Modem and mobile	0,5	450	0,7	0,05	0,7	0	0	0	0	0	0
Modems & DECT	0,5	900	0,35	0,05	0,35	0	0	0	0	0	0
RFID, Cellular & Tracker	2	900	0,35	0,1	0,35	0,35	0,35	0,35	0	0	0
Cellular & Tracker	2	1800	0,18	0,1	0,2	0,2	0	0	0	0	0
WiFi, Bluetoooth & Zigbee	0.1	2400	0,13	0,02	0	0	0	0	0	0	0

Notes:

- Green shaded blocks indicate that no exclusion zone should be necessary. (Note: At higher powers, exclusion distances may be required).
- Managing small exclusion distances with handheld radio equipment for different electric detonator sensitivities is difficult, and **a blanket exclusion zone of 2 m may be considered**. (This safe distance of 2 m is in line with the United Kingdom MOD recommendations[12]).
- In the case of fixed vehicle antennas, depending on the power and frequency, smaller safe distances, as indicated in the table, may be considered. Here, a conservative safety factor of two for exclusion distance is recommended to ensure variables such as modulation type and antenna gain are catered for. (For comparison, the United Kingdom MOD recommendations[13] indicate that a minimum distance of 0.2 m may be allowed, subject to certain provisions).
- RFID applications, requiring higher powers, can be considered, provided that measures are in place to ensure safe distances are not compromised.
- Low-power wireless data devices operating at 100 mW or less should be safe to use in the close proximity of all the listed electric detonators.

3. EMI AND ELECTRONIC DETONATORS

Electronic detonators, often termed electronic delay detonators or EDD's, are radically different from conventional electric detonators in that there is normally no direct connection between leading wires and initiation element (IE).

A specification for EDD systems is CEN/TS 13763-27[14], which describes the EMC qualification tests required as part of approval requirements by a European Notified Body.

Clause 0.3 of this specification shows the block diagram of a generic two-wire programmable electronic detonator, reproduced here in Figure 4.

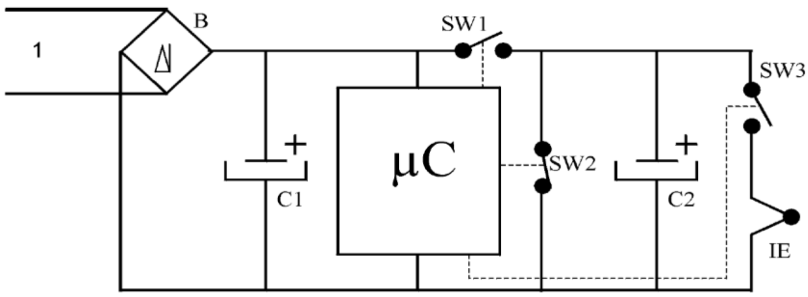

Figure 4: Generic two-wire electronic detonator

Key:
1 - Communication line
μC - Microcontroller or application specific integrated circuit (ASIC).
B - Full wave rectifier to make the system polarity insensitive (optional)
C1 - Power supply capacitor
C2 - The firing capacitor which supplies the energy required to fire the initiation element (IE). Switches SW1 and SW2 manage the energy in C2 and after charging SW3 is closed by the microcontroller to fire the device.

The microcontroller may be a "state machine" that responds to digital signals on the leading wires allowing it to pass through various sequential states before it will accept the firing instruction. **Simply applying a voltage to the leading wires will not normally cause the device to initiate, thus ensuring very good EMI resistance.**

EMI immunity for transport and storage of electronic detonators

CEN/TS 13763-27 clause 4.5.6.4 covers EMC testing of electronic detonators. It requires immunity to unintended initiation at field strength of 30 V/m from 80 Mhz to 2 GHz. This is a blasting application safety test rather than a safety test for storage and transport.

In light of the higher EMI resistance required in standards referenced above for air, sea and ground transportation, it is strongly recommended that the guidance of the electronic detonator manufacturer be sought on tolerable EMI levels for transport of their product.

Various manufacturers have taken the initiative in adopting high-intensity EMI testing of packaged electronic detonators for safety in storage and transit. Figure 5 shows such a test on electronic detonators without a base charge. (See reference 6).

