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# Exposure Assessment Methods for Low and Intermediate Frequency Electromagnetic Fields and Associated Uncertainties

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## Abstract

By the time the EU-Directive 2004/40/EC on the minimum health and safety requirements regarding the exposure of workers to electromagnetic fields comes into force, new demands for employers will arise. This includes the employers' duty to evaluate each workplace with respect to the workers' exposure. The present thesis has the aim of helping employers in this respect and is concerned with some major challenges on this way.

Investigations are performed on possible exposure setups in the welding industry facing high and complex exposure to electromagnetic fields. Exposure relevant welding applications are selected according to their exposure characteristics and frequency of use. Compact fluorescent lamps for lighting such workplaces as a second source of electromagnetic fields are discussed. Magnetic fields of up to some mT and frequencies between 0 Hz and about 1 MHz can be expected in welding applications, which typically show pulsed, non-sinusoidal, intermittent, and highly inhomogeneous characteristics. For compact fluorescent lamps electric fields of up to some 100 V/m and frequencies of several 10 kHz can be found.

To avoid adverse effects on the human body elicited by electromagnetic field exposure different regulations give exposure limits which have to be met as well as methods to evaluate compliance. However, other documents like standards specify the assessment methods applicable to quantitatively determine a specific exposure. These assessment methods are discussed in detail by means of a literature study. The given compilation reflects the state of the art in complex exposure assessment with focus on appropriate uncertainty evaluations. The necessary theoretical background for assessing incident fields and the appropriate handling of uncertainties is given. Challenges in complex exposure assessment and evaluation are discussed leading to a potential harmonized exposure assessment and evaluation protocol. If followed, this protocol gives a good measure of suitability for the applied assessment method and equipment via sound uncertainty estimations.

An example of such an exposure evaluation including detailed uncertainty estimations and appropriate compliance evaluation is given for an exposure scenario composed of a welding workplace with two sources of electromagnetic fields. These are an arc welding application and a compact fluorescent lamp lighting the workplace. Expanded uncertainties with a coverage factor of two and an assumed normal distribution for magnetic field measurements at the welding application were determined to be +51.78%/-51.98% (400 Hz-400 kHz) and  $\pm 48.52\%$  (1 Hz-400 Hz). An expanded uncertainty of  $\pm 37.4\%$  is given for electric field measurements of the compact fluorescent lamp, again with a coverage factor of two and an assumed normal distribution. With respect to compliance evaluation different possibilities were discussed leading to a potential overexposure at the welders' shoulder and head by a factor of in maximum 22.61 and an expanded uncertainty of +63.87%/-64.04%.

Literature on complex exposure assessment in the given frequency range was shown to be sparse, especially with regard to associated uncertainty estimations. Further studies need to be conducted. Investigations concerning associated uncertainties of evaluation for a representative number of exposure scenarios (e.g., in welding applications) seem necessary. Regulations and standards may beneficially account for the achieved findings by adopting proper limit values, compliance evaluation methods, exposure assessment methods and equipment requirements.



## Kurzbeschreibung

Die Inkraftsetzung der EU-Direktive 2004/40/EC, bezüglich der Mindestvorschriften zum Schutz von Gesundheit und Sicherheit der arbeitenden Bevölkerung bei Exposition durch elektromagnetische Felder, wird die ArbeitgeberInnen innerhalb der Europäischen Union mit neuen Herausforderungen konfrontieren. Die vorliegende Arbeit soll dazu beitragen, den neuen Anforderungen entsprechen zu können.

ArbeiterInnen in der Schweißindustrie sind häufig hohen und komplexen Expositionen durch elektromagnetische Felder ausgesetzt. Im Zuge dieser Arbeit wurden expositionsrelevante Quellen an entsprechenden Arbeitsplätzen untersucht. Neben der Schweiß- Applikation als offensichtliche Quelle wurde die mögliche Beleuchtung des Arbeitsplatzes mittels Energiesparlampen als expositionsrelevant identifiziert. In der Umgebung von Schweißgeräten treten magnetische Felder von bis zu einigen mT mit Frequenzen von 0 Hz bis etwa 1 MHz auf. Diese Felder zeigen häufig gepulstes, nicht-sinusförmiges, nicht kontinuierliches und hoch inhomogenes Verhalten. Energiesparlampen erzeugen elektrische Felder in der Größenordnung von einigen 100 V/m mit Frequenzen von einigen 10 kHz.

Es existieren internationale Regulierungen, die die Exposition durch elektromagnetische Felder begrenzen, um schädliche Wirkungen auf den menschlichen Körper zu verhindern, sowie Expositionsevaluierungsmethoden zur Überprüfung ihrer Einhaltung definieren. Standards andererseits beschreiben anwendbare Erfassungsmethoden zur quantitativen Bestimmung elektromagnetischer Exposition. Der aktuelle Stand der Technik solcher Erfassungsmethoden mit Schwerpunkt auf komplexe Expositionsszenarien und die Bestimmung von Unsicherheiten wurde anhand einer Literaturstudie aufbereitet und diskutiert. Die theoretischen Grundlagen hierzu sowie zum entsprechenden Umgang mit Unsicherheiten werden dargelegt. Ein Vorschlag zur Harmonisierung von Expositionserfassungen und Evaluierungen ermöglicht zuverlässige Aussagen über den sinnvollen Einsatz einer bestimmten Expositionserfassungsmethode und dem entsprechenden Equipment.

Anhand eines möglichen Expositionsszenarios in der Schweißindustrie wurden detaillierte Unsicherheitsabschätzungen sowie eine entsprechende Expositionsevaluierung durchgeführt. Als Quellen elektromagnetischer Felder dienten ein Lichtbogenschweißgerät sowie eine Energiesparlampe. Für die magnetischen Feldmessungen konnten erweiterte Unsicherheiten (ein Erweiterungsfaktor von zwei und Normalverteilung vorausgesetzt) von +51.78%/-51.98% (400 Hz-400 kHz) und  $\pm 48.52\%$  (1 Hz-400 Hz) bestimmt werden. Für Messungen an der Energiesparlampe ergab sich eine erweiterte Unsicherheit (Erweiterungsfaktor zwei und Normalverteilung) von  $\pm 37.4\%$ . Verschiedene Expositionsevaluierungen zeigten mögliche Grenzwert-Überschreitungen an der Schulter sowie am Kopf des Schweißers bzw. der Schweißerin von maximal einem Faktor 22.61 mit einer erweiterten Unsicherheiten von +63.87%/-64.04% auf.

Der geringe Umfang der aktuellen Literatur zum Thema der Expositionsevaluierung in komplexen Umgebungen sowie den dazugehörigen Unsicherheitsbetrachtungen verlangt zusätzliche Untersuchungen. Diesbezüglich erscheinen Unsicherheitsabschätzungen für eine repräsentative Anzahl an Arbeitsplätzen, z.B. in der Schweißindustrie, sinnvoll. Die Ergebnisse bzgl. passender Grenzwerte, Evaluierungsmethoden, Erfassungsmethoden sowie Anforderungen an Messequipment sollten Eingang in entsprechende internationale Dokumente (Regulierungen, Standards, etc.) finden.





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My sincerest thanks go to my mother, my whole family and friends for supporting me on my way. This work wouldn't have been possible without you!

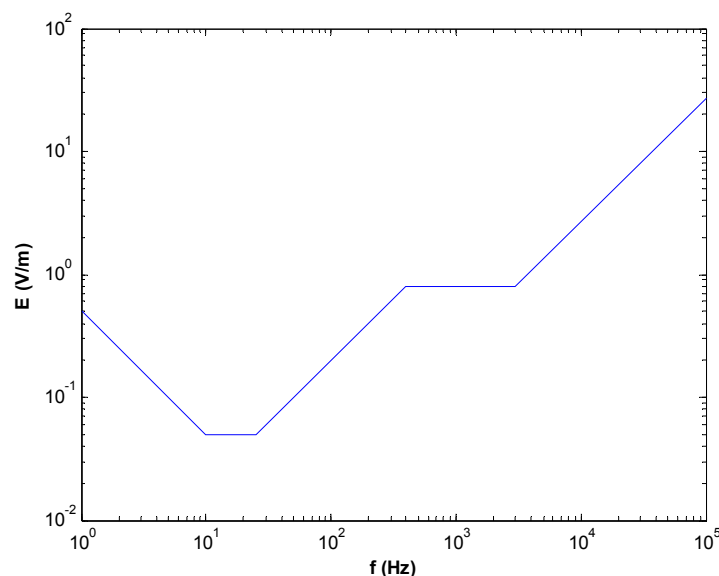


# 1 Introduction

Perception of possible health effects due to exposure to electromagnetic fields (EMFs) has increased in the last decades as sources of such fields dominate our lives. Thus, corresponding exposure limits set by appropriate organizational bodies with the aim of avoiding adverse health effects are continuously refined.

Exposure limits are based on sound scientific evidence reflecting the interaction of EMFs with biological tissue. From a physiological point of view two major effects have to be considered when looking at such interactions. These are athermal effects (in the given context nerve excitations) due to induced electric fields for frequencies below 10 MHz, as well as thermal effects due to induced electric fields for frequencies higher 100 kHz (ICNIRP, 2010). The given limit values are frequency dependent reflecting nerve cell and in general tissue reactions when exposed to EMFs.

Figure 1-1 shows the well known “bathtub curve” for central nervous tissue excitation. The induced electric field necessary to elicit nerve excitation decreases from 1 Hz to 10 Hz, is lowest for 10 Hz to 25 Hz, and increases again for higher frequencies (ICNIRP, 2010). Higher electric fields for frequencies below 10 Hz are permitted because of accommodation effects (active control mechanisms of cells limit excitability of nerves). For frequencies above 25 Hz higher fields are permitted taking into account the refractoriness of nerve cells as well as the bypassing of cell membranes by displacement currents<sup>1</sup>. (Pfützner, 2003)



**Figure 1-1 Frequency dependence of the occupational induced electric field strength  $E$  limit for central nerve excitation from ICNIRP (2010)**

Concerning thermal effects, due to the electrical conductivity of biological media  $\gamma$  an induced electric field  $E$  will provoke a current density  $J$  via  $J = \gamma E$  leading to an energy deposition in the media. Such energy deposition in consecution causes tissue heating. This especially gets effective for higher frequency fields causing displacement currents over cell membranes, and thus elicits extracellular as well as intracellular heating. (Pfützner, 2003)

<sup>1</sup> For frequencies above 400 Hz and occupational exposure limit values for peripheral nerve excitation start to apply in ICNIRP (2010). This allows the interpretation of the level-off between 400 Hz and 3 kHz in Figure 1-1.

In short, when looking at external fields, a difference in limit values for electric and magnetic fields can be observed (Appendix A). For magnetic fields the limit values at lower frequencies decrease much faster with frequency in comparison to those of electric fields. This reflects the principle of induction leading to higher induced electric fields for faster changes of external magnetic fields (Pfützner, 2003). Besides other more specific effects, these are the basic physiological phenomena adopted by organizational bodies in recommendations, guidelines, directives, laws, standards, and other documents.

Accounting for new scientific evidence on interactions of biological tissue with EMFs as well as the need of regulating exposure for workers, a new EU-Directive is currently under development. By the time the EU-Directive 2004/40/EC on minimum health and safety requirements regarding the exposure of workers to electromagnetic fields presumably becomes effective in October 2013 new demands on employers in the European Union will arise. This includes the employers' duty to evaluate each workplace with respect to the workers' exposure to EMFs.

### **Outline of the Thesis**

This thesis contributes to the EUREKA project WEMS (Worker Electro-Magnetic Safety) with the aim of providing suitable tools enabling employers in the metal fabrication, automotive, and railway industries to fulfill these requirements. Thus, within this work concepts on a suitable overall exposure assessment in complex electromagnetic field environments are examined in general and by means of a specific exposure scenario typical in welding industries. More specifically, assessment and evaluation methods for multi source exposure scenarios are lighted, comprising static (SF) (<3 Hz), extremely low (ELF) (3 Hz-300 Hz), and intermediate frequency (IF) (300 Hz-10 MHz) fields (Mild et al, 2009). Extensive but feasible uncertainty estimations for exposure evaluations are shown to be a proper tool to determine the suitability of a specific assessment method with respect to the given exposure scenario, evaluation method, and the tested exposure limits.

In the beginning of this work exposure relevant EMF sources on welding workplaces are identified. This includes different welding equipment as well as compact fluorescent lamps (CFLs). Brief explanations of the most exposure relevant welding techniques are given, followed by a review of typical utilized welding currents and the respectively emitted electromagnetic fields (Sections 2.1 and 2.2). CFLs are also briefly discussed from this point of view (Section 2.3).

To allow further insight into exposure limiting concepts some of the most important documents are presented in short (Section 3.1). Moreover, established exposure assessment methods are summarized from international standards (Section 3.2).

Taking up the idea of using uncertainty estimations as proper means for evaluating exposure assessment and evaluation methods, the theoretical background for such estimations is given. The term uncertainty is defined. Furthermore, possibilities to achieve a combined (expanded) uncertainty in exposure evaluations are given (Sections 4.1 and 4.4). Uncertainty budgets as well as the compliance assessment with limits accounting for uncertainties are discussed shortly (Sections 4.2 and 4.3).

The state of the art in assessing and evaluating complex exposure scenarios is presented by means of a literature study on exposure assessment in welding applications with focus on uncertainty evaluations (Section 5). Based on this various exposure

assessment methods are discussed in view of their suitability and reliability with respect to specific exposure scenarios, evaluation methods and tested limits. Following a compilation of questions to be answered (Section 6.1) two example scenarios of different complexity are given (Section 6.2 and 6.3). Furthermore, concepts on evaluating combined exposure from multiple sources are discussed (Section 6.4). A harmonized exposure assessment and evaluation protocol is given. If followed, this protocol gives a good measure of suitability for the specific applied assessment method via sound uncertainty estimations (Section 6.5).

To demonstrate the concept of extensive uncertainty estimations the evaluation of a specific (multi source) exposure scenario is presented. This scenario reflects a welders' exposure when operating a metal inert gas (MIG) welding application whereas standing in near proximity to a CFL lighting the workplace. The actual exposure setup as well as the measurement method, procedure and equipment are given for each of the two considered exposure sub-scenarios (Section 7.1). Measurement results showing the typical exposure pattern are presented followed by the established uncertainty budgets. A detailed description of the evaluation process follows. Furthermore, the origin of each included uncertainty component as well as the overall uncertainty of the evaluation (Sections 7.2 and 7.3) is given. The overall exposure accounting for the estimated uncertainties is evaluated (Section 7.4) and the achieved findings are discussed (Section 7.5).

This thesis discusses important issues in the application area of EMF exposure assessment and evaluation in complex environments. Various difficulties when performing such assessments and evaluations are addressed, whereas not all points are discussed in full detail as this will go beyond the scope of this work. However, extensive lacks of knowledge were identified in the given application area, especially when it comes to uncertainty estimations. Future investigations on several points in complex exposure assessment and evaluation are necessary. Suggestions addressing potential future steps to take are compiled (Section 8).



## 2 Exposure Sources

Exposure to manmade electromagnetic fields (EMF), in occupation and during off time, as well as the variety and number of sources rises continuously since more than one century. As this thesis aims to pave the way for a reasonable overall exposure assessment in complex environments, a specific exposure scenario is concerned for a first demonstration. This scenario constitutes a potential occupational setting in the metal fabrication industry, especially with regard to welding workplaces. However, to be able to discuss exposure assessment in such complex environments it is necessary to first give an overview on exposure relevant sources and their characteristics in such settings.

Thus, exposure relevant welding techniques (Section 2.1) and their exposure characteristics (Section 2.2), as well as the exposure characteristics of compact fluorescent lamps (CFLs) (Section 2.3), as a second possible source of EMFs on such workplaces, are summarized.

### 2.1 Welding Applications

In the years 2004 to 2008 extensive investigations on welding applications in the metal fabrication industry in Austria were examined by the Allgemeine Unfallversicherungsanstalt, the Austrian Research Centers<sup>2</sup>, Fronius International GmbH as well as the Schweißtechnische Zentralanstalt (Molla-Djafari et al, 2008). The focus was on welding applications with the highest frequency of use (mainly in Austria) and the highest or most disadvantageous possible exposure to EMFs. This section gives a short recapitulation of the identified welding techniques<sup>3</sup>.

In general, for metal work pieces DIN ISO 857-1 (2002) distinguishes two main welding processes: pressure and fusion welding. Moreover, a distinction in regard to the purpose of the process in joining and application is made, respectively. While joining describes the process of bounding two work pieces together to one work piece, application is the coating of a work piece with a weld additive.

Metal inert gas/metal active gas (MIG/MAG) and Tungsten inert gas (TIG), as fusion welding techniques, as well as spot welding, as pressure welding technique, were identified as the welding processes most frequently used and with the highest or most disadvantageous possible exposure to EMFs (Molla-Djafari et al, 2008). Figure 2-1 shows an overview of all welding techniques considered during the mentioned evaluation process.

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<sup>2</sup> In the meantime the Austrian Research Centers developed to the Austrian Institute of Technology (AIT) with the subsidiary companies Seibersdorf Laboratories and Nuclear Engineering Seibersdorf.

<sup>3</sup> Theory of welding applications mainly compiled from Matthes and Richter (2002), Killing (1997), Molla-Djafari et al (2008) as well as from personal communications with Fronius International GmbH.

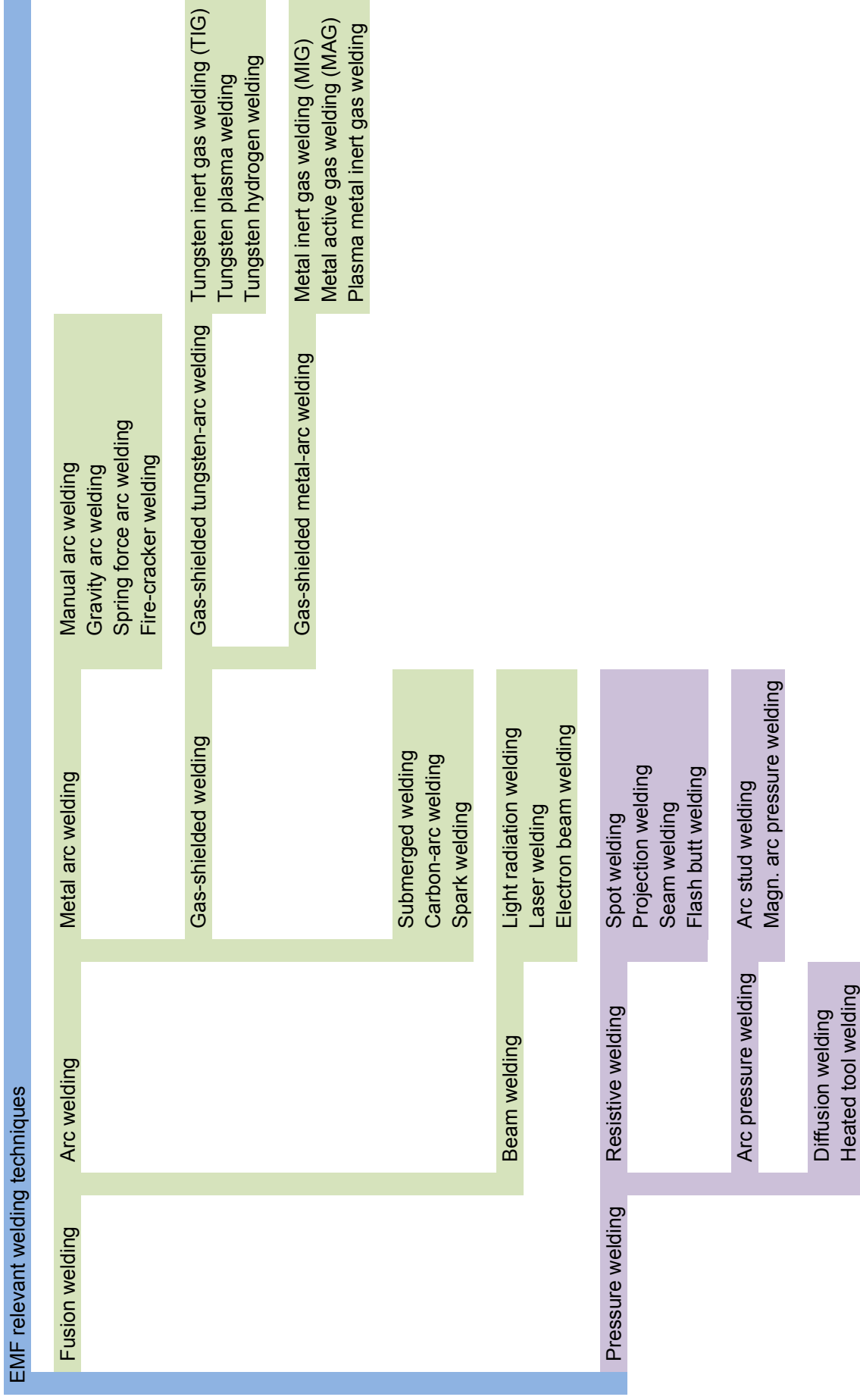


Figure 2-1 EMF relevant welding techniques from Molla-Djafari et al (2008), with changes



### 2.1.1 Arc Welding

Within arc welding the weld pool is generated by an electric arc, burning between the electrode of different material and the work piece. In gas-shielded welding this weld pool and the electrode are protected by a gas to avoid contact with the atmosphere and therefore oxidation. One can further distinguish between TIG, MIG, and MAG techniques with differences in the used electrode material and the used gas<sup>4</sup>.

In MIG and MAG welding an “endless” (consumable) electrode of a material similar to the work piece is used (principle shown in Figure 2-2). With 49% of all arc welding processes in Europe using MIG/MAG welding, it is the most common used arc welding technique. Either manually or automatically welding is possible. Pulsed direct currents (DC) for controlling the drop detachment and the heat contribution into the weld pool are used. A bias current is responsible for keeping the weld pool fluid whereas a pulsed current component controls the periodic drop detachment. Drop size and drop frequency are adjustable via the pulse parameters.

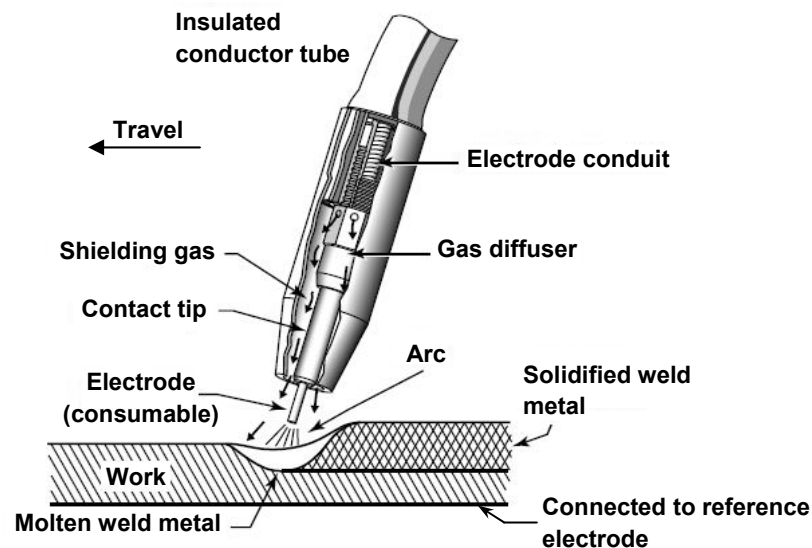


Figure 2-2 MIG/MAG welding scheme – torch cutaway from Web5 (2011), with changes

Within TIG welding the electrode is out of Tungsten and therefore non-consumable (principle shown in Figure 2-3). In 23% of all arc welding processes in Europe TIG welding is used. Mostly pulsed or non-pulsed DC signals are applied. However, for some materials like aluminum and brass only alternating currents (AC) are applicable.

For AC signals a rectangular signal shape with very sharp edges or a sine signal with an additional high frequency pulse after the zero crossing is applied. The sharp edges and the high frequency pulses are necessary for restart<sup>5</sup>, respectively, with rectangular pulses yielding to faster restarts and thus make the welding process more stable. Furthermore, the welding devices hold the possibility to change the ratio between positive and negative pulse widths by so called balance controllers.

<sup>4</sup> As inert gas e.g., Helium or Argon, as active gas e.g., Carbon Dioxide can be used.

<sup>5</sup> The arc is extinguished at each zero crossing and thus a restart of the arc becomes necessary.

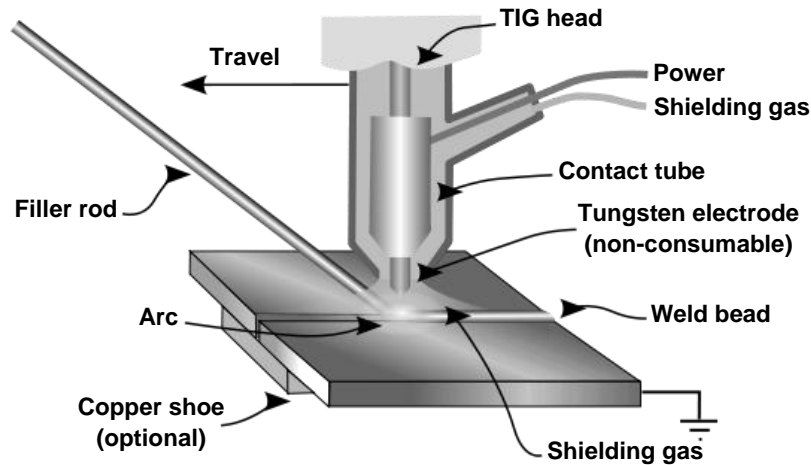


Figure 2-3 TIG welding scheme – torch cutaway from Web6 (2011), with changes

### 2.1.2 Resistive Welding

Resistive welding as a pressure welding technique is welding under the application of forces with or without weld additive. Local heating can alleviate the welding and is performed by a current<sup>6</sup> flowing over the resistance of the welding zone. The generated amount of heat depends on the actual current value, the resistance and the welding time.

#### Spot Welding

Within spot welding the welding process happens due to heating and application of force at one point (or more than one point in double point or multi point welding). Welding currents ((pulsed) DC or AC) are applied either on one side or on both sides of the work piece (principle of a two-sided method shown in Figure 2-4).

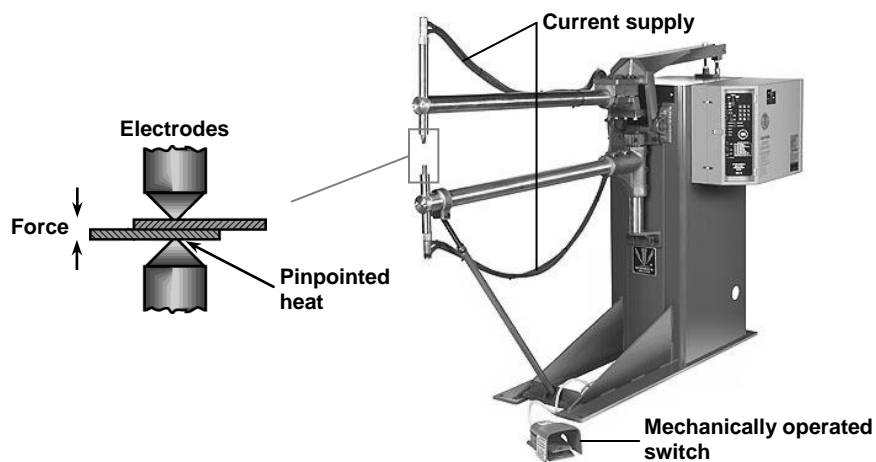


Figure 2-4 Spot welding scheme, stationary welding machine and electrodes with work piece (two sided current supply) from Web1 (2011) and Web2 (2011), with changes

The welding process starts with applying a force. After reaching a given pressure the current is turned on to additionally heat the welding spot. For giving the weld lens the possibility to congeal, the force needs to be hold for a short period after turning off the current again. One can further distinguish between stationary (e.g., Figure 2-4) and mobile (e.g., spot welding

<sup>6</sup> The current can be conveyed either by electrodes or inductors.

guns<sup>7</sup>) spot welding equipment, whereas mobile equipment uses much lower currents than stationary equipment. However, spot welding is mostly used in the processing of thin sheets, for example in the frame-and-body construction, and therefore of huge interest in the automotive industry.

## 2.2 Electromagnetic Fields in Welding Applications

In general, the lighted welding applications typically use high currents and relatively low voltages (see below). Thus, when assessing the exposure due to welding applications it is beneficial to know the welding current as well as the specific type of current source used, since the relevant magnetic fields are proportional to this current. Extensive variations of the applied currents and thus of the emitted magnetic fields can be observed according to the utilized welding technique and the capabilities of the current source (Mair, 2005). A detailed review on current sources and according specifications in arc and resistive welding should not be given here. However, detailed information on this can be found in e.g., Matthes and Richter (2002), Killing (1997), Web7 (2012) or Hackl (2005).

Measurements, numerical and analytical analyses of EMFs at welding sites in the past showed electric fields to be negligible concerning the exposure of workers<sup>8</sup>. However, due to the low voltages used throughout the issued welding processes as well as the completion of near-field conditions, dominant magnetic field exposure assessment gets applicable (Gonter, 2009)<sup>9</sup>. Furthermore, when having a look at the relevant European standards, the EN 50445 (2008) for demonstrating compliance of resistance welding, arc welding and allied processes with exposure restricting values for example quotes that electric fields in general have to be considered but typically won't reach reference levels<sup>10</sup>.

Concerning the frequency content of exposure relevant magnetic fields emitted by welding applications, the EN 50444 (2008) and the EN 50505 (2008) give upper frequency limits to be considered in exposure evaluation according to different welding currents used. However, one has to reckon with fields in a frequency range from DC to some 100 kHz with respect to the lighted welding techniques. Thus, in a lot of cases the current waveform is highly pulsed with high crest factors<sup>11</sup>. Furthermore, in some cases only short welding cycles (just a few current periods) are applied.

One further point to be clarified is the main loci of exposure in arc as well as in resistive welding. For arc welding the torch cable, the welding spot itself and the welding current source (i.e., the welding equipment) can be identified as possible origins of exposure due to the carried welding current, whereas the fields emitted by the welding equipment are typically small compared to the fields from the welding cable and welding spot (e.g., EN 50444 (2008) or Molla-Djafari et al (2008)). With regard to resistive welding the welding equipment, the

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<sup>7</sup> Spot welding guns are mainly used for repair works and material processing in industry and handcraft.

<sup>8</sup> The measured and calculated fields were shown to be far beneath the ICNIRP (1998) reference and basic values, for example in Molla-Djafari et al (2008) or Stuchly and Lecuyer (1989).

<sup>9</sup> Near-field conditions apply due to the given frequency range and workplace setup (welder stands in near proximity to the exposure source).

<sup>10</sup> The standard EN 50445 (2008) keeps with the exposure limiting values stated by the EU-Directive (2004).

<sup>11</sup> The crest factor of a periodic signal is defined as the quotient of the signals' peak to its RMS value. (IEC 61786, 1998)

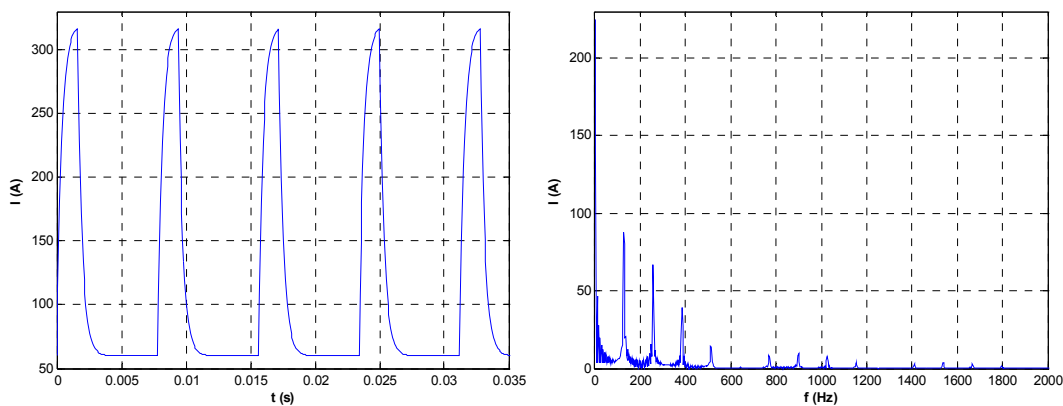
welding window (i.e., the electrode setup) as well as the welding cable for welding guns are the main origins of exposure (e.g., Lindemann et al (2008) or EN 50505 (2008)).

According to this, the welding circuit layout plays an important role concerning workers' exposure. This includes for example the size of the electrode window in resistive welding or the cable paths (torch and return cable) in arc welding (or in resistive welding with welding guns)<sup>12</sup>. This immediately gets clear if one recalls the typical (magnetic) field-distance-relationships for different circuit arrangements. Thus, the magnetic field decay from a straight single conductor can be estimated to be proportional to  $1/r$ , a parallel pair of conductors carrying opposite currents gives rise to a  $1/r^2$  relation, and a  $1/r^3$  relation can be used for describing fields in the vicinity of coils, transformers or compact circuits (e.g., welding equipment).

Summarizing, in welding applications one is obviously confronted with a very versatile spectrum of electromagnetic fields, especially being highly inhomogeneous in time and space. For further insight the following two sections give a short overview on typical welding currents and associated EMFs in arc- and resistive welding.

### 2.2.1 Arc Welding

Pulsed DC signals for controlling the drop detachment and the heat contribution into the weld pool with amplitudes of up to 750 A are used for MIG welding<sup>13</sup>. Typical pulse frequencies are between 50 Hz and 300 Hz. As already mentioned higher frequency components (up to a few MHz) are possible due to e.g., control circuits in the welding current loop. Figure 2-5 (left) for instance shows one example of a measured MIG welding current with a pulse repetition rate of approximately 120 Hz, a background current of 60 A, and pulse amplitudes of approximately 317 A<sup>14</sup>.



**Figure 2-5 (left) Time signal of a MIG welding current, and (right) according amplitude spectrum**

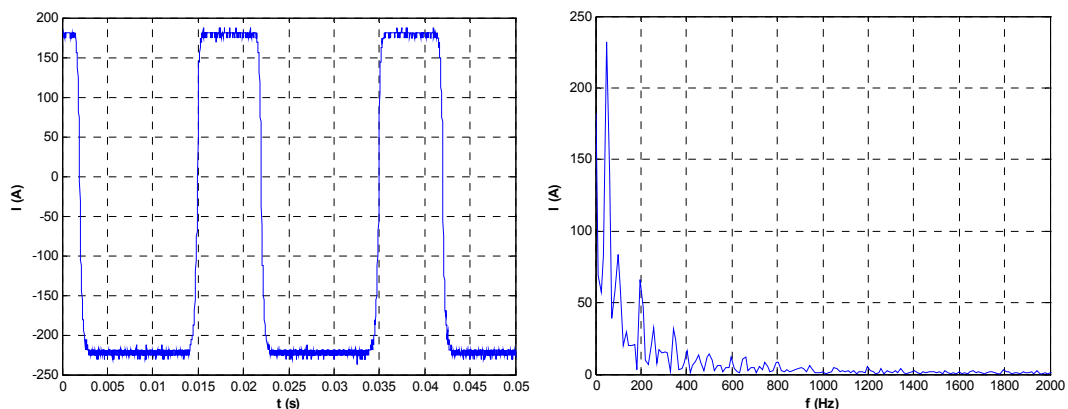
For manual TIG welding DC and AC signals of up to 800 A and 400 A are applied, respectively, with pulse frequencies of about 0.2 Hz to some kHz (Bolte and Pruppers, 2006).

<sup>12</sup> However, due to the inductive characteristics of the wiring the welding current is influenced by this layout, as for example high frequency components of the welding current will be attenuated by long cables. One should account for this. Unfortunately this fact can't effectively be used, as these high frequency components are necessary for arc controlling (Mair, 2005).

<sup>13</sup> In automated applications of MIG/MAG welding even current amplitudes of up to 900 A are possible.

<sup>14</sup> Measurements were performed on a TransSteel 5000 from Fronius with a low frequency LEM module (LT 500-S/SP11), a FCC F-51 high frequency current probe, as well as a LeCroy WaveRunner 204 Mxi-A. Unfortunately, due to limited dynamic range of the measurement setup it was not possible to capture higher frequency components typically present as described above.

Figure 2-6 shows the time signal and the according amplitude spectrum of a typical AC-TIG welding signal<sup>15</sup>. The current is rectangular shaped with a frequency of 50 Hz and an amplitude of 220 A (-20 A DC offset).



**Figure 2-6 (left) Time signal of a TIG welding current, and (right) according amplitude spectrum**

### Typical Magnetic Fields in Arc Welding

Investigations on a variety of different arc welding equipment (including MIG/MAG and TIG) in Stuchly and Lecuyer (1989) show magnetic fields of 5  $\mu\text{T}$  up to about 400  $\mu\text{T}$  (at typical working positions of the welder) with welding currents around 90 A to 500 A<sup>16</sup>. In addition, fields of 4  $\mu\text{T}$  to 300  $\mu\text{T}$  in 0.1 m distance to the welding cable with welding currents around 90 A to 140 A are reported. Supportive, Weman (2003) shows fields of about 200  $\mu\text{T}$  (50 Hz) in the surrounding of welding cables for arc welding processes. On the surface of such cables of course much higher fields of some mT can be measured (Fetter et al, 1996). Static field measurements around such cables in MIG/MAG welding by Skotte and Hjollund (1997) result in fields of about 2 mT (0.1 m distance). Furthermore, a mean value over the effective working time in three days for typical metal workers of about 7  $\mu\text{T}$  within MIG/MAG welding is reported. Measurements for a scenario of a worker putting the welding cable over the right shoulder during welding summarized in Molla-Djafari et al (2008) lead to reference level exceedance of up to a factor 15 for MIG/MAG welding (up to about 2 mT at the shoulder position and 320  $\mu\text{T}$  in average at the typical position of the welder) and seven for TIG welding, according to occupational reference levels of ICNIRP (1998) and the phase considering sum formula in ICNIRP (2003). Frequencies of the discussed fields are in the range of 50 Hz to 300 Hz with possible higher frequency components e.g., due to digitally controlled current sources or due to special welding applications (e.g., Weman (2003) or Molla-Djafari et al (2008)).

Summarizing, typical fields at the normal working position of the welder with amplitudes of (in maximum) some 100  $\mu\text{T}$  can be expected. Of course, putting the welding cable on the shoulder or standing in the current loop of arc welding devices influences the extent of exposure. In such cases fields in the mT range are definitely possible. Concerning the frequencies applied, base frequencies of up to some 100 Hz seem to be usual with the

<sup>15</sup> Measurements were performed on a MagicWave 4000 from Fronius with a low frequency LEM module (LT 500-S/SP11), a FCC F-51 high frequency current probe, as well as a LeCroy WaveRunner 204 Mxi-A.

<sup>16</sup> The highest value in the observed frequency range, mostly at 60 Hz or harmonics of this frequency, was reported.

possibility of superimposed high frequency components (up to a few MHz, but typically some 100 kHz).

### 2.2.2 Spot Welding

When looking at spot welding the welding currents can reach much higher values compared to those in arc welding processes. Some thousand Amperes (up to about 180 kA<sup>17</sup>) for short intervals with stationary devices are common. Operating currents and forces for spot welding guns are much lower, with currents up to a few 10 kA. Devices utilizing AC signals mostly operate at 50 Hz. Figure 2-7 shows the time signal and the according amplitude spectra of a possible resistive welding current<sup>18</sup>, with a welding pulse lasting approximately 0.47 s and an amplitude of 22.5 kA.

