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Safety of electronic circuits integrated into personal protective equipment (PPE)

J.-P. Buchweiller[a], A. Mayer[a], R. Klein[a,*], J.-M. Iotti[a], A. Kusy[a], D. Reinert[b], E. Christ[b]

[a]*Institut National de Recherche et de Sécurité, BP 27, F-54501 Vandoeuvre, France*
[b]*Berufsgenossenschaftliches Institut für Arbeitssicherheit, Alte Heerstrasse 111, D-53757 Sankt Augustin, Germany*

Abstract

Integrated electronics are being introduced into various type of personal protective equipment (PPE) to ensure information and alarm functions. This is the case for hearing protection devices and electro-optical filters for arc welding (protection) as well as for respiratory protective equipment (information and alarm). The use of electronics raises questions concerning the level of protection afforded by these types of PPE and their conformity to the essential requirements laid down in concerned European directive. The level of protection of PPE including electronics shall be at least equivalent to that of standard PPE.

In order to provide an answer to those concerned, this article proposes a method used in the machinery domain, which is based on one index of risk determination and the approach from the angle of safety. It leads to the determination of the category of EN 954-1 standard, also used in the safety of machinery domain, to which the PPE belongs. According to that category, technical measures are to be considered at the design stage of PPE including electronics in order to reach the required level of protection. These additional requirements are to be proposed for their insertion in national, European and international standards.

1. Introduction

Today, there are hundreds of thousands of types of PPE in use throughout the world for occupational, sport and leisure activities. In order to facilitate trade, compliance to specifications and test methods according to national standards

* Corresponding author. Tel.: +33-3-83502112; fax: +33-3-83502115.
E-mail address: klein@inrs.fr (R. Klein).

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(ANSI, BSI, DIN, NF,...)[1], European standards (CEN, CENELEC)[2] and ISO[3] international standards is generally required. None of the existing standards has dealt with the safety aspects related to the use of electronics in PPE.

Integrated electronics first appeared more than 20 years ago in the domain of personal protection, with the first liquid crystal optical filters for welders being placed on the market in the 1970s, soon to be followed by active noise reduction hearing protectors and ear muffs equipped with electronics for communication.

Today, electronics are being introduced into a number of isolating respiratory protective devices to replace the traditional pneumatic and mechanical safety devices currently fitted. The use of electronics raises a number of questions:

1. Is the "level of protection" (defined in Section 3.1) provided by this new generation of PPE at least equivalent to that of standard PPE that include a well-tried technology instead of electronic circuits?
2. What confidence can one have in the safety of equipment thus designed?
3. Are there new risks introduced by the new generation of PPE?

These are some of the questions that must legitimately be asked by designers, users, certification bodies and prevention specialists. It is indeed unacceptable that introducing such technologies could be accompanied by a deterioration in the level of protection of the corresponding products.

At a European level, the 89/686/EEC Directive relative to PPE (Council Directive, 1989) encompasses these safety requirements. It lays down that PPE must be designed and manufactured to guarantee the user appropriate protection in all foreseeable conditions of intended use (ESR[4] 1.1.1.). It furthermore requires (ESR 1.3.2) that they can adequately withstand the effects of ambient factors (climatic, mechanical, electrostatic, electromagnetic) inherent in their foreseeable conditions of intended use.

There are many publications dealing with the safety aspects of industrial systems. In general, however, these aspects are examined from the dependability point of view which encompasses others such as reliability, availability, maintainability (Bell and Reinert, 1993; Ciccotelli and Buchweiller, 1996; Mayer et al., 1998; Siewiorek and Swarz, 1998).

To our knowledge, no scientific publication specifically related to the safety of electronic circuits integrated into PPE is available and no methodology intended to answer the question of safety has yet been proposed.

This publication is meant to provide a comprehensive response to this question, primarily from the angle of the "risk assessment" and safety approach used for machines and their associated safety components. It also compares the new

[1] ANSI, American National Standards Institute; BSI, British Standards Institution; DIN, Deutsches Institut für Normung e.V.; NF, Norme Française.

[2] CEN, European Committee for Standardization; CENELEC, European Committee for Electrotechnical Standardization.

[3] ISO, International Organization for Standardization.

[4] Essential Safety Requirements.

generation of PPE with comparable standard PPE and gives an answer to the required safety based on the category approach of EN 954-1 (EN 954-1, 1996).