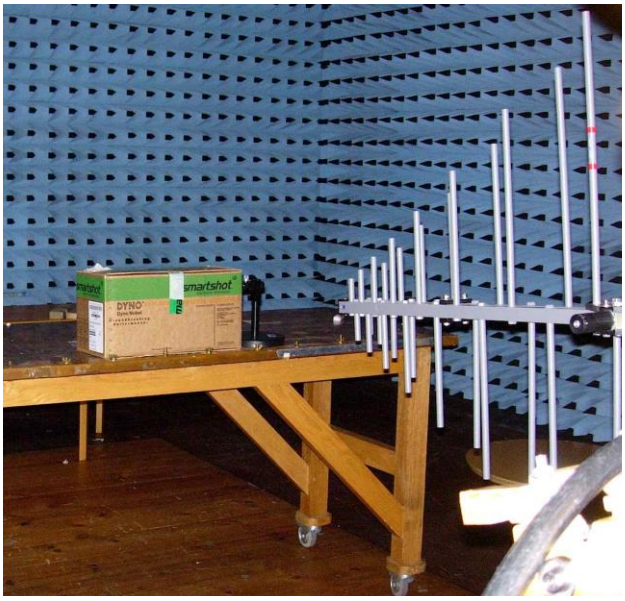

Figure 5: Testing packaged electronic detonators to MIL-STD 461F at 200 V/m in the range 80 MHz to 1 GHz. (Picture courtesy of DetNet (Pty) Ltd).

4. EMI AND EXPLOSIVES MATERIALS

In Section 2, covering electric detonators, the radio-frequency energy from the leading-wire antenna is focused into a small-dimension nichrome bridge and would need to heat the wire to about 200 ^{o}C to initiate the primary explosive. For blasting explosives, where heat, impact, or friction would be required for initiation, no such EMI-sensitive interface generally exists.

At the high-power end, putting explosive materials into a microwave oven, for example, with powerful fields, exceeding 300 V/m, could result in bulk heating and some explosive materials could deflagrate or initiate.

Use of low-power wireless systems or RFID tagging, for example, for propellants and low sensitivity explosives, should pose no significant risk of initiation. (See SAFEX Good Explosives Practice Series GPG 03(1) Rev 1[15] for a list of minimum initiation energies of various explosives.)

5. SUSCEPTIBILITY OF ELECTRONIC SYSTEMS

To achieve or maintain global competitiveness and to handle product diversity, computer integrated manufacturing (CIM) has accelerated in companies across the world. CIM encompasses the automation of most of the functions and processes in the manufacturing chain.

Automation, monitoring and electronic tracking enables the routine tasks in manufacture, handling, storage and transport of explosives and explosive devices to be handled securely, accurately, reproducibly and efficiently. Such equipment could be compromised by EMI. These risks may be dealt with using a two-pronged approach involving:

- Appropriate EMC test provisions for electronic systems
- Business continuity planning to reduce delays in delivery owing to the effects of EMI-induced data loss or delay and possible compromise to security systems.

It is necessary to consider the EMI susceptibility of electronic equipment in wider terms than to radiated signals alone, and these tests may include susceptibility to:

- Conducted disturbances via cables.
- Magnetic coupling.
- Electrostatic discharge.
- Power supply surges, dips and interruptions.

EMC - regulatory requirements

For EM emissions and transmissions:

- Unintended emissions from the equipment should meet specified levels.
- Transmission frequencies and powers are allocated by the International Telecommunication Union[16] and are adopted or modified for local use by member states. The radiated powers of equipment in use may be validated from test reports.

In Europe the EMC Directive[17] and Vehicle EMC Directive[18] are regulations for EMC requirements of electronic equipment for use in the EU that may impinge on explosives operations. The list of over fifty European EMC test standards[19] is comprehensive and the tests are widely used internationally.

"Self declaration" of electronic product conformity is generally allowed in Europe. In case of detonators and blasting equipment, approval by a Notified Body is required. One caveat is that self-declared equipment may not have been subjected to tests or tests at appropriate levels suitable for the envisaged explosives environment.

In the USA the Federal Communications Commission (FCC) regulations, Part 15, cover unlicensed radio-frequency transmissions and emissions, both intentional and unintentional. Susceptibility testing is not indicated, but the methods and levels in MIL-STD-461F (see reference 6) may be applied.

An example of radio exclusion distance

For a microcontroller regulating mixing and delivery of explosives from a mobile manufacturing unit (MMU), with a control unit certified to operate at an EMI field strength of 10 V/m, equation 1 shows an exclusion distance of 1,6 m for a 470 MHz 5 W ERP transceiver.

Controller malfunction leading to a bad blast in this application is real, and it will be good practice to apply a safety factor of two or more to take into account the possibility of constructive reflections increasing the intensity of the signal, thus giving *an exclusion zone of at least 3 m.*

An example of an MMU with a logging system

The following example, courtesy of AEL Mining Services, is a blasting intelligence system, called the Blast-*i*™ system. Information on an explosives delivery and location at a blast is captured by means of a PLC unit in the MMU using a GPS system and handheld PDA units. This system feeds real-time information via wireless Internet to the mine control room, logistics, blast design and a global monitoring centre.

The EMC characterization of this system included tests for emissions, and immunity to radiated and conducted signals, fast transients and electrostatic discharge. Industrial immunity levels were met indicating that interference with the system was unlikely. A risk assessment of the Blast-*i* system in the MMU was conducted and it was established that transmission power was insufficient to fire electric detonators. In addition the antennas are on top of the vehicle, well away from charging operations.