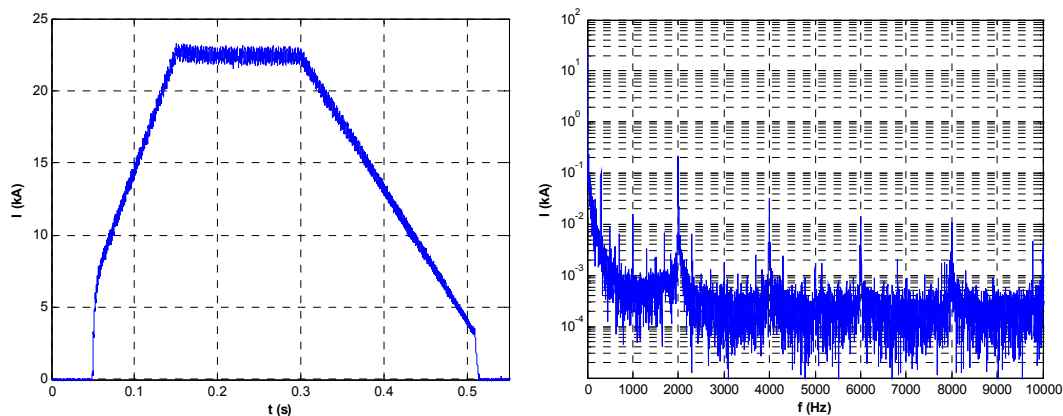


Figure 2-7 (left) Time signal of a resistive welding current, and (right) according amplitude spectrum

### Typical Magnetic Fields in Spot Welding

Typical magnetic fields on spot welding workplaces are in most cases high compared to those for arc welding. Fields in a range of 1 mT up to about 4 mT at the normal working position of the welder were for example evaluated by Nadeem et al (2004)<sup>19</sup> and Cooper (2002). Fields of 0.2 mT to 11.5 mT on usual positions of workers' head, chest, pelvis and hand are reported by Doebbelin et al (1999) and further supported by Weman (2003), LfAS (2002) and Melton (2005). Moreover, magnetic fields of about 2 mT/kA in near proximity to the electrode for stationary spot welding equipment are given in Doebbelin et al (2002), whereas Dilthey et al (2001) give 680 mT directly at the electrode caps for a current of 17 kA. However, measurements on a condenser discharge device with 100 kA show fields of about 5.2 mT in a distance of 25 cm to the electrodes.

Even though portable devices typically work with much lower currents with respect to stationary devices, fields of about 1 mT at the hand position of the welder were observed by Stuchly and Lecuyer (1989)<sup>20</sup>. Fields directly at the electrodes of portable welding guns of about 25 mT and currents of 12 kA are possible. In a distance of 30 to 40 cm from the

<sup>17</sup> Some special devices, so called condenser discharge machines, use even higher currents of up to 320 kA. Unexpectedly, lower fields compared with normal stationary devices build up in the surrounding of such machines (Mecke et al, 2002).

<sup>18</sup> Measurements were performed on a Fronius DeltaSpot Tong X450 with a TECNA current converter TE 1600 and a National Instrument PXI 1042Q system with PXI 6259 plug-in unit.

<sup>19</sup> Evaluations were performed for full load conditions and currents of 11 kA amplitude.

<sup>20</sup> This was evaluated for a current amplitude of 36 A, which is quite low for such devices.

electrodes the field declined already to about 1.6 mT (ARO, 2001). Furthermore, the highest fields for an 11 kA spot welding tong were measured 10 cm besides the tong with 45.8 mT (Ueding, 2000). Measurements on a coaxial feed cable to the tong in minimum distance give 0.58 mT.

Summarizing, typical fields on the working position of the welder using resistive welding equipment may range from some 100  $\mu$ T to some 10 mT. Directly at the electrode caps much higher fields of some 100 mT are possible. The used current source and current shape as well as the outreach of the electrode window (and the cable position for welding guns) massively affect the effective emitted fields. In most cases (pulsed) DC or 50 Hz signals are utilized with superimposed higher frequencies due to power control circuits (typically up to some kHz).

### 2.3 Electromagnetic Fields of Compact Fluorescent Lamps

For further investigations within this thesis it is necessary to introduce a second source of EMFs possibly present at welding workplaces, which are CFLs. Such as normal fluorescent lamps also energy saving bulbs, or CFLs, utilize so called electronic ballasts for lighting. These ballasts typically operate at a basic frequency of about 24 kHz to 100 kHz (Havas, 2008). Thus, with CFLs two main frequency components get relevant. This is once a 50 Hz component originating from the power supply, as well as a component in the intermediate frequency (IF) range (with according harmonics) due to the electronic ballast operation. Regarding possible health concerns the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR, 2008) gives an overview on conducted studies for CFLs. However, only a few publications on EMFs emitted by CFLs exist. Furthermore, since 2009 a standard on the assessment of exposure from lighting equipment exists (IEC 62493, 2009).

In opposite to welding applications, for CFLs the electric field is the exposure relevant quantity. All studies found report comparable small but also partly strongly varying magnetic fields<sup>21</sup>. In a distance of 30 cm<sup>22</sup> to the lamp about 10 nT for 50 Hz and 30 nT for the basic frequency of the built-in electronic ballast are for example given in Dürrenberger and Klaus (2004), who performed a representative study covering the Swiss market of CFLs. Even for smaller distances quite low magnetic fields compared with the ICNIRP (2010) general public reference level of 21 A/m (3 kHz to 10 MHz), were measured. Thus, Letertre et al (2009) reported 0.01 A/m to 1 A/m in a distance of 10 cm, and slightly less than 6 A/m directly at the lamp. Furthermore, the magnetic field decay was shown to be proportional to  $1/r^\alpha$ , for  $\alpha$  being between one and two.

In contrast, electric fields in the range of 430 V/m were measured by Nadakuduti et al (2011) in a distance of 15 cm to the light source. Supportive, Letertre et al (2009) showed electric field values to be between 80 V/m and 380 V/m at operating frequencies in close proximity to the lamps, with highest values at the ballast position. The authors in Bakos et al (2010) measured electric fields at operating frequencies of up to 216 V/m in the vicinity of CFLs, with all tested lamps having electric fields higher than 42 V/m. Amongst the reviewed studies only Dürrenberger and Klaus (2004) reported electric fields for the 50 Hz component with values between 70 V/m and 115 V/m.

<sup>21</sup> This is mainly caused by different locations of the electronic ballast and in general different lamp construction (e.g.,  $H$  field cancellation due to symmetric construction) as e.g., shortly discussed in Dürrenberger and Klaus (2004) or Nadakuduti (2011).

<sup>22</sup> This is the measurement distance also suggested in the IEC 62493 (2009).

However, metallic lampshades or other metallic objects surrounding the lamp may influence the emitted electric fields (Dürrenberger and Klaus, 2004). Resuming, it can be noted that quite high electric fields are present in the vicinity of CFLs leading to spatially inhomogeneous exposure when standing in near proximity to the lamp as e.g., shown in Nadakuduti et al (2011). Moreover, high peak electric fields can occur when switching-on the lamps and thus exposure assessment may get challenging (Letertre et al, 2009).



### 3 Exposure Limiting and Assessment Concepts

When exposed to electromagnetic fields people may exhibit changes of their physiological state to various extents. Thus, limits for incident (without the body present) and induced (“in-body”) fields were set with the aim of avoiding possible adverse health effects (i.e., unwanted deviations from the normal physiological state of the exposed persons).

Several organizational bodies give recommendations, guidelines, directives, laws, standards and other documents on limiting values for occupational and general public exposure to electromagnetic fields as well as some general concepts on how to evaluate compliance with these values. These documents are typically based on selected and representative studies concerned with fundamental biological effects investigated in vitro as well as in vivo via clinical, laboratory or epidemiological studies on e.g., possible adverse health effects or subjective perceived symptoms due to various kinds of exposure.

On the other hand, it seems necessary to standardize procedures for determining the quantities necessary for evaluating compliance with limits given in such documents. However, this is done in generic and basic standards on exposure assessment in general as well as in specialized basic and product family standards for particular applications (e.g., welding).

This thesis focuses on limiting concepts given in the EU-Directive 2004/40/EC (2004), the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines from 1998 as well as those from 2003 and 2010, and the German accident prevention regulation for electromagnetic fields from 2002. The Austrian pre-standard ÖVE/ÖNORM E 8850 (2006) is not discussed separately, as it is based on the covered documents<sup>23</sup>. Furthermore, one generic standard (EN 50499, 2008), the product family standard on exposure assessment in welding applications (EN 50445, 2008), as well as several basic standards on exposure assessment (e.g., EN 50413 (2009) and EN 50444 (2008)) should be highlighted.

Thus, this section gives an overview on the most important concepts on exposure limits and compliance evaluation, with focus on complex field assessment in general and on assessing welding workplaces in particular.

#### 3.1 Exposure Limiting Documents

##### ICNIRP

The protection concept of the ICNIRP is based on a vast amount of scientific literature on biological and adverse health effects elicited by electromagnetic fields as well as on dosimetric studies. In 1998 the ICNIRP published the „Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic and Electromagnetic Fields (up to 300 GHz)” with quoted limiting values for electromagnetic fields in the frequency range 0 to 300 GHz (ICNIRP, 1998).

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<sup>23</sup> However, one difference seems worthwhile to be mentioned: The Austrian pre-standard E 8850 recommends adding measurement uncertainties to the evaluation results before performing a compliance assessment. All other mentioned documents leave the specific handling of uncertainties for compliance assessment to exposure assessment documents or more specifically to product family standards.

In general, ICNIRP distinguishes between general public and occupational exposure, leading to different limiting values. Furthermore, ICNIRP differs between so called basic restrictions and reference levels, whereas these are frequency dependent. They consider possible nerve excitation due to EMFs up to frequencies of 10 MHz, thermal and nerve excitation effects from 100 kHz to 10 MHz, and thermal effects up to 300 GHz. Thus, also the relevant physical quantities for describing EMFs with respect to human exposure change over frequency. Table 3-1 summarizes these relevant quantities for the covered frequency range.

Frequency Range	Physical Quantity	
	Basic Restrictions	Reference Levels
up to 1 Hz	$J$ (mA/m <sup>2</sup> )	$H$ (A/m), $B$ (T), $I_C$ (A)
1 Hz – 100 kHz	$J$ (mA/m <sup>2</sup> )	$E$ (V/m), $H$ (A/m), $B$ (T), $I_C$ (A)
100 kHz – 10 MHz	$J$ (mA/m <sup>2</sup> ), $SAR$ (W/kg)	$E$ (V/m), $H$ (A/m), $B$ (T)
10 MHz – 110 MHz	$SAR$ (W/kg)	$E$ (V/m), $H$ (A/m), $B$ (T), $I_C$ (A), $I_L$ (A), $S_{eq}$ (W/m <sup>2</sup> )
110 MHz – 300 MHz	$SAR$ (W/kg)	$E$ (V/m), $H$ (A/m), $B$ (T), $S_{eq}$ (W/m <sup>2</sup> )
300 MHz – 10 GHz	$SAR$ (W/kg), $SA$ (J/kg)	$E$ (V/m), $H$ (A/m), $B$ (T), $S_{eq}$ (W/m <sup>2</sup> )
10 – 300 GHz	$S$ (W/m <sup>2</sup> )	$E$ (V/m), $H$ (A/m), $B$ (T), $S_{eq}$ (W/m <sup>2</sup> )

**Table 3-1 Relevant physical quantities with respect to human exposure (ICNIRP, 1998)**

According to Table 3-1 basic restriction values in ICNIRP (1998) are either induced current densities  $J$ , specific energy absorption rates  $SAR$ , specific energy absorptions  $SA$ , or power densities  $S$ . These restrictions were derived by taking the minimum values of the four quantities  $J$ ,  $SAR$ ,  $SA$ , or  $S$  for which adverse, acute health effects<sup>24</sup> could be observed. Additionally, safety factors of ten for occupational restrictions and 50 for the general public restrictions were applied.

Since induced, “in-body” electromagnetic quantities in most cases are hard to assess the concept of reference levels was adopted by ICNIRP. These reference levels are incident field quantities as the electric field strength  $E$ , the magnetic field strength  $H$ , the magnetic flux density  $B$ , the equivalent power density  $S_{eq}$ , as well as limb  $I_L$  and contact currents  $I_C$ . These reference levels were derived from the basic restrictions such as the specific absorption rate  $SAR$  or the induced current density  $J$  under so called worst-case<sup>25</sup> exposure conditions. This ensures that meeting the reference levels in all cases concludes meeting the basic restrictions. However, non-compliance with the reference levels does not necessarily imply non-compliance with the basic restrictions. It just raises the necessity of further investigations, since the important aim is to comply with the basic restrictions. If the

<sup>24</sup> The ICNIRP (1998) guidelines do not refer to any long-term effects.

<sup>25</sup> Worst-case assumptions include e.g., highest coupling factors due to field orientation and polarization with regard to the body position (e.g.,  $E$ -field vector parallel to body axis,  $H$ -field vector perpendicular to the body axis) or concerning frequency and height of the body (best energy coupling between 20 MHz and several 100 MHz), highest induced currents in ankle or neck, no consideration of phase relationships between different frequency components, etc. (ICNIRP, 1998)

assessed basic values exceed the basic restrictions further steps<sup>26</sup> have to be taken to prevent this exceedance.

Besides regulating maximum permitted values of exposure, ICNIRP gives concepts on combining exposure contributions appearing at different frequencies. This is for example the case if a signal exhibits harmonics or if more than one source of exposure operating on different frequencies is present. However, ICNIRP (1998) follows a weighted summation approach for these frequency components, again separated according to nerve excitation and thermal effects as well as to different quantities for basic restriction or reference level evaluations.

With regard to nerve excitations the relevant basic value is the induced current density  $J$  leading to a weighted summation according to

$$\sum_{i=1 \text{ Hz}}^{10 \text{ MHz}} \frac{J_i}{J_{L,i}} \leq 1, \quad (3-1)$$

where  $J_i$  is the induced current density, and  $J_{L,i}$  the according basic restriction both at frequency  $i$ <sup>27</sup>. For higher frequencies (above 100 kHz) the relevant quantity is no longer the induced current density but the SAR and the power density  $S$ , respectively, leading to a summation as given in the next equation.

$$\sum_{i=100 \text{ kHz}}^{10 \text{ GHz}} \frac{SAR_i}{SAR_L} + \sum_{i>10 \text{ GHz}} \frac{S_i}{S_L} \leq 1 \quad (3-2)$$

Following the same principle, reference values are limited according to Equations (3-3) and (3-4) for possible nerve excitations,

$$\sum_{i=1 \text{ Hz}}^{1 \text{ MHz}} \frac{E_i}{E_{L,i}} + \sum_{i>1 \text{ MHz}} \frac{E_i}{a} \leq 1 \quad (3-3)$$

$$\sum_{i=1 \text{ Hz}}^{65 \text{ kHz}} \frac{H_i}{H_{L,i}} + \sum_{i>65 \text{ kHz}} \frac{H_i}{a} \leq 1 \quad (3-4)$$

with  $a$  being constant over the whole frequency range of summation. Equations (3-5) and (3-6) apply concerning reference values and possible thermal effects,

$$\sum_{i=100 \text{ kHz}}^{1 \text{ MHz}} \left(\frac{E_i}{c}\right)^2 + \sum_{i>1 \text{ MHz}} \left(\frac{E_i}{E_{L,i}}\right)^2 \leq 1 \quad (3-5)$$

$$\sum_{i=100 \text{ kHz}}^{1 \text{ MHz}} \left(\frac{H_i}{d}\right)^2 + \sum_{i>1 \text{ MHz}} \left(\frac{H_i}{H_{L,i}}\right)^2 \leq 1 \quad (3-6)$$

with  $c$  and  $d$  being constant over the whole frequency range of summation.

<sup>26</sup> Such steps are for instance described in specific product standards as e.g., in the EN 50444 (2008) or the EN 50505 (2008) for welding applications.

<sup>27</sup> The same indexing is adopted in Equations (3-2) to (3-6).

In general ICNIRP (1998) gives root mean square (RMS) values as limits. However, for (rectangular) pulses up to frequencies of 100 kHz basic restrictions for peak values should apply. Thus, peak values of assessed current densities have to be compared with  $Y_{\text{RMS}} * \sqrt{2}$ , where  $Y_{\text{RMS}}$  is the according basic restriction given in ICNIRP (1998), at the equivalent frequency  $f = 1/2t_p$ , and  $t_p$  is the duration of the induced current pulse. This is the so called equivalent sinusoidal waveform approach (ICNIRP, 2003).

Furthermore, all *SAR* values in the frequency range of 100 kHz to 10 GHz have to be averaged over an interval of 6 minutes, as well as over a mass of 10 g when assessing localized *SAR*. However, for frequencies below 100 kHz no time averaging should be applied, accounting for the assumption that nerve excitations constitute immediate, acute effects<sup>28</sup>.

Concerning reference values, spatial whole body averaged RMS values are regulated, with the important provision of not exceeding the basic restrictions in any point of the body. The spatial averaging of induced currents should be performed over 1 cm<sup>2</sup> perpendicular to the flow direction.

However, new scientific evidence as well as new upcoming technologies (e.g., nuclear magnetic resonance imaging as prominent example) made changes regarding limiting values and concepts on compliance evaluation of ICNIRP necessary. Therefore, in 2003 new guidelines on the dealing with complex and non-sinusoidal exposure below 100 kHz, and in 2010 new guidelines on the dealing with extremely low frequency (ELF) fields, defined therein between 1 Hz and 100 kHz, were published.

In ICNIRP (2003) the equivalent sinusoidal frequency approach is considered not to be sufficient for a lot of real appearing exposure conditions (for frequencies up to 100 kHz). This is shown on the example of phase-coherent sinusoidal burst, non-coherent sinusoidal and phase-coherent non-sinusoidal signals. Burst signals for example may exhibit quite high peak values compared to their RMS value depending on the duty cycle. Furthermore, the problem of conservative exposure assessment with regard to nerve excitation<sup>29</sup> via the summation formulae above is discussed. Possible overestimations are due to the missing consideration of phase relations for the different frequency components. A way to avoid this shortcoming is presented.

However, to account for complex waveforms and biological interactions with incident fields, a weighted peak  $dB/dt$  assessment is adopted. The weighting should be performed using a frequency-dependent and phase related complex weighting function having low pass characteristic and a cut-off frequency of 820 Hz for occupational exposure<sup>30</sup>. Moreover, the introduced weighting in the time domain should avoid possible errors when performing Fast Fourier Transformations (FFTs) of assessed time signals, necessary for applying the sum

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<sup>28</sup> As already mentioned the ICNIRP (1998) only concerns acute effects.

<sup>29</sup> This especially holds true for broadband signals as they comprise a variety of frequency components. However, for non-coherent signals the summation formulae conform to the phase-consideration approach. Furthermore, for non-coherent, maybe instable fields it's important to consider the measurement time long enough to get a reasonable probability of catching the highest peak value. No phase considerations are necessary when looking at thermal effects for frequencies higher than 100 kHz (e.g., EN 50392 (2004)).

<sup>30</sup> Thus the system obviously behaves like an integrator for high values of  $dB/dt$ . However, this gives induced current densities proportional to  $dB/dt$  for low frequencies and proportional to  $B$  for higher frequencies, respectively. This accounts for the frequency dependent characteristics of biological tissue (e.g., Section 1, or Reilly (1989), and Reilly (1998)).

formulae<sup>31</sup>. These attempts should make the compliance evaluation less conservative. A summation according to

$$\left| \sum_i (WF)_i A_i \cos(2\pi f_i t + \theta_i + \varphi_i) \right| \leq 1 \quad (3-7)^{32}$$

will apply, with  $(WF)_i$  the value of the weighting function at frequency  $f_i$ ,  $A_i$  the amplitude of  $dB/dt$  at frequency  $f_i$ ,  $\theta_i$  the phase of  $dB/dt$  at frequency  $f_i$ , and  $\varphi_i$  the phase of the weighting function at frequency  $f_i$ <sup>33</sup>.

In ICNIRP (2010) finally a change was executed from induced current densities to induced electric fields in the body as the relevant basic restriction quantity. These values should be vector averaged over a Volume Pixel (Voxel) of  $2 \times 2 \times 2 \text{ mm}^3$  each. Moreover, for spatially inhomogeneous fields (<20 cm to appliances) the maximum field value at the actual position of the body should be assessed as representative. For bigger distances spatial averaging according to ICNIRP (1998) should apply. However, there is no detailed procedure given on how to deal with inhomogeneous fields, but this task is left to standardization bodies.

Furthermore, ICNIRP (2010) introduces separate basic restrictions for central nervous as well as peripheral nervous tissues and applies some major changes to the limit values based on new scientific evidence (Appendix A). However, most of the following discussed documents base their limits and compliance evaluation methods on those given by ICNIRP.

### EU-Directive 2004/40/EC

The EU-Directive 2004/40/EC (2004) on minimum health and safety requirements on the exposure of workers to electromagnetic fields is dedicated to protect the working population in the European Union against possible adverse health effects due to electromagnetic fields. According to this Directive, employers in the European Union have to ensure that all workplaces they provide to their employees comply with the limits therein. Thus, all these workplaces have to be evaluated with regard to EMF exposure. This obviously constitutes a hard and demanding task.

Such as ICNIRP, the EU-Directive only deals with acute effects in the frequency range from 0 Hz to 300 GHz and gives appropriate limits<sup>34</sup>. Furthermore, also this document commits the development of proper concepts on exposure assessment in specified applications to standardization bodies such as CENELEC<sup>35</sup>. In contrast to ICNIRP, within the Directive basic restrictions are called exposure limit values, and reference levels turned to action values. Furthermore, the rationale of deducing action values from exposure limit values still follows ICNIRP. Relevant physical quantities for different frequency ranges may be obtained from Table 3-1 via substituting basic restrictions with exposure limit values and reference levels with action values, respectively.

<sup>31</sup> Such errors may especially occur due to windowing in FFTs leading to spurious frequencies.

<sup>32</sup> For non-coherent, narrowband signals the worst case assumption, and thus the normal summation formulas in Equation (3-1) to (3-6), equal the approach of Equation (3-7). (ICNIRP, 2010)

<sup>33</sup> The validity of the procedure is restricted to a frequency range of 8 Hz to 65 kHz for occupational exposure. More detailed information on the rationale of this procedure can be found in Jokela (2000).

<sup>34</sup> Only central nervous system (CNS) values are limited, as in ICNIRP (1998).

<sup>35</sup> French: Comité Européen de Normalisation Électrotechnique, English: European Committee for Electrotechnical Standardization;

**BGV B11**

One last document, the accident prevention regulation for electromagnetic fields BGV B11 (2002), regulating occupational EMF exposure according to the EU-Directive 2004/40/EC in Germany, should be discussed. The rationale why it is worthwhile to mention this document is the adopted approach therein for showing compliance of pulsed low frequency (LF) fields.

Concerning limiting values in general the ICNIRP approach is followed with basic restrictions and deduced levels (Table 3-2)<sup>36</sup>. In addition a zoning system is presented dividing workplaces into different categories with respect to the limited level of EMF exposure<sup>37</sup>.

Frequency Range	Physical Quantity	
	Basic Restrictions	Deduced Levels
up to 1 Hz	$J$ (mA/m <sup>2</sup> )	$E$ (V/m), $B$ (T), $dB/dt$ (T/s), $I_C$ (A), $U_C$ (V)
1 Hz – 91 kHz	$J$ (mA/m <sup>2</sup> )	$E$ (V/m), $B$ (T), $dB/dt$ (T/s), $I_C$ (A), $U_C$ (V)
91 kHz – 100 kHz	$J$ (mA/m <sup>2</sup> )	$E$ (V/m), $B$ (T), $I_C$ (A), $U_C$ (V)
100 kHz – 1 MHz	$J$ (mA/m <sup>2</sup> ), $SAR$ (W/kg)	$E$ (V/m), $B$ (T), $I_C$ (A), $U_C$ (V)
1 MHz – 10 MHz	$J$ (mA/m <sup>2</sup> ), $SAR$ (W/kg)	$E$ (V/m), $H$ (A/m)
10 MHz – 30 MHz	$SAR$ (W/kg), $SA$ (J/kg)	$E$ (V/m), $H$ (A/m), $I_L$ (A)
30 MHz – 110 MHz	$SAR$ (W/kg), $SA$ (J/kg)	$E$ (V/m), $H$ (A/m), $S_{eq}$ (W/m <sup>2</sup> ), $I_L$ (A)
110 MHz – 10 GHz	$SAR$ (W/kg), $SA$ (J/kg)	$E$ (V/m), $H$ (A/m), $S_{eq}$ (W/m <sup>2</sup> )
10 – 300 GHz	$S$ (W/m <sup>2</sup> )	$E$ (V/m), $H$ (A/m), $S_{eq}$ (W/m <sup>2</sup> )

**Table 3-2 Relevant physical quantities with respect to human exposure (BGV B11, 2002)**

In contrast to ICNIRP the frequency range for considering both, nerve excitation and thermal effects, is defined between 29 kHz and 91 kHz. For frequencies higher 91 kHz the regulation keeps with the summation approach of ICNIRP, following the assumption that these signal components are additive in their biological effect. However, for pulsed signals with frequencies of up to 91 kHz a different approach was adopted. Such signals are more or less divided into fundamental signal components (sinusoidal, trapezoidal, triangular, and exponential shapes). By utilizing specific parameters these signals may be characterized and according values of  $\hat{B}$ ,  $dB/dt$ , and  $\overline{dB/dt}$ <sup>38</sup> are checked for compliance with given limit values<sup>39</sup>.

<sup>36</sup> In contrast to ICNIRP also the contact voltage  $U_C$  is limited.

<sup>37</sup> Work places are divided into four categories, namely: exposure area 1, exposure area 2, area of increased exposure, and danger area.

<sup>38</sup> Averaging performed over a specified time interval.

<sup>39</sup> Rationale for this approach may for example be found in Heinrich (2007). The main advantage in comparison to the compliance evaluation methods in ICNIRP (1998, 2010) is a lower overestimation of exposure for pulsed, non-sinusoidal and intermittent fields (and thus leading to lower costs by avoiding further evaluations due to wrong indications of reference level exceedance), as well as a better representation of interactions between EMFs and nervous tissue. Issues already brought up in Reilly (1998) on necessary conditions for the summation of nerve excitation effects not accounted for by ICNIRP are discussed, whereas the proposed method in Heinrich (2007) does not encounter the known problems.

## 3.2 Exposure Assessment Documents

Exposure assessment documents may be distinguished in product family and generic standards. Such standards include specific assessment procedures and reference specific exposure limits. Moreover, they refer to according basic standards for specific applications. These basic standards include details on the assessment process (e.g., measurement, calculation or simulation methods applicable, applications' modes of operation, etc.). Some relevant standards concerning the issues of this thesis should be shortly discussed, starting with non-product specific standards on human exposure.

### Important Non-Product Specific Standards on Human Exposure

As generic standard for the evaluation of occupational exposure to electromagnetic fields the EN 50499 (2008) gives a general method for such evaluations of workplaces necessary for the implementation of the EU-Directive (2004)<sup>40</sup>.

At the beginning of each evaluation the specific workplace needs to be specified according to the EMF sources present at this workplace, their mode of operation (e.g., frequency, power, operating duration, etc.), the typical position of the worker, or other influencing parameters (e.g. field sources on neighboring workplaces, or other workers)<sup>41</sup>.

According to Figure 3-1 this standard distinguishes between devices being in all operation conditions compliant with exposure limiting values and thus making an exposure evaluation unnecessary (listed in Table 1 of the EN 50499 (2008)), as well as devices which probably require further evaluations.

It is demanded to declare the evaluated uncertainty of the performed exposure assessment and account for it during compliance evaluation, according to the specific product family or basic standards followed.

For evaluating compliance with the EU-Directive (2004) of non-sinusoidal fields comprising more than one frequency component, the ICNIRP concepts given above are recommended. Additionally, the so called total exposure quotient (*TEQ*) concept is introduced. Thereby, an exposure quotient (*EQ*) is the result of a weighted summation according to ICNIRP. However, more generally a *TEQ* can be any combination of these summation results e.g., the sum of *EQs* for incident electric and magnetic fields, the sum over *EQs* evaluated for nerve excitation and thermal effects, the sum over *EQs* evaluated on a different basis (i.e., different limiting documents or limits for public and occupational exposure), or simply the sum over all eight evaluated *EQs* according to ICNIRP. The values are expressed as a percentage of the limit value.

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<sup>40</sup> This e.g., includes a zoning concept for defining areas at a workplace allowed to be accessed by different parts of the population (e.g., general public is allowed to enter if exposure limits for general public are met).

<sup>41</sup> Further discussions on this may be found in Section 5.1.

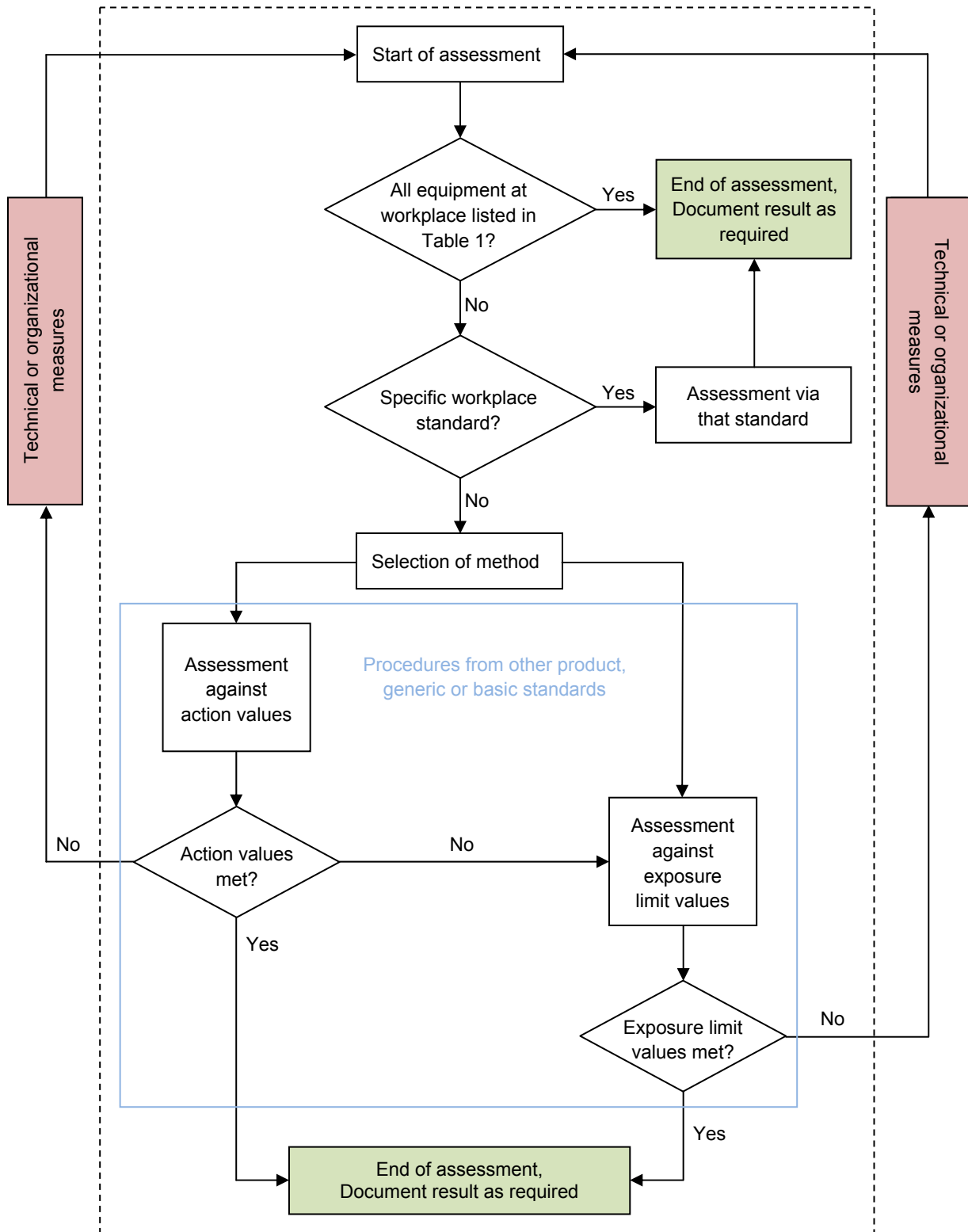


Figure 3-1 Flow chart describing the recommended procedure for occupational exposure to electromagnetic fields from the EN 50499 (2008), with changes



In accordance, a *TEQ* may be calculated as the sum of *EQs* for multiple exposure source environments, at which each device is attributed with one or several appropriate *EQs*<sup>42</sup>. However, the *TEQ* is given as a very conservative approach, which can never indicate non-compliance with a limiting value<sup>43</sup>.

The EN 50413 (2009) as a further important document gives information on procedures and methods for measurements and calculations of quantities associated with the assessment of human exposure. Thus, it constitutes a background document for more specific product family or basic standards discussed below. Concerning the uncertainty in exposure evaluations it says that the uncertainty has to be determined and declared. Some example uncertainty evaluations are given. No statements on compliance evaluation can be found.

More details on the operational methods of and requirements for measurement equipment in the low and intermediate frequency range, as well as further guidance for measurements may for example be found in the IEC 61786 (1998), also including important considerations on measurement uncertainties.

### **EN 50445**

More specific, the European product family standard for welding (EN 50445, 2008) gives advices on how to demonstrate compliance of equipment for resistance welding, arc welding and allied processes with the restrictions given in the EU-Directive (2004) related to human exposure to electromagnetic fields. Furthermore, important hints on simple measures to be taken by welders which help to reduce exposure to a minimum are given<sup>44</sup>. However, details on the exposure assessment process (e.g., points of investigation (POIs), modes of operation of the welding devices, etc.) can be found in the according basic standards EN 50444 (2008) and EN 50505 (2008).

The EN 50445 (2008) suggests the highest exposure from welding equipment in the inductive near-field. Besides the advices on temporal averaging given in the EU-Directive (2004), static magnetic fields should be averaged over a time interval of 8 hours, taking into account the duty cycle of equipment operation and of the welding current sequence, as applicable. Moreover, typical exposure situations at welding workplaces comprise strongly inhomogeneous and localized exposure of workers<sup>45</sup>. Thus, spatial averaging of these non-uniform fields may underestimate the exposure and seems not suitable to ensure compliance

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<sup>42</sup> If not determined in person, an *EQ* may be derived from manufacturer specifications or other reliable sources.

<sup>43</sup> A value of the *TEQ* higher one would only suggest using more sophisticated evaluation methods. Furthermore, the *TEQ* should only include contributions from devices not listed in Table 1 of the EN 50499 (2008). Thus, devices with in general low exposures have not to be considered, which may lead to problems if a lot of these sources or a combination with high field sources is present at a specific workplace.

<sup>44</sup> This includes e.g., keep forward and backward conductors as close together as possible, keep head and trunk away from welding current path, no standing between forward and backward conductor.

<sup>45</sup> This is due to the applied welding current (amplitude and waveform) as well as the dimensions and design of the welding circuit including the position and posture of the welder.

with basic restrictions in all cases<sup>46</sup>. However, for thermal effects spatial averaging is suitable.

Concerning the uncertainty of the evaluation process the so called shared risk approach should be used according to this standard (Section 4). Thus, uncertainties have not to be included for compliance evaluation as long as they are below specified values, or the assessment procedure has been proven to always overestimate the exposure. If these specified values are exceeded, uncertainty penalties for exposure limits have to be applied as follows

$$L_m \leq L * \left( \frac{1}{1 - \frac{u_p}{100} + \frac{u_m}{100}} \right), \quad (3-8)$$

with  $L_m$  being the new limit at a given frequency,  $L$  the specified limit at a given frequency,  $u_p$  the specified acceptable expanded uncertainty, and  $u_m$  the expanded uncertainty of the evaluation. However, for more details on the exposure assessment procedure the basic standards for arc and resistance welding have to be considered.

### **EN 50444 and EN 50505**

The EN 50444 (2008) gives specific advices on exposure assessment of electromagnetic fields from arc welding (and allied processes) equipment. This European standard provides procedures and tools to assess relevant exposure values, necessary to evaluate compliance of a specific workplace with limit values described in the EN 50445 (2008).

The aim of this document is to establish applicable exposure evaluation methods including measurement methods, standardized operating conditions of applications, measurement distances to current carrying paths (points of investigations representing highest exposure during typical use), as well as methods to show compliance with limit values.

In general DC- and AC-components of fields, as well as thermal and nerve excitation effects have to be assessed separately. For basic and reference values the summation formulas according to ICNIRP (2010) apply<sup>47</sup>. This includes the provision for pulsed or non-sinusoidal fields that the evaluation period equals one period of the assessed field, and the time increment for evaluation is set less or equal to 1/10 of the period of the highest concerned frequency component. Also the equivalent frequency approach for peak values of the induced current density from ICNIRP (1998) is given as a possible compliance evaluation method. Furthermore, upper frequency limits for evaluation are given according to the used welding current (Table 3-3).

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<sup>46</sup> Whole body spatial averaged action (or reference) values may keep with restrictions if only localized exposure exists, but at the same time basic values at specific points of the body may exceed exposure limit values (or basic restrictions).

<sup>47</sup> Frequency components with amplitudes smaller than 3% with respect to the amplitude of the basic frequency shall be disregarded.

Welding Current Type	Upper Evaluation Frequency
DC	1 kHz for single phase transformer-rectifier types
	3 kHz for three phase transformer-rectifier types
	10 times the ripple frequency for inverter types
Sinusoidal	10 times the welding current frequency
	10 times the ripple frequency for inverter types
Pulsed or Non-Sinusoidal	defined by the minimum rise or fall time $\tau_{p,\min}$ of the maximum welding current <sup>48</sup>
	10 times the ripple frequency for inverter types

**Table 3-3 Upper evaluation frequencies for different welding current types in arc welding and allied processes (EN 50444, 2008)**

As already mentioned the EN 50444 (2008) has the aim to identify applicable assessment methods for possible exposure in arc welding, which are given in Table 3-4 with respect to welding cables<sup>49</sup>. Furthermore, the standard gives general advices on suitable coil probes for magnetic field measurements, whereas for further details basic standards concerned with requirements for measurement devices used in exposure evaluation are referred (e.g., IEC 61786 (1998)).

It is denoted that some of the listed methods may result in conservative exposure estimations, but further details on this aspect are missing. Moreover, associated uncertainties for the suggested methods in relation to typical exposure situations will be useful but are lacking. However, a shared risk approach or an additive approach is suggested with regard to uncertainties in compliance evaluation (Section 4.3). In terms of the standard reasonable expanded uncertainties<sup>50</sup> for measurements are given in Table 3-5.

In some cases more than one measurement device will be necessary to cover e.g., the whole frequency range of exposure. Thus, one has to be careful to avoid overestimations of exposure due to possible overlapping frequency ranges. Furthermore, when using broadband probes a conservative comparison of the assessed exposure quantity with the lowest limit value in the considered frequency range is recommended. For such combined assessment procedures of single source exposure one may establish separate or one overall uncertainty budget. In the latter case the highest of the estimated uncertainties shall apply<sup>51</sup>. Furthermore, the structure of a typical uncertainty budget is given. Unfortunately no details on reasonable uncertainty components can be found.

<sup>48</sup> An upper evaluation frequency can be defined as  $f_{\max} = 10 \frac{1}{4\tau_{p,\min}}$ .

<sup>49</sup> The second and third columns of Table 3-4 have to be read independently of each other for all three welding current types.

<sup>50</sup> All values in Table 3-5 are given for a 95% level of confidence with a coverage factor  $k$  of 1.64 for an assumed normal distribution.

<sup>51</sup> However, it is often sufficient to evaluate only one uncertainty budget over the whole considered frequency range if uncertainties and/or exposure are low.

