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Guidance concerning the permissible temperature rise for parts of electrical equipment, in particular for terminals

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TECHNICAL REPORT

RAPPORT TECHNIQUE

Guidance concerning the permissible temperature rise for parts of electrical equipment, in particular for terminals

Guide concernant le chauffage admissible des parties des matériels électriques, en particulier les bornes de raccordement

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**GUIDANCE CONCERNING THE PERMISSIBLE TEMPERATURE RISE
FOR PARTS OF ELECTRICAL EQUIPMENT,
IN PARTICULAR FOR TERMINALS**

FOREWORD

- 1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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- type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

Technical reports of types 1 and 2 are subject to review within three years of publication to decide whether they can be transformed into International Standards. Technical reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

IEC 60943, which is a technical report of type 3, has been prepared by IEC technical committee 32: Fuses.

This consolidated version of IEC 60943 consists of the second edition (1998) [documents 32/142/CDV and 32/148/RVC] and its amendment 1 (2008) [documents 32/187/DTR and 32/188/RVC].

The technical content is therefore identical to the base edition and its amendment and has been prepared for user convenience.

It bears the edition number 2.1.

A vertical line in the margin shows where the base publication has been modified by amendment 1.

Annexes are for information only.

The committee has decided that the contents of the base publication and its amendments will remain unchanged until the maintenance result date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

- a) The temperature rise encountered in electrical assemblies as a result of the various losses in the conductors, contacts, magnetic circuits, etc. is of growing importance as a result of the development of new techniques of construction and operation of equipment.

This development has been particularly significant in the field of assemblies, where numerous components dissipating energy (contactors, fuses, resistors, etc.), in particular modular devices are found within enclosures of synthetic materials which are somewhat impermeable to heat.

This temperature rise results in a relatively high temperature of the basic elements constituting the electric contacts: a high temperature favours oxidation at the contact interface, increases its resistance and thereby leads to further heating, and thus to an even higher temperature. If the component material of the contact is unsuitable or insufficiently protected, the contact may be irreparably damaged before the calculated useful life of the equipment has expired.

Such temperature rises also affect connection terminals and the connected conductors, and their effects should be limited in order to ensure that the insulation of the conductors remains satisfactory throughout the life of the installation.

- b) In view of these problems, this report has been prepared with the following objectives:
- to analyze the various heating and oxidation phenomena to which the contacts, the connection terminals and the conductors leading to them are subjected, depending on their environment and their arrangement;
 - to provide elementary rules to product committees to enable them to specify permissible temperatures and temperature rises.
- c) Attention is drawn to the precautions to be taken for sets of components when parts are grouped together in the same enclosure.

The attention of users should be drawn particularly to the fact that the temperature rise of terminals permitted by particular switchgear standards results from conventional situations during type tests; these can differ appreciably from the situations met with in practice, which have to be taken into account, particularly because of the temperatures permitted by the insulation of the conductors which may be connected to the terminals under normal conditions.

- d) Attention is drawn to the fact that in the relevant product standards, the permissible temperature and temperature rise for the external terminals are measured during conventional type tests and therefore they may not reflect the actual situation likely to occur in normal use.

Suitable precautions should then be adopted to avoid exposure to temperatures that may affect the life of materials adjacent to the terminals of components.

In this case, it is essential to distinguish the concept of "external ambient temperature" which prevails outside the enclosure from that of "the temperature of the fluid surrounding a part" which comprises the external ambient temperature plus the internal temperature rise due to the parts. These concepts, as well as other complementary concepts such as the thermal resistance of an enclosure, are dealt with in clause 5 and explained by means of numerical examples.

In order to facilitate complete calculation, this report links up the temperature of the fluid surrounding a component to the external ambient temperature by the introduction of the concept of "coefficient of filling" and gives a numerical example (5.2.3.2) which specifies the values of the coefficient of filling to be used in several practical cases.

The quantities involved in calculating contact constriction resistance are subject to wide variations due to the physical conditions and degree of contamination of the surface in contact. By calculation alone, therefore, the contact resistance can be estimated to an accuracy of no better than an order of magnitude.