No confusion of EN 954-1 categories shall be made with the PPE certification categories (0–3) commonly used by those involved in PPE certification (PPE-useful facts, 1997).

2. PPE integrating electronics and the normative specifications

2.1. Electro-optical filters for arc welding

These "dynamic" liquid crystal filters have been developed both to improve the comfort of arc welders and to reduce the risk of "arc-eye". In the absence of an arc, they are sufficiently transparent to provide a clear view of both the visual task and the surrounding area; they reach their darkened state a few tenths of a second following the appearance of the arc to protect the eyes of the welder against the optical radiation emitted.

These filters are covered by the standard EN 379 (EN 379, 1994; currently being revised). It includes a certain number of "dependability" requirements that take two factors into consideration: the climatic environment to take account of the sensitivity of the liquid crystal to cold and to heat, and the risk of a power cut due to a battery failure.

2.2. Electronic hearing protection devices (HPD)

Three types currently exist:

1. "Level dependent" ear muffs or ear plugs, whose noise attenuation increases with the ambient sound level. Ear muffs are covered by pr EN 352-4 (pr EN 352-4, 1999) and ear plugs by pr EN 352-7 (pr EN 352-7, 1999). These draft standards do not encompass aspects related to "dependability".
2. "Active" or "active noise reduction" ear muffs. A microphone detects the residual noise level inside the cups and an electro-acoustic device generates a similar noise in the opposite phase to the residual noise. They are covered by pr EN 352-5 (pr EN 352-5, 1999).
3. "Transmission and inter-communication" ear muffs. In addition to protecting users against noise, they also allow the transmission of vocal messages and warning signals useful in carrying out the task. The link can be wire, radio or infra-red. They are covered by pr EN 352-6 (pr EN 352-6, 1999).

2.3. Self-contained breathing apparatus (SCABA type)

Traditionally, SCABAs are equipped to provide the wearer with information by means of an air pressure manometer and an alarm, in the form of a continuous or intermittent whistle, which automatically triggers when the remaining air has reached a critical value (55 ± 5 bars) and continues until it runs out. This equipment directly indicates how much air is left. To improve both the quality and quantity of the information supplied to the wearer, as well as the characteristics and performance of the equipment (e.g. the whistle consumes air and therefore reduces autonomy), manufacturers are beginning to offer, either as an option or as standard, electronic systems capable of managing this information and delivering it to the wearer. These information devices use "transducers", and no longer give a direct indication of how much air is left. They are covered by Standard EN 137 (EN 137, 1993) which encompasses "functional safety" aspects.

2.4. Nature of the electronic circuits integrated into PPE

The electronic circuits fitted to PPE generally employ discrete components (diodes, transistors, resistors, etc.) or simple integrated circuits (a few elementary functions). They are mainly logic and operate at low voltage levels, meaning that they are highly susceptible to electromagnetic perturbation. These circuits have not been strengthened to handle these perturbations, which are frequently encountered in the industrial environment (starting up of TIG-welding stations, regulation of motors, ovens, hand-held radios, etc.) and which may cause an impairment or even the loss of the safety function of the PPE. In general, they have been designed exclusively to fulfil their function (Sections 2.1–2.3), without taking into account failure of the components they employ.

3. Ability of the PPE to fulfil its safety function

3.1. Concept of "level of protection"

The concept of "level of protection", in the context of protective devices, represents the level of confidence afforded to the service provided by the device, i.e. *its ability to fulfil its safety function*.

The *level of protection* is determined by employing methods and techniques at the design stage and validating the electronic circuits.