Welding Current Type	Assessment Methods for DC Component	Assessment Methods for AC Component
DC	static field measurements time domain measurements analytical or numerical calculations	time domain field measurements in combination with spectral analysis broadband measurements frequency selective measurements time domain weighted measurements analytical or numerical calculations
Sinusoidal	not applicable	time domain field measurements broadband measurements frequency selective measurements time domain weighted measurements analytical or numerical calculations
Pulsed or Non-Sinusoidal	static field measurements time domain field measurements in combination with spectral analysis analytical or numerical calculations	time domain field measurements in combination with spectral analysis broadband measurements frequency selective measurements time domain weighted measurements analytical or numerical calculations based on time domain measurements analytical or numerical calculations

**Table 3-4 Applicable methods for exposure assessment in the surrounding of welding cables for arc welding devices (EN 50444, 2008)**

Frequency Range	Measurement Uncertainty
<10 kHz	+58%/-37% (±4 dB)
10 kHz – 1 MHz	+41%/-30% (±3 dB)
1 MHz – 30 MHz	+41%/-30% (±3 dB)
30 MHz – 1 GHz	+100%/-50% (±6 dB)
1 GHz – 30 GHz	+100%/-50% (±6 dB)

**Table 3-5 Reasonable expanded uncertainties for exposure measurements in welding applications (EN 50444, 2008)**

To ensure proper exposure assessment a set of required assessment parameters for measurements is given, including:

- basic welding current modes,
- worst-case welding current settings,
- typical test parameters for MIG/MAG welding,
- worst-case operation modes of ancillary equipment (e.g., wire feeders), and
- the use of conventional loads.

In general, measurements shall be performed in operator distance, whereas exact distances and positions are given in the EN 50444 (2008). Influences of the work piece are not considered, but influences of other metal objects have to be considered during evaluation<sup>52</sup>. Furthermore, measurements of typical background fields are recommended.

If a conservative approach for exposure assessment is preferred, single wire welding cable configurations should be used for exposure assessment<sup>53</sup>, as their field decay with distance is lowest compared to other configurations (Section 2.2). However, it is suggested to build the welding circuit in a way not to cause particular high exposure (e.g., no big current loops, minimum workers' distance to cable and equipment 50 cm).

The EN 50505 (2008) as the basic standard for resistive welding (and allied processes) constitutes the equivalent to the EN 50444 (2008) with keeping most of the concepts given there. Such as for arc welding when examining resistive welding (for stationary and portable equipment) one may expect highly non-homogeneous electromagnetic exposure, depending on the welding current characteristics as well as the welding circuit layout (e.g., electrode configuration or cable path for non-stationary applications).

However, more detailed discussions on the presented concepts are given below. This was a rough overview on a few relevant exposure limiting and assessment documents, giving relevant limit values, compliance evaluation methods, as well as applicable exposure assessment methods for evaluating human exposure to EMFs. The focus was put on relevance for welding applications.

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<sup>52</sup> It is recommended to keep field influencing metal objects in a distance of at least 2 m from the POIs.

<sup>53</sup> One possibility can be the welding cable from the welding power source running near to the welding workplace, whereas the ground cable back to the current source follows a track distant to the welding cable.



## 4 Dealing with Uncertainties

This section gives a short introduction on how to deal with uncertainties in EMF exposure evaluation. The given outline serves as background to the consecutive considerations concerning the reviewed literature in Section 5, the discussions on challenges in complex exposure assessment and evaluation in Section 6, as well as the establishment of uncertainty budgets and the exposure evaluation for a specific scenario in Section 7.

Uncertainties constitute an important factor concerning exposure assessment, especially when trying to draw conclusions on the compliance of the assessed (measured or calculated) field values with limiting values given in the documents discussed in Section 3.1. Basically, each measurement (or simulation) result should be attributed with an according uncertainty constituting a measure of reliability for the performed assessment. For convenience of the reader the most important terms, definitions, and concepts for handling uncertainties in measurements (and simulations) are summarized<sup>54</sup>. In advance, some considerations on uncertainty budgets as well as on the handling of uncertainties in compliance evaluation with limits are given.

### 4.1 Expression of Uncertainties

Uncertainty is defined as “the estimated amount or percentage by which an observed (measured) or calculated (analytically or numerically) value may differ from a true value (which is unknown)” (Web3, 2011). Therefore, it represents a “parameter associated with the result of a measurement (or in general an assessment) that characterizes the dispersion of the values that could reasonably be attributed to the measurand (or in general the result of an evaluation)” (BIPM, 2008)<sup>55</sup>.

The term uncertainty is not to be confused with the term error<sup>56</sup>. Due to imperfections of the measurement process errors (with random and systematic components) may occur. Unpredictable or stochastic temporal and spatial variations of influence quantities, called random effects, constitute random errors and give rise to variations in repeated observations of the measurand. Increasing the number of observations can reduce the random error (having an expected value of zero). However, the measurement (or calculation) result cannot be compensated for this type of error. Systematic effects of an influence quantity leading to systematic errors can often be quantified and a correction may be applied to compensate for these effects. It is important to point out that “error is an idealized concept and errors cannot be known exactly” (BIPM, 2008). Compensation of the systematic effects does not mean that the uncertainty of the measurand gets zero, since the exact value of the error cannot be known and there are still random effects contributing to uncertainty.

The result of a measurement after correction by known systematic deviations can for example be (unknowably) very close to a (unknown) true value of the measurand, thus

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<sup>54</sup> This is compiled amongst others from Taylor and Kuyatt (1994), NAMAS (1994), BIPM (2008), UKAS (2002), UKAS (2007), IEC 62232 (2011), EA-4/02 (1999), WECC (1990), DIN 1319-3 (1996), and IEC 61000-4-22 (2006).

<sup>55</sup> Remarks in brackets were added by the author.

<sup>56</sup> The error (of a measurement) is defined as the result of a measurement minus a true value of the measurand. However, as a true value cannot be determined, a conventional true value (assigned value, best estimate, reference value) is used instead. (BIPM, 2008)

having negligible error, even though it may have a large uncertainty. Uncertainty is an expression of doubt about how well the result of the measurement represents the value of the measurand. (BIPM, 2008)

However, the result of a measurement (or calculation) as an approximation or estimate of the real value of the measurand, is only complete (and viable) when accompanied by a quantitative statement of its uncertainty (Taylor and Kuyatt, 1994).

The measurand, as the quantity subject to measurement, usually depends on a number of different quantities and thus is not measured directly. If the measurand is seen as output  $Y$  and the influencing quantities as inputs of the measurement process (including the method of evaluation), this process may be modeled as a functional relationship given by

$$Y = f(X_1, X_2, \dots, X_N). \quad (4-1)$$

In this respect  $f$  is called the model function, whereas  $X_i$  ( $i = 1, \dots, N$ ) represents all quantities making the result uncertain<sup>57</sup>. The model function may be an analytical expression, a group of such expressions not representable by a single function, or may be determined experimentally and is of critical importance for the evaluation of the overall uncertainty of the measurand. (EA-4/02, 1999)

As already known, the result of a measurement can only be an estimate  $y$  of the output quantity  $Y$  and thus may be obtained from Equation (4-1) by using input estimates  $x_i$  for the  $N$  input quantities  $X_i$ , as given in the next equation.

$$y = f(x_1, x_2, \dots, x_N) \quad (4-2)$$

However, there are different possibilities to evaluate the input estimates in Equation (4-2). In particular, uncertainties could be divided into two categories according to their method of estimation. Uncertainties evaluated by statistical methods (statistical analysis of a series of independent observations)<sup>58</sup> are categorized as “type A uncertainties”, whereas so called “type B uncertainties” are uncertainties evaluated by other means.

Type A and type B evaluations of uncertainty are not to be confused with the categories “random” and “systematic”, i.e., the value of an uncertainty component may for example be obtained via statistical methods though it is a representation of a systematic uncertainty<sup>59</sup>. Thus, to stress this issue, the classification in type A and type B evaluations of uncertainty refers to the method of evaluation and not the nature of the components of uncertainty<sup>60</sup>.

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<sup>57</sup> These quantities may themselves depend on other quantities including correction factors for known systematic effects and can thus be seen as measurands.

<sup>58</sup> When assuming repeatability conditions to apply (DIN 1319-3, 1996).

<sup>59</sup> E.g., the uncertainty of the measurement result due to different orientations of a coil probe represents a systematic effect, though it may be evaluated by statistical means (type A evaluation).

<sup>60</sup> If just limited data is available type A evaluations of uncertainties are not necessarily more reliable than soundly based type B evaluations of uncertainty, even though this would often be expected on the first sight. For details see Annex E of BIPM (2008).



Anyway, each uncertainty component, no matter which type (A or B), is represented by an estimated standard deviation called standard uncertainty. The standard uncertainty  $u(x_i)$  for an uncertainty component of type A equals the statistical estimated standard deviation  $s_i$ . For characterizing such type of uncertainties a statement on the degrees of freedom  $\nu_i$  is necessary<sup>61</sup>. However, type A evaluations base on statistical analysis of available data (e.g., a bulk of measured datasets). These analysis include for example the calculation of the standard deviation of the mean of independent measurements, an analysis of variance (ANOVA), applying the method of least squares for curve fitting, etc.

Assume a repeatedly measured input quantity  $X_i$  and  $n$  statistically independent observations<sup>62</sup>  $X_{i,j}$  of this quantity. Then

$$\bar{X}_i = \frac{1}{n} \sum_{j=1}^n X_{i,j} \quad (4-3)$$

represents the arithmetic mean (or average) and thus may be applied as input estimate  $x_i$  in Equation (4-2). The uncertainty of the measurement associated with the estimate  $x_i$  can now be assessed via the experimental variance  $s^2(X_{i,j})$  according to the next equation.

$$s^2(X_{i,j}) = \frac{1}{n-1} \sum_{j=1}^n (X_{i,j} - \bar{X}_i)^2 \quad (4-4)$$

However, the experimental variance of the mean, constituting the best estimate of the variance of the arithmetic mean, may be given as

$$s^2(\bar{X}_i) = \frac{s^2(X_{i,j})}{n}. \quad (4-5)$$

Thus, the standard uncertainty associated with the input estimate is formed by the experimental standard deviation of the mean

$$u(x_i) = s(\bar{X}_i). \quad (4-6)$$

In contrast, the standard uncertainty  $u(x_i)$  for a type B component of uncertainty equals the approximation of the corresponding standard deviation obtained from an “assumed” probability distribution, based on all available information. Accordingly, a type B evaluation is based on scientific judgment including previous measurement data, experience with and knowledge of specific used instruments and environments, reference data in manufacturers’ handbooks and specifications, etc. Such type of evaluation is applied if only one or just a few observations of the quantity  $X_i$  are available and no statistical analysis is possible. If it is possible to assume a probability distribution (a priori distribution) for  $X_i$  from theory or experience, the appropriate expected value and the standard deviation of this distribution

<sup>61</sup> With  $\nu_i = n - 1$  for  $x_i = \bar{X}_i$  and  $n$  the number of independent observations in type A evaluations. Limitations for a low number of observations are discussed in BIPM (2008). The degree of freedom of a component determined by a type B evaluation is infinite if the value is known with a very high degree of reliability, otherwise it has to be obtained from a t-distribution table (Stratakis et al, 2009).

<sup>62</sup> In short, single values are termed independent if consecutive measurement values are not influenced by each other.

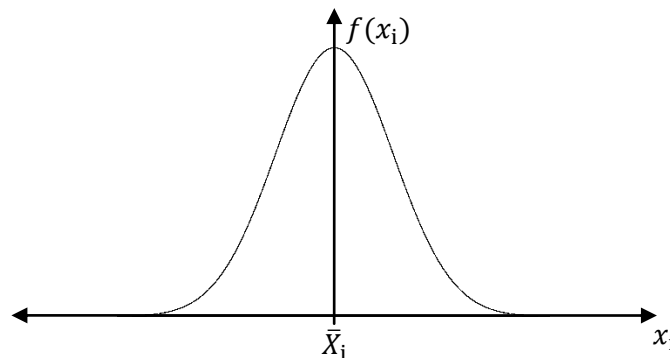
have to be taken as the estimate  $x_i$  and the associated standard uncertainty  $u(x_i)$ , respectively<sup>63</sup>.

The standard uncertainty for a type B component of uncertainty may be calculated from a quoted so called expanded uncertainty (see below) by applying a specified divisor according to its probability distribution (Table 4-1), or other information given (e.g., which multiple of the standard uncertainty was used to deduce the given value).

Distribution	Divisor (1)
Normal	$k^{64}$
Rectangular	$\sqrt{3}$
U-shaped	$\sqrt{2}$
Triangular	$\sqrt{6}$

**Table 4-1 Divisors for different probability distributions to derive the standard uncertainty from a given expanded uncertainty (BIPM, 2008)**

Usually, the uncertainty is indicated in combination with a so called level of confidence. Given such information, one may assume a normal distribution of the data, if not otherwise stated (Figure 4-1). However, if combined uncertainties are derived from multiple contributions given specific preconditions, a normal (Gaussian) distribution can be assigned to that combined uncertainty (Central Limit Theorem (CLT), see below).



**Figure 4-1 Normal (Gaussian) probability distribution**

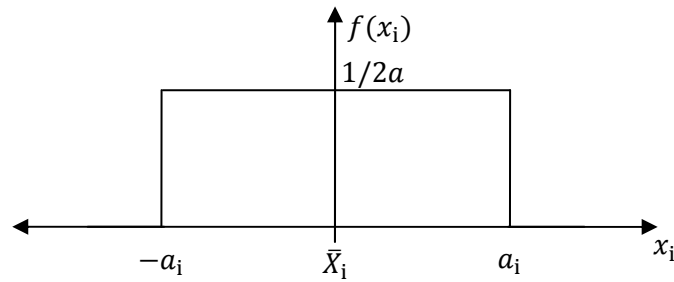
If only one lower and one upper limit for  $X_i$  are deducible (e.g., from manufacturers' specifications), with equal probability of the true value lying within these limits, or only inadequate knowledge on the probability distribution is available (default model), a uniform (rectangular) distribution may be assumed (Figure 4-2). In such cases the standard uncertainty could be derived as follows

$$u(x_i) = \frac{a_i}{\sqrt{3}}, \tag{4-7}$$

with  $a_i$  as the semi-range limit value.

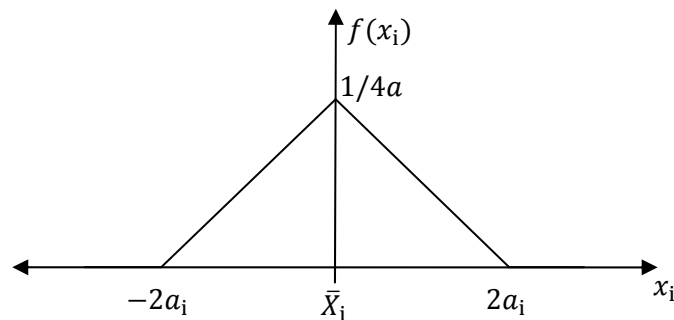
<sup>63</sup> The associated uncertainty should appropriately be written as  $u(X_i)$  in this case, but for convenience  $u(x_i)$  is used in this document.

<sup>64</sup> E.g., a coverage factor  $k$  of two applies for an approximately 95% level of confidence.



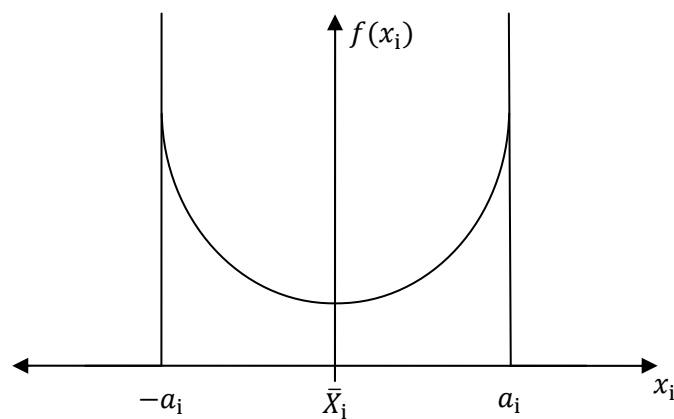
**Figure 4-2 Rectangular probability distribution with semi-range  $a_i$**

However, if it is known that values near the center of the variability interval are more likely to occur, a triangular (Figure 4-3) or a normal distribution will be better suited.



**Figure 4-3 Triangular probability distribution with semi-range  $2a_i$**

The same holds true for a so called U-shaped distribution, with values being most likely close to the limits of the variability interval (Figure 4-4).



**Figure 4-4 U-shaped probability distribution with semi-range  $a_i$**

Such distribution may be found as mismatch uncertainty, whereas the standard uncertainty can be calculated as

$$u(x_i) = \frac{a_i}{\sqrt{2}}, \quad (4-8)$$

with  $a_i$  as the limit of the uncertainty associated with the power transfer at a junction, as given in the next equation.  $\Gamma_G$  and  $\Gamma_L$  are the reflection coefficients of source and load, respectively.

$$a_i = 20 \log(1 \pm |\Gamma_G| |\Gamma_L|) \quad (4-9)^{65}$$

For combining all individual uncertainty components and thus estimating the standard deviation of the measurement result the so called combined standard uncertainty  $u_c(y)$  is used by applying the law of propagation of uncertainty as given below. This concept of combined standard uncertainties is applicable if the result of a measurement is obtained from the values of a number of influencing quantities, as given by the model function  $f$  in Equation (4-1). The law of propagation of uncertainty now constitutes a proper combination of the individual standard uncertainties of each influencing quantity and the appropriate covariances to the combined standard uncertainty of the measurement result. The result of the measurement should then be stated as

$$Y = y \pm u_c(y). \quad (4-10)$$

To stress it again, the statement of a measurement thus is only complete if it contains both, the estimate  $y$  of the measurand  $Y$  and the associated combined standard uncertainty  $u_c(y)$  of the measurement. The combined standard uncertainty  $u_c(y)$  representing the estimated standard deviation can now be given as the positive square root of

$$u_c^2(y) = \sum_{i=1}^N \left( \frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j). \quad (4-11)$$

With

$$u_i(y) = c_i u(x_i), \quad (4-12)^{66}$$

and

$$c_i = \frac{\partial f}{\partial x_i} = \frac{\partial f}{\partial X_i} \Big|_{X_i=x_i (i=1\dots N)}, \quad (4-13)$$

this may be written as

$$u_c^2(y) = \sum_{i=1}^N u_i^2(y) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N c_i c_j u(x_i, x_j). \quad (4-14)$$

Equation (4-11) constitutes a first-order Taylor series expansion. The partial derivatives therein are called sensitivity coefficients  $c_i$  associated with the input estimate  $x_i$ . Thus, these coefficients describe the extent to which the output estimate  $y$  is influenced by variations of

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<sup>65</sup> However, the mismatch uncertainty is asymmetric about the measurement result, thus the larger of the two limits should apply –  $M = 20 \log(1 - |\Gamma_G| |\Gamma_L|)$  (NAMAS, 1994).

<sup>66</sup> The contributions  $u_i(y)$  can be either positive or negative depending on the sign of  $c_i$ . This especially gets important when considering covariances.

the input estimates  $x_i$ <sup>67</sup>. Therefore, a change in  $y$  produced by a small change in  $x_i$  is given by

$$(\Delta y)_i = \left( \frac{\partial f}{\partial x_i} \right) (\Delta x_i). \quad (4-15)$$

Moreover,  $u(x_i, x_j) = u(x_j, x_i)$  is the estimated covariance associated with  $x_i$  and  $x_j$ . According to this, the combined variance  $u_c^2(y)$  may be seen as a sum of terms representing the estimated variance associated with the output estimate  $y$  generated by the estimated variance associated with each input estimate  $x_i$ .

If some of the influencing quantities  $X_i$  are correlated, the second term in Equations (4-11) and (4-14) needs to be taken into account. However, the covariance associated with two input estimates  $x_i$  and  $x_j$  amounts to

$$u(x_i, x_j) = u(x_i)u(x_j)r(x_i, x_j), \quad (4-16)$$

with  $r(x_i, x_j)$  as the so called correlation coefficient

$$r(x_i, x_j) = \frac{u(x_i, x_j)}{u(x_i)u(x_j)}, \quad (4-17)$$

representing the degree of correlation ( $|r| \leq 1$ ). Assuming  $n$  independent pairs of simultaneously repeated observations of  $X_i$  and  $X_j$ , the covariance associated with their arithmetic means  $\bar{X}_i$  and  $\bar{X}_j$  may for example be calculated as

$$s^2(\bar{X}_i, \bar{X}_j) = \frac{1}{n(n-1)} \sum_{k=1}^n (X_{i,k} - \bar{X}_i)(X_{j,k} - \bar{X}_j) \quad (4-18)$$

equating to the estimated covariance

$$u(x_i, x_j) = s(\bar{X}_i, \bar{X}_j). \quad (4-19)$$

However, input quantities may be correlated due to e.g., the same physical reference standard, measuring instrument, or common influences such as ambient temperature, humidity, and barometric pressure. In the simplest case, all uncertainty contributions are assumed to be uncorrelated, have the same units, sensitivity coefficients of 1 (absolute value) apply, and are combined by addition in a logarithmic scale (linear functional relationship)<sup>68</sup>. Then the combined uncertainty can simply be calculated by building the root

<sup>67</sup> The input quantity may not be given in the same units as the output quantity in all cases. Thus,  $c_i$  constitutes a conversion from one unit into another, and could for example be estimated by repeating the measurement at e.g.,  $x_i \pm u(x_i)$ , with  $u(x_i)$  being the standard uncertainty associated with the input estimate  $x_i$ . (UKAS, 2002)

<sup>68</sup> Calculation of the necessary partial derivatives may be difficult in practice and is not worthwhile the effort. Therefore, in most cases a linear approximation as  $\Delta f / \Delta x_i$  could be deemed sufficient. Furthermore, due to limitations in evaluations and a far more easier preparation of uncertainty

sum of squares (RSS), causing the second term in Equations (4-11) and (4-14) to vanish. (IEC 61000-4-22, 2006)

Building the RSS is sure not the only possibility of combining different uncertainty contributions to an overall uncertainty of a measurement. An even easier possibility would be the simple linear summation of all uncertainty contributions. This is in particular applicable for uncorrelated contributions with one dominant uncertainty component, leading to a rather small possibility of overestimating the combined uncertainty. In general this approach will lead to partly significant overestimations, and thus could be identified as a worst-case combination of uncertainty. (DIN 1319-3, 1996)

In a lot of applications (e.g., in commercial, industrial, and regulatory applications as well as in the health and safety industry) a measure of uncertainty defining an interval about the measurement result is necessary to be given. With a certain level of confidence or coverage probability this interval may be expected to encompass a certain fraction of the distribution of values that could reasonably be attributed to the measurand (BIPM, 2008). Anyway, this leads to the concept of the so called expanded uncertainty  $U$ , given by the multiplication of the combined standard uncertainty  $u_c(y)$  with a coverage factor  $k$

$$U = ku_c(y). \quad (4-20)$$

Correspondingly, the result of a measurement can be given as

$$Y = y \pm U. \quad (4-21)$$

The value of  $k$  is chosen on the basis of the level of confidence required as well as the assumed probability distribution (Table 4-1). Determining  $k$  and the according level of confidence requires extensive knowledge on the probability distribution characterized by the measurement result  $y$  and the combined standard uncertainty  $u_c(y)$ , which is often hard to achieve in practice.

However, in a lot of cases this probability distribution may be assumed approximately normal with  $u_c(y)$  having an effective degree of freedom  $\nu_{\text{eff}}$  of significant size. In these cases the coverage factors for normal distributions apply (e.g.,  $k$  is two for a level of confidence of approx. 95%,  $k$  is three for a level of confidence of approx. 99%).

Anyway, these assumptions are based upon the already mentioned Central Limit Theorem. If  $Y$  is given as

$$Y = \sum_{i=1}^N c_i X_i, \quad (4-22)$$

with all  $X_i$  being normal distributed, also the convolved probability distribution of  $Y$  is normal.

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budgets, a pragmatic approach setting the sensitivity coefficients to 1 (absolute value) is acceptable. However, this will typically cause an overall change in the reported uncertainty of less than 5%, though mathematically imprecise (slightly more pessimistic results). (UKAS, 2002)

In practice the following conditions need to be met in order for the CLT to apply:

- The estimate  $y$  of the measurand  $Y$  is obtained from estimates  $x_i$  of a significant number of input quantities  $X_i$  that are describable by well-behaved probability distributions, such as normal and rectangular distributions<sup>69</sup>.
- The standard uncertainties  $u(x_i)$  of all these estimates contribute comparable amounts to the combined standard uncertainty  $u_c(y)$  of the measurement result  $y$ <sup>70</sup>.
- The linear approximation implied by the law of propagation of uncertainty is adequate<sup>71</sup>.
- The uncertainty of  $u_c(y)$  is reasonably small because its effective degrees of freedom  $\nu_{\text{eff}}$  have a significant magnitude, say higher than 10.

Thus, even if the  $X_i$  are not normal distributed,  $Y$ , however, asymptotically is ( $N \geq 25$ ). This is especially true if the  $X_i$  are independent and  $u_c^2(y)$  is much larger than any of the  $c_i^2 u^2(x_i)$  from a non-normal distributed  $X_i$ . Applying the CLT implies that the probability distribution of a measurand may be assumed to be approximately normal. Then  $u_c(y)$  can be taken as a reasonably and reliable estimate of the standard deviation of that normal distribution given significant size of  $\nu_{\text{eff}}$ . (BIPM, 2008)

For reporting measurement uncertainties all contributing components, their standard uncertainties and probability distributions, their degrees of freedom<sup>72</sup>, and their type of evaluation (A or B) should be included. Moreover, a detailed description of the evaluation process is necessary. Finally, the evaluated expanded uncertainty may for example be denoted as follows:

*The reported expanded uncertainty of the evaluation (measurement or calculation) is stated as the standard uncertainty of measurement multiplied by a coverage factor  $k$  of two, which for a normal distribution corresponds to a coverage probability of approximately 95% (EA-4/02, 1999).*

## 4.2 Uncertainty Budgets

To fulfill the need of precisely documenting all known influencing quantities<sup>73</sup> in measurements and calculations of EMF exposure, uncertainty budgets may constitute a proper implement. These budgets should at least include all identified influencing quantities, their assigned probability distribution, and their associated standard uncertainties. The outcome of such an uncertainty budget will be an expression of the overall uncertainty, namely the combined standard uncertainty or expanded uncertainty of the whole assessment process.

<sup>69</sup> The single uncertainty contributions are allowed to be differently distributed.

<sup>70</sup> No dominant uncertainty contribution is allowed to be present.

<sup>71</sup> Uncertainty contributions have to be (sufficiently) independent (Web4, 2011).

<sup>72</sup> The effective degrees of freedom determine the reliability of the standard uncertainty assigned to the output estimate. However, if none of the concerned uncertainty contributions is obtained from a type A evaluation based on less than ten repeated observations, the reliability criterion is met. (EA-4/02, 1999)

<sup>73</sup> In practice, however, not all influencing quantities are known. Thus, an uncertainty evaluation is always afflicted with an additional "evaluation uncertainty".

In most evaluations uncertainties will differ for measurements in e.g., different frequency, power, or temperature ranges<sup>74</sup> and therefore, a splitting of uncertainty assessments for these different ranges may be advantageous. However, this may help in avoiding unnecessary overestimations of overall uncertainties. (NAMAS, 1994)

Uncertainties may be given in linear or dB values. The combination of uncertainties by means of an uncertainty budget can thus either be performed in linear or dB units, depending amongst other things on the better descriptiveness of the involved probability distributions in either of the two units. If most uncertainty components are given in linear values calculations should be performed in accordance (NAMAS, 1994). Furthermore, dB representations of uncertainties should only be used if single uncertainty contributions are relatively small. Otherwise high uncertainties may appear in the calculation of the expanded uncertainty. (Überbacher et al, 2006)

### 4.3 Compliance Evaluation

Evaluating compliance of the assessed exposure with given exposure limits is an important step in exposure evaluation processes, linking the measurement and calculation results to scientific evidence and legal regulations concerning the avoidance of adverse health effects. Although these issues do not constitute the major concerns of this thesis, an overview on common compliance evaluation approaches with respect to the handling of associated uncertainties is given.

Thus, Table 4-2 shows the four possibilities in evaluating compliance to an upper limit value. This upper limit is indicated with a horizontal line. The filled triangle represents the measured value. The interval thereabout specifies the according 95% level of confidence.

As indicated, case A and case D do not depend on any policy declared on compliance evaluation accounting for uncertainties. In case A the result complies with a confidence of more than 95%, in case D it does not. Case B and case C are more complicated. The situation should be explained by means of case B where the best estimate of the measurand in principle complies with the limit, but not within the indicated level of confidence of 95%.

Thus, an approach completely omitting uncertainties will lead to compliance with the limit. However, this is not a reasonable way as a result of a measurement is only complete (and viable) when attributed with its estimated uncertainty.

In contrary, the so called additive approach, demanding that the measured value lies below the limit with a certain level of confidence (here 95%), will lead to non-compliance with the limit<sup>75</sup>. Furthermore, the so called shared risk<sup>76</sup> (or direct comparison) approach asks for a compliance statement in a way that the measured value complies with the limit. Within this, the proviso applies that the attributed uncertainty does not exceed a given maximum value

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<sup>74</sup> One example can be the measurement of magnetic fields in a frequency range from 0 Hz up to about 1 MHz, at which it will most probably be necessary to use more than one measurement device or probe to be able to cover the whole frequency and dynamic range of the signal. Thus, also the uncertainties for these different measurements may deviate.

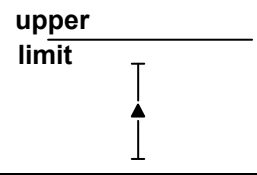
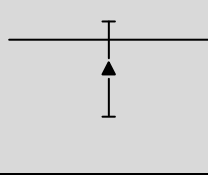
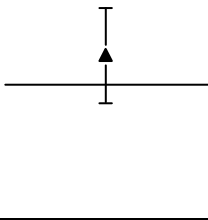
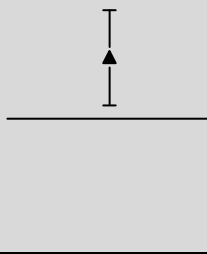
<sup>75</sup> Such an approach is not preferred by employers and regulators, as it may lead to unenforceable regulations for high uncertainties. Furthermore, a detailed uncertainty budget has to be established. (Chadwick, 2008)

<sup>76</sup> This approach is called shared risk, since the end-user (worker) takes some of the risk of non-compliance (UKAS, 2002). Such an approach is preferred by employers, as the uncertainty estimations turn out to be easier.



e.g., 3 dB or 30% (Section 3.2). Thus, the uncertainty has to be evaluated, but in far less detail compared to applying the additive approach.

Also hybrid approaches are possible, applying the direct comparison approach as long as the uncertainty is below a given maximum value. Otherwise, the uncertainty has to be added to the result of the measurement or calculation according to the additive approach. (Chadwick (2008) and UKAS (2002))

Case A	Case B	Case C	Case D
 <p>upper limit</p> <p>compliant with limit</p>	 <p>the measured result is below the limit by a margin less than the measurement uncertainty (level of confidence 95%)</p> <p>statement of compliance depends on the followed policy</p> <p>a higher probability that the result complies with the limit is indicated</p>	 <p>the measured result is above the limit by a margin less than the measurement uncertainty (level of confidence 95%)</p> <p>statement of compliance depends on the followed policy</p> <p>a higher probability that the result does not comply with the limit is indicated</p>	 <p>not compliant with limit</p>

**Table 4-2 Compliance evaluation with an upper limit accounting for the evaluated expanded uncertainty (NAMAS, 1994)**

#### 4.4 Summary

To summarize the previous sections, a list on how to proceed when performing uncertainty evaluations in measurements (or calculations) may be compiled as follows:

- Define the measurand and all influencing quantities.
- Identify all uncertainty contributions and evaluate their values, either utilizing type A or type B evaluations.
- Assign a probability distribution and determine the standard uncertainty of each contribution.
- Evaluate the covariances associated with the input estimates.
- Determine the combined standard uncertainty.
- Determine the expanded uncertainty.
- Summarize the findings by means of uncertainty budgets.
- Report the result.
- If intended, perform compliance evaluation including the estimated uncertainties.



## 5 Exposure Assessment in Complex Environments (Welding)

Exposure assessment in general and specifically in complex environments may hold ready a lot of difficulties and thus constitutes a demanding task. Only with extensive knowledge on exposure parameters it seems possible to adopt suitable measurement or calculation (analytical or numerical) methods with according suitable measurement equipment or calculation tools for such assessments.

Following a short introduction, this section lays down the common practice in exposure assessment of welding applications with focus on uncertainty evaluations, as one specific example for a complex exposure setup, by means of a literature study. The given results are summarized and taken as basis for the following thoughts on challenges in exposure assessment.

### 5.1 Introduction

As already noted, gathering comprehensive knowledge on operating characteristics of all present electromagnetic sources, typical scenarios of operation, and possible field influencing factors, is essential before a suitable assessment gets possible. Such preliminary investigations should for example include the following parameters<sup>77</sup>:

- Types of present field sources
- Type of fields emitted (electric, magnetic, static, electromagnetic)
- Operating frequency (base frequency, harmonics, time characteristics of emitted frequency spectrum – intermittency and transients)
- Operating power (emitted power, possible variations, peak and RMS values)
- Supply voltage and current
- Time characteristics (duration of operation, duty cycle of emission, sinusoidal, non-sinusoidal or pulsed fields)
- For electric field emission: identification of voltages and coupling parts (e.g., metallic surfaces)<sup>78</sup>
- For magnetic fields: identification of currents and coupling parts (e.g., coils)<sup>79</sup>
- For electromagnetic fields: identification of broadcasting equipment and all field radiating parts (e.g., antennas, coils)
- Contact currents in electric fields
- Whole and/or partial body exposure
- Spatial field characteristics (homogeneity of the emitted field (gradients), orientation, polarization)
- Near- or far-field exposure
- Dimension of the source (more than one origin of exposure, in relation to the emitted wavelength)
- Distance source – exposed person
- Influence of the body on emission characteristics of the source
- Designated application of the source (changes of exposure due to changed usage)
- Exposure in conjunction with other agents (e.g., chemical)

<sup>77</sup> List compiled from the EN 50392 (2004), the EN 50413 (2009), and Vulevic and Osmokrovic (2010).

<sup>78</sup> Objects influencing the charge distribution should be considered.

<sup>79</sup> Consider objects generating secondary magnetic fields due to primary induced currents.

Potential exposure metrics of biological significance have been identified to be<sup>80</sup>:

- Field intensity or corresponding flux density, RMS, average, peak value, or a function of the field strength (e.g., field squared)
- Exposure duration at a given intensity
- Daytime of exposure
- Single versus repeated exposure
- Frequency spectrum of the field
- Spatial field characteristics
- Separate or simultaneous exposure to different types of fields (e.g., static frequency (SF), ELF, radio frequency (RF))
- Exposure in conjunction with other agents (e.g., chemical)

However, in complex environments like welding applications one has to deal with highly inhomogeneous electromagnetic fields in space and time due to pulsed, non-sinusoidal signal shapes, field influencing (partly moving) objects in the environment (e.g., other persons or metallic objects), as well as a variety of simultaneously operating electromagnetic field sources (most often operating in different frequency and power ranges), with the exposed person located in the near- or far-field of different sources.

Besides giving an overview of common limiting values for human exposure to electromagnetic fields, as well as the common possibilities of checking compliance with these values, applicable methods for exposure assessment in welding applications were already given according to the basic standards EN 50444 (2008) and EN 50445 (2008) in Section 3. In principle, common assessment methods for fields with frequencies up to about 1 MHz may be categorized according to Figure 5-1<sup>81</sup>.

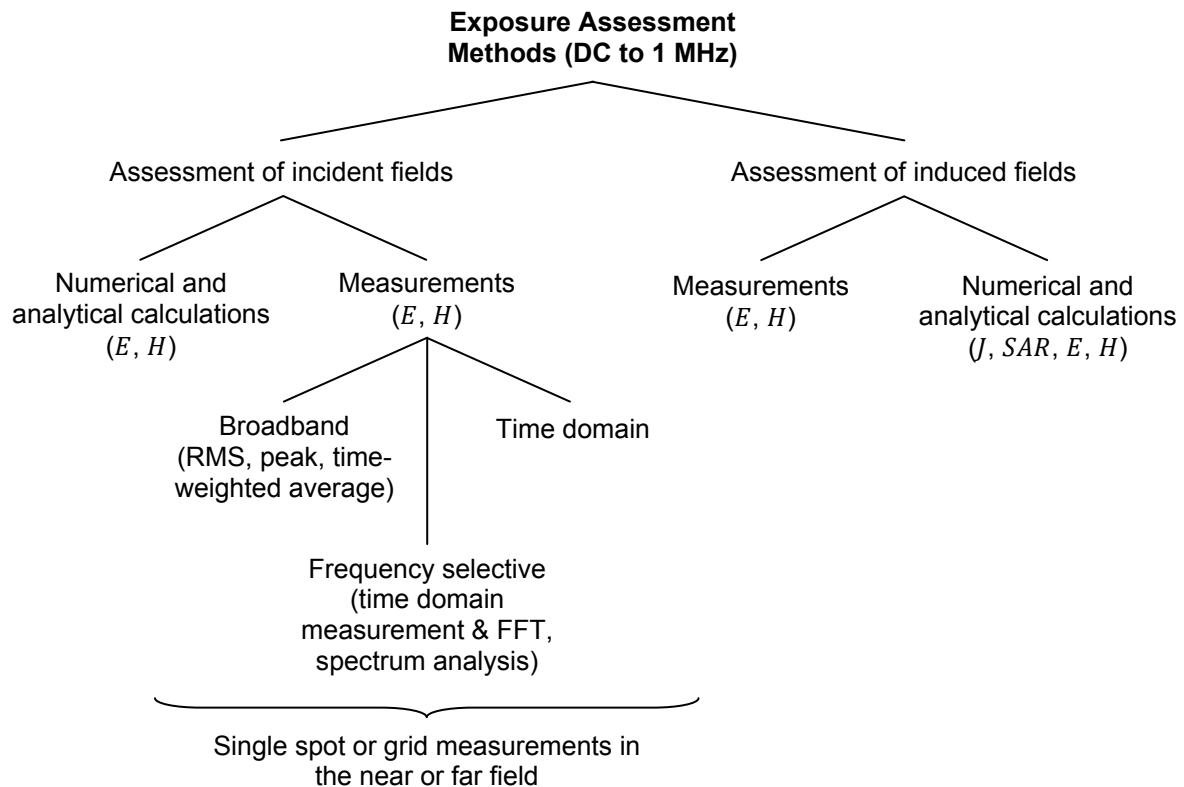
A first coarse classification can be made into the assessment of incident and the assessment of induced fields, with respect to the already discussed limiting concepts on basic (or exposure limiting) and derived (reference or action) values. Both field categories can be either assessed by measurements or calculations, whereas in the concerned frequency range for incident fields measurements and for induced fields calculations are the more common assessment method, respectively.

Numerical and analytical calculations of induced, “in-body” electric fields, magnetic fields, current densities, *SAs*, or *SARs* are possible. However, also measurements in so called body phantoms, mainly with respect to thermal effects, may be utilized. Furthermore, a new approach presented in Nadakuduti et al (2011) enables to assess induced electric and magnetic fields via incident field measurements using specialized probes in combination with numerical simulations.

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<sup>80</sup> List compiled from IARC (2002). However, the International Agency for Research on Cancer (IARC) indicates difficulties in defining relevant exposure metrics “not from the lack of ability to specify complete and unique characteristics for any given field, but rather from the large number of parameters requiring evaluation, and, more importantly, the inability to identify the critical parameters for biological interactions“. Also Martens (2007) for example suggests further research on better suited metrics for complex non-uniform, non-sinusoidal ELF exposure.

<sup>81</sup> As indicated, this section mainly deals with exposure assessment focused on measurements in welding applications and fields comprising SF, ELF and IF components ranging up to 1 MHz.