More precise and more accurate values should be obtained by direct measurement on given items of electrical equipment, because in practice it is often the case that other incalculable degradation mechanisms predominate.

This report is not meant to give guidance on the derating of components.

It is strongly advised that the reference literature quoted at the end of this report be studied before attempting to apply the data to a practical problem.

GUIDANCE CONCERNING THE PERMISSIBLE TEMPERATURE RISE FOR PARTS OF ELECTRICAL EQUIPMENT, IN PARTICULAR FOR TERMINALS

Section 1: General

1 General

1.1 Scope and object

This report is intended for guidance in estimating the permissible values for temperature and temperature rise of component parts of electrical equipment carrying current under steady state conditions.

This report applies to electrical power connections and materials adjacent to them.

This report is concerned with the thermal effects of currents passing through connections, therefore there are no voltage limits to its application.

This report is only applicable when referred to in the appropriate product standard.

The extent and manner to which the contents of this report are used in standards is the responsibility of individual Technical Committees.

Whenever "permissible" values are stated in this report, they mean values permitted by the relevant product standard.

The present report is intended to supply:

- general data on the structure of electric contacts and the calculation of their ohmic resistance;
- the basic ageing mechanisms of contacts;
- the calculation of the temperature rise of contacts and connection terminals;
- the maximum "permissible" temperature and temperature rise for various components, in particular the contacts, the connection terminals and the conductors connected to them;
- the general procedure to be followed by product committees for specifying the permissible temperature and temperature rise.

1.2 Reference documents

IEC 60050(441):1984, *International Electrotechnical Vocabulary (IEV) ± Chapter 441: Switch-gear and controlgear and fuses*

IEC 60085:1984, *Thermal evaluation and classification of electrical insulation*

IEC 60216-1:1990, *Guide for the determination of thermal endurance properties of electrical insulating materials ± Part 1: general guidelines for ageing procedures and evaluation of the test results*

IEC 60364-4-42:1980, *Electrical installations of buildings ± Part 4: Protection for safety - Chapter 42: Protection against thermal effects*

IEC 60694:1996, *Common specifications for high-voltage switchgear and controlgear standards*

IEC 60721-2-1:1982, *Classification of environmental conditions ± Part 2: environmental conditions appearing in nature. Temperature and humidity*

IEC 60890:1987, *A method of temperature-rise assessment by extrapolation for partially type-tested assemblies (PTTA) of low voltage switchgear and controlgear*

IEC 60947-1:1988, *Low-voltage switchgear and controlgear ± Part 1: General rules*

1.3 Definitions

Definitions of terms used in this report may be found in the International Electrotechnical Vocabulary. For the purposes of this technical report, the following terms also apply:

1.3.1

ambient air temperature θ_a

the temperature, determined under prescribed conditions, of the air surrounding the complete device [IEV 441-11-13]

NOTE For devices installed inside an enclosure, it is the temperature of the air outside the enclosure.

1.3.2

contact (of a mechanical switching device)

conductive parts designed to establish circuit continuity when they touch and which, due to their relative motion during an operation, open or close a circuit or, in the case of hinged or sliding contacts, maintain circuit continuity [IEV 441-15-05]

NOTE Do not confuse with "IEV 441-15-06 Contact (piece): one of the conductive parts forming a contact."

1.3.3

connection (bolted or the equivalent)

two or more conductors designed to ensure permanent circuit continuity when forced together by means of screws, bolts, or the equivalent [3.5.10 of IEC 60694]

1.4 Symbols

A list of symbols used in this report is given in annex F.

Section 2: Theory

NOTE This theory applies to both "contacts" and "connections" as defined in 1.3.2 and 1.3.3. For convenience, only the word "contact" only is used in this section to cover both applications.

2 General considerations concerning the nature of electric contact and the calculation and measurement of the ohmic resistance of contacts

2.1 Electric contacts and connection terminals

Electric contact, in its simplest and most general configuration, results from contact established between two pieces of (usually metallic) conducting material. In the case of connection terminals, these are the terminal itself and the conductor which is connected to it.

