

THE ENGINEERING EQUIPMENT AND MATERIALS USERS ASSOCIATION

A GUIDE TO RISK BASED ASSESSMENTS OF in situ LARGE Ex 'e' and Ex 'N' MACHINES

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PUBLICATION No 181 - ERRATA

Risk Based Assessments of In situ Large Ex 'e' and 'N' Machines

Following the release of the first printing, the following errors were noted. These in no way materially affect the result of any assessments which may have been made using the guidance given.

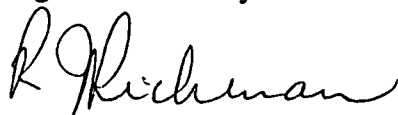
1) Power and poles.

There is an error on page 15 in 5.4.1.2. The kW per pole should be 250 and not 500.

o use kW per POLE is correct.

2) Addition or multiplication of factors

Factors under IPF, LPF and PPF should be added but the grand total should multiply them. Total risk probability factor is: $IPF(T) \times LPF(T) \times PPF(T)$ (as given on page 24). On page 40 addition of factors is given incorrectly.



R J Richman
Technical Secretary.
27.7.95

THE ENGINEERING EQUIPMENT AND MATERIALS USERS ASSOCIATION

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1 FOREWORD

During the past few years there has been a small number of explosions attributed to, or associated with, large high voltage motors.

Large machines of the type under consideration are typically designed for operation at specific voltages in the range 3.0 kV to 15 kV, and have power ratings in the range 500 kW to 5 MW, although exceptions outside these ranges will occur.

Work carried out by Manufacturers and The Electrical Research Association in the period 1985 to date has suggested that there are a number of mechanisms within large machines which may give rise to incendive activity and which hitherto have not been considered in setting out the standards which guide the manufacture, test, and deployment of machines in potentially explosive atmospheres. Notices issued by the HSE (UK Health and Safety Executive) and the former Department of Energy have highlighted the potential risk associated with the operation and use of Ex 'e' and Ex 'N' high voltage motors in potentially explosive atmospheres and it is necessary for these risks to be addressed.

In order to prioritise the introduction of improvements whilst targeting expenditure and effort in a meaningful manner, it is important, given all of the uncertainties of accurately pinpointing the source(s) of ignition, that the 'scale' of the 'risk' is evaluated and indicated by means of a simple and practical method.

This code of practice has been developed to provide a practical method which may be used to undertake a comparative evaluation of the risk due to the possibility of incendive discharges occurring in existing large Ex 'e' and Ex 'N' machines. It will be apparent from the results of the analysis which machines are in the greatest risk situation and those where the risk is minimal.

The object of a risk assessment is to take into account all the possibilities which are present and those which may be reasonably foreseen and from the findings to develop procedures aimed at ensuring that the risk is '**As Low As Reasonably Practicable**' (ALARP). The approach presented in this document by EEMUA has been adopted in consultation with the major operators and manufacturers of large machines. As a result a pragmatic view of ALARP has been adopted. This has led to the avoidance of an extensive research programme and rigorous Quantitative Risk Assessment programmes being applied to every machine circumstance or otherwise applied to support the development of a risk assessment similar to that presented in this document.

The management and operators of factories, process plants and other places where people are employed or have access, have a duty to ensure that their operations are carried out such that the risk of loss or injury to human life is ALARP. In the United Kingdom the enforcement of the many Regulations associated with the health and safety of workers is vested in the 'Health and Safety Executive' (HSE). Regulations of immediate concern to readers include the Factory Acts and the Electricity at Work Regulations. Legislation will be enacted to implement European Directives being developed to improve worker health and safety in a number of areas including those engaged in potentially explosive atmospheres.

This publication represents the culmination of considerable work conducted by EEMUA Member Companies. In particular without the contribution of their representatives on the EEMUA Electrical Engineering Committee it could not have been produced.

2 SCOPE.

This Publication is primarily concerned with the risks due to possible incendivity of large in- service machines with protection in accordance with British Standards as follows:-

BS 5000: Rotating Electrical Machines.

Part 15. Type. Ex 'e' (Increased safety) and

Part 16. Type, Ex 'N' (Reduced risk).

BS 5501; Part 6. Electrical Apparatus for Potentially Explosive Atmospheres.

Increased Safety Type 'e'. Note that BS EN 50019 is equivalent.