**Figure 5-1 Classification of exposure assessment methods for frequencies up to 1 MHz, focus on measurements of incident fields**

However, the focus of this thesis is on measurement methods and according measurement equipment for the assessment of incident electric and magnetic fields. Thus, no further details on the principles of simulation or calculation methods (for incident and induced fields) as well as on measurement methods of induced fields will be given here. Nevertheless, a short insight to simulations and calculations of complex exposure settings is given in the course of the reviewed literature. For the interested reader an overview on the skipped principles may for example be found in the EN 50413 (2009) or the EN 62226-1 (2005).

Anyway, regarding measurement methods for the assessment of incident fields one has the possibility of either perform broadband frequency domain measurements (AC), narrowband frequency domain measurements (AC and DC), or time domain measurements (AC and DC), a classification mainly taken with respect to the achieved results.

Within broadband measurements (AC) an entire frequency band (e.g., 1 Hz – 400 kHz) is evaluated at once, giving no information on the actual frequency content of the measured signal, but resulting in field parameters like RMS, peak, or weighted RMS and peak<sup>82</sup> values. These results are sometimes given as percentage of implemented limit values<sup>83</sup>.

Two types of measurement equipment are common in broadband measurements namely, broadband field meters with appropriate probes and exposimeters. Broadband field meters are measurement meters processing signals from a field sensor ( $H$  or  $E$  field probe), especially developed for spot (and grid) measurements at a single time instant. Following the same principle, exposimeters in contrast comprise a sensor unit directly integrated in the

<sup>82</sup> By following the approach of ICNIRP (2003) with an integrated filter function.

<sup>83</sup> This is done either by performing a time signal weighting or by performing an FFT with subsequent application of the ICNIRP sum formulae.

meter. They have especially been developed for single spot measurements over a longer period of time.

When evaluating RMS or peak values it is necessary to specify an evaluation time window for which these values are given. For RMS evaluations this window is often called integration time (EN 50413, 2009). However, especially for pulsed or non-stable fields this time gets important, as only for a proper combination of integration time and repetition rate as well as signal period of the measured signal reliable RMS measurements are possible<sup>84</sup>.

Moreover, when measuring RMS values one may distinguish between rectified average<sup>85</sup> and true RMS assessment. This differentiation is especially reasonable for measurement probes providing a signal proportional to the rate of change (e.g., when using magnetic field probes) of a measured non-sinusoidal field. The true RMS is assessed by performing a step of integration (of the probe signal) prior to building the RMS according to

$$Y_{\text{tRMS}} = \sqrt{\frac{1}{T} \int_0^T (y_i(t))^2 dt}, \quad (5-1)$$

with  $T$  being the integration time,  $y_i(t)$  the integrated probe signal, and  $Y_{\text{tRMS}}$  the “true RMS” value<sup>86</sup>. (IEC 61786, 1998)

However, exposimeters and broadband field meters deviate significantly in their use as already shortly mentioned. Whereas broadband field meters are utilized in spot as well as in grid measurements (for assessing spatially distributed fields) mainly in the absence of the body in a given exposure scenario, exposimeters are worn by the exposed person and thus only give local field information (e.g., on the persons’ belt or chest). Therefore, the main application of such exposimeters is time series measurements over some hours, days, or even longer periods enabling to deduce the time characteristic of exposure, for example on a specific workplace.

For more detailed field evaluations, frequency selective, narrowband measurements of the exposures’ amplitude spectrum are necessary (AC and DC). Therefore, some of the common broadband field meters also enable frequency selective field analysis by performing time measurements with subsequent (in-built) FFT or allow separate narrowband evaluation (e.g., DC or 50 Hz). Furthermore, a field sensor providing a time signal proportional to the measured field may directly be used with subsequent frequency analysis by a spectrum analyzer. These two methods are mainly used in practice if no or nearly no information on the given exposure situation is available, but a detailed assessment is aimed. Frequency selective measurements may enable a proper selection of other measurement equipment for future exposure measurements.

For full information of the exposure, time domain measurements (AC and DC) with subsequent signal analysis are applicable. As already mentioned some of the common

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<sup>84</sup> This may develop into a challenging task, as for highly varying signals the RMS value could hardly be defined and is highly dependent on the chosen integration time.

<sup>85</sup> The signal from the probe is rectified and the detector gives the true rms value for a sinusoidal signal. (IEC 61786, 1998)

<sup>86</sup> Only the true RMS value properly accounts for the harmonic content of a signal. If only building a rectified average value and even when performing a prior integration of the probe signal, an inherent weighting of the higher frequency components remains. Thus, the achieved signal is not any longer a full representation of the actual measured signal. (IEEE Std 1308, 1994)

broadband field meters perform signal analysis on the provided sensor signal. Furthermore, they offer the possibility of capturing the measured time signal with external equipment and thus enable to analyze the full waveform, the amplitude and the phase spectrum of the field, as well as the storing of this information for future utilization.

Statements on the principle applicability of specific methods as well as on single spot or various types of grid measurements with respect to exposure and compliance evaluation for specific exposure scenarios may in most cases be found in according basic standards, as for example in the EN 50444 (2008) for arc welding equipment<sup>87</sup>. If such a standard is not available one has to utilize common procedures defined e.g., in generic or product family standards, or develop fitted procedures, including measurement methods and appropriate measurement equipment, based on the available knowledge about the evaluated exposure scenario<sup>88</sup>.

Furthermore, measurement methods have to be designed in a way to account for near or far field conditions dependent on the exposure setup. Due to the considered frequency range as well as the workplace setups always near field conditions apply<sup>89</sup>. Thus, the electric and magnetic field are independent of each other and have to be assessed separately.

Regarding the design and requirements for measurement probes in electric and magnetic field exposure measurements in the considered frequency range, standards as for example the IEC 61786 (1998) need to be consulted. In general, such probes should be designed in a way that they merely slightly influence the measured field. The size of the probe should be in accordance with the requirements stated in limiting and assessment documents as well as with the spatial variation of the field<sup>90</sup>. One axis or three axis, isotropic probes suited to the given frequency and power range may be used<sup>91</sup>.

Within the presented investigations three-axis magnetic field coil probes, three-axis electric field probes and three-axis Hall magnetic field probes are used. For such probes in a lot of cases the resultant is given as

$$Y = \sqrt{Y_x^2 + Y_y^2 + Y_z^2}, \quad (5-2)$$

with  $Y_x$ ,  $Y_y$  and  $Y_z$  as the spatial field components in  $x$ ,  $y$  and  $z$  direction, and  $Y$  as the total calculated field value. However, when following Equation (5-2) for calculating the resultant value, the phase relation between the three spatial components is omitted, most probably leading to an overestimation of the actual resulting field.

<sup>87</sup> This does not include statements on the suitability of specific equipment for typical exposure scenarios with regard to associated uncertainties and compliance evaluations with limits. Though uncertainties get very important if measurement equipment is used, which not fully suitable for the given scenario (e.g., too long integration times, too big probe dimensions for the given field gradients).

<sup>88</sup> E.g., measurement grid size and distance between points of investigation depend for example on the used measurement method and measurement frequency (EN 50413, 2009).

<sup>89</sup> The distance to the field emitting source is always smaller than the wavelength  $\lambda$ .

<sup>90</sup> In practice not always adequate probes are used, sometimes simply because of a lack of availability (Section 5.2).

<sup>91</sup> Isotropic probes in principle have to be preferred in exposure assessment.

The given overview on exposure evaluation methods should now be recessed by summarizing the results of a literature study on EMF exposure assessment in welding applications with an additional focus on uncertainty considerations for such assessments<sup>92</sup>.

## 5.2 Literature Review on Exposure Assessment in Welding Applications

Exposure relevant welding applications mostly use complex pulsed, non-sinusoidal currents, and thus emit equally complex magnetic fields, leading to inhomogeneous field distributions in space and time (Section 2). In accordance, measurement methods and systems able to assess the necessary frequency and power range, and able to represent the spatial distribution of such fields get necessary, but unfortunately were found to be rare.

Most of the evaluated studies, however, utilized RMS or peak value measurements (weighted or unweighted) via broadband field meters or exposimeters for magnetic field<sup>93</sup> exposure assessment in welding applications. Regarding the evaluation time window (or integration time) values of 1 second or longer were shown to be common concerning the evaluated studies. This may not be suitable with respect to most typical welding signals.

Field assessments with a Standard EMDEX Lite and a Multi Wave System III exposimeter worn by welders, line workers and four further occupational groups in McDevitt et al (2002)<sup>94</sup> showed problems, in particular underestimation of exposure, with RMS value determinations of fast changing fields in relation to the utilized integration time of 4 seconds for the EMDEX meter. However, the maximum and partial time weighted average (*TWA*)<sup>95</sup> value, by far the most common exposure metric in epidemiologic studies was shown to result in more stable exposure evaluations of the given settings (Portier and Wolfe, 1998).

Earlier epidemiologic studies by e.g., Skotte et al (1997)<sup>96</sup> and Zhang et al (1997)<sup>97</sup> showed further problems in single spot exposimeter measurements at the belt of metal processing and shipyard workers<sup>98</sup>. Comprehensible, different field values for different positions of the exposimeter on the workers' body are reported, which does not enable to draw reliable conclusions on the actual exposure by solely performing such measurements.

Further investigations on ELF exposure assessment via body worn exposimeters were examined by Delpizzo (1993)<sup>99</sup> giving consistently underestimation of whole-body average and head exposure for hip worn exposure meters. However, better estimates could be achieved for chest worn meters.

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<sup>92</sup> Literature research conducted using the key words: "welding", "welding electric", "welding magnetic", "welding exposure magnetic", "welding electromagnetic field exposure", "elektromagnetische Felder Schweißen", "Exposition Schweißen", "welding uncertainty", and "uncertainty exposure".

<sup>93</sup> Rationale of only assessing magnetic fields is given in Section 2.

<sup>94</sup> No information on the welding techniques assessed is given. Therefore, it cannot be concluded if for example the frequency range of the Standard EMDEX Lite meter and the Multi Wave System III was sufficient.

<sup>95</sup> The *TWA* represents the workers' exposure normalized to a specific time period e.g., an 8 hour work day. This weighted average may be calculated via  $TWA = \frac{Y_a T_a + Y_h T_h + \dots + Y_i T_i + \dots}{8}$ , with  $Y_i$  being a constant value in a certain time during the period  $T_i$  (Sakurazawa et al, 2003), or more generally  $TWA = \frac{1}{T} \int_0^T y(t) dt$  (Portier and Wolfe, 1998).

<sup>96</sup> Measurements were performed with an EMDEX Standard Lite, an EMDEX High Field, and a T2B Hall Probe from Heme International.

<sup>97</sup> Measurements were performed with an EMDEX II.

<sup>98</sup> RMS and arithmetic mean values (for each workday) were measured.

<sup>99</sup> Measurements were performed with AMEX-3D exposure meters.



Exposimeter measurements in the course of extensive investigations at welding sites in Belgium showed a good and simple method of pre-evaluating applicable field measurement equipment by performing preceding current measurements and subsequent base- and harmonic-frequency calculations (Broeckx et al, 2008)<sup>100</sup>. These preceding evaluations beneficially enable to estimate for example the fields' power and frequency range as well as its temporal and spatial characteristics in advance.

However, besides using exposimeters a vast amount of field measurements in the past were performed with broadband field meters (using inductive or Hall probes), usually assessing incident flux density and flux density changes in a frequency range from 0 Hz to 400 kHz or less. In a lot of cases also welding current parameters (e.g., rise and fall time, pulse width) were assessed prior to the field measurements with adequate equipment.

Measurements of the exposure due to resistive welding equipment may for example be found in Doebbelin et al (1999)<sup>101</sup>. The welding current was measured under shorted output conditions<sup>102</sup>. Moreover, magnetic field assessment was performed along defined lines off the welding cable, with distinction between open conductor loop and double wire circuit design, as well as in a 360° angle around the conducting parts of the equipment and at normal operating positions of the workers' head, chest, pelvis and hands<sup>103</sup>. Further evaluations of inverter type resistance welding equipment based on peak field evaluations for AC field components and arithmetic mean field evaluations for DC field components are summarized in Doebbelin et al (2002)<sup>104</sup>. Time signal field measurements for such applications performed in a horizontal plane around the welding spot can be found in Mecke et al (2002)<sup>105</sup>. Outreach and arm distance of the resistive welding device were shown to influence the exposure, whereas the magnetic field gradient decreases for bigger welding windows (i.e., the field reaches farther).

Summarizing the last paragraphs, typical exposure metrics to be assessed in welding environments were found to be RMS field values, peak field values, as well as arithmetic mean or TWA values of the field<sup>106</sup>. Less common full time signal measurements were performed. However, the quite complex possible current waveforms used in welding, as discussed earlier in this work, inevitably lead to the necessary analysis of the fields' frequency spectrum or its transient characteristics, if a thorough exposure assessment is aimed. Anyhow, this is also favorable if compliance evaluation with frequency dependent

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<sup>100</sup> Measurements were performed with an EMDEX Lite meter, an EMDEX II in combination with a linear data acquisition (Linda) wheel, an ETM-1 3-axis Hall magnetometer (for static field measurements), a PMM 8053 portable field strength meter, an EHP50A magnetic field analyzer, and an ELT-400 with a 100 cm<sup>2</sup> magnetic field probe.

<sup>101</sup> Especially the influence of the load circuit on the exposure was assessed.

<sup>102</sup> Measurements performed with a MM-315A (Myachi). The according time signals were measured with the Rogowski method. The Rogowski method describes the time signal measurement of currents by using a toroid coil and subsequent integrate and processing circuits.

<sup>103</sup> Measurements were performed with an EFA-3 analysis system (Wandel & Goltermann), and a high precision H-field probe ( $A = 100 \text{ cm}^2$ ). The fields' time signal was utilized for analysis.

<sup>104</sup> Measurements were performed with an EM 2000 system (Symann & Trebbau) with according AC- and DC-probes.

<sup>105</sup> Measurements were performed with an EM 2000 system (Symann & Trebbau) with DCM30, DCM30e, M400e, and E80 probes. A huge catalog of typical field distributions in the surrounding of resistive welding equipment is given, which enables easy pre-evaluation and classification of such workplaces without the necessity of extensive measurements.

<sup>106</sup> In studies presented later in this document further exposure metrics like the change rate of the field will also be discussed.

limits should be performed. Thus, a preliminary frequency spectrum or transient analysis of the welding current is also viable to ease the selection of proper measurement equipment.

In a more methodological context Sicree et al (1993) gives investigations on deviating readings of 14 different field meters utilizing different types of detector circuits, namely true RMS detectors (integrating), rectified average detectors (integrating, RMS reading), corrected peak detectors (integrating, RMS reading) or scaled derivative detectors (no integration), for residential exposure (non-uniform exposure with harmonics and elliptical polarization). Different amounts of variation are shown to the total RMS flux density suggesting caution when comparing results from different measurement studies. However, the differences between the meter responses occurred because of slightly different measured parameters of the magnetic flux density, which does not imply any meter inaccuracy.

Measurements and FFT analysis of magnetic and electric fields in the surrounding of different arc welding applications in distances of 0.1 m from the current carrying welding cable as well as at the usual welders' position were for example performed by Stuchly and Lecuyer (1989)<sup>107</sup>. Further frequency selective measurements in the vicinity of welding cables of MIG welding equipment, particularly in a distance of 0.1 m from a 90° cable bend, may be found in Mild et al (2003)<sup>108</sup>. Time signals were assessed by welding current measurements and the frequency spectra were calculated via FFT.

Equal evaluations, additionally considering the phase relations of the three spatial field components, for representative exposure scenarios in MIG/MAG, TIG and resistive spot welding can be found in Molla-Djafari et al (2008)<sup>109</sup>. Preliminary current measurements showed the utilized measurement equipment to be suitable. The exposure measurements were executed subsequently with two different field meters for different frequency ranges at the normal working position of the welder in a vertical plane, with simulation of the cable guide over the welders' shoulder.

To further deepen the insight into exposure assessment in welding environments, attempts to simulate and calculate exposure scenarios in such environments are given. This is followed by some publications specifically concerned with methodological issues regarding pulsed fields in the examined frequency range.

With respect to typical welding circuit configurations as for example shown in Figure 2-4 for a stationary spot welding equipment, or in Figure 7-2 for MIG welding equipment with welding cables and electrodes as the exposure relevant parts of the circuit, respectively, calculations utilizing the Biot-Savart formulae as well as Finite Element Method (FEM) simulations of incident fields seem favorable. Measurements accompanied with such investigations for various resistive welding equipment may for example be found in Doebbelin et al (2003), Mecke et al (2002), Mecke et al (2003) and Lindemann et al (2008), whereas the first of the mentioned studies also includes investigations on arc welding equipment. Furthermore, the authors in Herms et al (2007) as well as in Lindemann et al

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<sup>107</sup> Measurements were performed with a bifilar, aluminum coated coil (diameter of 18 cm, 2x1000 turns) and an EFM 112 field meter (calibration from 50 Hz – 10 kHz).

<sup>108</sup> Measurements were performed with an ELF-BMM3 (Radians Innova), and a VLF-BMM5 (Radians Innova).

<sup>109</sup> Measurements were performed with a Gaussmeter 460 (Lake Shore), an ELT-400 (Narda) with a 100 cm<sup>2</sup> coil probe, and a NI 6120 (National Instruments). AC current measurements were performed with a "Rogovski-Gürtel" (Fronius).

(2008) investigate the influence of shielding and field compensation on the welders' exposure utilizing equal methods.

If not only incident but also induced fields or currents should be analyzed, numerical body models and appropriate simulation tools need to be applied. Such a possible combination is for example the utilization of the Visible Human model in combination with the Impedance Method in Nadeem et al (2004)<sup>110</sup> or the Finite Differences in Time Domain (FDTD) method in Molla-Djafari et al (2008). The last mentioned study compares the simulation results with preliminary measurements finding good agreement for the considered resistive welding scenario, whereas differences of up to about 100% could be observed in the evaluated TIG welding scenario. They ascribed this effect to an uncertainty due to shortcomings in the model of the measured scenario (e.g., due to field changing objects present in measurements but not in the model). However, this shows the difficulties in modeling complex exposure environments and the problem with drawing reliable conclusions from such simulations. Further simulations utilizing the FDTD method for cable welding guns in shoulder and elbow position as well as spot welding tools in elbow position are summarized in Cecil and Neubauer (2007). Simulations on exposure of two human body models<sup>111</sup> to time-varying magnetic fields produced by a resistive welding device by Dughiero et al (2010) were, in contrast to the above mentioned studies, performed using FEM tools<sup>112</sup>.

However, recent publications in the field of exposure assessment are increasingly concerned with pulsed and complex fields as well as with exposure due to more than one EMF source at a time. Attempts for calculating induced current densities in a round disc model<sup>113</sup> for analysis of pulsed currents with frequencies below 100 kHz utilizing the Biot-Savart formulae as well as a FFT and a parametric analysis for determining exposure relevant parameters according to ICNIRP (1998, 2003) are given in Desideri et al (2008). Furthermore, it is shown that utilizing the sum formulae according to ICNIRP (1998) always leads to overestimation of exposure for such pulsed signals in comparison to the phase considering approach given in ICNIRP (2003).

Different methods for compliance evaluation<sup>114</sup> of complex, non-sinusoidal or non-periodic waveforms with frequencies below 100 kHz given in relevant exposure limiting and assessment documents were lighted and compared in Canova et al (2010a). Scalar Potential Finite Differences (SPFD) simulations with the human body model Hugo for an exposure scenario comprising a resistive spot welding gun were utilized. However, the resulting problem of having no definite method for compliance evaluation of pulsed fields available is shown by laying down partly extremely different results on compliance for the three tested methods. Further details on this can be found in Canova et al (2010b) and Freschi et al (2010).

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<sup>110</sup> Investigating were performed for spot welding equipment.

<sup>111</sup> A homogeneous cylindrical model and a Computed Tomography (CT) deduced, more detailed, model were used.

<sup>112</sup> However, FEM simulations are suitable for homogeneous and only simple non-homogeneous models. As the memory requirements increase exponentially with the number of simulation points for FEM, FDTD tools, with a linear relation between the number of simulation points and memory requirements, are better suited for simulating exposure scenarios including non-homogeneous body models.

<sup>113</sup> The hypothesis of uniform magnetic flux density perpendicular to a homogeneous round disc was applied.

<sup>114</sup> These methods are the equivalent sinusoidal waveform approach, a Fourier series expansion (ICNIRP sum formulae) and a transient analysis.

In Crotti and Giordano (2009) investigations on effects of different evaluation methods as well as different time (and frequency) assessment windows with regard to non-sinusoidal, transient magnetic fields (8 Hz to 65 kHz) in arc welding applications are reported. A high variability with deviations of some 100% may occur due to the different utilized evaluation methods<sup>115</sup> and acquisition windows, making reliable and comparable evaluations impossible. Supportively, such findings are discussed e.g., in Molla-Djafari et al (2008) for welding equipment and in Leitgeb et al (2007) for drilling machines, also exhibiting complex fields. Problems with overrating harmonics due to the ICNIRP linear sum formulae or the underrating of harmonics and thus underestimation of exposure due to the quadratic summation of field strengths suggested in other documents (e.g., EN 50366 (2004)) are reported. However, it is mentioned that most measurement equipment in the ELF range only allows to measure RMS values of fields without frequency weighting. Furthermore, for power controlled sources as drilling machines and also some welding applications the ICNIRP (2010) phase consideration approach seems not to be applicable, as there is no favorable or stable phase relation given for different load conditions. This, however, makes filtering the time domain signal not appropriate.

Mathematical methods applicable for source oriented evaluation of three dimensional measurement data implementable directly in measurement equipment are presented by Rueckerl et al (2009). Pulsed and broadband magnetic fields may be analyzed giving information if the measured field is a superposition of fields and, certain conditions provided, the number of field sources provoking exposure. Thus, the presented methods may reduce time consumed by processing of complex exposure data.

Calculations (utilizing the Spatially Extended Non-Linear Node (SENN) model), RMS and spectral measurements of the magnetic flux density were performed by Karpowicz et al (2002). The RMS  $dB/dt$  value was found to be the metric suitable for correct ELF pulsed magnetic field assessment (5 Hz to 2 kHz). However, RMS magnetic flux density evaluations result in an underestimation of exposure. Also confusions on the utilization of either peak or RMS values for pulsed field assessment below 100 kHz in ICNIRP (1998) are shortly discussed.

The authors in Doebbelin et al (2003) and Mecke et al (2003) show how to assess magnetic fields in the vicinity of resistive and arc welding installations with regard to the BGV B11 (2002). Measurement grids for measurements at arc welding applications with smaller distances between the POIs near to the torch (10 mm) are suggested. For higher distances the POI separation was increased to 50 mm.

Further problems with performing evaluations according to ICNIRP with respect to inhomogeneous fields are discussed in Nadeem et al (2004). Possible local non-compliance with basic restrictions is reported, though the whole body spatial average magnetic field keeps with the reference levels. However, the approach of spatial averaged field values for inhomogeneous exposure seems questionable.

Karpowicz and Gryz (2007) identify the following points as the necessary steps in occupational EMF exposure assessment: EMF characteristic identification, selection of EMF assessment criteria (i.e., exposure evaluation methods), selection of measurement protocol, selection of measurement devices, measurement execution, analysis of measurement

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<sup>115</sup> This includes the ICNIRP sum formulae without phase consideration, and the weighted peak approach with and without phase consideration.

results including uncertainty considerations, interpretation of the EMF level of exposure, as well as decisions on the need for further actions. However, they state that harmonized standards should be provided giving advices to all these steps for the use with the Directive 2004/40/EC (2004).

Furthermore, Leitgeb and Cech (2008) indicate problems with standards' and guidelines' advices to separately evaluate effects due to electric and magnetic fields even at simultaneous exposure, ignoring possible superposition of induced current densities. However, this was shown to lead to underestimations of up to about 29% of current densities in the CNS considering worst-case conditions ( $E$  – vertical,  $H$  – horizontal, grounded body model).

However, despite all methodological concerns in quite a lot of reviewed publications ICNIRP reference value exceedance in welding applications were reported, making further analysis necessary. Mair for example states that this is in dept to the multiple worst-case considerations in deducing reference limits from basic restrictions and thus reference limits almost have to be exceeded in near proximity to e.g., welding cables (Mair, 2005).

Summarizing the above paragraphs on pulsed field assessments a definite, suitable method for evaluation of these fields is not yet available in the relevant exposure assessment and limiting documents. However, following different suggested methods may lead to extremely different statements on compliance with limits for pulsed fields. Furthermore, the pulsed signal types lead to problems in assessment due to different results for different concerned signal periods. The rate of change of the magnetic field is identified to be a possible proper exposure metric for pulsed fields accordant to the approach in the BGV B11 (2002). Additionally, concepts on spatial and time averaging as well as on typical worst-case assumptions seem necessary to be reviewed with respect to complex exposure scenarios including welding. Concluding, there is a lot of confusion left by the relevant exposure limiting and assessment documents with respect to complex field exposure by pulsed low and intermediate frequency fields making further investigation reasonable.

### **Dealing with Uncertainties in Exposure Assessment**

Regardless of which compliance evaluation approach, discussed in Section 4.3 or others, is utilized, extensive uncertainty evaluations are beneficial and increase the reliability of the assessment result. However, this is not feasible in many situations due to high efforts and costs associated with such evaluations, especially true in industrial environments. The following paragraphs present some additional concepts to Section 4 as well as the literature reviewed on uncertainties in complex SF, ELF, and IF exposure assessments.

When determining the uncertainty of measurements the so called repeatability of measurements gets relevant (DIN 1319-3, 1996). Repeatability refers to repeated assessments of the same property of the same "object" performed by the same observer, utilizing the same measurement procedure (method, instrument, and laboratory) with short time intervals between measurements. Such observations may give important information on environmental or other influences during measurements<sup>116</sup>, whereas they normally do not

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<sup>116</sup> More details on these possible influences enabling to split up the repeatability into several independent terms are given below in Section 7 by means of a specific example.

enable conclusions on systematic disturbances<sup>117</sup>. However, repeated observations of a measurand are in a lot of cases not feasible.

In most situations positive and negative systematic deviations will be set equal due to lack of further knowledge. If a systematic component is quantitatively known, the result has to be corrected for this value. If the systematic component or the evaluation of the systematic component is not statistically uncertain, there is no need for an additional uncertainty component. Otherwise, an uncertainty component has to be included to account for a statistical variation of the given systematic effect.

With regard to health concerns, worst-case estimations of uncertainty are suggested. Most exposure assessment documents mention uncertainties as important to be considered during occupational exposure evaluation, but unfortunately no comprehensive compilations or detailed observations on such uncertainties are given. Also advices on procedures to be followed for compliance evaluation vary between these documents. However, information on uncertainties in exposure assessment and evaluation in the scientific literature is found to be sparse. Thus, no definite common line on assessing and declaring uncertainties in complex static, extremely low and intermediate frequency exposure scenarios could be found.

Most of the reviewed studies focused on uncertainty evaluations of measurement equipment. Some include other possible contributions summarized under the repeatability of the measurements. Only very few studies performed detailed breakdowns of considerable methodological or environmental uncertainties. Thus, the following gives a short compilation of possible uncertainties and the reviewed practices on how to deal with such uncertainties in (static, extremely low, and intermediate frequency) exposure assessment at (welding) workplaces.

A good overview on possible sources of uncertainty in measurements and calculations in such environments may for example be found in Hamnerius (2007) and Cecil and Neubauer (2007). For electric field measurements

- influences of the measurement equipment and
- the persons performing the measurement on the field distribution,
- the anisotropy of the used instruments,
- the averaging of the measured field over the whole body (which is only possible performing multiple measurements using common measurement equipment but necessary for the proof of compliance with the reference values),
- influences of environmental changes (e.g., humidity changes cause changes in the electric field distribution), and
- other factors like instrument errors (e.g., calibration, accuracy), complex waveforms, FFT parameters, positioning uncertainties, variations in the field source, variations in posture, movement of the field source, or the worker or other field influencing objects are given as possible contributions.

In contrast to measuring electric fields the measurement equipment used and the persons performing the measurements are given to have only a negligible influence on the magnetic field distribution. Furthermore, most magnetic field probes have a better isotropic

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<sup>117</sup> Systematic disturbances mostly stay the same if the same procedure is followed by the same observer. They may be determined from literature or evaluations specific for a given scenario based on experience.

characteristic. Nevertheless, uncertainties at the measurement of magnetic fields exist, as there are:

- the averaging of the field due to size and shape of the measurement probes (usually coils),
- the actual position of the probe in relation to the planned measurement points (positioning uncertainty),
- the calibration or stated accuracy of the measurement instrument,
- interactions between the equipment under evaluation and the measurement equipment and environment (e.g., external electric fields),
- the repeatability,
- environmental changes (e.g., temperature, barometric pressure),
- complex and non-repeatable waveforms,
- frequency analysis of time signals with spectrum analyzers, FFT, or time domain measurements applying weighting filters, and
- other factors like phase relations between frequency components, non-repeatable or single pulses as input of a FFT, and movement of the field source, the worker or other field influencing objects.

Further factors contributing to the overall uncertainty of both types of measurements are influences due to the attention and experience of the measuring (operating) person. Moreover, the choice of inadequate measurement methods, instruments, or data analysis may influence the measurement uncertainty.

In short, also in analytical and numerical modeling uncertainties may for example arise due to:

- difficulties in modeling dielectric properties of different organs (homogeneous dielectric properties lead to uncertainties),
- differences in anatomical model size, weight, and posture compared to the real assessed situation,
- tissue electric properties,
- Voxel sizes and shapes that cannot account for fine anatomical details,
- problems with stair casing and convergence in the calculations, especially at single Voxel level,
- modeled parameters of the source equipment, and
- averaging over Voxels.

Going a bit more into detail of pulsed, non-continuous fields, investigations on time averaging of ELF magnetic fields for example summarized in Mild et al (2009) may be mentioned. A common averaging period (integration time) for measuring RMS values is 1 second, recommended in assessment documents as well as implemented in measurement equipment. This, however, may lead to wrong exposure estimations if for example welding applications are considered, since welding processes often take place in only some tens or hundreds of milliseconds. Furthermore, averaging approaches may lead to misvaluations of exposure if devices are assessed, drawing much more current in the first few milliseconds compared to the whole current cycle. In addition, different exposure limiting and assessment documents give different advices on averaging such fields, inevitably leading to confusion. It is for example questionable if the RMS of more than one period or of each signal period

individually should be assessed. These questions are directly linked to the question of biological effects elicited by pulsed EMF exposure (in the low and intermediate frequency range). Unfortunately, comprehensive knowledge on these issues is still lacking.

However, Mild et al (2009) suggests using peak value assessments for pulsed fields omitting averaging problems at a whole, an approach for example followed by ICNIRP (2003). This may be a quite good approach, as it will be difficult to find measurement equipment able to perform adequate RMS measurements, but it omits change rates of the field.

Concerning the used magnetic field probes, circular (100 cm<sup>2</sup>), squared loop (80 cm<sup>2</sup>) or even Hall probes (<1 cm) lead to highly different results, especially for small distances to the EMF source. Furthermore, coupling effects can influence the results for short distances between measurement equipment and EMF source. Regarding measurement distances, fixed regulations for evaluating compliance with limits seem not to be adequate, as real scenarios may deviate enormously. (Mild et al, 2009)

Moreover, for different considered periods (affecting the frequency resolution, and leading to problems if the signals vary in each period) significantly different results may appear with respect to windowing applied in FFT analysis (Mild et al, 2009). Also discrepancies in spatial grids necessary for averaging fields over the workers' body in different standards are discussed. For worst-case evaluations, especially for strongly inhomogeneous exposure no spatial averaging is suggested in Mild et al (2009), as this will underestimate the real exposure.

More specifically, the authors in Caldara et al (2010) present an uncertainty budget for power frequency magnetic field measurements resulting in an overall uncertainty of 14.7%<sup>118</sup>. Their considerations include uncertainties due to calibration, linearity, anisotropy, frequency flatness, as well as temperature and humidity response of the measurement probe, evaluated by type B evaluations of uncertainty. Furthermore, the repeatability was included in the budget, evaluated by type A evaluations utilizing various measurements including changes in field intensity, field frequency, probe orientation, presence of operator and ferromagnetic surfaces as well as external electric fields<sup>119</sup>. Unfortunately, no detailed considerations on these single uncertainty components are given. However, they propose a method for reducing the highest uncertainty contribution, namely the anisotropy (only for homogeneous fields), by accounting for the special measurement situation. By considering especially the relevant frequency and power range (the uncertainty usually changes in different ranges) they achieved a reduction in the overall uncertainty of about 73%.

Investigations on measurement probe and meter contributions (broadband and isotropic) to the assessment uncertainty are also given in Karabetsos and Filippopoulos (2005) including calibration, frequency response, linearity (over amplitude range), anisotropy (in homogeneous fields), thermal and modulation response (multi-frequency fields).

Further principle investigations on uncertainty evaluations in measurements of environmental EMFs are summarized in Vulevic and Osmokrovic (2010). Uncertainties associated with the used field meter (calibration, stability and bandwidth with regard to the

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<sup>118</sup> Measurements performed using a NARDA EHP-50C electric and magnetic field analyzer.

<sup>119</sup> Obviously this is a wrong understanding of the repeatability according to DIN 1319-3 (1996), as the measurement procedure has to stay the same in the performed subsequent measurements.



fields emitted by the observed sources), spatial inhomogeneous fields (with regard to probe dimension and isotropy of the probe), field source variations (load variations), temporal variation of the field (with regard to the meters time constant), positioning uncertainty, environmental conditions as well as the short-term repeatability, presence of ferromagnetic and conducting objects, external low-frequency electric fields, and ambient fields are named to be significant components in magnetic field measurements. Proximity effects and low-frequency magnetic fields disturbing the meter have additionally to be considered for electric field measurements. The positioning uncertainty and uncertainties due to the probes dimension in inhomogeneous fields were evaluated to be the major contributions. Furthermore, problems with calibrating field probes in homogeneous fields when typically used in non-homogeneous fields are discussed.

Not only focusing on the uncertainties brought in by the use of the field meter, Borsero et al (2001) discuss problems in identifying and quantifying uncertainties in measurements of environmental EMFs due to the applied measurement procedure including the field source characteristics and the present environmental conditions. The same considerable uncertainty contributions as in Vulevic and Osmokrovic (2010) are named. They for example give an uncertainty budget for measurements of a 50 Hz three-phase busbar trunking system<sup>120</sup>. A value of 6.2% is given as relative contribution to the overall uncertainty due to the non-uniformity of the field in relation to the size of the probe in a distance of 0.2 m to the field source. This value was estimated from stated data in the IEC 61786 (1998) and in Misakian and Fenimore (1996) as a function of distance and probe diameter. The data, however, also accounts for the orientation of the probe in the field giving the worst-case value for various orientations. A positioning uncertainty of 6.1% for the same distance was evaluated, given an estimated positioning deviation of  $\pm 1$  cm. Other contributions are found not to be significant in relation to the stated uncertainties (also instrumental uncertainty and uncertainty in current measurements are included). Uncertainty increased in close proximity to the source due to increasing field inhomogeneity.

The authors in Bertocco et al (2007) state uncertainties in readings arising from rotating a (not-centered) three axial magnetic field probe in a non-homogeneous field in industrial environments by performing FEM simulations and measurements. The problem with isotropy uncertainties given by manufacturers only valid for uniform fields is again discussed. In addition to the isotropy of the probe also the finite size of the probe and the according averaging of the field contribute to the given uncertainties. As one possibility to reduce problems with different readings due to the orientation of the probe in a non-homogeneous field they give the use of smaller probes. If not feasible, one may at least try to bring one axis of the probe in parallel to the direction of the field at the measurement position. However, this is difficult in industrial exposure assessments as the field distribution is usually unknown.

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<sup>120</sup> Busbar trunking systems are elements collecting and distributing the current from busbars of different pathways.

### 5.3 Summary

The state of the art in exposure assessment of complex environments and especially of welding applications was presented with a focus on pulsed static, extremely low frequency, and intermediate frequency fields and the associated uncertainties in assessment.

Exposure measurements in the considered environments have preferably been performed either by using exposimeters for mainly determining RMS, peak or averaged field values over a longer period of time, or broadband field meters performing RMS, time weighted average, or in general time domain measurements for a single time instance. Problems with exposimeters due to their nearness to the persons' body and the discrete field representation at a single point were mentioned. Furthermore, difficulties in assessing complex exposure utilizing RMS, peak, and averaged field values were discussed for both exposimeters and broadband field meters. When performing time signal measurements with subsequent signal analysis, care should be taken on the specific signal waveform.

A lot of the presented studies performed assessments with equipment and analysis not fully suitable to reliably assess exposure in the surrounding of welding applications, although giving some good qualitative information. The transient characteristic of the currents and thus of the produced fields was not always adequately taken into account. Any kind of averaging for example may neglect short, high field variations rather important for acute nerve excitations. It seems necessary to perform time signal measurements with subsequent frequency analysis to be able to cope with the complex signal shapes typically used in welding applications.

Suitable metrics for pulsed static, low, and intermediate frequency magnetic field exposure are still an issue. Standards and other documents deviate in their statements concerning exposure assessment and evaluation. This also holds true for statements on the proper consideration of uncertainties in evaluations. Only few detailed investigations on uncertainties in complex exposure assessments were found. Most of the reviewed studies focused on uncertainty evaluations of measurement equipment but not on methodological or environmental contributions to the assessment uncertainty. However, a common practice in static, extremely low frequency, and intermediate frequency workers' exposure assessment as well as in evaluating and expressing uncertainty in such assessments is not available yet.

## 6 Challenges of Exposure Evaluation in Complex Environments

Exposure conditions get influenced by various parameters (Section 5.1). However, a reliable exposure assessment should preferably consider all these influences enabling to evaluate suitable measurement procedures and equipment accounting for the specific situation. Challenges to face in finding and applying such suitable measurement procedures and equipment for complex exposure assessments and evaluations are discussed. In conclusion a suitable and reliable harmonized exposure assessment and evaluation protocol is given.

### 6.1 Introduction

Industrial environments may exhibit quite complex EMF exposure situations. This includes the simultaneous exposure to several sources of electromagnetic fields operating in different frequency and power ranges, independently or simultaneously. In combination with the given workplace setup, maybe including (moving) field influencing objects, this will lead to an exposure highly inhomogeneous in space and time.

When aiming at evaluating such fields by performing measurements or calculations with subsequent compliance evaluation a few questions should be considered, based on the evaluations of the exposure parameters summarized in Section 5.1<sup>121</sup>:

- Which assessment and compliance evaluation methods are applicable?
- Which measurement equipment is applicable?
- Is it necessary to perform measurements with more than one measurement device?
- Are additional numerical or analytical calculations reasonable?
- What possible uncertainties are associated with each of the considered methods?
- What's about the uncertainties of each considered measurement equipment (or calculation setup)?
- According to the evaluated uncertainties and the considered limits, are the specific chosen assessment method and equipment suitable for the exposure evaluation?
- How to deduce appropriate exposure quotients with respect to the chosen compliance evaluation method from the assessed data?
- How to deduce appropriate uncertainties for the given exposure quotients?

By means of two exposure setups increasing in complexity, possible answers to these questions are given, constituting an overview on these wide issues. Although, compliance evaluation is an important step in exposure evaluations this point is only discussed marginally, as the focus should be on suitable measurement methods and equipment. However, evaluations of uncertainty are shown to be a possible measure of suitability for the selected measurement method and equipment with regard to a specific exposure evaluation.

### 6.2 Exposure to a Mono-Frequency Magnetic Field

An easy example of exposure to electromagnetic fields, although only existing in practice when applying simplifications, is constituted by one single current carrying conductor emitting

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<sup>121</sup> However, if no exposure evaluation but just an assessment with respect to a defined assessment method is aimed, decisions on the suitability of the assessment method and equipment will vary (see below).

a continuous wave, single frequency 50 Hz sine magnetic field. The exposed person stands besides this conductor in the near free field without any additional field influencing obstacles (ideally conducting plane earth). Electric fields were evaluated to be negligible.