The active zone is the contact "interface" which is the region where the current passes from one piece to the other. It is in this area that the contact resistance occurs, causing heating by Joule effect, and it is also where ageing occurs through chemical reaction with the surrounding atmosphere.

2.2 Nature of electric contact

When one piece of metal is applied to another, contact is not made over the whole apparent contact area, but only at a certain number of points called "elementary contacts".

The effective total cross-sectional area of these contacts is equal to the effective contact area S_a ¹⁾ if the possible presence of impurities is ignored (dust, etc.) at the contact interface.

There is also a fine layer of air or of oxide normally present, the effect of which upon the contact resistance will be examined later (see 2.3).

In the following, for ease of calculation and for a better understanding of the contact mechanisms, the simplifying assumption is made that there are n elementary contacts on the apparent contact area, uniformly distributed, of average constant radius a (see figure 1). The average distance between these elementary contacts is l .

The effective contact area is then:

$$S_a = n \pi a^2$$

1) For an explanation of the symbols used in this report, see annex F.

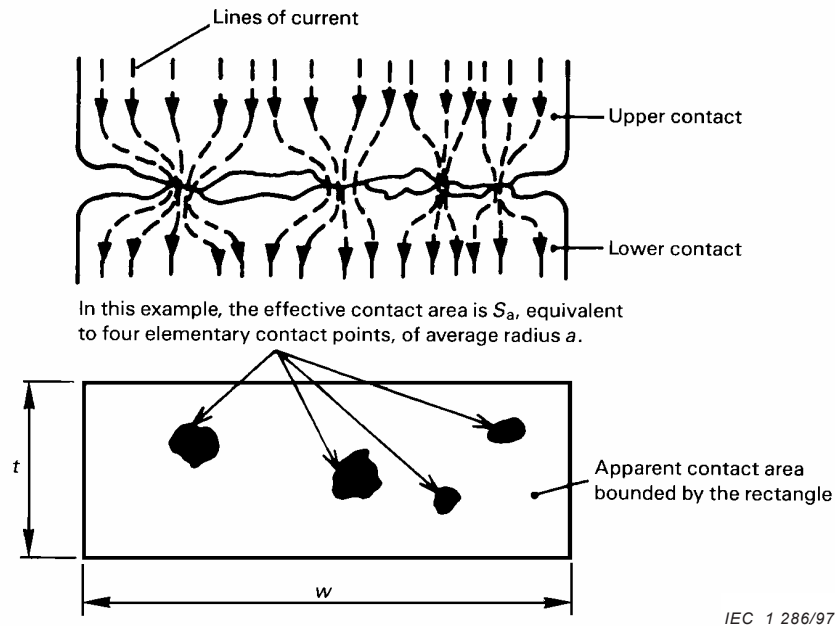


Figure 1 ± Illustration of apparent contact and effective contact areas

The contact area S_a depends upon how hard the contacts are pressed against each other, i.e. upon the force applied, the surface state of the contacts, and the hardness of the material used.

For the forces normally found in electrical technology, the contact area is, in practice, the area over which the force applied reaches the ultimate strength of the contact material characterised by the "hardness" of that material.

In fact, the asperities on each of the two surfaces before they are brought into contact and which are due to previous preparation of the surface are of small dimension (of the order of 1/100 mm) and are crushed even by small forces of the order of 0,1 N.

Assuming that the pressure exerted upon the contact area is equal to the contact hardness of the metal (H), then the following equation is obtained:

$$\frac{F}{S_a} = \xi H$$

However, this equation applies only for a contact force of $F \geq 50$ N, in fact:

$$S_a = n\pi a^2 = \frac{F}{\xi H}$$

where ξ is a dimensionless "coefficient of flatness" dependent upon the state of the surfaces in contact, usually having a value of between 0,3 and 0,6 for normal forces, but which can be much smaller after extensive polishing of the contact surfaces against each other.