3.2. Proposed approach

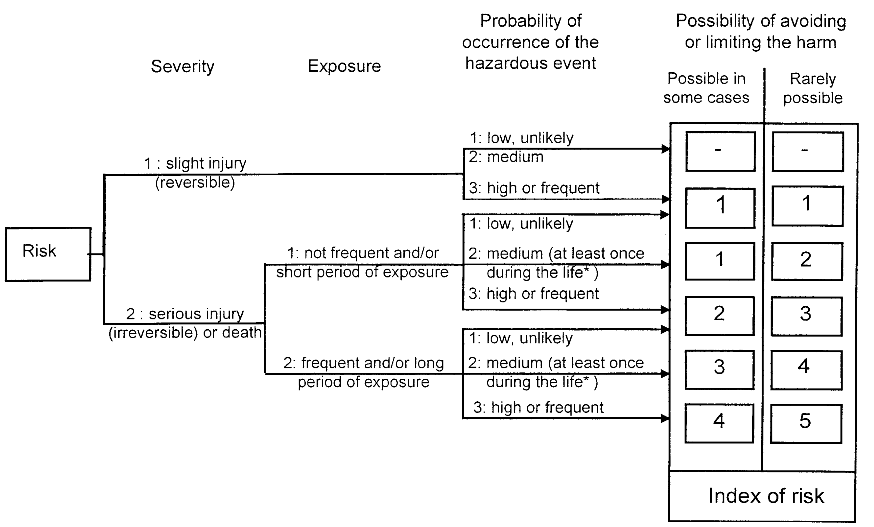
Designers of PPE that incorporate electronics are, at present, only concerned with the robustness of the equipment and aspects of its performance, sometimes in extreme climatic conditions. This approach is insufficient to assess the level of protection of the PPE in all foreseeable conditions of use. To define a more comprehensive approach, it is proposed that reference is made to the methodology employed in the safety of machinery.

In the first stage, the risks inherent to using PPE, i.e. the risks run by the person to be protected in the case of equipment malfunction are assessed. This assessment must always be the result of collective work and of exchange between specialists in using the device in question and specialists in the technology encountered. It could be carried out on the basis of European standard EN 1050[5]: "Safety of machinery—Principles for risk assessment" (EN 1050, 1996). This standard is easy to apply and has proved to be effective in the field of electronic control circuits. Other methods dedicated to assessing the risks of complex systems exist (Lewis et al., 1978; Raafat, 1989; Taylor, 1994), but are not particularly well suited to the simple electronic circuits fitted to PPE.

Fig. 1, established from standard 1050, can be used to estimate an *index of risk* for a particular PPE in relation to various parameters (severity, exposure, probability of occurrence of the hazardous event, possibility to avoid or limit the harm).

For PPE including electronics, the index of risk must be estimated with a standard functional electronic circuitry in mind. In this case, "severity" is the possible hazard with the new design when this electronic circuit is faulty and causing incorrect operation of the safety function.

The "exposure" parameter is not influenced by the design of the PPE. When the "probability of occurrence of the hazardous event" has a technical origin, it is a function of the components and the design of the system related to the protection function. Both depend on the implemented category of this system. The "possibility of avoiding or limiting the harm" can also be influenced by the introduction of electronic circuits into PPE.



* : The product life time

Fig. 1. Index of risk estimation according to standard EN 1050.

[5] This standard, which is normally employed for machinery safety problems, can serve as a reference for this type of approach.

The possibility, for instance, exists for hearing protection devices. The wearer can remove the HPD in the case of a malfunction leading to noise amplification instead of attenuation (Section 4.2). There is no such possibility for the respiratory protective equipment used in dangerous atmospheres (Section 4.3).

Using the index of risk as a starting point, the proposed method leads to the determination of a category according to European standard EN 954-1; the concept of these categories is defined briefly in the following section.

3.3. The categories

According to European standard EN 954-1, the designer can specify and design the device in relation to:

1. the ability of the device to fulfil a nominal safety function in a particular environment;
2. the conditions of maintaining the safety function, i.e. the expected behaviour of the device in the case of component faults.

To achieve this, the standard defines a particular concept: categories (Table 1). These give no direct indication of any functional safety level but define several types of device behaviour in the presence of component faults or environmental perturbation.

Although, strictly speaking, the use of categories only applies to "safety-related parts of the control system", it can, by analogy, be extended to any device ensuring safety functions, which is the case for PPE.

Once the category claimed for the device has been integrated into the design and development of the device, depending of course on the state of the art[6], and subsequently validated, users are then able to justify the level of confidence expressed in the device.

In the particular case of the technological upgrade of an existing device, the category of the devices of the preceding generation should be estimated and serve as a reference to determine both the test and design specifications of new products.

4. Analysis of the functional safety of PPE incorporating electronic circuits

Three types of PPE—an electro-optical filter, two HPD (using electronic circuits for safety functions) and a respiratory protective device (SCABA type)—are analyzed in this section to illustrate the method described in Section 3.

[6] In the spirit of the new approach, the state of the art is that which provides users with the highest level of protection that can be attained taking into account current scientific knowledge, technical possibilities and economic constraints. It is not synonymous with that most often encountered technically, which can lead to a lower than expected level of protection. In contrast, the state of the art does not correspond to that which can be best achieved from a technical point of view.