### **Compliance Evaluation Methods**

According to the given exposure setup, compliance evaluation can be performed by simply comparing the measured (or calculated), incident or induced, RMS value of the external magnetic field or the induced current density (or electric field) at a specific position with the given limits. Following for example ICNIRP the incident values have to be averaged over the whole body of the exposed person before compared with the limits. Basic values have to be averaged equally over a small Voxel volume (e.g., 2x2x2 mm<sup>3</sup> in ICNIRP (2010), 1 cm<sup>2</sup> in ICNIRP (1998)). In general, uncertainties of assessment have to be considered for compliance evaluation.

### **Exposure Assessment Methods**

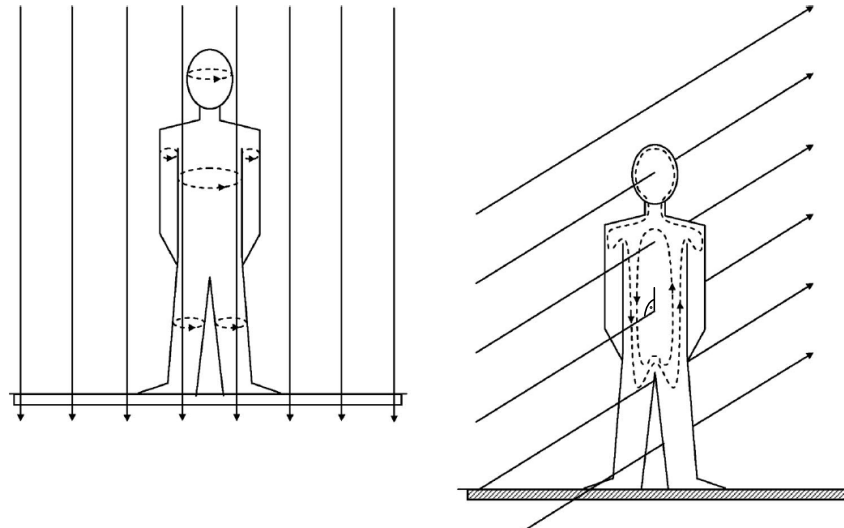
Incident fields may be measured at the typical position of the exposed person. This can be done by either performing single spot measurements e.g., at the typical position of the head of the exposed person, assuming the field distribution to be sufficiently uniform over the whole body, or by performing grid measurements with several measurement points in the volume typically occupied by this person. Both methods will lead to different estimates of the real field distribution, which should follow a monotonically decrease proportional to  $1/r$  in direction off the field source. Appropriate uncertainties should account for this. These uncertainties will depend on the distance to the field source, the figure and the posture of the exposed person. Furthermore, deviations in positioning of the measurement probe as well as its size will contribute to the uncertainty.

Incident fields may also be measured by performing single (or less common multi spot) measurements using measurement equipment worn by the exposed person. For this, one has to consider that the field distribution may change due to presence of the body. Applying single spot measurements introduce uncertainties in deducing whole body exposure. Furthermore, the measurement device will be influenced by the nearness of the body. Again appropriate uncertainties have to account for this. However, such assessments are common for deducing temporal variations of exposure for longer periods of time (e.g., one working day).

According to the chosen compliance evaluation method (or other aims besides compliance evaluation) different exposure metrics have to be determined. This can be the RMS, peak, or arithmetic mean with regard to the given exposure scenario. These values may either be determined directly by the used field measurement equipment or via signal analysis of the captured time signal. However, environmental influences as well as variations of the emitted magnetic field can cause temporal variations of the measurement results. Appropriate uncertainties have to account for this.

Besides measurements also analytical and numerical calculations may be performed for determining incident as well as induced field (or current density) distributions. Equal to measurements such calculations show uncertainties with respect to the real exposure situation.

Furthermore, measurements as well as calculations have preferably to take into account all known parameters of the assessed field as e.g., its polarization. Measurement probe positions as well as calculation parameters should be defined appropriate. For illustration, Figure 6-1 shows the exposure situation for a vertical and a horizontal polarized magnetic field, leading to different induced current paths and strengths in the body. If any field parameter influence on the exposure assessment is not known, appropriate uncertainties have to account for this.



**Figure 6-1 Induced current density in a human body for, (left) a vertical, and (right) a horizontal polarized magnetic field from Martens (2007), with changes**

### Measurement Equipment

A variety of different measurement equipment is available for assessing the given single frequency magnetic field. These are (most common) exposimeters<sup>122</sup> (frequency selective at 50 Hz or broadband) as well as broadband field meters with inductive coil or Hall Effect probes (also often including frequency selective measurement modes for 50 Hz), all capable of assessing the above mentioned exposure metrics.

In addition to field measurements also current measurements are applicable e.g., for performing a first survey of the prospective fields. Common equipment is for example current shunts or inductive coil probes.

### Suitable Exposure Assessment Method with Appropriate Measurement Equipment

The suitability of a measurement method in combination with appropriate measurement equipment may be defined as the ability to assess all required exposure parameters given a defined maximum expanded uncertainty. This maximum uncertainty is defined with regard to an adequate compliance evaluation method and the according limits<sup>123</sup>.

Most obvious, all possible frequency components at all possible field strengths emitted by the field source have to be measurable. Furthermore, the spatial and temporal variations

<sup>122</sup> Shortcomings of exposimeters were already addressed in Section 5.2. If the aims of a study force to use exposimeters, appropriate uncertainties have to account for these shortcomings. Exposimeters are for example a favored means of measurement equipment for epidemiologic long term studies.

<sup>123</sup> If no exposure evaluation is aimed, the definition of a maximum reasonable expanded uncertainty has to be based on other criteria.

of the field are necessary parameters to be assessed. Any identified shortcomings have to be accounted for by appropriate uncertainties.

With regard to compliance evaluation a maximum expanded uncertainty of the assessment may be defined depending on the relative exposure in relation to the appropriate exposure limit. However, a concept asking for lower permissible uncertainties when approaching the limits seems beneficial, i.e., a large uncertainty may be allowed for low exposure without any problematic effect on the final compliance statement, as the level of confidence of being below the limit is still high<sup>124</sup>.

Concerning the given exposure scenario a frequency selective RMS measurement for 50 Hz at a few points on a grid utilizing a (broadband) field meter and an appropriate probe is suitable. Either inductive coil probes or Hall probes can be applied. No loss of information about the exposure is caused by solely RMS measurements due to the sinusoidal character of the field. Measurement uncertainties for such equipment are typically low in (nearly) homogeneous fields. Deviations due to an inhomogeneity of the field have to be accounted for by additional uncertainty components. Proper grids may be found in appropriate exposure assessment documents or may be designed from experience (e.g., assessing the field at the typical torso position of the exposed person). The uncertainty due to imprecise positioning of the probe typically dominates and has to be considered. Its value increases when approaching the field source. For close proximity Hall probes may lead to smaller assessment uncertainties as their outline is smaller and averaging of the inhomogeneous field over the probe is reduced in comparison to inductive coil probes<sup>125</sup>. Furthermore, in close proximity to the source, field levels will increase and may approach the limits. Thus, equipment with preferably low uncertainty should be used for measurements (e.g., no exposimeters worn by the exposed person). Huge time variations and environmental influences are not to be expected. If so, appropriate uncertainties have to be added.

However, associated uncertainties of the described assessment method including the appropriate equipment will remain comparably small. Thus, the assessment may be termed suitable.

If field values are rather low compared to stated limits and compliance evaluation is aimed, also single point measurements using exposimeters or (broadband) field meters leading to higher averaging uncertainties may be suitable. On the other hand, if lower uncertainties are needed, at least for such simple scenarios, numerical and analytical calculations can be suitable. Moreover, simulations get necessary if the assessed incident fields exceed relevant limits and induced fields need to be checked for compliance. However, a sound decision may be made based on proper uncertainty evaluations.

It was demonstrated how proper uncertainty evaluations can be utilized for formulating a suitability statement for a specific assessment with regard to the assessed exposure scenario as well as an appropriate compliance evaluation method (or other criteria).

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<sup>124</sup> A concept also suggested e.g., in Chadwick (2008). However, for exposure assessment without subsequent compliance evaluation such concepts do not apply. Varying allowed uncertainties may only be reasonable due to (technical) limitations in assessment (e.g., different measurement uncertainties of the equipment for different frequency or power ranges).

<sup>125</sup> For measurements in the near field the size of the probe should be small in comparison to the wavelength of the measured signal. Otherwise spatial variations of the field over the probe volume will occur, additionally to the spatial variations due to any field gradient. However, this is always fulfilled in the concerned exposure scenarios.

However, for more complex exposure scenarios this may develop to a hard task, as investigations on uncertainties in complex environments were found to be sparse.

### 6.3 Exposure to a Multi-Frequency Electromagnetic Field

A slightly more complex exposure scenario may be constituted by two conductors building a current loop carrying a pulsed, non-sinusoidal current with frequencies up to 100 kHz. The exposed person stands besides these conductors in the near free field without any field influencing obstacles (ideally conducting plane earth). Electric fields were evaluated not to be negligible. The pulsed character of the current will lead to a broad frequency spectrum.

#### Compliance Evaluation Methods

According to the given exposure setup, compliance evaluation can be performed using different evaluation methods for (SF, ELF, and IF) pulsed fields presented in Section 3.1. Following for example the time weighted peak average in ICNIRP (2010) the frequency components of the (time derivative of the) field may be summed up with respect to the frequency dependent limit values as well as the phase relation of the single frequency components (Equation (3-7))<sup>126</sup>. Simple frequency selective summation of the RMS field amplitudes without any phase considerations or the equivalent sinusoidal waveform approach is also possible (ICNIRP, 1998). Transient analysis of the assessed signals may be performed with accordance to the BGV B11 (2002), giving the peak  $dB/dt$  as well as the averaged  $dB/dt$  value as the proper exposure metrics for pulsed (SF, ELF, and IF) fields.

Concerning spatial averaging of incident and induced fields different approaches are suggested by the above mentioned documents. However, no time averaging has to be applied for the given frequency range<sup>127</sup>, as no thermal effects are to be expected.

Different approaches concerning the additivity of electric and magnetic fields are suggested. However, both field types induce electric fields in the body of the exposed person which add vectorially. In a conservative approach the induced maxima with the same phase will be suggested at the same point, and at the same time. Given such conservative assumption the contributions of  $E$  and  $H$  can be summed up arithmetically. Far more conservative will be a separate evaluation of both contributions without any summation. In general, uncertainties of assessment have to be considered for compliance evaluation.

#### Exposure Assessment Methods

Possible applicable exposure assessment methods equal the given ones in the previous lighted scenario. However, due to another source setup, the field distribution will not any longer follow a  $1/r$  decrease, but will more probably be proportional to  $1/r^2$ . This should be accounted for when defining the POIs and estimating the associated uncertainties.

According to the chosen compliance evaluation method (or other aims besides compliance evaluation) various exposure metrics in addition to the RMS, peak or arithmetic mean value have to be determined for a suitable assessment. This may include rise and fall times as well as the peak and averaged time derivative of the field, various time weighted averages, or the full amplitude and phase spectrum of the field. All these metrics are based

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<sup>126</sup> However, this may not be favorable if no stable phase relation between the single frequency components exists, as e.g., the case for power controlled signals (Leitgeb et al, 2007).

<sup>127</sup> Except in the BGV B11 (2002), which gives averaging of induced current densities for 1 second.

on full waveform assessment. Appropriate uncertainties have to account for any shortcomings in assessing the above metrics.

### **Measurement Equipment**

Possible applicable measurement equipment equals the given one in the previous lighted scenario. For the assessment of electric fields proper electric field measurement equipment (e.g., capacitive probes with free body meters or exposimeters) has to be adopted<sup>128</sup>. Furthermore, frequency selective measurements using appropriate probes in combination with spectral analysis (via spectrum analyzers or FFT analysis) get applicable. In addition to current measurements also voltage measurements could be used to pre-evaluate electric fields.

### **Suitable Exposure Assessment Method with Appropriate Measurement Equipment**

Concerning the frequency content of the assessed fields (0 Hz to in maximum 100 kHz) one single measurement device normally won't suffice to assess the full frequency content. Thus, with respect to magnetic fields, it will for example be necessary to apply Hall Effect measurements for the low frequency components accompanied by inductive coil probe measurements for the higher frequency components, both being able to assess the encountered field strengths. If such a setup is chosen, one may account for possibly overlapping frequency ranges of these devices by proper corrections avoiding overestimations of exposure. If only broadband measurements without specific information on the signals frequency content are performed, such corrections won't be possible. However, no gaps in frequency should appear. Appropriate uncertainties for each measurement device as well as for the complete setup have to be established.

When performing broadband field measurements the result will be a simple RMS, peak or time weighted average value giving no information on the actual frequency content of the field<sup>129</sup>. For complex pulsed fields showing high crest factors and varying duty cycles single signal parameter values as the above mentioned won't give the full information of the signal. Anyway, there may be problems with finding proper evaluation windows for these parameters especially for short, varying duty cycles. If such broadband measurements have to be applied due to lacking other possibilities, at least devices with a proper short evaluation time need to be used. In arc welding for example an evaluation time of one pulse period with a measurement interval of at least 1/10 of this period should apply (EN 50444, 2008). However, besides the problems in evaluating proper RMS representations of pulsed fields its suitability as exposure metric for such signals is still under discussion.

Thus, high uncertainties may be associated with broadband RMS or time weighted average evaluations of pulsed signals, strongly depending on the actual signal waveform. However, such measurements can be suitable for a first exposure survey, or if the measured field values are far beneath the limits allowing for a high uncertainty. Furthermore, if time development of the assessed fields is of interest, exposimeter measurements are a possibility to observe the long term characteristic, at least qualitatively. Peak measurements may be better suited, although omitting the actual signal shape and thus possibly exposure relevant signal change rates. Appropriate measurement equipment has beneficially to be

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<sup>128</sup> Possible configurations can for example be found in the IEC 61786 (1998).

<sup>129</sup> Measurements performed by either broadband field meters with appropriate probes or exposimeters with its already discussed additional shortcomings.



capable of assessing the peak value in each signal period. If not, additional uncertainties have to account for this.

With respect to compliance evaluation broadband measurements giving single field parameters for the whole assessed frequency range may lead to overestimation of exposure. This appears as the achieved value has to be compared with the lowest given exposure limit in the considered frequency range. As further possibility in broadband measurements, field meters with implemented appropriate filters having transfer functions according to given frequency dependent limits may be applied. These meters output a single exposure quotient in percent of the limit value either with or without considering the signals phase relation. However, such an implementation does not require any frequency decomposition of the measured signal and further accounts for all possible signal shapes. Thus, no uncertainties with respect to any additional signal processing have to be considered.

Finally, frequency selective measurements using appropriate probes in combination with a spectrum analyzer can be an appropriate means of assessment, although they are not that common due to more convenient methods (at least in the concerned frequency range). The use of broadband field meters performing time signal measurements and subsequent signal analysis including FFTs can be such a convenient method. When assessing the time signal of a field all information of the exposure at one specific point and one specific time instant is available. Furthermore, this is independent of any specific exposure metric, thus all possible compliance evaluation methods can be applied. Methodological uncertainties may appear according to the specific type of signal analysis. One may for example think on a FFT analysis using windowing for non-periodic, pulsed signals. As already discussed in Section 5.2 the specific window design (i.e., window type, length, and position with respect to the investigated signal) will significantly affect the resulting frequency spectrum. However, lowest possible uncertainties may be achieved using such time signal analysis. Thus, this method can be termed most suitable with respect to the given exposure scenario. Nevertheless, thorough uncertainty evaluations have to be performed.

To emphasize, not in all cases such detailed assessments are necessary or affordable. Less accurate methods may also be suitable, as long as the specific evaluated uncertainties do not exceed a defined maximum value. Numerical simulations get necessary for reference (or deduced) level exceedance if a compliance evaluation is aimed. Such simulations are usually associated with relatively high uncertainties for complex scenarios.

Equal considerations hold true for the encountered electric fields. The decision process on the suitability of specific measurement methods and the appropriate equipment should also be based on thorough uncertainty evaluations.

Accounting for the given exposure scenario and the need of performing measurements with different equipment, one may keep in mind that uncertainties in general are different for different equipment and different frequency and power ranges. If detailed evaluations are necessary e.g., due to high exposure levels, this point has to be considered.

With regard to an overall exposure evaluation considering all sources of EMFs present in a specific scenario, appropriate concepts need to be given. Such concepts have to account for the various emitted frequency spectra and field types. An outline on this is presented in the following section.

## 6.4 Exposure Combination in Compliance Evaluation

Exposure to SF, ELF, and IF pulsed fields with frequencies between 0 Hz and 1 MHz, emitted by one or several sources, simultaneously or independently operating, has to be assessed separately for electric and magnetic fields if near-field conditions apply. Furthermore, exposure limiting documents generally give frequency dependent limits accounting for different physiological reactions (e.g., nerve excitations and thermal effects) in different frequency ranges.

When for example following the ICNIRP summation approach discussed in Section 3.1 in principle eight distinct exposure quotients have to be evaluated. This includes evaluations of the induced electric field strength (or the induced current density), the *SAR* (whole body average, head and trunk, or limb) and the power density, as well as the incident electric and magnetic field strength for both nerve excitation and thermal effects, respectively. However, the degree of detail for such evaluations may vary in practice. This can be due to non-significant field contributions e.g., for frequencies above 100 kHz, and thus no further need for the evaluation of thermal effects. On the other hand, not all of the mentioned *EQs* may be given due to lacking evaluation possibilities, or the evaluation result is not given for each of the eight contributions but simply as a sum of these.

Assuming two EMF sources operating at different frequency and power ranges (all two with frequencies between 0 Hz and 1 MHz) in short but different distances to a workplace, some approaches of assessing an overall exposure based on a *TEQ* concept (Section 3.2) are discussed. However, different approaches are necessary due to varying available exposure data. Without loss of generality only incident fields should be considered in the following explanations. Proper uncertainty evaluations are assumed.

As a first example exposure measurements were performed at the workers' position separately for each of the two sources giving only one single *EQ* per source with an associated uncertainty and no further detail<sup>130</sup>. As there is only one single *EQ* for each source obviously no breakdown in evaluating these quotients for nerve excitation and thermal effects according to the utilized limit document, or a distinction between electric and magnetic field components has been applied. Thus, only a very rough and conservative, the physiological effects omitting, first survey of exposure is possible. This is found in the literature as the most conservative possibility of the *TEQ* concept presented in Section 3.2. Thus, this is the worst situation for a reasonable exposure evaluation, besides having no information on the exposure at all. However, if the *TEQ* as the sum of both *EQs* is higher one, this does not necessarily implies that reference limits are exceeded, but that further detailed investigations need to be conducted. An overall uncertainty can be evaluated as the RSS of the *EQs'* standard uncertainties.

Little more detailed, different exposure quotients for different frequency ranges are available for both sources. This makes it possible to deduce separate *TEQs* accounting for nerve excitation (lower frequencies) and thermal effects (higher frequencies). However, if a *TEQ* for one source over more than one (frequency) range is reasonable, the highest of the given uncertainties for each (frequency) range may apply. Again no information on the separate contributions of electric and magnetic fields can be deduced. This still constitutes a

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<sup>130</sup> Evaluation performed according to any exposure limiting or assessment document in Section 3 or others.

very conservative approach, giving only little information on the assessed exposure situation, allowing for no more detailed investigations.

A far more convenient situation will be the availability of full amplitude spectra at the considered workplace with appropriate uncertainties separated for magnetic and electric field components and different ranges. Each compliance evaluation method based on frequency dependent limits can be applied. External electric and magnetic fields may be considered separately or added in their effect. However, no phase information of the fields is available, thus only a worst-case summation of the two source contributions is possible. More detailed uncertainty estimations separately for different equipment and (frequency) ranges are possible. This may especially be reasonable for high exposure values close to limits.

Further detail can be achieved if the full time signal or the full amplitude and phase spectra of each of the sources is available. With this, also phase considering compliance evaluation methods are applicable, most probably leading to less conservative results.

Nevertheless, assessing all two sources while simultaneously operating by performing full time signal measurements will give even better results, as the field appears during measurements as during real working situations. All available compliance evaluation methods are applicable<sup>131</sup>. Phase relations may be included when evaluating the combined effect of electric and magnetic fields on induced electric fields. Furthermore, detailed uncertainty estimations are possible. However, in most cases such an assessment is not reasonable as a lot of sources were already investigated in the past. Thus, more or less detailed measurement or simulation data is already available. This in general is appreciable, as repeated assessments of equal devices are bypassed, saving money and time, especially true for manufacturers committed to evaluate their produced devices with respect to EMF emissions. Although more feasible and cost effective this may lead to overestimations of exposure.

In all the above mentioned possible *EQ* combinations it further has to be considered if the available data represents whole or partial body exposure. However, it doesn't seem reasonable to directly combine two *EQs* with one representing exposure of the head and the other of the pelvis region, respectively. Such problems are handled for example in ICNIRP (1998) by building whole body averages. However, this will not account for the real inhomogeneous exposure. Thus, it may probably be a good approach to define several regions of the body typically exposed at the same time for typical applications (e.g., welding: right hand and arm, shoulder; drilling machine – hand and upper thorax, or head and hand for overhead drilling) to build more representative averages. The most conservative approach will be the consideration of just the highest assessed value for highly inhomogeneous exposure (ICNIRP, 2010).

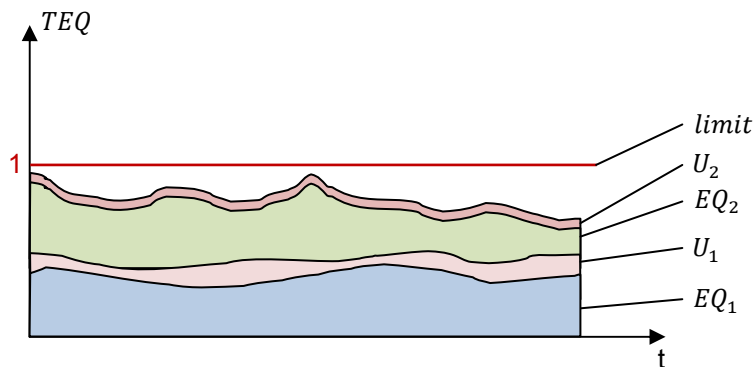
For some exposure scenarios it will be advantageous to include the time development of exposure in the evaluation of the *TEQ*<sup>132</sup>. One just has to think of a welding workplace with one further welding workplace in close distance, but with different operating times. There may for example be an exposure limit exceedance if both appliances are operated simultaneously, but no exceedance if only one is operated. However, such an evaluation will

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<sup>131</sup> For the discussion on possible shortcomings when looking at pulsed, non-sinusoidal fields see the sections above.

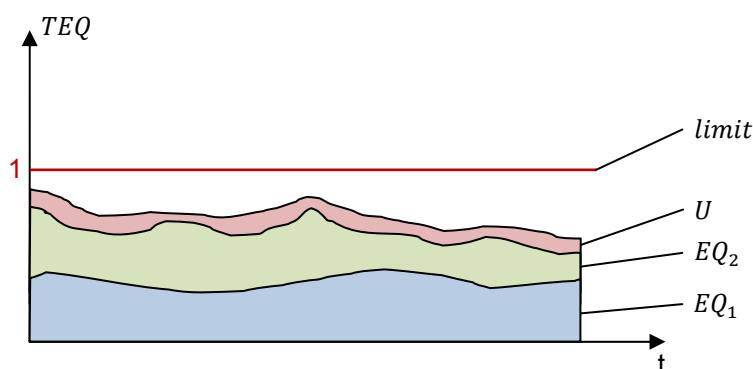
<sup>132</sup> This can be established by e.g., using exposimeters. Time averaging with regard to thermal effects may also be included here, but should not further be discussed.

lead to a  $TEQ$  representing the real exposure with a given overall uncertainty both varying with time<sup>133</sup>. An illustration is shown in Figure 6-2, giving the time development of a  $TEQ$  as the sum of  $EQ_1$  and  $EQ_2$  with associated expanded uncertainties  $U_1$  and  $U_2$ . Furthermore, the concept of reducing the evaluation uncertainty when expecting higher values of exposure in relation to a defined limit is indicated in principle.



**Figure 6-2** Time development of a  $TEQ = EQ_1 + EQ_2$  with associated expanded uncertainty  
 $U = U_1 + U_2$

Figure 6-2 illustrates the case of just adding the single  $EQ_s$  as well as their uncertainties. However, adding the uncertainties is a very conservative approach<sup>134</sup>. For combining uncertainties from several single source assessments, building the RSS of the single uncertainty estimates is reasonable as given in Figure 6-3.



**Figure 6-3** Time development of a  $TEQ = EQ_1 + EQ_2$  with associated expanded uncertainty  
 $U = \text{sqrt}(U_1^2 + U_2^2)$

Anyway, these were some of the possibilities for evaluating total exposure quotients with associated uncertainties in multi source exposure scenarios. Exposure data from different EMF sources is often already available coming from different data sources with different degree of detail, thus sometimes making an overall exposure evaluation challenging without performing additional measurements or calculations. This is especially true for complex, high exposure settings. The outline was given with respect to incident SF, ELF and IF fields. Equal considerations are possible for higher frequencies, induced fields or a combination of incident and induced fields, respectively.

<sup>133</sup> Variation of uncertainty with time will account for e.g., changing emitted powers or frequencies by the exposure sources. However, uncertainties in inhomogeneous fields will also strongly vary due to the typical movement of the worker during the shift. Appropriate approaches how to deal with this in exposure evaluation have to be developed.

<sup>134</sup> This is only reasonable if the two  $EQ_s$  are highly correlated or one of the components is dominating (Section 4.1).

## 6.5 Summary

An outline on possibilities for assessing and evaluating exposure in complex scenarios was given. Such possibilities were shown to be many and hold ready a lot of difficulties. Thorough uncertainty estimations are an important tool to handle these difficulties but unfortunately are rare in common practice. This may be due to high efforts necessary to achieve such estimates in complex environments, the sparse literature on this, and the partly ambiguous statements on the establishment and dealing with such uncertainties in diverse exposure assessment documents. However, the exemplary investigations given in the previous sections may be summarized by an attempt on a harmonized exposure assessment and evaluation protocol, as follows:

- Make sure about all necessary exposure parameters.
- If a lot of these parameters are unknown make a first survey using most simple methods and equipment.
- Select relevant exposure metrics to be assessed according to an appropriate compliance evaluation method or other objectives.
- Select an applicable assessment method and according applicable equipment or tools.
- Establish appropriate and feasible uncertainty evaluations for the selected setup.
- Make a decision on the suitability of the selected assessment method and equipment based on the established uncertainties with regard to the exposure scenario, the selected compliance evaluation method as well as the given exposure limits, or other criteria if no compliance evaluation is aimed.
- If the decision is **not suitable**, select other assessment methods and equipment, or at least define why using the chosen assessment procedure (e.g., no better suited assessment procedure available).
- If the decision is **suitable**, start with performing the assessment and, if compliance evaluation is aimed, establish proper exposure quotients given with its total estimated expanded uncertainty.
- If the evaluated exposure quotients with its associated uncertainties indicate overexposure, think about further actions (e.g., more detailed assessment if necessary, or technical measures to reduce exposure at the assessed workplace).

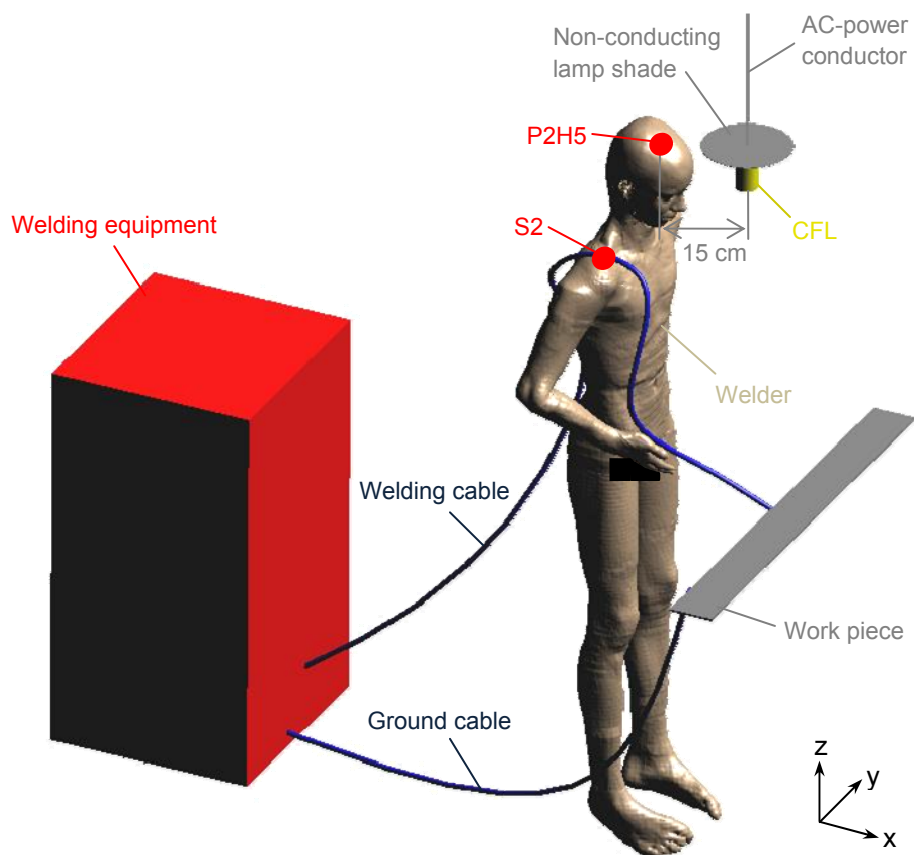
Thus, to follow this protocol the central step is feasible uncertainty evaluations. As uncertainties may deviate much for different exposure scenarios a good approach can be to find a group of representative scenarios on workplaces for which extensive uncertainty evaluations are conducted in the future. Based on this it is eventually possible to deduce conclusions for further similar scenarios. This may lead to better cost effectiveness, as no separate evaluations have to be conducted for each assessment and better reliability of exposure assessments and evaluations in general. To demonstrate such an extensive uncertainty evaluation a specific representative example is implemented in the following section, potentially constituting a prototype for further investigations.



## 7 Uncertainty Evaluations in Complex Exposure Scenarios

To further discuss and clarify the approaches described above regarding the uncertainties of exposure assessment as well as the overall exposure evaluation in complex EMF environments a specific example is implemented. The given uncertainty evaluations may constitute a prototype for further investigations.

An occupational environment in the metal fabrication industry, in particular a MIG welding workplace lighted by a CFL is considered (scheme shown in Figure 7-1). To assess the exposure of the welder to EMFs distinct measurements on the typical working position of the welder are performed. These measurements include the assessment of magnetic fields generated by the welding application as well as of electric fields emitted by the CFL at the workplace. Thus, the chosen example includes field measurements from two different sources of EMFs considering both electric and magnetic fields. Fields in a frequency range from 0 Hz to 400 kHz and field strengths from in maximum some 100  $\mu\text{T}$  and some 100 V/m are expected at the workers' typical position, respectively (Section 2).



**Figure 7-1 Exposure scenario scheme showing a welding workplace with two sources of EMF – the MIG welding application (welding power source and cables) as well as the lighting of the workplace via a CFL**

Data from different sources are used for the given exposure evaluation, including measurements at welding applications performed by the Austrian Institute of Technology as

well as measurements for CFLs taken from the literature<sup>135</sup>. This should emphasize the fact that in most cases of exposure evaluations one may have to deal with exposure data from different data sources (own or external measurements/simulations, complete data or reduced data from publications) as it is not reasonable to perform repeated measurements (or simulations) if not absolutely necessary due to the high costs of such assessments. However, for external data the specification of the used methodology and equipment is often sparse and thus the depth of possible investigations (especially on the uncertainties of assessment) is limited.

The rationale for choosing specific measurement methods and equipment suitable for the considered exposure scenario as well as a description of these is given. The measured data for the welding application and the referenced data for the CFL are presented.

Extensive uncertainty investigations for the welding measurements are given. These investigations are based on previously performed measurements and simulations, newly performed measurements as well as on data given in the literature. The uncertainty evaluations for the CFL measurements are taken from the literature. Overall uncertainties for the described exposure scenario are evaluated. Different possible approaches of dealing with the estimated uncertainties, the use of uncertainty evaluations as one criterion for selecting suitable measurement methods, as well as the handling with multi source exposure with associated uncertainties are further discussed by means of the given example.

### **7.1 Materials and Methods**

The presented exposure scenario may be divided into two sub-scenarios namely, the exposure of the welder due to the welding process (MIG welding) and the exposure due to the lighting (CFL). The chosen measurement methods including the precise exposure setup (e.g., source configuration, position of the welder) and the followed measurement procedure (e.g., time signal grid measurements) as well as the measurement equipment (e.g., broadband field meter with appropriate probe) are described for both sub-scenarios.

#### **7.1.1 Metal Inert Gas Welding Application**

Magnetic fields in MIG welding applications constitute complex exposure, strongly inhomogeneous in time and space. This is due to the pulsed character of the welding current with an additionally superimposed higher frequency current ripple, as well as the workplace setup itself (Section 2.2.1). However, exposure assessment via measurements in such environments is demanding and needs a sound understanding of the given exposure situation (Section 5).

The AIT can look back on extensive experience in exposure assessment in complex environments in general and at welding workplaces in particular. Based on this and in accordance with the literature study presented above, the measurement method described below was chosen from all possible methods previously described in Section 5 as the most suitable one for a detailed exposure evaluation. The suitability is checked by thorough uncertainty evaluations.

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<sup>135</sup> Measurement data for the welding application is summarized in Molla-Djafari et al (2008). Data for the CFL measurements is taken from Nadakuduti et al (2011).



## Exposure Setup

Measurements were performed for a typical MIG welding workplace shown in Figure 7-2. The current carrying, and thus field generating part of the setup consists of the welding equipment (with the welding power source and the control unit), the welding cable (a cable guide over the right shoulder of the welder is simulated as typical and non-advantageous concerning the welders' exposure), the welding torch, the work piece, and the ground cable back to the equipment (fixed to the work piece). The welders' position is beside the current loop on the left side (Figure 7-2 (right)).

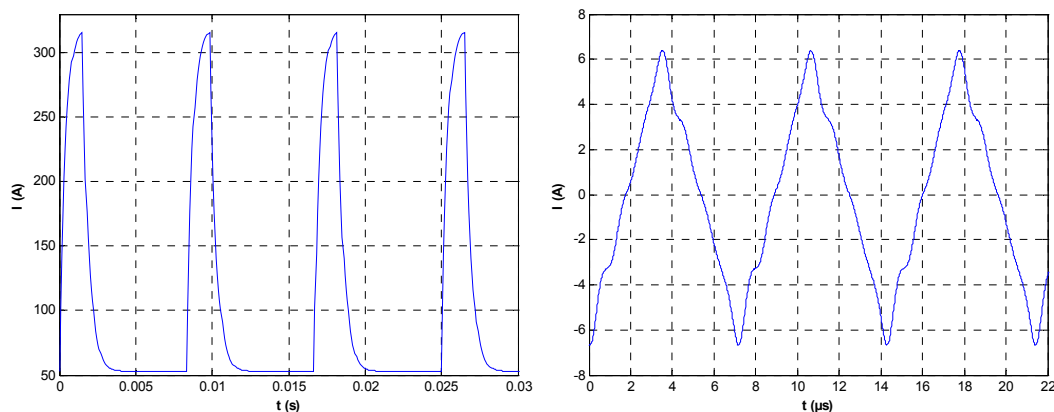


**Figure 7-2 (left) Exposure setup for the MIG welding application with indicated measurement grid, and (right) typical position of the welder (Molla-Djafari et al, 2008)**

The observed MIG/MAG welding equipment was a Fronius Transpuls Synergic 5000, TPS 5000 Doppelkopf from Fronius International GmbH with the following operational settings:

- MIG, 100% Argon
- Pulsed mode
- Material: Al Mg 5
- 1.2 mm wire, 6 m/min feed left (AW 5000 JM, H-flute)
- Only left feed used

The utilized welding current is shown in Figure 7-3 giving the low and high frequency components. Current measurements were performed with the equipment already given in Footnote 14.

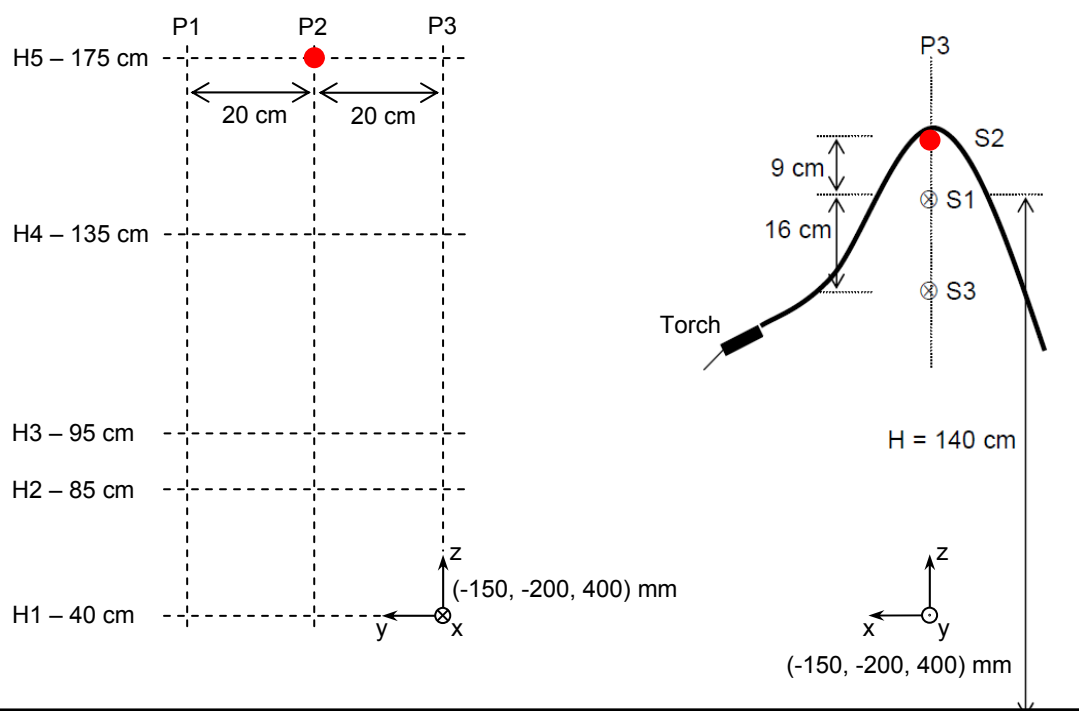


**Figure 7-3 Welding currents' (left) low frequency, and (right) high frequency component**

## Measurement Procedure

Due to the character of the emitted field and the aim of performing detailed exposure analysis for the assessed MIG welding workplace, time domain field measurements utilizing broadband field meters with appropriate probes and subsequent frequency analysis were executed. This has the advantage of having all necessary information of the measured field available (amplitude, waveform, phase relation of the three spatially perpendicular sensors, polarization), and thus enables arbitrary subsequent data analysis, but also the disadvantage of being costly in time and money. Furthermore, performing measurements with such extensive methods gives evidence to low achievable uncertainties, maybe important due to typically high fields in welding applications near or above the reference values. Other possibilities like the use of exposimeters or broadband field meters assessing simply the RMS or other descriptive values of the measured field were excluded due to shortcomings in assessing pulsed, non-sinusoidal fields as already discussed in Section 5 and 6. A further applicable method will be numerical simulations of the given scenario. However, this should not be discussed within this thesis.

Exposure measurements were executed at the normal working position of the welder in a vertical grid on 15 measurement points and three additional measurement points in the plane of the shoulder loop. Positioning was performed in a way that the center of the used probe overlaps with the measurement points. The grid measurement, however, enables to assess the field over the whole body of the welder. This is especially important for the existing spatial inhomogeneity of the field and accounts for the fact that spatial averaging of the maximum field over the whole body is not applicable in the given scenario following the EN 50445 (2008). The measurement positions with respect to the described exposure setup are shown in Figure 7-4<sup>136</sup>.