BS 6941: Specification for Electrical Apparatus for Explosive atmospheres

with type of protection 'N'

Reference should also be made to IEC Standard 79. Parts 7 and 15

Research has shown that there is a probability that large machines designed and installed to existing Standards may, under certain circumstances, produce discharges capable of igniting explosive gas mixtures. Thus if an explosive gas mixture is present within the casing of the machine, coincidental with ignition capable incendive activity, the consequences could be far reaching. In machines with loose covers, sparking at joints has been noted. Such sparking might ignite an external explosive atmosphere.

The machines under consideration in this document are those with protection type Ex 'e' and type Ex 'N'. With these machines it is possible that, if an internal explosion should occur, this in turn could precipitate ignition of any external flammable gas. Flameproof Ex 'd' and pressurised Ex 'p' machines may have internal ignition sources but their design is such that any external source of flammable gas will not become ignited.

High voltage is considered to be above 1.0 kV. Whilst this document is primarily concerned with high voltage machines the scoring system may be used to evaluate the risk presented by very large LV machines.

All in-service machines do not impart the same degree of risk. A number of factors contribute to the actual risk. These are not all of equal value and weighting factors are required to enable a simple 'Risk Value' to be obtained. These factors are discussed, and values are given, based on experience gained during many years of operation. These will enable the comparative risks identified with different machines to be evaluated.

As an aid for those whose task is to assess the risk associated with existing HV machines installed in potentially explosive atmospheres, Decision Trees have been prepared. The use of the first Decision Trees (APPENDIX A) will quickly eliminate many machines not requiring more detailed assessment and by following the additional procedures appropriate action can be determined for the vast majority of the remaining units. It is probable that the need to carry out a more rigorous Quantitative risk assessment (beyond the scope of this document) will apply only to an exceptionally small percentage of the machines in service.

By pursuing the procedures outlined in this document the user will have :-

- assessed the risk associated with all motors he is responsible for
- highlighted those which require attention
- selected the most effective solution
- discharged his legal duties.

3 BASIS FOR THE SELECTION OF MACHINES

3.1 General

Machines are selected in accordance with the environment in which they may be working. Assessment of the type of environment in relation to the probability of an explosive gas being present is referred to as 'Area Classification'. Machines themselves vary in the construction details adopted to make them suitable for operating safely in the various allotted Zones.

3.2. Area classification

Area Classification is carried out in accordance with procedures developed over many years in consultation with Manufacturers, Users and Government Health and Safety departments. A number of British, European and International Standards give guidance on procedures to employ. Amongst these IEC 79-10 'Classification of Hazardous Areas' is the most relevant international work.

Areas are divided into Zones based on the probability and duration of an Explosive gas or vapour being present.

Zone 0. Higher risk.

Defined as :- An area in which an explosive gas atmosphere is present either continuously or for long periods.

Zone 1. Intermediate risk.

Defined as :- An area in which an explosive gas is likely to occur in normal operation.

Zone 2. Area at lower risk.

Defined as :- An area in which an explosive gas atmosphere is unlikely to occur in normal operation and, if it does occur, is likely to do so infrequently and will exist for a short time only.

Note: Further consideration of zones and classification is included in Section 6.4

3.3 Equipment - Type of protection.

It is not within the scope of this document to discuss in detail the types of protection available at the present time. Detailed information may be obtained by reference to the relevant Standards as listed in Appendix D. The following brief details of the types suitable for large machines may be useful.

Ex 'd'. Flame proof (Explosion protected)

A strong machine such that if an internal ignition of gas did occur there is no possibility of an external flammable gas being ignited. The casing has sufficient strength to withstand any internal pressure resulting from an ignition and any allowable gaps such as at flanged covers, breathers and bearings are designed to

prevent the passage of combustion products having sufficient energy to ignite an external flammable gas.

Ex 'p'. Pressurised apparatus.

A machine which is pressurised internally by air (or inert gas) drawn from a safe area. The fact that the machine is pressurised prevents any possibility of an external flammable gas entering into the machine enclosure. In certain instances it is permissible to draw air from a Zone 2 Area provided that gas monitoring equipment is used to ensure that the air inside the motor has a gas content below the LEL (Lower Explosive Limit) of that gas. Continuous dilution of the gas inside a machine with air drawn from a safe or zone 2 area in association with gas detectors to monitor the gas content is also possible.

Ex 'N'. Reduced risk.