Figure 6: An MMU showing the WiFi antenna of Blast-*i*TM system. The GPS antenna is on the other side of the vehicle cab.

Figure 7: Logging computer in cab.

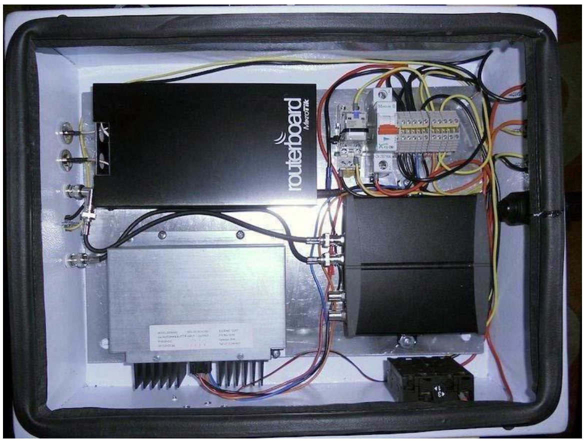

Figure 8: The component box with a DC-to-DC converter, video server and wireless router.

6. THE IMPORTANCE OF RISK ASSESSMENT (RA)

In an EM environment the need for risk assessment for safety of devices, materials and systems is important as:

- The EMI sources, environment and susceptible devices and systems are unique to each set of operating conditions.
- Guidelines given in this paper are not absolute and validation is important.
- Consequences of an EMI-induced event may vary from inconsequential to disastrous.
- Worker protection must be shown to be adequate or risks treated to meet the required safety level.

Generally a team of stakeholders, under independent leadership and with subject matter expert(s) present, should perform a risk analysis. With numerous standards and publications on risk assessment procedures available, this clause looks primarily at risk identification.

ISO/IEC context of risk assessment in the risk management loop

The principles of risk management are given in IEC/ISO 31000[20] and IEC/ISO 31010[21]. Risk assessment is considered in the context of the overall risk management process, as shown in Figure 9.

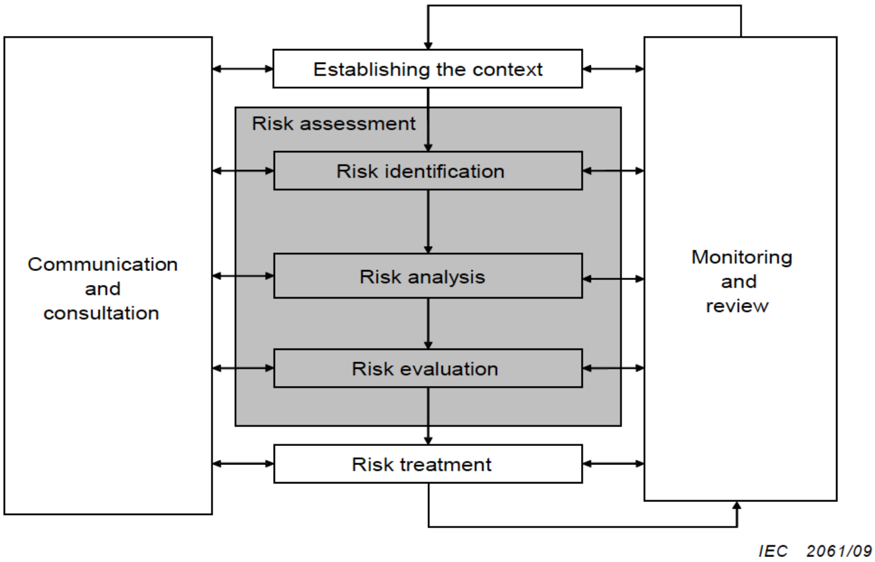

Figure 9: Context of risk assessment in the risk management process

Risk identification

For an EM environment it is necessary to identify the interference sources, and the interfaces to susceptible devices and products. Examples of these are shown in Table 3.

Table 3: Some electromagnetic sources and susceptible products and devices

	Typical sources of EM disturbance		Potentially susceptible products or devices in the supply chain
1	Wireless data systems	I	
2	Radios fixed and mobile	N	
3	Alarms and surveillance systems	T	Electro-explosives devices
4	Satellite communications systems	E	Electronic detonators
5	Cellular/mobile telephone systems	R	Explosives
6	RFID systems	F	Control systems
7	Other electrical/electronic equipment	A	Monitoring systems
8	Electrostatic discharge	C	
9	Power cables, lines and switchgear	E	

The interface may be via air, cabling, magnetic coupling or contact, or a combination of these.

Table 4 is an example of risk identification for EMI hazards with electronic devices, machines, electric detonators and electronic detonators that might be encountered in an explosives manufacturing and distribution chain.