**Figure 7-4 Measurement grid in a plane perpendicular to the welding cable path, P3 in the plane of the shoulder loop with three additional POIs from Molla-Djafari et al (2008), with changes**

<sup>136</sup> Red points indicate the positions also highlighted in Figure 7-1. Relative grid position is given in Figure 7-2. Position of the coordinate systems' origin is given in style (x, y, z).

Measurements were executed subsequently with two different field meters at each measurement point shown in Figure 7-4. The selected meters with the appropriate probes enable measurements over the whole dynamic and frequency range of the magnetic field emitted by the welding application. The measurement equipment provides a time signal, which is sampled (via a PXI 8184 RT with PXI 6250 and PXI 6120 data acquisition units from National Instruments) and further processed via a LabVIEW application. An offset and linearity correction of the DC probe as well as an optional high pass filtering of the AC data is included. Frequency analysis is done via a FFT of the captured time signals, including the correction for frequency overlaps of the two probes<sup>137</sup>.

### Measurement Equipment

Two different field meters were used to assess the magnetic flux density  $B$  at the MIG welding workplace described above: one Hall meter (Lake Shore Gaussmeter type 460) for the DC and lower frequency field components, and one inductive field meter for the higher frequency field components (Narda ELT-400). Both meters provide three voltages proportional to the three orthogonally measured magnetic flux densities ( $B_x$ ,  $B_y$ , and  $B_z$ ).

The Lake Shore 460 with the MMZ-2512-UH magnetic field probe measures the magnetic flux density in a frequency range from 0 Hz to 400 Hz. The device has three measurement modes (DC, RMS, and peak) as well as the possibility to directly output the measured signal on an interface (used for the presented measurements). The specification of the meter and probe is listed in Table 7-1.

**Lake Shore 460 Gaussmeter Specification**

<b>AC Frequency Range</b>	10 Hz to 400 Hz
<b>Full Scale Ranges (Probe)</b>	3 mT, 30 mT, 300 mT, 3 T
<b>Corrected Accuracy (Probe)</b>	±0.25% (up to 2 T)
<b>Temperature Coefficient (Probe)</b>	±0.015%/°C
<b>DC Accuracy</b>	±0.10% of reading ±0.005% of range
<b>DC Temperature Coefficient</b>	±0.05% of reading ±0.003% of range per °C
<b>AC RMS Accuracy</b>	±2% of reading (50 Hz to 60 Hz)
<b>AC RMS Frequency Response</b>	0 to -3.5% of reading (10 Hz to 400 Hz) <sup>138</sup>
<b>Corrected Analog Output Accuracy</b>	±0.1%
<b>Sampling Frequency</b>	18 Hz

**Table 7-1 Specification of the Lake Shore 460 Gaussmeter and the MMZ-2512-UH magnetic field probe (Web8, 2012)**

The Narda ELT-400 in combination with the according 100 cm<sup>2</sup> inductive coil probe measures the magnetic flux density (STD<sup>139</sup>, peak, RMS, or direct output of the time signals proportional to the measured field) in a frequency range from 1 Hz<sup>140</sup> up to 400 kHz with a

<sup>137</sup> This correction is performed in a way that, if both probes provide a field value at the same frequency one of them is omitted to avoid overestimation. Ideally the higher of the two values (if they deviate from each other) is chosen for further evaluation following a worst-case approach.

<sup>138</sup> All AC RMS specifications are given for sinusoidal inputs >1% of range.

<sup>139</sup> This is the so called shaped time domain mode (Narda, 2004), implementing the peak weighted average approach according to ICNIRP (2010).

<sup>140</sup> If measurements with both probes are performed (as always the case within the presented setup) the lowest frequency measured by the Narda meter should not go below 100 Hz.

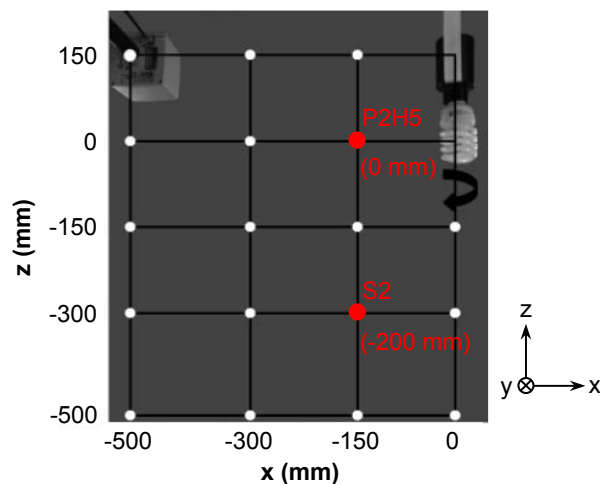
measurement range of 32  $\mu\text{T}$  to 80 mT. The combined measurement uncertainty is given with  $\pm 4\%$  (95% level of confidence, 50 Hz to 120 kHz). The sampling time is in the order of 1  $\mu\text{s}$ . (Narda, 2004)

### 7.1.2 Compact Fluorescent Lamps

Exposure data for the second source of EMFs in the treated exposure scenario, namely a CFL lighting the welders' workplace, is compiled from the literature (Nadakuduti et al, 2011). The dominance of electric fields at frequencies of some 10 kHz as well as the spatial inhomogeneity of these fields in near proximity to the lamps was already discussed in Section 2.3. The measurement method including the exposure setup and the measurement procedure as well as the measurement equipment utilized in Nadakuduti et al (2011) is summarized.

#### Exposure Setup and Measurement Procedure

Electric field measurements were performed given the setup shown in Figure 7-5. The center of the welders' head is positioned at P2H5 (Figure 7-1). To be able to capture the maximum fields in the surrounding of CFLs, time domain measurements with subsequent maximum peak-hold analysis were executed (evaluation window 30 s, resolution bandwidth 10 kHz) at the 18 labeled measurement points shown in Figure 7-5<sup>141</sup>, representing again the position of the probes' center. Measurements were performed in a shielded enclosure to easily control the setup and minimize disturbances due to other EMF sources. Furthermore, the measurements were repeated for different rotations of the CFL as also indicated in Figure 7-5, again to ensure capturing the maximum possible fields.



**Figure 7-5 Exposure setup for the CFL showing the EHP-200 field analyzer in the left upper corner and the CFL in the right upper corner from Nadakuduti et al (2011), with changes**

Eleven CFLs were measured in total, whereas the one with the highest electric field values showed a basic frequency (of the electronic ballast) of 47.1 kHz. Existing odd harmonics do not contribute significantly to the exposure quotient calculated according to the ICNIRP (1998) sum formulae.

<sup>141</sup> Directly at the position of the lamp no measurements are possible, thus no measurement points are indicated. Red points indicate the positions also highlighted in Figure 7-1. Values in brackets at S2 and P2H5 give the y-position; z-position is given relative to P2H5.

## Measurement Equipment

A Narda EHP-200 electric and magnetic field analyzer was utilized. This device is able to measure electric fields in a frequency range from 9 kHz up to 30 MHz in three orthogonal directions with an in-built spectrum analyzer. The analyzer may be controlled and the data further analyzed by a software application. The specification of the Narda EHP-200 is given in Table 7-2.

**Narda EHP-200 Field Analyzer Specification**

<b>Frequency Range</b>	9 kHz to 30 MHz
<b>Measurement Range</b>	0.1 – 1000 V/m (10 kHz resolution bandwidth)
<b>Sensitivity</b>	0.1 V/m (10 kHz resolution bandwidth)
<b>Resolution</b>	0.01 V/m
<b>Frequency Flatness</b>	±0.5 dB (0.1 to 27 MHz; 20 V/m)
<b>Anisotropy</b>	±0.8 dB (1 MHz)
<b>Linearity</b>	0.5 dB (1 MHz)
<b>Temperature Coefficient</b>	0.02 dB/°C

**Table 7-2 Specification of the Narda EHP-200 field analyzer (Web9, 2012)**

## 7.2 Results for Metal Inert Gas Welding

Based on the exposure sub-scenario, the assessment method and the according measurement equipment presented in Section 7.1.1 an overview on the achieved measurement results is given. Furthermore, extended uncertainty budgets with detailed information on meaning, significance and evaluation process of each uncertainty component are discussed. Different possibilities for establishing these budgets as well as an overall uncertainty are presented.

### 7.2.1 Measurement Results

Important measurement results for the described MIG welding application setup are presented, giving insight into the field distribution at the considered workplace. Therefore, Table 7-3 shows the compiled exposure quotients at the measurement points from Figure 7-4 according to the sum formulae in ICNIRP (1998)<sup>142</sup>. Thus, values higher than one indicate an exceeded reference value. As can be seen, for 15 of 18 measurement points such an exceedance occurs, with the highest values under the shoulder loop (S1 and S2) and directly besides the loop (P3H4). Furthermore, it can be observed that fields obviously decay relatively fast above the shoulder loop (P1H5, P2H5, and P3H5). Non-continuous field decays along the vertical lines P1H4-P1H1 and P2H4-P2H1 were measured. However, the field decay along the vertical line P3H4-P3H1 was assessed to be continuous.

No reference level exceedance could be evaluated with respect to thermal effects, though there is a marginal possibility of an exceedance at S2. In general, higher frequency components (>100 kHz) leading to thermal effects are much smaller in amplitude than the lower frequency components. This may be seen from the highly deviating amplitudes in Figure 7-3 for the low and the high frequency component of the utilized current, respectively.

<sup>142</sup> Formulas used for calculating the *EQs* are Equations (3-4) and (3-6). According reference values are given in Appendix A.

Measurement Point	EQ Evaluation According to ICNIRP (1998)	
	Nerve Excitation (1 Hz – 400 kHz) (rel. to limit value)	Thermal Effects (100 kHz – 400 kHz) (rel. to limit value) <sup>143</sup>
P1H1	1.58	<ldl <sup>144</sup>
P1H2	2.18	0.0056
P1H3	2.12	0.0061
P1H4	1.25	<ldl
P1H5	0.081	<ldl
P2H1	2.57	0.0064
P2H2	3.68	0.0126
P2H3	4.36	0.0113
P2H4	4.29	0.0160
P2H5	0.43	<ldl
P3H1	3.32	0.0086
P3H2	4.39	0.0184
P3H3	5.51	0.0177
P3H4	12.91	0.184
P3H5	0.93	<ldl
S1	16.31	0.391
S2	22.35 <sup>145</sup>	not measurable <sup>146</sup>
S3	9.53	0.126
	$B_{max}$ (μT)	
P1H5	341.8	
S2	2135.45	

**Table 7-3 Compilation of calculated exposure quotients at the measurement points shown in Figure 7-4, and amplitude values of the magnetic field strength  $B_{max}$  at two measurement positions from Molla-Djafari et al (2008), with changes**

To get a sense of the measured field amplitudes, these amplitudes measured at the positions with the highest and lowest exposure are summarized at the end of Table 7-3. However, it is shown that the field distribution at the typical working position of the welder is highly inhomogeneous in space. The highest exposure is obviously found under the shoulder loop leading to a possible reference level exceedance of up to a factor of about 22<sup>147</sup> and a maximum amplitude of about 2 mT.

## 7.2.2 Uncertainty Budget

Based on measurements and simulations, as well as on datasheets, specifications and calibration certificates of the measurement equipment, it is discussed how appropriate uncertainty budgets for the above described exposure scenario at the MIG welding workplace are arranged.

<sup>143</sup> No 6 minute averaging was performed.

<sup>144</sup> Values <3.16% of the reference level are indicated as smaller than the lower detection limit (ldl) (ICNIRP, 1998).

<sup>145</sup> Due to the size of the 100 cm<sup>2</sup> coil probe for the ELT-400 no measurements could be performed for frequencies higher than 400 Hz. This is the highest assessed value of exposure.

<sup>146</sup> see Footnote 145

<sup>147</sup> Even when utilizing ICNIRP (1998) limits for possible nerve excitation and occupational exposure in compliance assessment, and considering the phase relations between the three orthogonally measured fields (summation formulae according to ICNIRP (2003) for phase consideration), a reference level exceedance by a factor of in maximum 15.4 was evaluated (Molla-Djafari et al, 2008).

However, it seems beneficial to establish separate budgets for both measurement devices, the ELT-400 (Table 7-4) and the Lake Shore 460 (Table 7-5), as distinct frequency ranges are covered by these devices. Furthermore, uncertainty contributions identified below may contribute to varying extent to the expanded uncertainty for each meter due to different operating principles. In general, to get a good understanding of the present situation, it is advisable to split up uncertainty evaluations with respect to any parameter (e.g., frequency or power range, type of measurement equipment) showing significant influence on the uncertainty.

A classification of uncertainty components in four major categories, namely “Field Source”, “Measurement Equipment”, “Methodology”, and “Environment” is adopted to improve the readability. Uncertainty components were established by using both type A and type B evaluations of uncertainty in all conscience. The appearance of the established uncertainty budgets as well as the defined uncertainty categorization follows the IEC 62232 (2011) and other documents referenced in Section 4.

Uncertainty budgets are established assuming the single uncertainty contributions to be (sufficiently) independent from each other, and the overall uncertainty to be normal distributed. This enables to build the expanded uncertainty as the RSS of all standard uncertainties multiplied by a coverage factor of two (leading to a coverage probability of approximately 95%). A realistic approach is followed, i.e., realistic uncertainty values and not necessarily the worst-case values are included in the budget. Nevertheless, worst-case assumptions are discussed in the text.

In general, percentage representations of uncertainty are given in this document ( $u_{\%}$ ). Transformation from linear to dB ( $u_{dB}$ ) values was performed following the next equation, if not otherwise stated<sup>148</sup>.

$$u_{dB} = 20 * \log \left( 1 + \frac{u_{\%}}{100} \right) \quad (7-1)$$

For sound uncertainty evaluations, reasonable in such complex exposure scenarios, all imaginable uncertainty contributions need to be included in the uncertainty budgets, even if they turn out not to be significant. This at least shows their consideration and thus enhances the traceability and reproducibility of the performed investigations<sup>149</sup>.

Unfortunately, due to a general lack of knowledge on complex exposure assessment of SF, ELF, and IF EMFs in combination with sound uncertainty evaluations (Section 5), not all included uncertainty contributions in Table 7-4 and Table 7-5 are currently known. Those contributions are labeled as n.a.y. (not available yet). Others, though important to be considered, do not apply in the special scenario and are labeled as n.a. (not applicable). Values  $v_i$  in Table 7-4 and Table 7-5 are quoted uncertainties or semi-ranges  $a_i = (a_+ - a_-)/2$ . If uncertainties are asymmetric, both values are given. A detailed description and the according evaluation process for each component are presented (Section 7.2.3), followed by the determination of an overall expanded uncertainties for the assessment including a short discussion of the results (Section 7.2.4).

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<sup>148</sup> Field quantities like the electric and magnetic field strength or the magnetic flux density are considered. For power quantities a factor of ten instead of 20 has to apply in Equation (7-1).

<sup>149</sup> However, the compiled uncertainty budgets do not claim completeness.

Uncertainty Evaluations in Complex Exposure Scenarios

No.	Source of Uncertainty	Unit	Prob. Distrib. Type	Value $v_i$	Divisor $d_i$	Sens. Coeff. $c_i$	$u_i =  c_i  * v_i / d_i$
<b>1</b>	<b>Field Source</b>						
1.1	Stability of the Welding Current	%	normal	5.08	1	1	5.08
<b>2</b>	<b>Measurement Equipment</b>						
2.1	Combined Measurement Uncertainty of the Field Meter / Probe	%	normal	4	2	1	2
2.2	Field Meter Resolution	%	rect	n.a.	$\sqrt{3}$	1	n.a.
2.3	Out of Band Responses of the Field Meter / Probe	%	rect	n.a.	$\sqrt{3}$	1	n.a.
2.4	Calibration of the Field Meter / Probe	%	normal	15	2	1	7.5
2.5	Calibration of the Data Acquisition Unit	%	normal	n.a.y.	2	1	n.a.y.
2.6	Drift of the Field Meter / Probe	%	rect	n.a.	$\sqrt{3}$	1	n.a.
2.7	Data Acquisition Unit – Input Reading	%	rect	0.08	$\sqrt{3}$	1	0.05
2.8	Data Acquisition Unit – Output Reading	%	rect	0.05	$\sqrt{3}$	1	0.03
<b>3</b>	<b>Methodology</b>						
3.1	Positioning of the Probe	%	rect	$\sqrt{3} * 2$ cm	$\sqrt{3}$	10%/cm	20
3.2	Measurement Grid Position	%	rect	n.a.	$\sqrt{3}$	1	n.a.
3.3	Averaging of the Probe in Inhomogeneous Fields	%	normal	-5 / 4.7	1	1	-5 / 4.7
3.4	Isotropy of the Probe in Inhomogeneous Fields	%	rect	n.a.y.	$\sqrt{3}$	1	n.a.y.
3.5	RMS Integration Time	%	rect	n.a.	$\sqrt{3}$	1	n.a.
3.6	Time Constant of the Meter	%	rect	n.a.	$\sqrt{3}$	1	n.a.
3.7	FFT Analysis	%	normal	n.a.	2	1	n.a.
3.8	Spatial Averaging	%	rect	n.a.	$\sqrt{3}$	1	n.a.
3.9	Time Averaging	%	rect	n.a.	$\sqrt{3}$	1	n.a.
3.10	Influence of the Measurement Equipment on the Field	%	rect	n.a.	$\sqrt{3}$	1	n.a.



No.	Source of Uncertainty	Unit	Prob. Distrib. Type	Value $v_i$	Divisor $d_i$	Sens. Coeff. $c_i$	$u_i =  c_i  * v_i / d_i$
<b>4</b>	<b>Environment</b>						
<b>4.1</b>	Combined Temperature a. Humidity Response of the Field Meter	%	rect	n.a.	$\sqrt{3}$	n.a.y.	n.a.
<b>4.2</b>	Combined Temperature a. Humidity Response of the Probe	%	rect	n.a.	$\sqrt{3}$	n.a.y.	n.a.
<b>4.3</b>	Temperature Response of the Data Acquisition Unit	%	rect	n.a.	$\sqrt{3}$	0.0006%/°C	n.a.
<b>4.4</b>	Humidity Response of the Data Acquisition Unit	%	rect	n.a.	$\sqrt{3}$	n.a.y.	n.a.
<b>4.5</b>	Coupling of Interfering Signals with the Measurement System	%	rect	n.a.	$\sqrt{3}$	1	n.a.
<b>4.6</b>	Environmental Changes during Measurement	%	rect	n.a.	$\sqrt{3}$	1	n.a.
<b>4.7</b>	Influence of the Measurement Person	%	rect	n.a.	$\sqrt{3}$	1	n.a.
<b>4.8</b>	Influence of the Welder's Body on Electric Fields	%	rect	n.a.	$\sqrt{3}$	1	n.a.
<b>4.9</b>	Influence of the Welder's Body on Magnetic Fields	%	normal	2.06	1	1	2.06
<b>4.10</b>	Background Fields and Noise	%	rect	20	$\sqrt{3}$	1	11.55
	<b>Combined Standard Uncertainty, <math>u_c = \sqrt{(u_i)^2}</math></b>						+25.4%/ -25.5%
	<b>Coverage Factor for a 95% Level of Confidence, <math>k</math></b>						2
	<b>Expanded Uncertainty, <math>U = k * u_c</math></b>						<b>+50.8%/-51%</b>

Table 7-4 Uncertainty budget for magnetic flux density measurements with an ELT-400 field meter and according 100 cm<sup>2</sup> inductive coil probe in a distance of 20 cm to the welding cable shoulder loop

Uncertainty Evaluations in Complex Exposure Scenarios

No.	Source of Uncertainty	Unit	Prob. Distrib. Type	Value $v_1$	Divisor $d_1$	Sens. Coeff. $c_1$	$u_1 =  c_1  * v_1/d_1$
<b>1</b>	<b>Field Source</b>						
1.1	Stability of the Welding Current	%	normal	5.08	1	1	5.08
<b>2</b>	<b>Measurement Equipment</b>						
2.1	RMS Frequency Response of the Meter (AC)	%	rect	n.a.	$\sqrt{3}$	1	n.a.
2.2	Accuracy of the Meter (DC)	%	rect	n.a.	$\sqrt{3}$	1	n.a.
2.3	RMS Accuracy of the Meter (AC)	%	rect	n.a.	$\sqrt{3}$	1	n.a.
2.4	Corrected Analog Output Accuracy	%	rect	0.1	$\sqrt{3}$	1	0.06
2.5	Corrected Accuracy of the Probe	%	rect	0.25	$\sqrt{3}$	1	0.14
2.6	Field Meter Resolution	%	rect	n.a.	$\sqrt{3}$	1	n.a.
2.7	Out of Band Responses of the Field Meter / Probe	%	rect	n.a.y.	$\sqrt{3}$	1	n.a.y.
2.8	Calibration of the Field Meter / Probe	%	normal	n.a.y.	2	1	n.a.y.
2.9	Calibration of the Data Acquisition Unit	%	normal	n.a.y.	2	1	n.a.y.
2.10	Drift of the Field Meter / Probe	%	rect	n.a.	$\sqrt{3}$	1	n.a.
2.11	Data Acquisition Unit – Input Reading	%	rect	0.01	$\sqrt{3}$	1	0.006
2.12	Data Acquisition Unit – Output Reading	%	rect	0.01	$\sqrt{3}$	1	0.006
<b>3</b>	<b>Methodology</b>						
3.1	Positioning of the Probe	%	rect	$\sqrt{3} * 2$ cm	$\sqrt{3}$	10%/cm	20
3.2	Measurement Grid Position	%	rect	n.a.	$\sqrt{3}$	1	n.a.
3.3	Averaging of the Probe in Inhomogeneous Fields	%	rect	n.a.	$\sqrt{3}$	1	n.a.
3.4	Isotropy of the Probe in Inhomogeneous Fields	%	rect	n.a.y.	$\sqrt{3}$	1	n.a.y.
3.5	RMS Integration Time	%	rect	n.a.	$\sqrt{3}$	1	n.a.
3.6	Time Constant of the Meter	%	rect	n.a.	$\sqrt{3}$	1	n.a.
3.7	FFT Analysis	%	normal	n.a.	2	1	n.a.

No.	Source of Uncertainty	Unit	Prob. Distrib. Type	Value $v_i$	Divisor $d_i$	Sens. Coeff. $c_i$	$u_i =  c_i  * v_i/d_i$
3.8	Spatial Averaging	%	rect	n.a.	$\sqrt{3}$	1	n.a.
3.9	Time Averaging	%	rect	n.a.	$\sqrt{3}$	1	n.a.
3.10	Influence of the Measurement Equipment on the Field	%	rect	n.a.	$\sqrt{3}$	1	n.a.
4	<b>Environment</b>						
4.1.	Temperature Response of the Field Meter (DC)	%	rect	n.a.	$\sqrt{3}$	0.0503%/°C	n.a.
4.2	Temperature Response of the Field Meter (AC)	%	rect	n.a.	$\sqrt{3}$	n.a.y.	n.a.
4.3.	Humidity Response of the Field Meter (DC/AC)	%	rect	n.a.	$\sqrt{3}$	n.a.y.	n.a.
4.4.	Temperature Response of the Probe	%	rect	n.a.	$\sqrt{3}$	0.015%/°C	n.a.
4.5.	Humidity Response of the Probe	%	rect	n.a.	$\sqrt{3}$	n.a.y.	n.a.
4.6.	Temperature Response of the Data Acquisition Unit	%	rect	n.a.	$\sqrt{3}$	0.0006%/°C	n.a.
4.7.	Humidity Response of the Data Acquisition Unit	%	rect	n.a.	$\sqrt{3}$	n.a.y.	n.a.
4.8.	Coupling of Interfering Signals with the Measurement System	%	rect	n.a.	$\sqrt{3}$	n.a.y.	n.a.
4.9.	Environmental Changes during Measurement	%	rect	n.a.	$\sqrt{3}$	n.a.y.	n.a.
4.10.	Influence of the Measurement Person	%	rect	n.a.	$\sqrt{3}$	1	n.a.
4.11.	Influence of the Welder's Body on Electric Fields	%	rect	n.a.	$\sqrt{3}$	1	n.a.
4.12.	Influence of the Welder's Body on Magnetic Fields	%	normal	2.06	1	1	2.06
4.13.	Background Fields and Noise	%	rect	20	$\sqrt{3}$	1	11.55
<b>Combined Standard Uncertainty, <math>u_c = \sqrt{(u_i)^2}</math></b>							$\pm 23.74\%$
<b>Coverage Factor for a 95% Level of Confidence, k</b>							2
<b>Expanded Uncertainty, <math>U = k * u_c</math></b>							<b><math>\pm 47.48\%</math></b>

Table 7-5 Uncertainty budget for magnetic flux density measurements with a Lake Shore 460 Gaussmeter and according MMZ-2512-UH Hall probe in a distance of 20 cm to the welding cable shoulder loop

### 7.2.3 Uncertainty Components

A detailed description of all uncertainty components from Table 7-4 and Table 7-5 including details on the evaluation process and grouped into the four given categories is presented.

#### Field Source

When performing exposure measurements, exposure conditions should be kept constant during the whole assessment. However, this is not achievable in practice, as already the field source to be evaluated exhibits variations in the generated fields.

Thus, uncertainties ascribed to the field source (Table 7-4, Table 7-5 – 1.1), i.e., the MIG welding equipment, may account for deviations of the current waveform from the assumed ideal waveform. In addition to an inherent variation of the generated welding current produced by the welding power source there are possible variations in the arc<sup>150</sup>. These current variations certainly lead to according magnetic field fluctuations.

To achieve a measure of typical source stabilities in welding, two different measurements were conducted on an electrode hand welding application<sup>151</sup>:

- A resistance was connected to the welding equipment giving the possibility to observe the inherent current variations of the welding power source ( $u_i$ ), without any artifacts due to changes in the arc<sup>152</sup>.
- The resistive connection was removed by the setup shown in Figure 7-2 with a welder holding the torch during the measurement process, giving the possibility to observe variations due to both, the inherent current variation ( $u_i$ ) as well as the variations in the arc ( $u_{arc}$ ), respectively ( $u_{total}$ ).

However, the total standard uncertainty  $u_{total}$  of the welding current may be calculated according to the next equation, assuming that both uncertainty contributions are independent.

$$u_{total} = \sqrt{u_i^2 + u_{arc}^2} \quad (7-2)$$

Four periods of the investigated high frequency current component with a basic frequency of about 200 kHz are shown in Figure 7-6. In total 40.000 periods of the high frequency current

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<sup>150</sup> Current changes are due to e.g., changes in the workpiece and the electrode as well as movements of the torch.

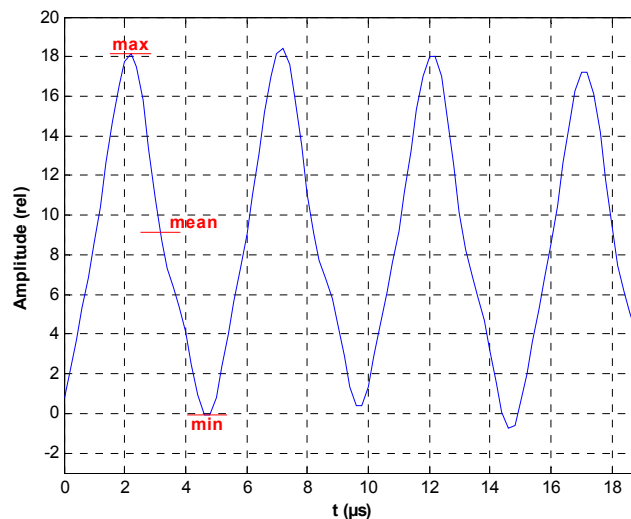
<sup>151</sup> Within electrode hand welding the arc is burning continuously, with the current not having a pulsed character as shown above in Figure 7-3 (left) (leading to a DC current with superposed higher frequency components – current ripple). This enables an easier evaluation of current fluctuations, which is assumed similar to those in MIG welding. However, the variability of the current is evaluated via the higher frequency components (>10 kHz). Measurements were performed on a TransPocket 5000 from Fronius International GmbH with an F-51 inductive current probe, measuring the time derivative of the current, from Fischer Custom Communications, Inc. Integration of the probe signal was performed using LabVIEW from National Instruments to achieve the appropriate current waveform shown in Figure 7-6 (approximately equal to the higher frequency component used in MIG welding Figure 7-3 (right)). No offset correction was performed. Values are given in relative units (rel) – voltage proportional to the actual current.

<sup>152</sup> The cable guide was kept equal to the setup shown in Figure 7-2 best possible.

waveform were measured and taken as a sample for the performed statistical analysis<sup>153</sup>. Measurements to derive  $u_{\text{total}}$  were repeated two times, whereas the measurement with a resistive connection between the torch and the work piece (to derive  $u_i$ ) was only performed once.

However, with respect to the available data, fluctuations between each period of the waveform may either be observed utilizing the mean, the maximum, the minimum, or the peak-peak<sup>154</sup> current value per period, indicated in Figure 7-6. In view of the possibly evoked physiological response in the scenarios' frequency range, namely a possible nerve excitation<sup>155</sup>, the peak-peak current value was supposed to be the most suitable measure for evaluating the current variations<sup>156</sup>.

The probability distribution of this parameter for both measurement setups and the three performed measurements were approved to be (approximately) normal. As one example Figure 7-7 shows the histogram for the peak-peak values and the second measurement setup in measurement number 1.



**Figure 7-6 High frequency component of the welding current used for evaluating the typical source stability, with indication of the maximum (max), the minimum (min) and the mean value of the first period**

Uncertainty Component	Waveform Parameter	Value (rel)		$\overline{u_{\text{total}}}$ (rel)
		Meas. No. 1	Meas. No. 2	
$u_{\text{total}}$	peak-peak	0.9773	0.8279	<b>0.9026</b>
$u_i$	peak-peak	0.4529	-	-
$u_{\text{arc}}$ <sup>157</sup>	peak-peak	0.8661	-	-

**Table 7-6 Standard uncertainties of the peak-peak current value per period for all performed measurements**

<sup>153</sup> A sampling frequency of 5 MHz (one measurement each 0.2  $\mu\text{s}$ ) and an overall measurement time of 0.2 s were utilized.

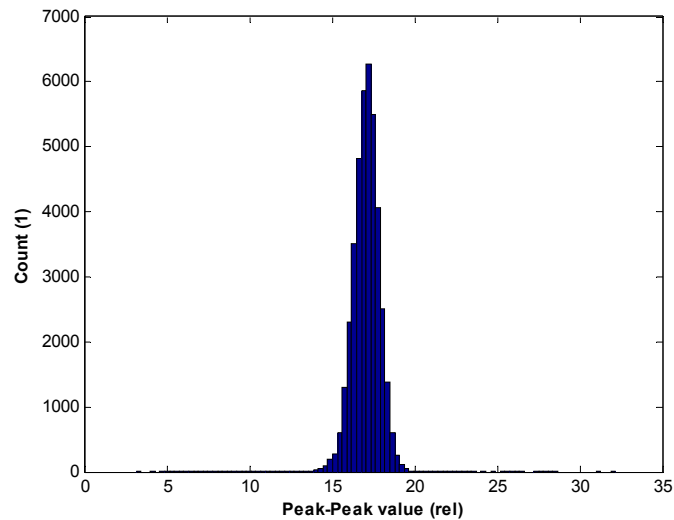
<sup>154</sup> The peak-peak value was calculated as the maximum minus the minimum value per period.

<sup>155</sup> No thermal effects are considered (Section 7.2.1).

<sup>156</sup> Besides carrying out the peak-peak variations of the current, it seems reasonable to evaluate the fluctuations of the time derivative of the welding current, as the  $dB/dt$  can also be seen as an appropriate exposure metric (e.g., BGV B11 (2001), ICNIRP (2010)). When doing so, variations of about  $\pm 7.95\%$  can be achieved.

<sup>157</sup> The value of  $u_{\text{arc}}$  was calculated from the two measured quantities  $u_{\text{total}}$  and  $u_i$  via Equation (7-2).

The standard uncertainties of the peak-peak value for all three performed measurements were calculated (Table 7-6). Furthermore, the arithmetic mean  $\overline{u_{total}}$  was determined for the repeated observations of  $u_{total}$ .



**Figure 7-7 Probability distribution of the peak-peak-value for measurement number 1 to deduce the total current variation ( $u_{total}$ )<sup>158</sup>**

The mean of the two peak-peak standard uncertainties is included in the uncertainty budgets, normalized to the mean of the peak-peak values over all periods and all measurements (17.769 (rel)). This leads to a typical percentage variation of the welding current of  $\pm 5.08\%$  (68% level of confidence). However, it can further be assumed from Table 7-6 that fluctuations due to variations in the arc ( $u_{arc}$ ) are far higher compared to the inherent current fluctuations ( $u_i$ ).

### Measurement equipment

The measurement equipment can be identified as the second important source of uncertainties in exposure evaluation. As described in Section 7.1.1 the utilized equipment consists of a Narda ELT-400 field meter with a 100 cm<sup>2</sup> coil probe, a Lake Shore 460 Gaussmeter with appropriate probe (MMZ-2512-UH), as well as a data acquisition unit from National Instruments (PXI 8184 RT with PXI 6250 and PXI 6120 data acquisition units) connected to a personal computer.

Information on typical uncertainties associated with the measurement equipment is most often taken from datasheets, specifications, manufacturer handbooks or calibration certificates. However, in some cases this information turns out to be sparse, with most often providing combined uncertainties including a variety of uncertainty contributions with no detailed breakdown. In such situations, especially for measurements in complex exposure scenarios, reliable uncertainty estimation gets challenging<sup>159</sup>.

<sup>158</sup> The histogram was produced for 100 bins.

<sup>159</sup> Just to mention one example: most probes' isotropy uncertainty is given for sinusoidal fields and homogeneous spatial field distributions. This is, however, not the case in the issued exposure scenario. Thus, if no separate value for the isotropy uncertainty is given in the datasheet of the probe or elsewhere, it is difficult to finally obtain the correct value of the overall measurement equipment uncertainty in inhomogeneous fields.

Anyhow, the combined measurement uncertainty<sup>160</sup> of the ELT-400 field meter with the appropriate probe is found to be  $\pm 4\%$  (95% level of confidence) specified in the datasheet (Narda, 2004; Table 7-4 – 2.1). The specification of uncertainties for the Lake Shore 460 with the appropriate probe is more detailed and was already given in Table 7-1 (Web8, 2012), whereas only the corrected analog output accuracy  $\pm 0.1\%$  as well as the corrected accuracy of the probe  $\pm 0.25\%$  apply (Table 7-5 – 2.1 to 2.5). Concerning the read out of the probe signal, the resolution (Table 7-4 – 2.2, Table 7-5 – 2.6) of the field meter has to be considered. Since in the present measurement setup the analog signal of the probe is just handed over to the data acquisition unit by the field meter, no such contribution needs to be included in the overall uncertainty. However, as already mentioned the readout is performed by the data acquisition unit, and thus an according uncertainty for the input reading has to be stated there (Table 7-4 – 2.7, Table 7-5 – 2.11).

Furthermore, out of band responses of the field meter and probe (Table 7-4 – 2.3, Table 7-5 – 2.7) may contribute to the overall uncertainty. Unfortunately, no information on this was found in the literature for the used equipment till now and therefore no value is included in the budgets. However, these out of band responses may easily be evaluated by performing additional measurements with a set of arbitrary signals showing a frequency spectrum outside the measurement band of the equipment. It can be suggested that there is less evidence to out of band responses of the Narda probe as fields outside its frequency range should not have been present during measurements. This was checked by preliminary background field measurements. On the other hand, the readings of the Lake Shore Gaussmeter may suffer more from signals out of band ( $>400$  Hz).

Calibration of the meter in combination with the probe and of the data acquisition unit is also associated with uncertainties, which should be included in the budgets (Table 7-4 – 2.4 and 2.5, Table 7-5 – 2.8 and 2.9). According values are taken from calibration certificates. A value of  $\pm 15\%$  (normal distributed with  $k$  is two) is given for the Narda ELT-400 calibration. The other contributions are unfortunately not available yet.

Moreover, even when calibrated the equipment is prone to temporal drifts. These drifts may be reduced by periodic re-calibrations of the equipment, following the recommendations of the manufacturer. However, an uncertainty contribution accounting for such drifts should be included in evaluations (Table 7-4 – 2.6, Table 7-5 – 2.10), though this contribution is not applicable in the presented measurements, as the probes were calibrated according to the manufacturers' recommendations.

Besides the input reading<sup>161</sup> also the output reading<sup>162</sup> of the data acquisition unit contributes to the overall uncertainty of the measurement. The mentioned uncertainty components were taken from the according datasheets of the PXI 6250 (Lake Shore 460) and the PXI 6120 (Narda ELT-400) data acquisition units (Web10 (2012) and Web11 (2012)). To compile the correct values from the datasheets the necessary nominal voltage range of the analog input and output need to be defined. Since the Lake Shore 460 provides a maximum output voltage of  $\pm 3$  V, a full scale nominal range of  $\pm 5$  V was chosen for the PXI

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<sup>160</sup> This includes the frequency response, the isotropy as well as the absolute and linearity uncertainty from 50 Hz to 120 kHz (frequency range sufficient for the given scenario as no high exposure contributions above 120 kHz are expected, and frequencies lower 50 Hz are measured with the Hall probe).

<sup>161</sup> This includes offset, gain and quantization error as well as noise uncertainty.

<sup>162</sup> This includes gain and offset error.

6250. The Narda ELT-400 provides a maximum voltage of 0.8 V leading to a necessary full scale range of  $\pm 1$  V for the PXI 6120. The absolute input accuracy can thus be given as  $\pm 0.079\%$  of reading for the Narda probe (Table 7-4 – 2.7) and as  $\pm 0.0101\%$  for the Lake Shore probe<sup>163</sup> (Table 7-5 – 2.11). The absolute output accuracy amounts to  $\pm 0.0529\%$  for the ELT-400 (Table 7-4 – 2.8) and to  $\pm 0.0105\%$  for the Lake Shore 460<sup>164</sup> (Table 7-5 – 2.12).

### Methodology

As the third category of possible uncertainty sources, the methodology used for assessing a specific exposure scenario is considered.

One obvious and significant contribution to the overall uncertainty arises from the positioning of the probe. As in most cases inhomogeneous field distributions have to be assessed, a deviation of the real probe position from the intended position defined during the design of the assessment method, will lead to deviating field readings. The amount of deviation, however, also depends on the distance of the POI to the field source, as for smaller distances the field typically decays faster. For the present scenario the typical field decay over distance perpendicular to the welding current loop can be assumed to be approximately proportional to  $1/r^2$  ( $\alpha$  is two, Section 2.2). Furthermore, a possible positioning deviation  $\Delta r$  of  $\pm 2$  cm was estimated. Following a worst-case approach a short distance  $r$  of 10 cm to the field source can be assumed for the measurement point. With these assumptions and the definition of the magnetic flux density  $B$

$$B = c_{\text{pos}} \left( \frac{1}{r^\alpha} \right), \quad (7-3)$$

the sensitivity coefficient for the positioning uncertainty  $c_{\text{pos}}$  may be derived as the partial derivative of  $B$  with respect to  $r$

$$\partial B = B \left( -\frac{\alpha}{r} \right) \partial r, \quad (7-4)$$

for small changes of  $r$ , as given in the next equation (IEC 61786, 1998).

$$c_{\text{pos}} = \frac{\alpha}{r} B \quad (7-5)$$

Assuming a rectangular distribution finally a semi range  $a_{\text{pos}}$  of  $\pm 23.1\%$  is achieved, following

$$a_{\text{pos}} = \frac{\alpha}{\sqrt{3}} \frac{\Delta r}{r} B. \quad (7-6)$$

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<sup>163</sup> Value was calculated from the given absolute accuracy at full scale (for  $\pm 5$  V full scale)

$AA_{\text{fs}} = 1010 \mu\text{V}$  via  $u_{0\%} = \frac{1010 \mu\text{V} * 100\%}{10 \text{ V}} = 0.0101\%$

<sup>164</sup> Value was calculated from the given absolute accuracy at full scale (for  $\pm 5$  V full scale)

$AA_{\text{fs}} = 1045 \mu\text{V}$  via  $u_{0\%} = \frac{1045 \mu\text{V} * 100\%}{10 \text{ V}} = 0.0105\%$



This is a quite high value if one considers equal variations of the field in the other two spatial directions. In such a worst-case assumption a positioning uncertainty of in total  $\pm 40\%$  will arise according to the next equation.

$$a_{\text{pos}} = \sqrt{(0.231)^2 + (0.231)^2 + (0.231)^2} = 0.40 \quad (7-7)$$

For a more realistic estimation in a mean measurement distance of 20 cm the uncertainty is still high with values of  $\pm 11.54\%$  in one and  $\pm 20\%$  in all three spatial directions (Table 7-4, Table 7-5 – 3.1)<sup>165</sup>. Of course the assumption of having equal variations in each spatial direction is extremely conservative, thus simulations will be a possibility to derive more realistic values for this contribution accounting for real field decay characteristics in all three directions.