Table 1
Requirements for the categories of safety-related parts of machinery control systems according to standard EN 954-1

Category	Requirements (in brief)	System behaviour	Principle
B	Safety-related parts of control systems and/or their safety devices and components must be designed, constructed, selected, assembled and combined in accordance with the relevant standards such that they can withstand the expected influence	The occurrence of a fault can lead to the loss of the safety function	Mainly characterized by the selection of components
1	The requirements of B shall apply. Well-tried components and well-tried safety principles shall be used	The occurrence of a fault can lead to the loss of the safety function, but the probability of occurrence is lower than in category B	
2	The requirements of B and the use of well-tried safety principles shall apply. The safety function shall be checked at suitable intervals by the machinery control system	The occurrence of a fault can lead to the loss of the safety function between the checks. The loss of the safety function is detected by the check	Mainly characterized by the structure
3	The requirements of B and the use of well-tried safety principles shall apply. Safety-related parts shall be designed such that: 1. a single fault in any of these parts does not lead to the loss of the safety function, and 2. the single fault is detected whenever reasonably practicable	If the single fault occurs, the safety function is still maintained. Some, but not all faults are detected. Accumulation of undetected faults can lead to the loss of the safety function	
4	The requirements of B and the use of well-tried safety principles shall apply. Safety-related parts shall be designed such that: 1. a single fault in any of these parts does not lead to the loss of the safety function, and 2. the single fault is detected during or prior to the next demand on the safety function or, if this is not possible, an accumulation of faults should not as a result lead to the loss of the safety function	If faults occur, the safety function is still maintained. Faults are detected in good time to prevent the loss of the safety function	

4.1. Electro-optical welding filters

4.1.1. Estimation of their index of risk as per standard EN 1050 (Fig. 2)

4.1.1.1. Severity. According to Standard EN 379 "Specifications for welding filters with switchable luminous transmittance and welding filters with dual luminous transmittance", which is applicable to these products, protection against ultraviolet and infrared radiation is ensured by "passive" optical filters that are independent of the electronic system. For visible rays, the level of protection must remain above a prescribed value (tears, lid closure reflex, etc.) in the case of the device breaking down. This limit, associated to the natural defence mechanism of the user (tears, lid closure reflex, etc.), leads to a risk of minor and reversible eye injury.

4.1.1.2. Probability of occurrence of the hazardous event. Welding masks are usually employed in industrial situations where the environmental conditions (cold, heat, temperature variations, interference emitted by arc welding stations, electrostatic discharges, mechanical shocks, etc.) are likely to perturb the electronics of these systems both severely and permanently.

4.1.1.3. Possibility of avoiding or limiting the harm. Visual detection of filter malfunction will be immediate, as it will be locked either in the "Dark State" or "Clear State" position. In the latter case, if users are carrying out welding operations manually, stopping welding thereby stops emission of the dangerous radiation. If, however, an automatic welding operation is being monitored, they can look away to avoid the danger. The possibility of avoidance is therefore guaranteed.

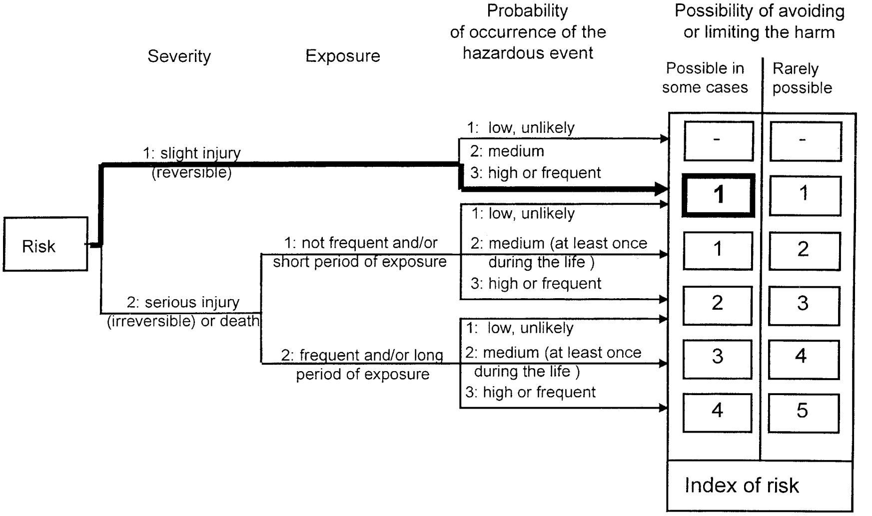


Fig. 2. Index of risk estimation for electro-optical welding filters.