Following risk identification, risk analysis, evaluation and treatment would be performed. The processes used should be acceptable to the industry and in the country of operation.

Useful information and procedures for the risk analysis may also be found in:

- IEC 61508[22], which provides a comprehensive risk analysis and safety assurance methodology for electronic systems.
- PD CLC/TR 50426:2004[23], which presents a flow diagram for risk assessment of blasting sites on land. With adaptation, this process could be applied to storage and transport of explosives and explosive devices.

Table 4: Risk identification for EMI-induced events in the supply chain

No.	Device or RF service	Likely area of use	Likely malfunction risk (explosives risk in red, business risk in yellow)
1	Automated guided vehicle (AGV)	Manufacturing, storage & shipping	Stoppage, delay
			Product damage
2	Robot	Process and packaging	Stoppage, delay
			Product damage
3	RFID and barcode	Storage, transport site delivery	Inventory control and security compromise
			RFID - possible hazard with electric detonators
4	Wi-Fi & other data communications	Manufacturing & storage	Inventory control and security compromise
5	Security cameras & sensors	Storage, transport & delivery	Compromise of operation recording & security
6	SatNav and tracking	Transport & delivery	Delays and security
			Possible electric detonator hazard for cellular communicating
7	Radio and cellular communications	Transport & delivery	Reliability, safety and security in distribution
			Possible electric detonator hazard
8	Ship or aircraft radar	Transport	Possible electric or electronic detonator hazard
9	Mobile manufacturing unit (MMU)	Pumped emulsion data logging and positioning	Data to manufacturer delayed or compromised.
10	MMU	Pump and mix control	Incorrect charge or sensitization - bad blast.

7. TAKE-HOME MESSAGES

The recommendations to reduce the risk of EMI-induced events are:

- With packaged electric detonators Table 2 lists minimum exclusion distances for various radio-frequency sources. Low-power systems under 100 mW should pose no significant risk.

- Electronic detonators may have higher inherent resistance to EMI than electric detonators, but the manufacturer should be consulted for recommendations on electromagnetic immunity in storage, transport and handling of their product.
- Low-sensitivity explosives and propellents are unsusceptible to low-power wireless systems as there is no effective energy coupling mechanism.
- Electronic systems used in servicing, monitoring and distribution of explosives and explosive devices should be adequately EMC certified.
- Considerations on joining the "Wireless Revolution":
    - Become familiar with the EMC regulatory environment in your region: electrical and electronic equipment should comply.
    - Equipment for explosives application should be accompanied by EMC certification documentation. This is information of public interest and manufacturers generally list this as part of the product specification.
    - EMC test levels should be for an industrial environment, as products for domestic use may not have adequate immunity. Safety-critical operations will require higher immunity test levels.
    - Where systems are constructed from different electronic modules, for example, a microcontroller, power supply and communication module, the EMC properties will change and the full system should be EMC certified for the application.
    - Use of radios and wireless systems may still require appropriate radio exclusion distances from susceptible explosive devices and other electronic systems.
- Risk assessment is an essential part of the loop to ensure that radios and wireless systems are safe to use in the explosives storage, transport and handling environments.

8. GLOSSARY

Term	**Description**
ASIC	Application-specific integrated circuit
CIM	Computer integrated manufacture
d_{crit}	Critical distance from a radiating antenna for 100 V/m in Table 2
EDD	Electronic delay detonator
EM	Electromagnetic
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
EMS	Electromagnetic susceptibility
ERP	Effective radiated power from an antenna
Far field	Distances above about 1 wavelength from the radiating antenna
GHz	Gigahertz = 10^9 Hertz
IE	Initiation element of a detonator, typically a fusehead
Λ	Lambda: wavelength
MHz	Megahertz = 10^6 Hertz
MMU	Mobile manufacturing unit explosives vehicle
MOD	United Kingdom Ministry of Defence
mW	milliwatt
Near field	Distances below about 1 wavelength from the radiating antenna
PDA	Personal digital assistant

Term	Description
RF	Radio frequency
RFID	Radio-frequency identification
RMS	Root mean square (power)
SatNav	Global positioning system satellite navigation
RA	Risk assessment
V/m	Volt/metre - a measure of electric field strength of a transmission
W	Watt

9. REFERENCES

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[20] ISO 31000 Ed. 1 2009-11-15 Risk management — Principles and guidelines.
[21] IEC/ISO 31010 Edition 1 2009-11 Risk management – Risk assessment techniques. Figure 1.
[22]IEC 61508 - Functional safety of electrical/electronic/programmable electronic safety-related Systems. Part 1. Clause 8 - Functional safety assessment.
[23]British Standards Institution - PD CLC/TR 50426:2004 - Assessment of inadvertent initiation of bridge wire electro-explosive devices by radio-frequency radiation. Guide. Figure 7.