These machines are similar in design to a standard machine but special attention is given to bearings, concentricity of rotor/stator, and the impact resistance of some constructional parts.

Ex 'e'. Increased safety machine.

A machine where special attention is paid to the following:-

- mechanical features similar to type Ex 'N'
- increased terminal clearances
- minimisation of static pick up on plastic fans by choice of material.
- temperature rise of windings (usually 10°C cooler than a standard machine),
- limitation of rotor/stator temperature rise during any start by use of specified starting equipment which is tested and certified with the motor.

3.4 Test and Certification

Test and certifying authorities such as BASEEFA, SIRA, INIEX, PTB etc, test equipment in accordance with requirements set out in Standards. Certification follows for equipment meeting the requirements. Not all electrical equipment has to be certified before it can be used in a Zone 2 hazardous areas. Equipment with type of protection 'N' may be used in Zone 2 provided that it complies with the relevant standards. In the UK manufacturers will often have their Ex 'N' equipment 'Certified' for use in Zone 2 as this enhances user confidence in the product.

European Directives concerned with the safe use of equipment in potentially explosive atmospheres suggest that, as an alternative to the use of Standards for certification, judgements on suitability of equipment for a given application, may rely on, or incorporate an analysis of risk. Any such risk based assessments would need to take into account many differing features for each proposed application. This will include knowledge of the behavioural patterns of different types of construction, an understanding of ignition phenomena and of the propagation of explosions in air and in confined spaces, and full information of the topography of each proposed installation. In order for such an assessment to have credibility it should not be undertaken lightly or haphazardly. It will require to be undertaken by persons who have the highest possible knowledge and experience.

Risk assessment as an adjunct to the use of Standards is a practical possibility where experience has indicated that related Standards do not fully address all situations which

may have come to light since they were developed. Where it is to be considered in this context it should be concerned with practical issues and should not involve extensive detail. Such types of assessment may be undertaken by less senior engineers but they should be checked by persons possessing superior knowledge and experience.

Reliance on the availability of certified equipment is, therefore, preferred to undertaking multiple risk assessments. Without Standards for certification, Test and Certifying Bodies, such as those listed above, could not function effectively and decisions could always be coloured by personal preferences or other issues.

Electrical and mechanical design has improved over the years and machines now have exceptional life in normal operation. However, recent evidence suggests that some machines may have internal winding discharges having a tendency to increase with age and any contamination of the windings. There may also be some form of rotor sparking, and this may also increase with age and operation. Both of the above are potential ignition sources which could ignite any flammable gas which may be within the machine at the time. Such potential sources of ignition were not regarded as significant when the Standards were first developed.

The small number of notified incidents, which have involved large high voltage machines, has received considerable attention and it is seen that the continued use of existing machines in service will need to be addressed to identify the very few capable of causing a future incident.

Risks are sometimes emotive issues but a risk assessment based on this Guidance Document will assess any potential risk in relation to life, the equipment and the environment.

3.5 Repairs to Certified Equipment.

Where it is found necessary to carry out repairs, other than those attended to by competent persons during routine or general maintenance, it is a fundamental requirement that these are entrusted to repairers having appropriate knowledge and who can demonstrate their competence.

It is to be expected that Repairers will have Quality Assurance to BS 5750 and that repair work would be generally in accordance with IEC Standard 79 part 19. This Standard is currently being developed and its future adoption as a European Standard is most likely.

3.5.1 Certification and test requirements for repaired machines.

Where machines were manufactured in conformity with Standards and the original design details, as used to obtain Certification, are available it is acceptable for any repairs that may be required to conform with these original designs. Should these be unobtainable it is essential for detailed sketches and/or drawings to be prepared by the repairer during the stripping down procedure. These may be useful at a later date and will demonstrate the competency of the repairer in such matters.

For machines repaired in accordance with the original designs, which were those to which the machine was originally tested and certified, it is not a requirement that a new certificate is obtained on completion. The repairer is to carry out, or have carried out, the type tests as detailed in the appropriate Standard. eg BS 4999 and other Standards as listed in APPENDIX D. At the discretion of the User it may be acceptable to exclude certain tests or conduct them in a restricted form. Eg. a full load, temperature rise test

may be curtailed if loading facilities and equipment are not available. However dielectric tests as required by the Standard should be carried out, and the machine run under no load conditions, at which time no load losses should be determined. A test report is to be submitted to the User.