4.1.1.4. Estimated index of risk. The *index of risk* of this type of device, applicable to the function of protecting the sight of an operator against the visible radiation emitted by a welding operation, *is estimated as a maximum of one* on the retained scale (maximum index 5).

4.1.2. Proposition of measures to be considered for electro-optical welding filters

The measures to be taken to reduce the risk in such an application could simply consist of juggling with the parameter "probability of occurrence of a hazardous event". This could involve the systematic verification of the suitability of the device for use in an environment that perturbs electronic circuits, i.e. in addition to the specifications already laid down in EN 379 to verify electro-magnetic radiation and discharges of static electricity.

These measures meet the requirements of *category B* as laid down in EN 954-1. This means the electronic equipment will withstand the expected operating stresses and all relevant external influences.

4.2. Hearing protection devices (HPDs): level dependent ear muffs

4.2.1. Estimation of their index of risk as per standard EN 1050 (Fig. 3)

4.2.1.1. Severity. In the case of non-operation, the user is protected by HPD passive noise attenuation. In the case of malfunction, the rise in sound level depends on the power of the incorporated amplifier.

4.2.1.2. Probability of occurrence of hazardous event. The protectors are employed at work places liable to electro-magnetic fields likely to induce malfunction of the electronic modules of these HPD.

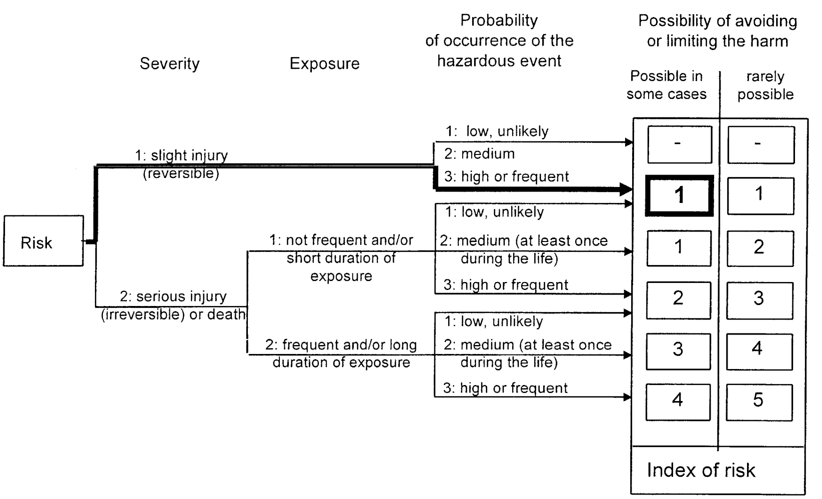


Fig. 3. Index of risk estimation for level dependent ear muffs.

4.2.1.3. Possibility of avoiding or limiting the harm. In the case of a sudden rise in the restitution sound level, the user can quickly remove the ear muff to limit the period of exposure to the noise due to the malfunction, and leave the noisy environment of the work place.

4.2.1.4. Estimated index of risk. The *index of risk* of this type of device is estimated as a *maximum of 1* on the retained scale (maximum index of 5).

4.2.1.5. Proposition of measures to be considered for level dependent ear muffs. The measures to be taken to reduce the risk in such an application could simply consist of juggling with the parameter "probability of occurrence of hazardous event", for example, by systematically verifying the suitability of the device for use in an environment that perturbs electronic circuits (i.e. climatic environment, electro-magnetic radiation, and discharges of static electricity). Recourse to electronic circuits that, through their design, limit the sound power restored inside the protector, could also be envisaged.

Detailed propositions based on the values adopted for other families of devices could be drawn up with this in mind. These measures meet the requirements of *category B* as laid down in EN 954-1. This means the electronic equipment will withstand the expected operating stresses and all relevant external influences.

4.2.2. Active noise reduction (ANR) ear muffs

4.2.2.1. Estimation of their index of risk as per standard EN 1050 (Fig. 4). This new design creates new hazards because a faulty electronic circuit could actively generate noise peaks in addition to the residual noise level.