Assessing a proper representation of the welders' exposure requires proper positioning of the measurement grid for typical positions of the welder. The positioning has to be performed with respect to a defined reference point and can be assumed to be sufficiently accurate in the given case (Table 7-4, Table 7-5 – 3.2). This is especially reasonable with respect to the typical movements of the welder during welding also leading to uncertainties. However, the defined measurement grid is stated to be representative for the typical position of the welder. For significantly deviating positions of the welder separate assessments have to be conducted. Uncertainties due to a wrong determination of the representativeness of the grid are included in an additional evaluation uncertainty (Section 7.2.4).

Magnetic field coil probes can never be produced ideally isotropic<sup>166</sup>. This is due deviations between the center of the probe as the ideal measurement point and the centers of the sensing coils. Thus the reading of the probe depends on the orientation of the probe in the field. This deviation and the according impact on the probe reading can be accounted for by calibration factors as well as the isotropy uncertainty given by the probe manufacturer. However, calibrations of the probes are most often performed for sinusoidal, linearly polarized fields with a homogeneous spatial distribution. If these conditions are not met, as it is the case in a lot of exposure setups and especially in the considered one, another uncertainty will apply.

Furthermore, due to the finite size of the inductive coil probe for the Nara ELT-400 and the non-uniform field distribution, a field gradient over the volume of the probe may occur, leading to an averaged probe reading which does not equal the field at the center of the probe. This deviation may be accounted for by an appropriate uncertainty.

However, in inhomogeneous fields the above two uncertainty components are not to be evaluated separately in measurements. This is only possible if measurements are combined with analytical or numerical calculations. Investigations on uncertainties due to averaging of (ideally isotropic) three-axis magnetic field probes in an inhomogeneous field proportional to  $1/r^3$  via analytical calculations are given in Misakian and Fenimore (1996)<sup>167</sup>. Assuming a

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<sup>165</sup> The  $\sqrt{3}$  in Table 7-4, Table 7-5 – 3.1  $v_i$  accounts for equal positioning deviations in all three spatial directions.

<sup>166</sup> Ideal isotropy, however, would mean equal readings of the probe for arbitrary orientations of the sensing coils and arbitrary polarizations of the measured field.

<sup>167</sup> Calculations were performed for arbitrary orientations of the probe (three circular coils orthogonally oriented with a common center) as well as the field source as a function of  $r/p$ , with  $p$  as the probe

measurement distance of again approximately 20 cm from the source<sup>168</sup> and a probe radius of 5.64 cm<sup>169</sup>, maximum deviations between the resulting averaged and the center field of -10.8%<sup>170</sup> and 7.6% are stated with values of -5% and 4.7% according to a 68% level of confidence<sup>171</sup>. For shorter distances Misakian and Fenimore (1996) give even higher deviations<sup>172</sup>. To be careful, as the given distribution of measurement deviations is asymmetric the estimated standard deviation has not the same interpretation in giving a level of confidence as is the case for a Gaussian distribution. However, a rough estimate of the according contribution to the total standard uncertainty can be made using the asymmetric values given for a 68% level of confidence.

Although the presented investigations may be too conservative due to a higher field gradient in comparison to the welding exposure, the values of -5% and 4.7% are included in the uncertainty budget for the ELT-400 (Table 7-4 – 3.3). However, following a worst-case approximation for the given distance and the given data one may consider the maximum symmetric deviation of 10.8% in the budgets.

Unfortunately, no specific investigations concerning isotropy uncertainties in inhomogeneous fields comparable with the assessed ones could be found<sup>173</sup>. Thus, no according uncertainty value could be included in the uncertainty budget (Table 7-4 – 3.4). To achieve proper uncertainty values for inhomogeneous fields, in addition to the calculations presented in Misakian and Fenimore (1996), measurements with a similar probe have to be conducted. These measurements will give a combination of both uncertainties, due to the isotropy and the averaging of the probe, respectively. Taking the established uncertainties from calculations one may derive a separate contribution accounting for the isotropy uncertainty.

Hall probes like the MMZ-2512-UH work according to a completely different principle. Thus, the values given above for uncertainties due to averaging of the probe in inhomogeneous fields may not apply here. Such an uncertainty component should, however, be negligible for the Hall probe taking into account the small size of the sensing elements (Table 7-5 – 3.3). On the other hand, also Hall probes may not be produced ideally isotropic, thus an appropriate uncertainty appears in inhomogeneous fields usually not indicated by the manufacturer. Unfortunately, no data was found on this till today (Table 7-5 – 3.4). Measurements with the probe in combination with simulations of typical field distributions should be conducted to deduce appropriate estimates of the isotropy uncertainty in non-homogeneous fields.

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radius, to obtain maximum deviations between the actual field at the center of the probe and the averaged magnetic field. The measurement position is assumed not being too close to the field source (radius of the field source  $\ll r$  has to be satisfied).

<sup>168</sup> Values for a distance of 22.5 cm are taken from Misakian and Fenimore (1996).

<sup>169</sup> Value obtained from an area of the probe of  $A = 100 \text{ cm}^2 \rightarrow A = p^2\pi \Rightarrow p = \sqrt{A/\pi} = 5.64 \text{ cm}$ .

<sup>170</sup> A negative value shows underestimation of the actual field in the center of the probe.

<sup>171</sup> Values were calculated as the 16<sup>th</sup> and 84<sup>th</sup> percentile of the cumulative probability distribution.

<sup>172</sup> Maximum deviations for a distance of about 17 cm to the field source are given with -19.6% and 14.4%. These values or extrapolated ones for even shorter distances may be included in the uncertainty budget following a worst-case approach.

<sup>173</sup> Investigations in Bertocco et al (2007) mentioned in Section 5 are not suitable, as both simulations and measurements were conducted for realistic probes having non-centered coils. Furthermore, the low number of investigated orientations, the different probe design in comparison to the one used in the presented assessment as well as the utilized source setups, would not allow to deduce reliable uncertainty values for the MIG welding scenario.

Standards like the IEC 61786 (1998) give requirements on measurement equipment for electric and magnetic fields with regard to human exposure. One of these requirements is a correct RMS representation of the measured magnetic field for crest factors up to three. Such a correct representation depends on the integration time of the field meter<sup>174</sup>. As already discussed in Section 5.2, typical integration times are in the range of one to a few seconds. For harmonic, pulsed, non-sinusoidal or intermittent fields with high crest factors and short periods, this may lead to huge deviations between the calculated and the real RMS value. However, an uncertainty component due to the integration time does not apply for the present measurement setup, as the ELT-400 and the Lake Shore 460 do not perform any data analysis (Table 7-4, Table 7-5 – 3.5).

Too early readings of a field meter result after probe placement, or inadequate signal processing time for fast changing fields may constitute another uncertainty contribution (IEC 61786, 1998). Also such uncertainties due to time constants of the meter do not apply here, as no readings are taken from the field meters (Table 7-4, Table 7-5 – 3.6).

No noteworthy uncertainty is received when applying a FFT to perfectly periodic signals. However, if the analyzed signals are non-periodic (pulsed, intermittent, and non-stationary), huge deviations in the results can be expected. These deviations depend amongst others on the used window function (e.g., Rectangular, Hann, Hamming, Flattop, etc.), window size, window position, and sampling rate. Discussions on this may for example be found in Mild et al (2009). Specific investigations on deviations due to different window positions with respect to the observed field are given in Crotti and Giordano (2009). No detailed results especially for complex signal shapes as e.g., partly present in welding were found. However, in the presented exposure evaluation a Flattop window<sup>175</sup> was used with a sampling rate of 10 kS/s (massive oversampling) and a window length of 1 second for the Lakeshore 460, as well as a sampling rate of 800 kS/s (Nyquist limit) and a window length of 0.1 seconds for the ELT-400<sup>176</sup>.

Given for example the field measured at position P3H4 shown in Figure 7-8, with a pulse repetition rate of approximately 120 Hz, and given that there are no intermittencies in the welding process during measurements<sup>177</sup>, the utilized windowing will most likely lead to only minor uncertainties in comparison to other uncertainty contributions as e.g., the one accounting for positioning deviations. Thus, no contribution accounting for FFT uncertainties is included in the uncertainty budgets for the moment (Table 7-4, Table 7-5 – 3.7). However, specific investigations on suitable FFT parameters for typical fields in various applications should be conducted to be able to specify standardized procedures for such assessments in complex field environments.

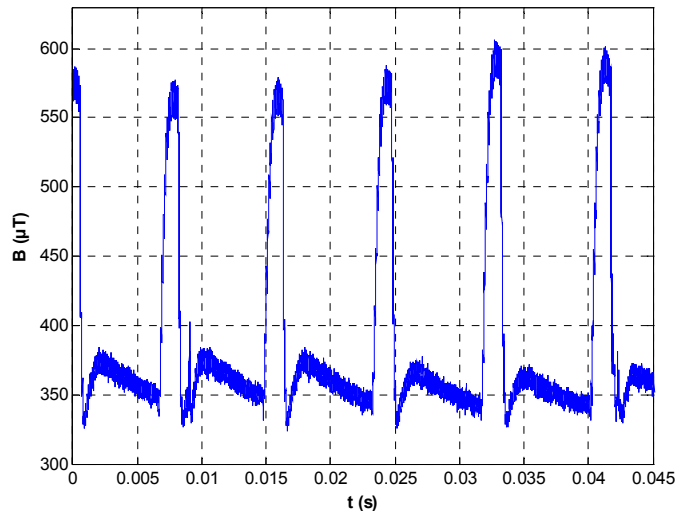
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<sup>174</sup> This integration time has to be sufficiently short. On the other hand, to achieve stable RMS readings the integration time has to exceed the period of the signals' lowest frequency component or the period of the signal's modulation (EN 50413, 2009).

<sup>175</sup> Regarding possible amplitude errors according to different window functions, Meyer (2003) for example gives -3.8 dB for rectangular and 0 dB for flattop windows. The authors in Rauscher et al (2000) state a slightly different value for the flattop amplitude error of about 0.05 dB. Thus, with the flattop window low amplitude errors may be achieved. On the other hand the frequency resolution is reduced, making a window length 3.8 times higher in comparison to a rectangular window necessary.

<sup>176</sup> These settings result in frequency resolutions (1/window length) of 1 Hz (Lake Shore) and 10 Hz (ELT-400), respectively.

<sup>177</sup> The signal can be said to be (quasi-)periodic.



**Figure 7-8 Measured field at position P3H4 according to Figure 7-4 using the Narda ELT-400**

As already discussed in Section 3.1, ICNIRP (1998) gives all reference limits to be compared with spatial whole body averaged RMS values. Furthermore, concerning thermal effects the relevant quantities have to be time averaged<sup>178</sup>. However, ICNIRP (2010) indicates to use the maximum measured field value in the space occupied by the exposed person for highly inhomogeneous fields near EMF sources (<20 cm). For distances bigger typically 20 cm spatial whole or partial body averages are suggested again. Following the EN 50445 (2008) no spatial and time averaging has to be applied on quantities relevant for acute nerve excitation effects in welding applications. The reverse is true when concerning thermal effects. Thus, a variety of different approaches on averaging concepts, spatial and temporal, for compliance evaluation exist. Furthermore, some standards give standardized measurement grids for assessing the typical exposure as e.g., the EN 50357 (2001) does for electrical article surveillance and radio frequency identification applications, while others do not. Such standardized grids are missing for welding applications, leading to problems in comparability of results from different measurement campaigns.

However, due to that it seems beneficial to conduct studies on the effects of spatial (e.g., whole or partial body) and temporal averaging for different grids assessed, as well as different averaging methods applied, as no such investigations could be found for complex SF, ELF, and IF exposure scenarios till now. Investigations in the RF range comparing grid averaged values, using various grid designs all positioned within a defined cubic volume, with the global mean of the cube for typical GSM, UMTS, and UHF signals summarized in Preiner (2004) could establish a first step also for the SF, ELF, and IF range. Such research may enable the evaluation of typical uncertainties in assessing fields via a specific measurement grid and equipment, and thus maybe enable a reduction of necessary measurement effort if associated uncertainties are reasonable. Further approaches in the RF range on evaluating overall uncertainties for time domain magnetic field grid measurements with appropriate broadband meters and probes including subsequent spatial averaging may be found in Stratakis et al (2009). Anyway, for the present assessment no spatial averaging applies due to the high inhomogeneity of the welders' exposure following the EN 50445 (2008) (Table 7-4, Table 7-5 – 3.8).

<sup>178</sup> With the proviso that given peak limit values are met.

Concerning temporal averages in complex industrial environments, often showing pulsed and intermittent fields, high underestimations of exposure may occur when completely omitting the signals transient characteristics. Investigations to harmonize the currently given assessment methods for averaged thermal effects in different exposure limiting and assessment documents seem beneficial. Due to the low values of thermal relevant components reported in Table 7-3 no investigations were conducted on temporal averaging (Table 7-4, Table 7-5 – 3.9).

When measuring electric and magnetic fields with appropriate equipment, this equipment inevitably affects the measured field, especially true in electric field measurements, as every conducting element strongly influences the charge distribution and thus the electric field. As long as no magnetic material (e.g., ferromagnetic cores in coil probes for sensitivity enhancement, etc.) is brought in, such strong disturbances of the magnetic field are not to be expected in magnetic field measurements. Thus, the influence of the equipment on the magnetic field can be said to be negligible in the given frequency range (Table 7-4, Table 7-5 – 3.10). However, the probe should preferably be positioned via a non-conducting and non-field-influencing tripod (or something equal), with the field meter connected to the probe over a long, preferably optical, cable link.

## Environment

Uncertainties due to environmental factors constitute the last category considered, starting with the temperature and humidity response of the measurement equipment. Given that all measurements with the Narda ELT-400 (and the appropriate 100 cm<sup>2</sup> coil probe) were performed in the denoted tolerance range of operating temperature (23±3°C) and relative humidity (40%-60%) no additional uncertainties have to be expected (Table 7-4 – 4.1 and 4.2). This also holds true for the Lake Shore 460<sup>179</sup> (and the appropriate MMZ-2512-UH Hall probe) with a temperature response of the field meter (DC) of 0.0503%/°C<sup>180</sup> as well as a temperature response of the probe of 0.015%/°C (Table 7-5 – 4.1 to 4.5). For the data acquisition unit a temperature drift of 0.0006%/°C is given. The equipment warmed up before measurements and they were performed in a range of ±10°C around calibration temperature (typically 20°C) (Table 7-4 – 4.3, Table 7-5 – 4.6). The stated relative humidity range of 10%-90% was also adhered to (Table 7-4 – 4.4, Table 7-5 – 4.7). (Narda (2004), Web8, 10, and 11 (2012))

As another possible contribution, interfering fields produced e.g., by fields generated in the measurement equipment or other objects due to presence of the welding magnetic or electric field, may couple back into the measurement path. Such fields are not to be classified as background fields. Robustness to such contributions may be termed as immunity of the measurement equipment. Avoidance or reduction of this contribution can be achieved by placing the field meter in sufficient distance to known field sources or field influencing objects and by using appropriately shielded cables. However, in the given setup no such contribution should apply (Table 7-4 – 4.5, Table 7-5 – 4.8).

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<sup>179</sup> The given accuracy applies for 15°C-35°C. No specific humidity range is given in Web8 (2012), thus 10%-90% applies (non-condensing). However, little humidity effects typically <1% are for example given in the IEC 61786 (1998).

<sup>180</sup> However, these factors only apply if the temperature is measured uncertain, otherwise a deterministic factor may account for changes in the temperature.

Further environmental changes like moving objects or persons of course have to be considered (Table 7-4 – 4.6, Table 7-5 – 4.9). This factor can be kept small for proper measurement design. In the presented assessment no such changes have to be accounted for. Also influences due to the measurement person can be neglected, as the probe was fixed by a wooden tripod and the measurement person operates the equipment from an adequate distance (Table 7-4 – 4.7, Table 7-5 – 4.10).

Influences of the welder’s body on the assessed incident fields may be an important factor if the field distribution changes to a high extent, mainly evident in electric fields. However, electric fields were not assessed in the presented scenario due to their insignificance in the concerned MIG welding application. Thus, no uncertainty value is included for possible influences on electric fields (Table 7-4 – 4.8, Table 7-5 – 4.11). Influences on magnetic fields may play a role, but are expected to be small for the assessed scenario due to the magnetic properties of the human body in the lower frequency range ( $\mu_r \approx 1$ ). Comparative measurements were performed with the Narda field meter according to the measurement grid shown in Figure 7-4 with and without the welder present, respectively<sup>181</sup>. According observed deviations are shown in Table 7-7.

	Welders’ Influence on Magnetic Fields (%)		
	P1	P2	P3
H5	-0.04	-5.74	0
H4	0	0	0.21
H3	-0.09	2.57	0
H2	0.90	-1.91	-13.50 <sup>182</sup>
H1	0.41	0.21	3.32

**Table 7-7 Deviation of the measured magnetic flux density for measurements with and without the welder, following the grid given in Figure 7-4 and measured with the ELT-400 field meter**

Maximum deviations of -5.74% and 3.32% could be found with an estimated standard uncertainty of 2.06% for a tested normal distribution<sup>183</sup> (Table 7-4 – 4.9). For now this value is included in the uncertainty budget of the ELT-400 measurements. No separate investigations were performed for the Lake Shore measurements, which will more adequately resolve lower frequencies. Thus, the same uncertainty is included for the moment (Table 7-5 – 4.12). However, it may be suggested that influences of the welders’ body on the field are smaller for lower frequencies, thus leading to lower uncertainties in the Hall probe measurements. Further simulations and measurements on this seem beneficial, especially for various complex current waveforms.

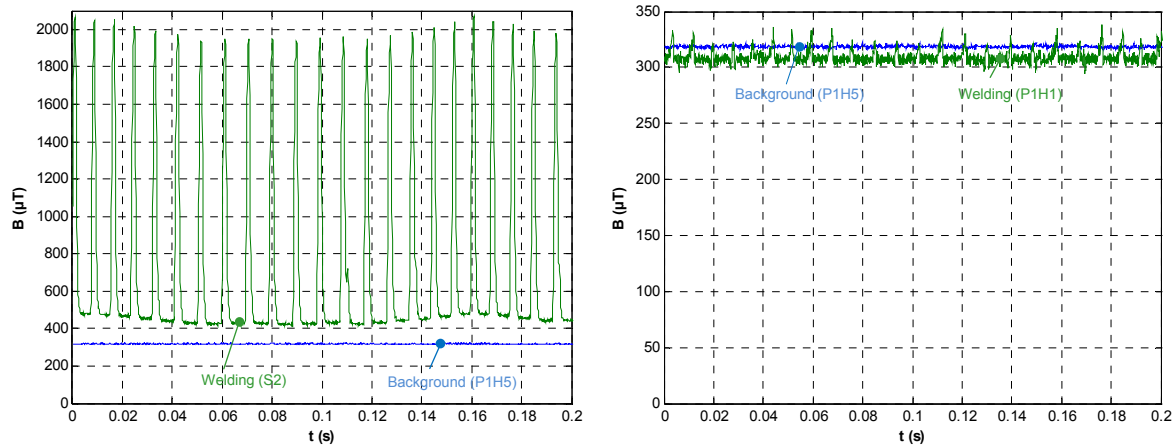
For measurements in industrial settings, as in the present scenario, one has typically to expect background fields arising from other power consuming applications or simply the power distribution in an industry building. To account for this, each exposure assessment should be preceded by a measurement of the background fields present near the planned

<sup>181</sup> Probe position was not changed due to presence of the welder. The welder stands directly in front of the probe between probe and workpiece (Figure 7-2).

<sup>182</sup> Value was identified as outlier via a Dean-Dixon outlier test (data normal distributed, small sample), giving a test statistics of 0.833 and a critical value of 0.524 ( $\alpha = 0.05$ ). Thus this data point is removed for further analysis.

<sup>183</sup> Test on normality was performed applying a Kolmogorov-Smirnov test, giving a test statistics of 0.2953 and a critical value of 0.3490 ( $\alpha = 0.05$ ).

measurement positions. However, such measurements were performed on position P1H5<sup>184</sup> (Figure 7-4) with the Lake Shore Hall probe, as lower frequency background fields were expected to be more significant according to possible disturbing appliances and the power distribution system operating at 50 Hz. Figure 7-9 shows the measured background fields as well as the low frequency field component measured during welding at positions S2 and P1H1 (Figure 7-4).



**Figure 7-9 Typical background field at position P1H5 in comparison with the assessed fields during welding at positions (left) S2, and (right) P1H1 (Figure 7-4) using the Lake Shore 460**

Quite high background fields in the range of about 320  $\mu\text{T}$  could be observed. However, this is small in comparison to the fields measured directly under the welding cable shoulder loop at position S2 (Figure 7-9 (left))<sup>185</sup>, and thus will lead to minor uncertainties. On the other hand, the background and the measured fields at position P1H1 are in the same range (Figure 7-9 (right)) leading to high uncertainties.

However, to calculate an appropriate uncertainty accounting for background fields possibly influencing the results, calculations of the expected incident field values  $B_c$  at the planned measurement positions have to be performed. Also field measurements on these positions, ensuring no background fields during assessment, are applicable, although hardly to achieve in practice. One possibility, however, will be measurements in anechoic chambers. Anyway, with the measured background field  $B_b$  and the calculated or measured incident fields during welding  $B_c$ , the maximum possible deviations due to the background field may occur for simply adding or subtracting its value from  $B_c$ . As no such calculations or measurements of incident fields excluding background fields are available, only a worst-case approximation of uncertainty is reasonable. However, this will lead to an actual value of the measured exposure being higher by  $B_b$ . Thus, considering the peak values of the measured signals, exposure underestimations of about 15.5% at position S2 and 105% at position P1H1 may occur. When considering a mean measurement distance of 20 cm to the exposure source, a value of about  $\pm 20\%$  (semi range, rectangular distributed) for the uncertainty due to background fields seems reasonable (Table 7-4 – 4.10, Table 7-5 – 4.13).

<sup>184</sup> Measurements performed with the welding device powered but no welding process in progress.

<sup>185</sup> Variations in the measured magnetic flux density can be observed originating from the already assessed field source instability due to the inherent variations of the welding current  $u_i$ . When calculating the peak-peak variations of the magnetic field shown in Figure 7-9 (left) with normalization to the mean peak-peak value over all periods, a relative fluctuation of about 1.6% is achieved. This corresponds well with the investigations summarized in Table 7-6 leading to a relative fluctuation of about 2% (measurement number 1,  $u_i$ ). Uncertainties due to the movement of the welder cannot be assessed, as no such field measurements were performed.

This contribution can be reduced by reducing the operation of field generating appliances in the surrounding during measurements. Noise contributions of the measurement equipment do not apply due to their typically low values in comparison to the measured fields. Noise floor measurements may be performed on the free field or in anechoic chambers excluding the influence of any field source.

#### 7.2.4 Overall Uncertainty Determination

Uncertainty budgets for the measurements with the Narda ELT-400 and the Lake Shore 460 field meter with associated probes were established and discussed in-depth. Unfortunately, not all applicable uncertainty components in Table 7-4 and Table 7-5 could be evaluated quantitatively yet. Information in this regard was found to be rather sparse, indicating the need of further investigations.

As already mentioned, uncertainty contributions were assumed to be (sufficiently) uncorrelated. This may probably not hold true for the applied, averaging and isotropy uncertainty, as well as the uncertainty due to the coupling of interfering signals with the measurement system and the background fields (Table 7-4 – 3.3, 3.4, 4.5, and 4.10, Table 7-5 – 3.3, 3.4, 4.8, and 4.13), as all of these quantities depend on the positioning of the probe. However, with defining an additional independent uncertainty component for the positioning (Table 7-5, Table 7-6 – 3.1) these quantities may be redefined to be uncorrelated. Unfortunately, no physical investigations could be performed on possible correlations till now. If such correlations can be identified, the standard uncertainties of the correlated components may be added arithmetically before calculating the combined standard uncertainty, with the sum being treated as one single uncertainty component<sup>186</sup> (UKAS, 2002).

Furthermore, the CLT was assumed to apply leading to an overall uncertainty being normal distributed. However, if certain criteria are met the CLT applies even for not equal distributed contributions as well as for slight dependencies between them (Section 4.1). Uncertainty components with non-normal distribution high in relation to other normal distributed contributions have to be checked for dominance. Such a check may easily be performed for a rectangular contribution by comparing its standard uncertainty with the combined standard uncertainty of the remaining components. If the single standard uncertainty is more than 1.4 times higher than the combined standard uncertainty, the rectangular contribution is said to be dominant and the CLT does not apply anymore. If not, the coverage factor of the combined uncertainty will be within 5% of the usual value<sup>187</sup>. (UKAS, 2007) This was checked to be fulfilled for the highest uncertainty in Table 7-4 but not in Table 7-5, namely the positioning uncertainty<sup>188</sup>. Thus, the uncertainty associated with the Lake Shore 460 measurements cannot be stated normal distributed with the same level of confidence in comparison to the uncertainties associated with the ELT-400 measurements. This may be attributed to the fact that some of the important, maybe normal distributed and

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<sup>186</sup> However, this is correct only for perfect correlation ( $r = 1$ ). Otherwise Equation (4-14) applies. (BIPM, 2008)

<sup>187</sup> Appropriate coverage factors for the convolution of uncertainty contributions with different distributions are given in UKAS (2007).

<sup>188</sup> No dominance of the positioning uncertainty was found for Table 7-4, as the combined standard uncertainty of the remaining components was determined to be 15.68% leading to a ratio of  $20\%/15.68\%=1.28 < 1.4$ . For Table 7-5 a dominance of this component can be shown with the combined standard uncertainty of the remaining components of 12.79% and thus a ratio of  $20\%/12.79\%=1.56 > 1.4$ .



high contributing uncertainty components are not yet known for the Hall probe measurements. However, pragmatically also for these measurements an expanded uncertainty being normal distributed and giving an approximate level of confidence of 95% may be assumed for the moment.

When now determining the overall uncertainty of the measurement the indication of two values, for the two probes and thus two frequency ranges, as well as the indication of only one of these values, obviously the higher one (worst-case), as the overall uncertainty of the exposure assessment is possible. The decision on which of these two possibilities to choose will depend on the degree of detail necessary in compliance evaluation. If for example the exposure quotients of the assessment are determined in detail, partitioned according to different frequency ranges and physiological effects, it will be beneficial to use the first approach stating both values. This would also be reasonable if the assessment results are close to given limits. On the other hand, if only a rough survey of the exposure situation is aimed, the worst-case uncertainty should be declared. However, when performing measurements with subsequent frequency selective compliance evaluation, one should always take care on possible frequency overlaps or gaps due to the used equipment. According measures to account for this have to be taken. Furthermore, to account for potential shortcomings in evaluation of the uncertainty budgets<sup>189</sup>, it may be beneficial to add an additional evaluation uncertainty. For the presented assessment a value of about  $\pm 5\%$  seems reasonable.

Summarizing, expanded uncertainties of **+51.78%/-51.98%** for measurements with the Narda ELT-400 as well as  **$\pm 48.52\%$**  for measurements with the Lake Shore 460 Gaussmeter could be found, assuming all uncertainty contributions to be uncorrelated. The reported expanded uncertainty of measurements is stated as the standard uncertainty of the measurement multiplied by a coverage factor  $k$  of two, which for an assumed normal distribution corresponds to a coverage probability of approximately 95%. Although, the achieved expanded uncertainty seems high, no better suited assessment methods were found during research. Nevertheless, some components may be reduced by better controlling the measurement setup, as for example uncertainties due to background fields can be reduced by trying to stop appliances operating near the assessed workplace during measurements. Moreover, better positioning systems with higher precision can reduce the positioning uncertainty. Smaller inductive field probes reducing averaging effects are possible, although their sensitivity decreases for smaller coil areas<sup>190</sup> (IEEE Std 1308, 1994).

### 7.3 Results for Compact Fluorescent Lamps

Measurement results and according uncertainty evaluations for the CFL sub-scenario are given (Section 7.1.2). These results taken from Nadakuduti et al (2011) are discussed in detail with the aim of combining them with the results of Section 7.2 in a reasonable way.

#### 7.3.1 Measurement Results

Electric field measurements were performed according to Figure 7-5. Measurements executed directly below the light bulb at z-positions of -15 cm and -30 cm (relative to P2H5)

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<sup>189</sup> These shortcomings can include e.g., missing or partial information, wrong selection of information, wrong data given in reference materials, wrong estimated sensitivity coefficients or probability distributions, etc. (BIPM, 2008)

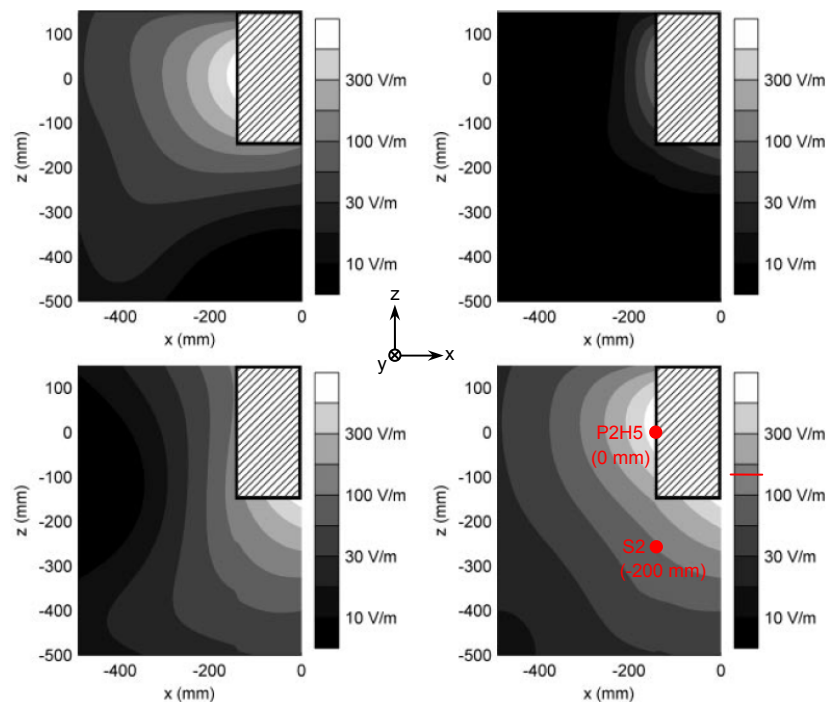
<sup>190</sup> However, this should not be a problem for the high measured fields.

showed differences in the measured fields of up to 400%<sup>191</sup> for the eleven evaluated CFLs. However, the closer of the two positions would lead to general public reference level exceedance following ICNIRP (1998) for seven of the tested bulbs.

The highest value measured around the light bulb was 546 V/m<sup>192</sup>, leading to a ICNIRP (2010) occupational reference level exceedance of about 321%. The according field distribution in the plane of Figure 7-5 is given in Figure 7-10<sup>193</sup>, showing a radially radiating field  $E_{total}$ . However, high electric fields may occur at the position of the welders' head. The field is highly inhomogeneous distributed in space.

### 7.3.2 Uncertainty Budget

The uncertainty budget compiled by Nadakuduti et al (2011) for the Narda EHP-200 electric field measurements described in Section 7.1.2, and specifically for a distance of 30 cm from the CFLs' center, is presented. It is established assuming the single uncertainty contributions to be (sufficiently) independent from each other, and the overall uncertainty to be normal distributed, enable to build the expanded uncertainty as the RSS of all standard uncertainties multiplied by a coverage factor of two (leading to a coverage probability of approximately 95%). A realistic approach is followed, i.e., realistic uncertainty values and not necessarily the worst-case values are included in the budget.



**Figure 7-10 Electric field distribution in the plane shown in Figure 7-5 for the bulb having the highest measured electric fields, (upper left)  $E_x$ , (upper right)  $E_y$ , (lower left)  $E_z$ , and (lower right)  $E_{total}$  from Nadakuduti et al (2011), with changes**

<sup>191</sup> Comparison was performed between the RMS exposure quotients evaluated at the respective basic frequency of each lamp and rated according to the ICNIRP (1998) general public exposure limits.

<sup>192</sup> Measurements were performed in five horizontal planes with relative z-positions of (12, 0, -12, -25, -50) cm and a closest distance between probe and bulb of 12 cm in all three spatial directions.

<sup>193</sup> Measurements at meshed regions were not possible due to presence of the bulb and size of the probe. The red line in the scaling of  $E_{total}$  indicates the ICNIRP (2010) occupational reference level of 170 V/m at 47.1 kHz. Red points indicate the positions also highlighted in Figure 7-1. Values in brackets at S2 and P2H5 give the y-position; z-position is given relative to P2H5.

No.	Uncertainty Component	Tolerance (± %)	Probability Distribution	Divisor	Uncertainty (± %)
1	Bulb stability	1.2	rect	1.73	0.7
2	Positioning with Respect to the Bulb	4.9	rect	1.73	2.8
3	Positioning with Respect to Enclosure	1.3	rect	1.73	0.7
4	Isotropy	9.6	rect	1.73	5.6
5	Orientation	27.6	rect	1.73	15.9
6	Temperature	1.2	rect	1.73	0.7
7	Linearity	5.9	rect	1.73	3.4
8	Averaging Time	9.5	rect	1.73	5.5
9	Noise	2.0	rect	1.73	1.1
10	Frequency response	5.9	rect	1.73	3.4
<b>Combined Standard Uncertainty (RSS of Uncertainty Terms)</b>					<b>18.7</b>
<b>Expanded Uncertainty (95% Confidence Interval)</b>					<b>37.4</b>

**Table 7-8 Uncertainty budget for electric field measurements with an EHP-200 field meter using a peak-hold detector and 10 kHz resolution bandwidth at 30 cm distance to the CFL center from Nadakuduti et al (2011), with changes**

### 7.3.3 Uncertainty Components

A description of all uncertainty components in Table 7-8 with respect to the evaluation processes according to Nadakuduti et al (2011) is given. Concerning the field source, bulbs were allowed to warm up at least 10 minutes. To assess the bulb stability after warm up variations in the peak amplitude of the electric fields were measured (Table 7-8 – 1).

For positioning an apparatus build up of Plexiglas, polyoxymethylen plastic and dry wood was used obviously enabling high precision positioning (Table 7-8 – 2 and 3) not or only minimally influencing the field distribution. Thus, also no effect of the measurement person on the field needs to be accounted for<sup>194</sup>. Positioning occurred via motors outside the measurement chamber, turned off during measurements. Changes in orientation of the probe lead to the highest uncertainty contribution of  $\pm 27.6\%$  (Table 7-8 – 5). Uncertainties due to isotropy, temperature<sup>195</sup>, linearity and frequency response (Table 7-8 – 4, 6, 7, 10) have apparently been taken from manufacturer specifications, but unfortunately no detailed information is given on that.

One further high uncertainty contribution originating from time averaging in maximum peak-hold analysis is given (Table 7-8 – 8). This may either be a contribution given by the manufacturer accounting for uncertainties in determining the average time or a contribution derived by detailed signal analysis of the electric field in relation to the averaging window to account for wrong exposure estimates.

Additionally, noise levels (both equipment as well as laboratory noise) were shown to be less than 1% of the ICNIRP (1998) general public reference levels, leading to an uncertainty contribution as low as  $\pm 2\%$  (Table 7-8 – 9). Furthermore, the authors in Nadakuduti et al (2011) indicate that uncertainties due to calibration of the probe as well as uncertainties due to possible drifts over time are not included.

### 7.3.4 Summary

Summarizing the last two sections, the information given by Nadakuduti et al (2011) on the stated uncertainties and their evaluation process in electric field exposure assessment of CFLs was found to be quite extensive in comparison to other reviewed publications. However, a reasonable expanded uncertainty of  $\pm 37.4\%$  was achieved. Nevertheless, details on some contributions are not given in the publication.

In accordance to the investigations given in Section 7.2 the uncertainty due to displacements of the probe dominate the uncertainty budget, with the difference that here the changes in orientation of the probe constitutes the highest contribution<sup>196</sup>.

However, in typical electric field measurements also proximity effects to metallic objects should be considered. Thus, probes should be operated at least in a distance of two times their largest diagonal dimension to the conducting object (IEC 61786, 1998).

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<sup>194</sup> This influence will, however, be huge in comparison to magnetic field measurements if no adequate remote positioning and reading would be performed. An observer may in minimum keep a distance of 2 m to a free-body electric field meter (IEC 61786, 1998).

<sup>195</sup> Temperature and humidity effects may be much more significant in electric field compared to magnetic field measurements, thus quantification is necessary (IEC 61786, 1998).

<sup>196</sup> Value was determined by measuring the electric fields in several probe orientations.

Furthermore, it is necessary to check for significant magnetic fields at the measurement points, as they may affect the electric field readings. In the presented measurements magnetic fields should be sufficiently low.

In general, it should be emphasized again, that at least all possible uncertainty contributions have to be considered, even if they are insignificant or cannot be estimated. This should at least show that they were considered. However, the uncertainty budget given in Table 7-8 should be detailed enough for a first exposure evaluation.

#### 7.4 Determination of the Overall Exposure

Accounting for the specific exposure scenario shown in Figure 7-1 and the results of Sections 7.2 and 7.3, the overall exposure of the worker at two representative points (P2H5 and S2) is evaluated. Therefore, Table 7-9 gives the appropriate exposure quotients for the MIG welding sub-scenario at points P2H5 and S2 with the associated uncertainties (Table 7-3 and Section 7.2.4), as well as the appropriate  $EQ_s$  for the CFL sub-scenario again with the associated uncertainties (Section 7.3.2)<sup>197</sup>. Furthermore, in a conservative approach both  $EQ_s$  were added for each position (Section 6.4). The  $EQ_s$  were calculated according to the ICNIRP (1998) occupational reference levels for nerve excitation.

	<b><i>EQ</i> relative to limit value</b>	<b>Uncertainty (%)</b>
<i>EQ</i> <sub>MIG,P2H5</sub>	0.43	+51.78/-51.98
<i>EQ</i> <sub>MIG,S2</sub>	22.35	+51.78/-51.98
<i>EQ</i> <sub>CFL,P2H5</sub>	0.66 <sup>198</sup>	±37.4
<i>EQ</i> <sub>CFL,S2</sub>	0.26 <sup>199</sup>	±37.4
<i>EQ</i> <sub>total,P2H5</sub>	1.09	+63.87/-64.04
<i>EQ</i> <sub>total,S2</sub>	22.61	+63.87/-64.04

**Table 7-9 Evaluated exposure quotients with associated uncertainties for positions P2H5 and S2 with respect to the ICNIRP (1998) occupational reference levels for nerve excitation**

Anyway, a decision on compliance now depends on the selected approach for considering the associated uncertainties. Following an additive approach with just adding the positive uncertainty to the given  $EQ$ , the exposure due to the MIG welding application at P2H5 as well as the exposure due to the CFL lighting at S2 will comply, whereas the others will show non-compliance. Applying a shared risk approach utilizing for example the reasonable overall uncertainties given in the EN 50444 (2008) for welding evaluations<sup>200</sup>, non-compliance is achieved for all evaluated exposures. Furthermore, a hybrid approach will lead to the same results compared to the additive approach. Applying the concept of uncertainty penalties again according to the EN 50444 (2008) will lead to compliance of the CFL exposure on both points as well as of the MIG exposure at point P2H5.