Where the original design data is unobtainable the repairer may, of necessity, or in agreement with the owner, develop a new design. Circumstances may suggest that the design is to cater for a changed supply voltage or possibly for a different speed. In this event the repaired machine must be re-certified by a Notified body.

The ATEX 100A Directive, in common with other engineering product Directives requires the Manufacturer, or his agent in the Territories, to retain copies of manufacturing details against which equipment was Certified, for a period of not less than 10 years after the last item was sold. This may be of some help but as most large machines have a life span of 20 years and more it would be advantageous to obtain winding details for every certified machine purchased.

4 IGNITIONS AND IGNITION MECHANISMS.

4.1 Ignitions which have been notified.

Since 1980 six gas explosions within machines with protection Type Ex'e' or Ex 'N' have been attributed to machine failures. In at least one further occasion sparking at cover joints of a Type Ex 'N' motor, was noticed and reported. In addition one explosion has occurred in a hydrogen cooled alternator

- 1) Motor driving a gas compressor. Minor explosion within motor attributed to either circulating currents or other mechanism. Evidence of damage noticed some time later. Motor type Ex 'N'. 11kV, 6.5MW
- 2) Motor driving gas compressor. Major damage to motor some 4 minutes into its start cycle. No confirmation of ignition source. Motor Ex 'N' 11kV, 5.5 MW.
- 3) Motor driving gas compressor. Fitted with bonding straps. Explosion immediately on start caused severe damage to motor. Gas believed to have entered motor via common lube-oil system. Motor Ex 'N', 13.8 kV, 5.3 MW.
- 4) Motor driving gas compressor. Few details available but Manufacturer discovered a mechanical fault [fracture ?] in end ring. This type of design now obsolete. Motor repaired and returned to service. Motor Ex 'N' 6.6kV, Power not available.
- 5) Motor NOT in an explosive atmosphere. It is believed that the motor overheated liberating flammable gas following decomposition of insulation materials. This ignited but actual means of ignition unknown. The rotor in this machine had an insulated cage. Motor 11.0 kV 1.8 MW.
- 6) Motor in Mexico driving a gas compressor. Type Ex 'e' but no further details available.
- 7) Motor driving gas compressor. Motor recently overhauled. Exploded on start-up. Motor details not available.

For the incidents numbered 1, 3 and 7, no apparent ignition method could be found. This lack of causal effect has led to the deeper theoretical and laboratory investigations underlying the concerns which this document addresses.

Apart from the above recorded incidents it may well be that other minor explosions have passed unnoticed if the motors continued to operate without apparent damage. In addition there have been a number of general failures which have led to motors needing to be repaired.

4.2 Ignition mechanisms

Subsequent to the above details becoming available, and as a result of work carried out by manufacturers, major users and others, the following conclusions are drawn:

4.2.1 Circulating currents in non-active parts and bonding straps.

All machines have stray magnetic fields which induce voltages and circulating currents. It is only in large machines that these result in currents with magnitudes sufficient to produce sparks having incendive capability at any point where they are interrupted.

For example, where a machine is subjected to severe vibration, cover fastenings could work loose. This looseness could create a high resistance or open circuit in the circulating current circuit path. Dependent on the inductance in the circuit any sparks (arcs) might have sufficient energy to ignite any surrounding flammable gas.

4.2.2 Internal sources of ignition.

As an outcome of the investigations a number of mechanisms were considered including the following:-

4.2.2.1 Stator coil movement.

The likelihood of coil movement depends on coil construction. (The motor speed, voltage, rating and coil bracing are significant here), Frequency of starting is important since it is during starting that thermal electro-magnetic and dynamic forces are at their maximum. Coil damage due to movement can allow other degradation effects to be initiated.

4.2.2.2. Coil/rotor bar movement and effect on rotor currents.

Whilst the majority of the currents flowing in the rotor follow a complete path via rotor bars and end-rings, a significant proportion will flow between bars through the laminations. Interruption of this current at the point of transference from copper to iron, whether due to magnetic or dynamic forces, has been shown to be a possibility. This results in the presence of visible arcing and the production of minute globules of molten material.

Sparking as noted in the above paragraph would appear to be more demonstrable with rotors built with radial cooling slots or ducts. A number of theories may account for this. However, even where such ducts are omitted the effect has been observed particularly where the rotor is displaced from its magnetic centre.