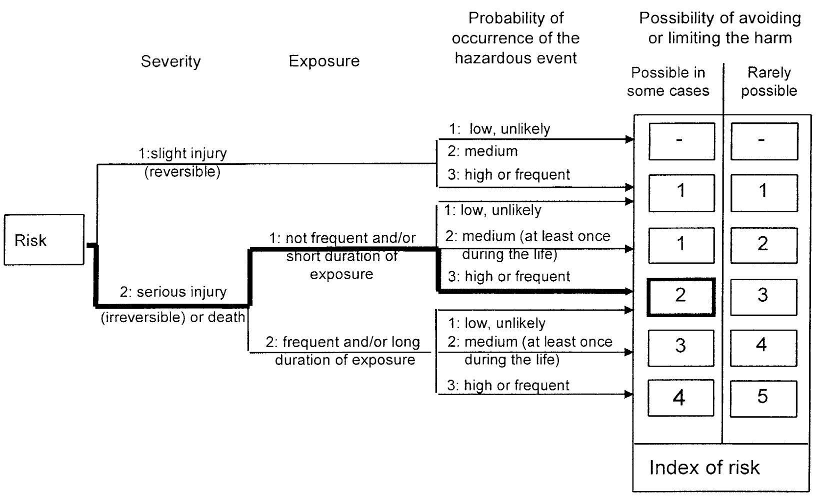


Fig. 4. Index of risk estimation for active noise reduction (ANR) ear muffs.

4.2.2.1.1. Severity[7]. The phase opposition attenuator can go out of tune and transform the device into an amplifier. The sudden rise in sound level inside the HPD which could result from this malfunction is likely to cause a temporary or even partial permanent hearing loss of the user.

4.2.2.1.2. Exposure. The period of exposure is limited to the time taken for the user to remove the ear muff in the case of a rise in the sound level due to phase addition.

4.2.2.1.3. Probability of occurrence of hazardous event. The protectors are employed at work places liable to electro-magnetic fields likely to induce malfunction of the electronic modules of these HPDs.

4.2.2.1.4. Possibility of avoiding or limiting the harm. In the case of a sudden rise in the restitution sound level, the user can quickly remove the protector to limit the period of exposure to the noise due to the malfunction, and leave the noisy working environment.

4.2.2.1.5. Estimated index of risk. The *index of risk* of this type of device is estimated as a *maximum of 2* on the retained scale (maximum index of 5).

4.2.2.2. Proposition of measures to be considered for active noise reduction ear muffs. The measures to be taken to reduce this risk index from 2 to 1 could consist of juggling with the parameter "probability of occurrence of hazardous event", for example, by reinforcing the immunity of these devices to electro-magnetic radiation and to discharges of static electricity, and by using an electronic circuit limited in power or with a better performance in the presence of a component fault.

Detailed propositions based on the values adopted for other families of devices could be drawn up with this in mind after consultation with the various parties involved.

These measures meet the requirements of *category B* according to EN 954-1. This means the electronic equipment will withstand the expected operating stresses and all relevant external influences.

4.3. Respiratory protective equipment (SCABA type)

In the area of respiratory protection, all equipment that has or may have recourse to electronics for correct use must fulfil the following requirements:

1. a prior performance check,
2. a permanent check of the factors influencing the level of protection,

Falling within this category are:

[7] Only the risk of injury to the hearing of the wearer in the case of protective device malfunction has been take into account in this analysis. It should be noted that the sudden rise in the sound level under the ear muff can cause the wearer to make an uncontrolled movement, leading to a dangerous situation where the risk would be of another nature, depending on the work place conditions.

1. powered filtering devices against particles and/or gases,
2. self-contained compressed air devices used, for instance, in fire fighting.

4.3.1. Estimation of their index of risk as per standard EN 1050 (Fig. 5)

In contrast to the preceding categories of PPE, the electronic devices integrated into these types of respiratory protective equipment (RPE) could simply replace mechanical components without modifying the characteristics. In this case, it is therefore interesting to compare the category estimated for standard RPE (without electronics) to those including electronic circuits.

The results of the analysis presented later highlight a divergence, primarily linked to varying degrees of possibility of avoidance from one case to another.

4.3.1.1. Severity. The risk of a break in the air supply when using a SCABA will lead to serious injury or death of the wearer, whatever the technology employed.

4.3.1.2. Exposure. From the moment of donning the equipment, the wearer is permanently exposed, whatever the technology employed.

4.3.1.3. Probability of occurrence of the hazardous event. A break in the air supply can happen at least once during its lifetime or shelf life, whatever the technology employed.