<sup>197</sup> It is to remember that in the above observations uncertainty budgets for a distance of 20 cm to the source in the MIG welding scenario, and for 30 cm to the source in the CFL scenario were given. Thus, for precise evaluations further uncertainties especially at the evaluated positions have to be determined, following the investigations given in Section 7.2.3. However, just a rough estimate with the presented uncertainty values is given here.

<sup>198</sup> Taking an approximate value of the electric field of 400 V/m at position P2H5 (Figure 7-10), at the basic frequency of 47.1 kHz and applying the ICNIRP (1998) reference value of 610 V/m.

<sup>199</sup> Taking an approximate value of the electric field of 160 V/m at position S2 (Figure 7-10), at the basic frequency of 47.1 kHz and applying the ICNIRP (1998) reference value of 610 V/m.

<sup>200</sup> The EN 50444 (2008) states: +58%/-37% for frequencies smaller 10 kHz and +41%/-30% for frequencies between 10 kHz and 1 MHz.

However, the main exposure due to the CFL is localized to the head region of the welder, whereas exposure due to the MIG welding application is highest, although less concentrated, at the welding cable shoulder loop. No averaging was applied for any of the two exposures accounting for their high inhomogeneity. If considering ICNIRP (2010) occupational reference levels e.g., at position P2H5 lower  $EQ$ s appear for the MIG sub-scenario whereas higher  $EQ$ s appear for the CFL sub-scenario as well as for the overall evaluation (Table 7-10).

	<i>EQ</i> relative to limit value	Uncertainty (%)
$EQ_{MIG,P2H5}$	0.05	+51.78/-51.98
$EQ_{CFL,P2H5}$	2.35	±37.4
$EQ_{total,P2H5}$	2.40	+63.87/-64.04

**Table 7-10 Evaluated exposure quotients with associated uncertainties for positions P2H5 and S2 with respect to the ICNIRP (2010) occupational reference levels for nerve excitation**

Concluding, due to the localized exposure of both sources as well as the reference level exceedance discussed above, numerical simulations seem beneficial to clarify a possible exceedance of basic restrictions. This will enable to properly account for additive effects of electric and magnetic fields with respect to induced electric fields.

## 7.5 Summary

Observations on a reasonable exposure scenario in the metal fabrication industry were presented. The exposure scenario was split up into two sub-scenarios. The given investigations do not claim completeness, but should rather be an attempt of a thorough complex exposure assessment and evaluation with emphasis on uncertainty estimations. Additional measurements as well as simulations were found to be beneficial to clarify the quantitative contributions of some of the concerned uncertainty components.

However, expanded uncertainties for magnetic field measurements were determined to be +51.78%/-51.98% (400 Hz-400 kHz) and ±48.52% (1 Hz-400 Hz) for the MIG welding sub-scenario. An expanded uncertainty of ±37.4% was given for electric field measurements in the CFL lighting sub-scenario. The reported expanded uncertainties of the evaluations are stated as the standard uncertainty of measurement multiplied by a coverage factor  $k$  of two, which for a normal distribution corresponds to a coverage probability of approximately 95%. Exposure quotients evaluated with respect to ICNIRP (1998, 2010) occupational reference levels were shown to either comply or not comply depending on the applied compliance evaluation approach. Numerical simulations may be performed to further evaluate if basic restrictions are exceeded. Due to the high exposure, technical measures to reduce this exposure at the welders' position are necessary<sup>201</sup>.

<sup>201</sup> This may for example include other types of lighting, no welding cable guide over the shoulder, no current loops, etc.

## 8 Conclusion and Outlook

Electromagnetic field exposure assessments and evaluations of complex scenarios were shown to be challenging with regard to several aspects. For example, approaches on evaluating the results of exposure assessments with regard to given limits are many. This for example includes the ICNIRP sum formulae for evaluating exposure with multiple frequencies, the time weighted average approach for pulsed, non-sinusoidal signals according to ICNIRP (2010), or the parametric approach for evaluating such signals given in the BGV B11 (2002). All of these approaches will lead to different compliance statements for a specific exposure scenario.

Applicable exposure assessment methods and requirements for equipment can be found in international standards. Such documents also include statements on uncertainty estimations and their consideration during compliance assessment with limits. These statements may vary to different extent when comparing documents. However, no detailed specifications of proper uncertainty evaluations are given. In general literature on complex exposure assessment especially with regard to associated uncertainty estimations was shown to be sparse. A common practice in static, extremely low and intermediate frequency workers' exposure assessment and evaluation as well as in expressing uncertainty in such investigations is not available yet. Thus, it is necessary to conduct further studies concerned with proper exposure metrics for pulsed and non-sinusoidal fields in the given frequency range in combination with suitable compliance evaluation methods, suitable exposure assessment methods, as well as suitable assessment equipment.

With respect to the determination of suitable exposure assessment methods and equipment thorough uncertainty investigations were presented as a possible tool. It was suggested to perform such extensive uncertainty estimations for a representative number of exposure scenarios in the given frequency range. Regarding this, it seems beneficial to perform additional measurements and simulations utilizing common assessment methods and equipment giving further insight in possibly significant uncertainty contributions. Such evaluations should include:

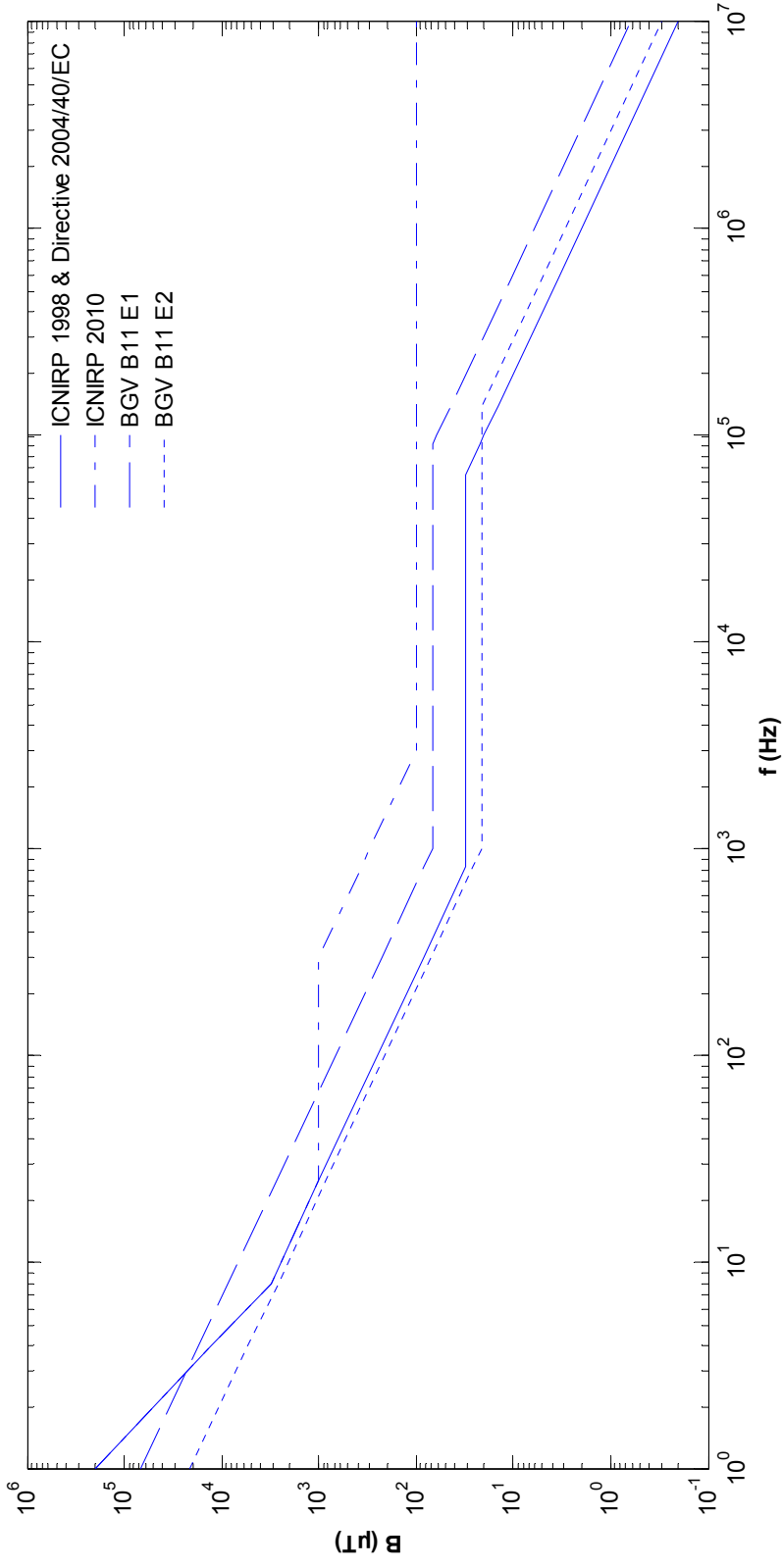
- Measurements of out of band responses for several common types of field meters utilized in exposure assessment of complex scenarios.
- Measurements and simulations helping to find proper estimates of uncertainties arising from measurements in spatial inhomogeneous fields including e.g., the averaging of the probe as well as the isotropy of the probe.
- Measurements and simulations on spatial and temporal averaging of exposure metrics in pulsed, non-sinusoidal fields according to given compliance evaluation methods.
- Analysis of windowing influences in FFTs for typical pulsed, non-sinusoidal fields.
- Measurements and simulations concerned with the influence of the human body on magnetic and electric field distributions in the given frequency range.
- Others.

Regulations and standards may beneficially account for the achieved findings by adopting proper limit values, compliance evaluation methods, exposure assessment methods and equipment requirements. Clarifying the discussed issues will alleviate the scientific basis for complex exposure assessments, especially with regard to the handling of uncertainties.





## Appendix A Comparison of Exposure Limit Values



**Figure A-1 Comparison of incident magnetic flux density limit values for occupational exposure of different exposure limiting documents<sup>202</sup>**

<sup>202</sup> Values given in Figure A-1 and Figure A-2 as “BGV B11 E1” and “BGV B11 E2” correspond to according values for exposure area 1 and exposure area 2 in the BGV B11 (2002), respectively. Values for frequencies higher 91 kHz are given for 6 minute averaging in the BGV B11 (2002).

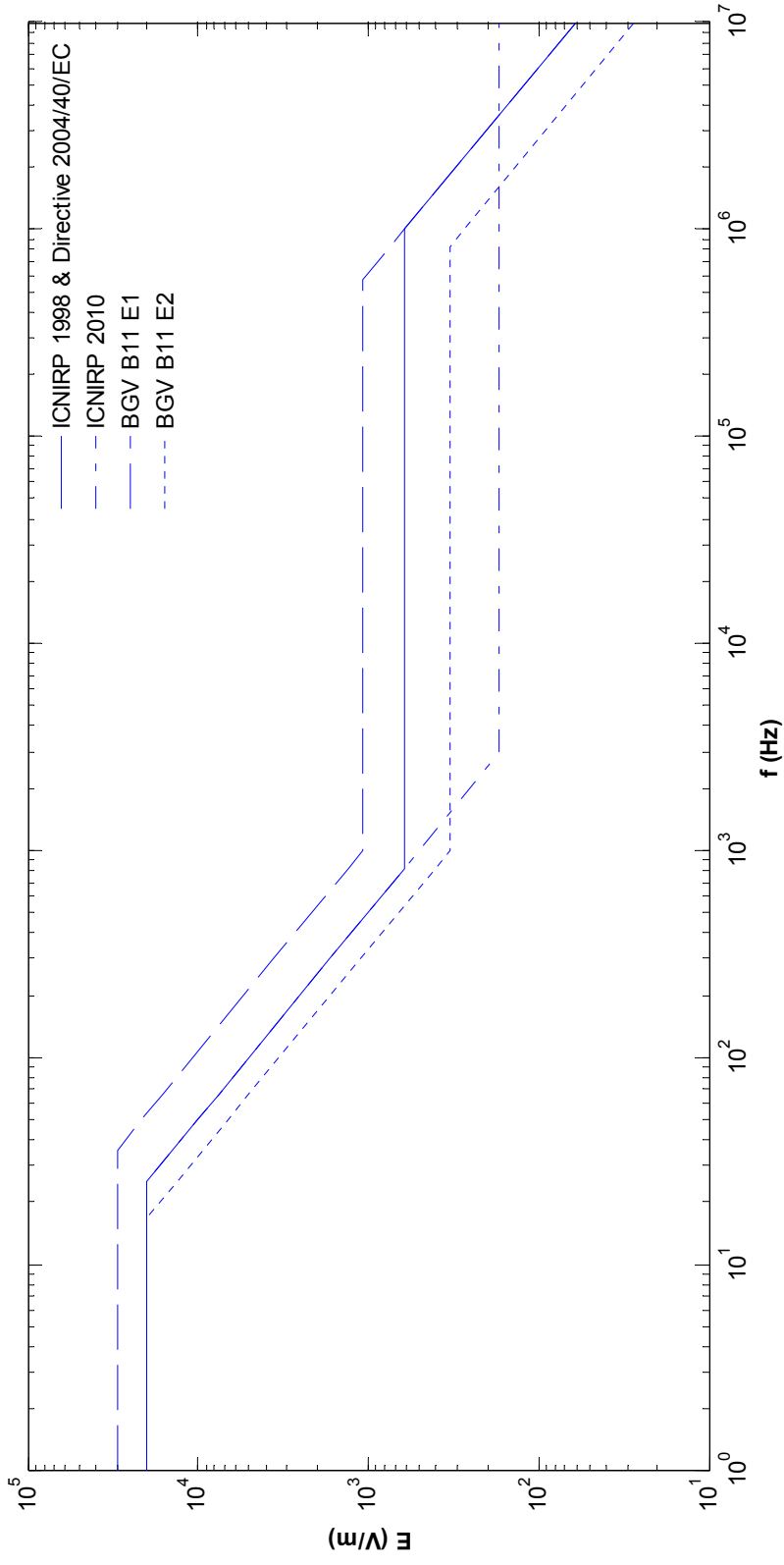


Figure A-2 Comparison of incident electric field limit values for occupational exposure of different exposure limiting documents

## Symbols

Symbol	Description	Unit
$A$	area	m <sup>2</sup>
$AA$	absolute accuracy	1
$a$	semi-range limit value	[ $X$ ] or 1
$B$	magnetic flux density	T
$c$	sensitivity coefficient	[ $Y$ ]/[ $X$ ]
$d$	divisor	1
$E$	electric field strength	V/m
$EQ$	exposure quotient	1
$f$	frequency	Hz
$H$	magnetic field strength	A/m
$I$	current	A
$J$	current density	A/m <sup>2</sup>
$N$	number of input quantities	1
$n$	number of observations	1
$p$	radius	m
$r$	distance, correlation coefficient	m, 1
$S$	power density	W/m <sup>2</sup>
$s$	estimated standard uncertainty	[ $X$ ], [ $Y$ ], or 1
$SA$	specific energy absorption	J/kg
$SAR$	specific energy absorption rate	W/kg
$T$	time period	s
$t$	time	s
$TEQ$	total exposure quotient	1
$TWA$	time weighted average	[ $Y$ ]
$U$	voltage	V
$u$	standard uncertainty	[ $X$ ], [ $Y$ ], or 1
$v$	quoted uncertainty	[ $X$ ] or 1
$X$	input quantity	[ $X$ ]
$x$	estimate of $X$ , time function of $X$	[ $X$ ]
$Y$	resultant	[ $Y$ ]
$y$	estimate of $Y$ , time function of $Y$	[ $Y$ ]
$\alpha$	exponent, level of significance	1
$\Gamma$	reflection coefficient	1
$\gamma$	electrical conductivity	S
$\lambda$	wavelength	m
$\nu$	degrees of freedom	1
$\tau$	time period	s



## Acronyms

<b>AC</b>	alternating current
<b>AIT</b>	Austrian Institute of Technology
<b>ANOVA</b>	analysis of variance
<b>CENELEC</b>	European Committee for Electrotechnical Standardization
<b>CFL</b>	compact fluorescent lamp
<b>CLT</b>	central limit theorem
<b>CNS</b>	central nervous system
<b>CT</b>	Computed Tomography
<b>DC</b>	direct current
<b>EQ</b>	exposure quotient
<b>EUREKA</b>	European Research Coordination Agency
<b>ELF</b>	extremely low frequency
<b>EMF</b>	electromagnetic field
<b>FDTD</b>	Finite Differences in Time Domain
<b>FEM</b>	Finite Element Method
<b>FFT</b>	Fast Fourier Transformation
<b>GSM</b>	Global System for Mobile Communications
<b>IARC</b>	International Agency for Research on Cancer
<b>ICNIRP</b>	International Commission on Non-Ionizing Radiation Protection
<b>IF</b>	intermediate frequency
<b>ldl</b>	lower detection limit
<b>LF</b>	low frequency
<b>MAG</b>	metal active gas
<b>MIG</b>	metal inert gas
<b>n.a.</b>	not applicable
<b>n.a.y.</b>	not available yet
<b>POI</b>	point of investigation

<b>RF</b>	radio frequency
<b>RMS</b>	root mean squared
<b>RSS</b>	root sum of squares
<b>SA</b>	specific energy absorption
<b>SAR</b>	specific energy absorption rate
<b>SCENIHR</b>	Scientific Committee on Emerging and Newly Identified Health Risks
<b>SENN</b>	Spatial Extended Non-Linear Node
<b>SF</b>	static frequency
<b>SPFD</b>	Scalar Potential Finite Differences
<b>sqrt</b>	square root
<b>STD</b>	shaped time domain
<b>TEQ</b>	total exposure quotient
<b>TIG</b>	tungsten inert gas
<b>TWA</b>	time weighted average
<b>UHF</b>	ultra high frequency
<b>UMTS</b>	Universal Mobile Telecommunications System
<b>Voxel</b>	volume Pixel
<b>WEMS</b>	Worker Electromagnetic Safety

## References

- ARO, 2001. *Electromagnetic Fields and Resistive Welding*. Report, France
- Bakos, J., Nagy, N., Juhász, P. & Thuróczy, G., 2010. Spot Measurements of Intermediate Frequency Electric Fields in the Vicinity of Compact Fluorescent Lamps. *Radiation Protection Dosimetry*, Vol. 142(2-4), pp. 354-357.
- Bertocco, M., Gregio, C. & Sona, A., 2007. Magnetic Field Measurement in Industrial Environment. *IMTC 2007 - IEEE Instrumentation and Measurement*, Warsaw.
- BGV B11, 2002. *Unfallverhütungsvorschrift Elektromagnetische Felder*. Berufsgenossenschaft der Feinmechanik und Elektrotechnik.
- BIPM, 2008. *Evaluation of Measurement - Guide to the Expression of Uncertainty in Measurement*. Joint Committee for Guides in Metrology.
- Bolte, J. F. B. & Pruppers, M. J. M., 2006. *Electromagnetic Fields in the Working Environment*. Report, Netherlands
- Borsoero, M., Crotti, G. & d'Amore, G., 2001. Calibration and Evaluation of Uncertainty in the Measurement of Environmental Electromagnetic Fields. *Radiation Protection Dosimetry*, Vol. 97(4), pp. 363-368.
- Broeckx, K., Decat, G., Casteels, M. & Mild, K. H., 2008. *Meten en Evalueren van de Blootstelling van Lassers aan Elektromagnetische Velden in het Kader van de Nieuwe Europese EMF-Richtlijn 2004/40/EC*. Report, Belgium.
- Caldara, S., Nuccio, S. & Spataro, C., 2010. Uncertainty Evaluation in the Low-Frequency Magnetic Field Measurements with Regard to Exposure of Human Beings. *6th International Workshop on Biological Effects of Electromagnetic Fields*, Bodrum.
- Canova, A., Freschi, F. & Repetto, M., 2010a. Evaluation of Workers Exposure to Magnetic Fields. *The European Physical Journal – Applied Physics.*, Vol. 52(2).
- Canova, A., Freschi, F., Giaccone, L. & Repetto, M., 2010b. Exposure of Working Population to Pulsed Magnetic Fields. *IEEE Transactions on Magnetics*, Vol. 46(8), pp. 2819-2822.
- Cecil, S. & Neubauer, G., 2007. *Numerical Simulation of Current Densities in the Central Nervous System of Resistance Welders*. Report, Austria.
- Chadwick, P., 2008. *Assessment Uncertainties Relating to Electromagnetic Fields (EMF) Measurement and Computation*. Report, United Kingdom
- Cooper, T., 2002. *Occupational Exposure to Electric and Magnetic Fields in the Context of the ICNIRP Guidelines*. National Radiological Protection Board Report, United Kingdom.
- Crotti, G. & Giordano, D., 2009. Analysis of Critical Situations in the Evaluation of Human Exposure to Magnetic Fields with Complex Waveforms. *Radiation Protection Dosimetry*, Vol. 137(3-4), pp. 227-230.

- Delpizzo, V., 1993. Misclassification of ELF Occupational Exposure Resulting from Spatial Variation of the Magnetic Field. *Bioelectromagnetics*, Vol. 14(2), pp. 117-130.
- Desideri, D., Maschio, A. & Matavelli, P., 2008. Human Exposure to Pulsed Current Waveforms Below 100 kHz. *EMC Europe*, Hamburg.
- Dilthey, U. et al., 2001. *Elektromagnetische Verträglichkeit von Widerstandsschweißmaschinen unter arbeitsmedizinischem Gesichtspunkt*. Report, Aachen
- DIN 1319-3, 1996. *Grundlagen der Messtechnik*. Deutsches Institut für Normung.
- DIN ISO 857-1, 2002. *Begriffe, Einteilung der Schweißverfahren*. Deutsches Institut für Normung.
- Doebbelin, R., Heyder, D. & Mecke, H., 1999. Einfluss des Lastkreises von Widerstandsschweißmaschinen auf die Intensität entstehender niederfrequenter Magnetfelder. *Fachtagung Leistungselektronik und intelligente Bewegungssteuerung*, Magdeburg.
- Doebbelin, R., Winkler, T., Mecke, H. & Czarnecki, T. K., 2002. Measurement and Evaluation of Pulsating Environmental Magnetic Fields by the Example of Resistance Welding Installations. *3rd International Symposium on Electromagnetic Compatibility*, Peking.
- Doebbelin, R., Czarnecki, T. K., Mecke, H. & Winkler, T., 2003. Magnetic Fields in the Vicinity of Welding Installations. *15th International Zurich Symposium and Technical Exhibition on Electromagnetic Compatibility*, Zurich.
- Dughiero, F., Forzan, M. & Sieni, E., 2010. A Numerical Evaluation of Electromagnetic Fields Exposure on Real Human Body Models Until 100 kHz. *The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, Vol. 29(6), pp. 1552-1561.
- Dürrenberger, G. & Klaus, G., 2004. *EMF von Energiesparlampen: Feldmessungen und Expositionsabschätzungen mit Vergleich zu anderen Quellen im Alltag*. Report, Switzerland
- EA-4/02, 1999. *Expression of the Uncertainty of Measurement in Calibration*. European Co-Operation for Accreditation.
- EN 50357, 2001. *Evaluation of Human Exposure to Electromagnetic Fields from Devices used in Electronic Article Surveillance (EAS), Radio Frequency Identification (RFID) and Similar Applications*. CENELEC.
- EN 50366, 2004. *Household and Similar Electrical Appliances. Electromagnetic Fields - Methods for Evaluation and Measurement*. CENELEC.
- EN 50392, 2004. *Generic Standard to Demonstrate the Compliance of Electronic and Electrical Apparatus With the Basic Restrictions Related to Human Exposure to Electromagnetic Fields (0 Hz - 300 GHz)*. CENELEC.
- EN 50413, 2009. *Basic Standard on Measurement and Calculation Procedures for Human Exposure*. CENELEC.



- EN 50444, 2008. *Basic Standard for the Evaluation of Human Exposure to Electromagnetic Fields from Equipment for Arc Welding and Allied Processes*. CENELEC.
- EN 50445, 2008. *Product Family Standard to Demonstrate Compliance of Equipment for Resistance Welding, Arc Welding and Allied Processes With the Basic Restrictions Related to Human Exposure to Electromagnetic Fields (0 Hz - 300 GHz)*. CENELEC.
- EN 50499, 2008. *Procedure for the Assessment of the Exposure of Workers to Electromagnetic Fields*. CENELEC.
- EN 50505, 2008. *Basic Standard for the Evaluation of Human Exposure to Electromagnetic Fields from Equipment for Resistance Welding and Allied Processes*. CENELEC.
- EN 62226-1, 2005. *Exposure to Electric or Magnetic Fields in the Low and Intermediate Frequency Range - Methods for Calculating the Current Density and Internal Electric Field induced in the Human Body - Part 1: General*. CENELEC.
- EU-Directive 2004/40/EC, 2004. Minimum Health and Safety Requirements Regarding the Exposure of Workers to the Risks Arising from Physical Agents (Electromagnetic Fields). *Official Journal of the European Union*.
- Fetter, J. G., Benditt, D. G. & Marshall, S. S., 1996. Electromagnetic Interference from Welding and Motors on Implantable Cardio-Defibrillators as Tested in the Electrically Hostile Work Site. *Journal of the American College of Cardiology*, Vol. 28(2), pp. 423-427.
- Freschi, F., Guerrisi, A. & Repetto, M., 2010. Computation of Eddy Currents in Human Body due to Pulsed Magnetic Fields. *14th Biennial IEEE Conference on Electromagnetic Field Computation*, Chicago.
- Gonter, J., 2009. *Electromagnetic Exposure Assessment for Welding Workers (up to 10 MHz)*. Master Thesis, Vienna University of Technology.
- Hackl, H., 2005. *Stromquellen zum MIG- und WIG-Schweißen*. Fronius International GmbH Report, Austria.
- Hamnerius, Y., 2007. Uncertainties in Assessment of Worker Exposure of Low Frequency Electric and Magnetic Fields. *ICNIRP/EMF-NET/WHO Workshop on Current Trends in Health and Safety Risk Assessment of Work Related Exposure to EMFs*, Italy.
- Havas, M., 2008. Health Concerns associated with Energy Efficient Lighting and their Electromagnetic Emissions. *SCENIHR Request for an opinion on "Light Sensitivity"*
- Heinrich, H., 2007. Assessment of Non-Sinusoidal, Pulsed or Intermittent Exposure to Low Frequency Electric and Magnetic Fields. *Health Physics*, Vol. 92(6). pp. 541-546.
- Herms, R., Bartels, G., Doebbelin, R. & Lindemann, A., 2007. Field Compensation for Resistance Welding. *18th International Zurich Symposium on Electromagnetic Compatibility*, Zurich.
- IARC, 2002. *Volume 80 - Non-Ionizing Radiation, Part 1: Static and Extremely Low-Frequency (ELF) Electric and Magnetic Fields*. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, France.

- ICNIRP, 1998. Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic and Electromagnetic Fields (up to 300GHz). *Health Physics*, Vol. 74(4), pp. 494-522.
- ICNIRP, 2003. Guidance on Determining Compliance of Exposure to Pulsed and Complex Non-Sinusoidal Waveforms below 100 kHz with ICNIRP Guidelines. *Health Physics*, Vol. 84(3), pp. 383-387.
- ICNIRP, 2010. Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields (1 Hz to 100 kHz). *Health Physics*, Vol. 99(6), pp. 818-836.
- IEC 61000-4-22 (Draft), 2006. *Radiated Emission and Immunity Measurements in Fully Anechoic Rooms (FARs)*. International Electrotechnical Commission.
- IEC 61786, 1998. *Measurement of Low-Frequency Magnetic and Electric Fields with Regard to Exposure of Human Beings – Special Requirements for Instruments and Guidance for Measurements*. International Electrotechnical Commission.
- IEC 62232 (Draft), 2011. *Determination of RF Field Strength and SAR in the Vicinity of Radiocommunication Base Stations for the Purpose of Evaluating Human Exposure*. International Electrotechnical Commission.
- IEC 62493, 2009. *Assessment of Lighting Equipment Related to Human Exposure to Electromagnetic Fields*. International Electrotechnical Commission.
- IEEE Std 1308, 1994. *IEEE Recommended Practice for Instrumentation: Specifications for Magnetic Flux Density and Electric Field Strength Meters - 10 Hz to 3 kHz*. Institute of Electrical and Electronics Engineers.
- Jokela, K., 2000. Restricting Exposure to Pulsed and Broadband Magnetic Fields. *Health Physics*, Vol. 79(4), pp. 373-388.
- Karabetsos, E. & Filippopoulos, G., 2005. Uncertainty Estimation in Electromagnetic Field Measurements for Assessing Compliance with Safety Limits. *28th General Assembly of the International Union of Radioscience*, New Delhi.
- Karpowicz, J., Gryz, K. & Wincenciak, S., 2002. Non-Sinusoidal ELF Magnetic Field - Electrophysiological Rules of Measurement and Exposure Evaluation. *27th General Assembly of the International Union of Radioscience*, Maastricht.
- Karpowicz, J. & Gryz, K., 2007. Practical Aspects of Occupational EMF Exposure Assessment. *The Environmentalist*, Vol. 27(4), pp. 525-531.
- Killing, R., 1997. *Kompodium der Schweißtechnik, Band 1: Verfahren der Schweißtechnik*. Deutscher Verlag für Schweißtechnik DVS-Verlag GmbH.
- Leitgeb, N., Cech, R. & Schröttner, J., 2007. Electromagnetic Field Spectral Evaluation Problems in Exposure Assessment. *Radiation Protection Dosimetry*, Vol. 124(2), pp. 124-129.
- Leitgeb, N. & Cech, R., 2008. Dosimetric Assessment of Simultaneous Exposure to ELF Electric and Magnetic Fields. *IEEE Transactions on Biomedical Engineering*, Vol. 55(2.1), pp. 671-674.

- Letertre, T. et al., 2009. Characterization of Compact Fluorescent Lights RF Emissions in the Perspective of Human Exposure. *International Symposium on Electromagnetic Compatibility*, Kyoto.
- LfAS, 2002. *Elektromagnetische Felder am Arbeitsplatz - Ergebnisse einer Messreihe des LfAS*. Report, Germany.
- Lindemann, A. et al., 2008. *Beurteilung und Beeinflussung von Magnetfeldexpositionen beim Widerstandsschweißen*. Report, Germany.
- Mair, P., 2005. Assessment of EMF (Electromagnetic Fields) and Biological Effects in Arc Welding Applications. *International Institute of Welding, Commission XII, Intermediate Meeting*, Wels.
- Martens, L., 2007. Different Basic Dosimetric Quantities for the Characterization of Exposure to Low-Frequency Electric and Magnetic Fields and the Implication for Practical Exposure Conditions and Guidelines. *Health Physics*, Vol. 92(6), pp. 515-520.
- Matthes, K.-J. & Richter, E., 2002. *Schweißtechnik. Schweißen von metallischen Konstruktionswerkstoffen*. Fachbuchverlag Leipzig.
- McDevitt, J. J., Breyse, P. N., Bowman, J. D. & Sassone, D. M., 2002. Comparison of Extremely Low Frequency (ELF) Magnetic Field Personal Exposure Monitors. *Journal of Exposure Analysis and Environmental Epidemiology*, Vol. 12(1), pp. 1-8.
- Mecke, H. et al., 2002. *EMVU-relevante Feldemissionen von Widerstandsschweißmaschinen*. Report, Germany.
- Mecke, H. et al., 2003. Umgebungsmagnetfelder von Widerstandsschweißeinrichtungen. *Schweißen & Schneiden*, Vol. 55(10), pp. 550-558.
- Melton, G., 2005. *Measurements and Analysis of Magnetic Fields from Welding Processes*. HSE Books.
- Meyer, M., 2003. *Signalverarbeitung - Analoge und digitale Signale, Systeme und Filter*. Vieweg Verlag.
- Mild, K., Stensson, O., Sandström, M. & Wilen, J., 2003. *Magnetic Field Near Electrical Welding Equipment - A Change from ELF to VLF*. Presentation.
- Mild, K. H. et al., 2009. Exposure of Workers to Electromagnetic Fields. A Review of Open Questions on Exposure Assessment Techniques. *International Journal of Occupational Safety and Ergonomics*, Vol. 15(1), pp. 3-33.
- Misakian, M. & Fenimore, C., 1996. Distributions of Measurement Error for Three-Axis Magnetic Field Meters During Measurements Near Appliances. *IEEE Transactions on Instrumentation and Measurement*, Vol. 45(1), pp. 244-249.
- Molla-Djafari, H. et al., 2008. *Belastung von Schweißern durch elektromagnetische Felder am Arbeitsplatz*. Report, Austria.
- Nadakuduti, J. et al., 2011. Application of an Induced Field Sensor for Assessment of Electromagnetic Exposure from Compact Fluorescent Lamps. *Bioelectromagnetics (online)*.

- Nadeem, H., Hamnerius, Y., Mild, K. H. & Persson, M., 2004. Magnetic Fields from Spot Welding Equipment - Is the Basic Restriction Exceeded?. *Bioelectromagnetics*, Vol. 25(4), pp. 278-284.
- NAMAS, 1994. *NIS 81 - The Treatment of Uncertainty in EMC Measurements*. National Physical Laboratory.
- Narda, 2004. *ELT-400 Exposure Level Tester - Operating Manual*. Narda Safety Test Solutions GmbH.
- ÖVE/ÖNORM E8850, 2006. *Elektrische, magnetische und elektromagnetische Felder im Frequenzbereich von 0 Hz bis 300 GHz - Beschränkung der Exposition von Personen*. Österreichischer Verband für Elektrotechnik.
- Ozelsberger, G., 2008. *Evaluierung elektromagnetischer Felder am Arbeitsplatz*. Master Thesis, Vienna University of Technology.
- Pfützner, H., 2003. *Angewandte Biophysik*. Springer-Verlag.
- Portier, C. & Wolfe, M., 1998. *Assessment of Health Effects from Exposure to Power-Line Frequency Electric and Magnetic Fields*, National Institute of Environmental Health Sciences of the National Institute of Health Report, USA.
- Preiner, P., 2004. *Evaluation of Electromagnetic Field Distribution Near Mobile Communication Base Stations*. Master Thesis, Vienna University of Technology.
- Rauscher, C., Janssen, V. & Minihold, R., 2000. *Grundlagen der Spektrumanalyse*. Rohde & Schwarz GmbH & Co. KG.
- Reilly, J., 1989. Peripheral Nerve Stimulation by Induced Electric Currents: Exposure to Time-Varying Magnetic Fields. *Medical & Biological Engineering & Computing*, Vol. 27(2), pp. 101-110.
- Reilly, J., 1998. Maximum Pulsed Electromagnetic Field Limits Based on Peripheral Nerve Stimulation: Application to IEEE/ANSI C95.1 Electromagnetic Field Standards. *IEEE Transactions on Biomedical Engineering*, Vol. 45(1), pp. 137-141.
- Rueckerl, C., Eichhorn, K. F. & Bauer, H., 2009. On the Signal Processing for an Exposure Assessment of Superimposed Magnetic Fields. *IEEE International Symposium on Electromagnetic Compatibility*, Austin.
- Sakurazawa, H. et al., 2003. Assessment of Exposure to Magnetic Fields in Occupational Settings. *Journal of Occupational Health*, Vol. 45(2), pp. 104-110.
- SCENIHR, 2008. *Light Sensitivity*. Scientific Committee on Emerging and Newly Identified Health Risks Opinion, Belgium.
- Sicree, R. M., Rauch, G. B. & Dietrich, F. M., 1993. Comparison of Magnetic Flux Density Meter Responses Over a Database of Residential Measurements. *IEEE Transaction on Power Delivery*, Vol. 8(2), pp. 607-619.
- Skotte, J. H. & Hjollund, H. I., 1997. Exposure of Welders and Other Metal Workers to ELF Magnetic Fields. *Bioelectromagnetics*, Vol. 18(7), pp. 470-477.

- Stratakis, D. et al., 2009. On the Uncertainty Estimation of Electromagnetic Field Measurements Using Field Sensors: A General Approach. *Radiation Protection Dosimetry*, Vol. 133(4), pp. 240-247.
- Stuchly, M. A. & Lecuyer, D. W., 1989. Exposure to Electromagnetic Fields in Arc Welding. *Health Physics*, Vol. 56(3), pp. 297-302.
- Taylor, B. & Kuyatt, C., 1994. *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*. National Institute of Standards and Technology Technical Note, USA.
- Überbacher, R., Samaras, T., Giczi, W. & Neubauer, G., 2006. *Measurement Uncertainty*. Report, Austria.
- Ueding, R. R., 2000. *Messung gepulster magnetischer Felder an handgeführten Widerstandsschweißgeräten und Bewertung nach der neuen Berufsgenossenschaftlichen Vorschrift BGV B11 Elektromagnetische Felder*. Master Thesis, Fachhochschule Köln.
- UKAS, 2002. *Lab 34 - The Expression of Uncertainty in EMC Testing*. United Kingdom Accreditation Service.
- UKAS, 2007. *M3003 - The Expression of Uncertainty and Confidence in Measurement*. United Kingdom Accreditation Service.
- Vulevic, B. & Osmokrovic, P., 2010. Evaluation of Uncertainty in the Measurement of Environmental Electromagnetic Fields. *Radiation Protection Dosimetry*, Vol. 141(2), pp. 173-177.
- WECC, 1990. *Guidelines for the Expression of the Uncertainty of Measurement in Calibrations*. Western European Calibration Cooperation.
- Weman, K., 2003. *Health Hazards Caused by Electromagnetic Fields During Welding*. Article, Royal Institute of Technology Stockholm - Department of Material Processing, Stockholm.
- Zhang, J., Nair, I. & Sahl, J., 1997. Effects Function Analysis of ELF Magnetic Field Exposure in the Electric Utility Work Environment. *Bioelectromagnetics*, Vol. 18(5), pp. 365-375.



## Web Page References

Web1, 2011.

Available at: <http://metallurgyfordummies.com/welding/spot-welding-machine/>, accessed September 2011.

Web2, 2011.

Available at: <http://www.lucasmilhaupt.com/en-US/brazingfundamentals /brazingvswelding/>, accessed September 2011.

Web3, 2011.

Available at: <http://www.thefreedictionary.com/uncertainty>, accessed August 2011.

Web4, 2011.

Available at: [http://de.wikipedia.org/wiki/Zentraler\\_Grenzwertsatz](http://de.wikipedia.org/wiki/Zentraler_Grenzwertsatz), accessed August 2011.

Web5, 2011.

Available at: <http://www.lincolnelectric.com>, accessed September 2011.

Web6, 2011.

Available at: [http://en.wikipedia.org/wiki/Gas\\_tungsten\\_arc\\_welding](http://en.wikipedia.org/wiki/Gas_tungsten_arc_welding), accessed September 2011.

Web7, 2012.

Available at: <http://www.esabna.com/us/en/education/esab-university.cfm>, accessed February 2012.

Web8, 2012.

Available at: <http://www.lakeshore.com/products/Gaussmeters/Model-460-3-Channel-Gaussmeter/Pages/Specifications.aspx>, accessed April 2012.

Web9, 2012.

Available at: [http://www.narda-sts.us/pdf\\_files/DataSheets /EHP200\\_DataSheet.pdf](http://www.narda-sts.us/pdf_files/DataSheets /EHP200_DataSheet.pdf), accessed April 2012.

Web10, 2012.

Available at: <http://sine.ni.com/nips/cds/view/p/lang/de/nid/14123>, accessed April 2012.

Web11, 2012.

Available at: <http://sine.ni.com/nips/cds/view/p/lang/de/nid/11944>, accessed April 2012.