Cast rotor bar construction is a construction method used in many machines as an alternative to fabrication. Currently available information suggests that where rotor conductors are cast under significant pressure, adhesion and good contact between the bars and laminations is provided and that this remains high at all times. The possibility of 'rotor sparking' is consequently virtually eliminated. Cast rotors are standard in motors up to a few hundred kW's but the technique poses manufacturing difficulties in power sizes much above one megawatt.

Resolving the rotor sparking issues is a long term project. Dangers resulting from this phenomenon should not over colour the general findings. Currently available information suggests that, provided gas can be excluded from the motor during and immediately prior to starting, this aspect is highly unlikely to be an issue. As this is an effect present only during start up it may be ignored once the machine is running normally.

4.2.2.3 High voltage discharges.

The high voltages under consideration here are those which are impressed on the windings during the normal operation of the machine. Other high voltages which may be impressed, such as those attributable to lightning strikes to power lines, are excluded. Effective measures for attenuating any high voltages due to lightning may be required and it is customary for these to be considered by a competent person during initial site studies. Based on these studies appropriate recommendations will have been made.

Motors operating on high voltages experience corona and capacitive discharges. Tests indicate that the energy developed, particularly where machines are rated at above 11 kV may have incandive capability even with a clean winding.

Discharges may be present at any time and will be influenced by switching surges and other line voltage excursions. They may be fundamental to design and be influenced by operating conditions. They should be considered in the light of known knowledge of general deterioration of insulating materials. The age of the motor will need to be taken into consideration together with its location and maintenance history. Modification and improvement may be difficult to implement but attention to cleanliness of end windings is most important.

This document is directed primarily at 'High Voltage' machines and thus machines operating on 'Low Voltages' which is defined by the UK Electrical Equipment Safety Regulations 1994¹ as being below 1000 Volts are generally excluded. The tendency for high voltage discharges to occur in machines designed for voltages greater than 1000V will be dependent to some degree on design. However, tests² have indicated that their presence in a form capable of being incandive, is unlikely in motors operating on voltages below 3.0 kV. In extreme cases with windings heavily polluted with saline sludge incandive conditions have been demonstrated at voltages as low as 3.3 kV. Although this level of pollution is unlikely to be encountered in practice the possibility can not be totally ignored. The risk will increase progressively with increasing voltage.

4.2.2.4 Contamination

The level of contamination manifesting itself within a machine after a prolonged period of use, is a function of the environment in which the motor is sited, its enclosure and wear and tear on bearings and seals. It is minimised, in the majority of cases, by the use of screens and shelters to give protection from the elements and the adoption of totally enclosed machines fitted, when required, with coolers. Cooler heat-exchangers may use water from a variety of sources and, where this is sea water, or otherwise polluted water, special care should be taken to ensure that all materials used in the cooler heat exchanger which are in contact with the coolant are corrosion resistant to avoid serious contamination problems if coolant entered the machine.

Contamination will lead to an increase in high voltage discharge phenomena and excessive levels will lead to discharges with incandive capability. Sound maintenance procedures will minimise danger from this source.

¹The UK Safety Regulations of 1989 transposed into UK law the 1973 Low Voltage Directive (73/23/EEC) and the 1994 update included requirements of the CE Marking Directive (93/68/EEC)

²See REMA report REM505 1990

4.2.2.5 Thermal ageing

Thermal ageing is a function of the length of time the motor has been in service and also of the temperatures attained by the windings. Thermal ageing reduces the effectiveness of the insulation and may eventually lead to its breakdown.

4.2.3 Common seal and lube oil systems.

It has been shown that where a common motor lubrication and compressor bearing seal oil system is used on a gas compressor set, there is a potential for gas to be absorbed into the oil at the seals and later released into the motor.

Should the concentration of gas inside a machine be within its upper and lower explosive limits an internal explosion would occur if any incendive activity is present having an energy level greater than that required to ignite the gas. SEE APPENDIX C for ignition levels of a range of gases.

The pressures and temperatures developed following any internal explosion is likely to cause internal damage together with an emission of hot gas and particles at points of least resistance. This release to the external atmosphere could ignite any explosive or ignitable material which may be in its range.

Separation of the oil systems will assist in the total elimination of potential failures from this cause. As an alternative measure it may be possible to provide degassing measures where separation of the systems is not practical. See also Chapter 6.