4.3.1.4. Possibility of avoiding or limiting the harm. Although stemming from the same source, two types of information are available to the user, namely the manometer and the whistle, both unlikely to break down simultaneously. In addition, the continuous analogical reading of the cylinder pressure, a fundamental rule

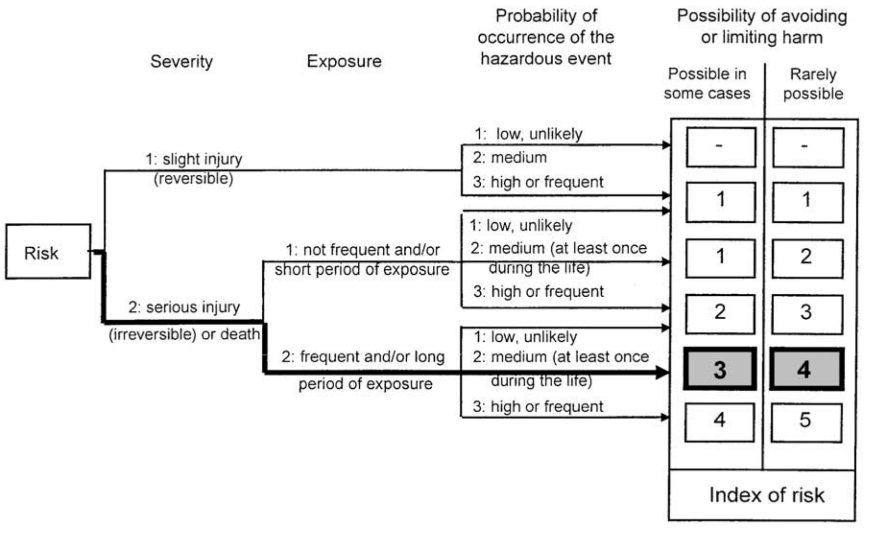


Fig. 5. Index of risk estimation for respiratory protective equipment (SCABA type).

for specialized wearers, allows them to assess the situation in which they find themselves, thereby leaving them the possibility of avoidance. (e.g. a manometer indicating that a bottle is still full after a short period of use, possibly due to the needle being jammed, is interpreted as a malfunction which should lead to withdrawal from the dangerous zone). This analysis shows that a single failure will not lead to a dangerous situation and that such a failure will normally be detected by the user

Taken from the same source and processed by the same electronic circuit, the different numerical information provided to wearers can deteriorate simultaneously (risk of common mode failures linked to environmental factors), leaving them no possibility of analysis and therefore avoidance.

4.3.1.5. Estimated index of risk. The comparison clearly shows that the *index of risk* of the new design (**4**) is higher than that of the standard PPE (3) of the same type. In this case changes to the electronics would be proposed.

4.3.2. Proposition of technical measures to be considered for SCABAs

The measures to be taken to reduce this high index of risk could consist of juggling with the parameter "probability of occurrence of the hazardous event", for example, by using an electronic circuit with a performance in the presence of component faults at least equal to that of the standard PPE.

The electronic circuit should be designed to meet the requirements of *category 3* according to EN 954-1.

5. Conclusion

The introduction of electronics into PPE can generally be viewed as a factor of progress, greatly improving both the level of protection and comfort provided to users. However, as for all electrical systems intended to perform safety functions, particular precautions have to be taken at design and certification level to prevent a component failure due, for example, to their sensitivity to certain environmental factors causing discomfort and even, in certain cases, real danger for the wearers.

The review of the relevant scientific literature did not show any specific methodology currently available to achieve a given level of protection for PPE including electronics. The methodology based on an analysis carried out on the basis of the EN 1050 and 954-1 standards has shown that it could be advantageous to introduce additional specifications relative to functional safety into the PPE standards. Proposed categories according to 954-1 depend on the estimated index of risk related to each type of PPE.

This methodology was largely discussed and accepted by all European stakeholders (people involved in standardization, authorities...). It is already being used to draft additional requirements to be included in existing European standards and, of course, needs to be validated on a European scale by all those involved: manufacturers, users, certification bodies, CEN "PPE Technical Committee" and European Co-ordination of Certification Notified Bodies.

Because of the increasing globalization of trade, it would be desirable that these elements are taken into account in ISO standards. The close co-operation between ISO and CEN within the framework of the Vienna Agreement (ISO/CEN, 1990) should make this evolution easier.

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