As a result, the elementary contact radius a is given by the equation:

$$a = \sqrt{\frac{F}{n\pi\xi H}} \quad (1)$$

The number n of elementary contacts can be worked out approximately by the formula:

$$n = n_k H^{0,625} F^{0,2} \quad (2)$$

where $n_k \approx 2,5 \times 10^{-5}$ (SI units)

The above expression gives only the order of magnitude of the number of elementary contacts. Values of n_k can differ significantly from the value estimated, for example between $0,5 \times 10^{-5}$ and 30×10^{-5} (SI units).

2.3 Calculation of contact resistance

Contact resistance is made up of two components:

- a) constriction resistance, due to the drawing together of the lines of current as they pass through the elementary contacts;
- b) film resistance, corresponding to the film of oxide or of adsorbed molecules at the interface.

2.3.1 Calculation of the constriction resistance

Consider (see figure 2) an idealised elementary contact of radius a . If the electrical conductors are large in relation to the elementary contact, the lines of current are hyperbolae with foci located at the ends of the elementary contact diameter and the equipotential surfaces are flattened ellipsoids of the same foci.

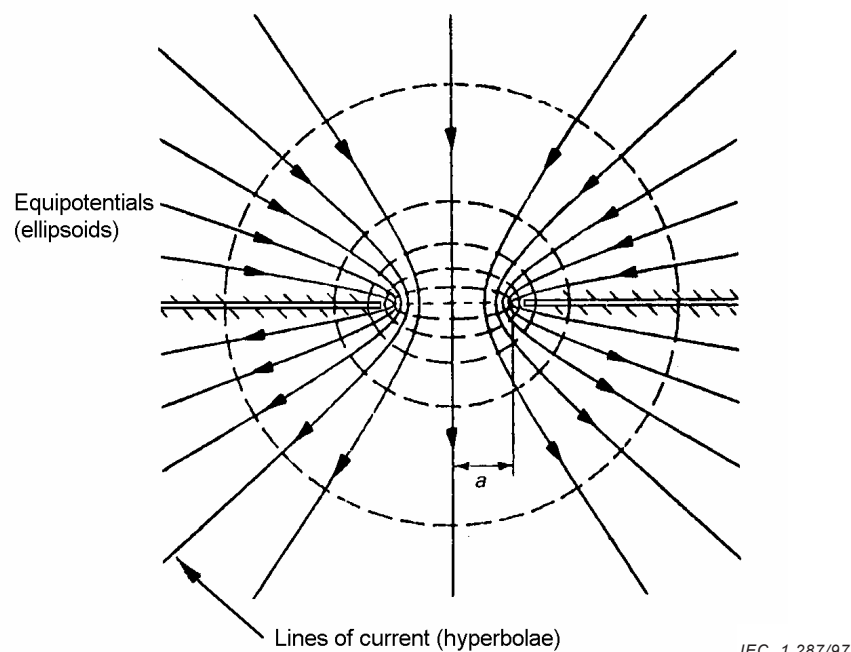


Figure 2 ± Equipotentials and lines of current at an elementary contact point

The resistance $R_{(a,l)}$ between the point of contact (heavy broken line in figure 2) and the semi-ellipsoid of major semi-axis l (l being the average distance between neighbouring elementary contacts and ρ the resistivity of the metal) is equal to half the contact resistance, and is written:

$$R_{(a,l)} = \frac{\rho}{2\pi \cdot a} \arctan \frac{\sqrt{l^2 - a^2}}{a}$$

If l is large compared with a , which is the more common case:

$$R_{(a,l)}(l/a \rightarrow \infty) = \frac{\rho}{4a}$$

since the constriction resistance is the sum of both halves

$$R_{(e)} = \frac{\rho}{2a} \quad (3)$$

For an actual contact comprising n relatively widely spread elementary contact points, the constriction resistance is thus:

$$R_e = \frac{\rho}{2na} \quad (4)$$

2.3.2 Calculation of the film resistance

The elementary contact points generally do not have a corrosion-free interface. Indeed, any initially pure metal surface becomes covered with a molecular layer of oxygen, leading in a few minutes to the formation of a homogeneous layer of oxide a few nanometres thick. If this layer is sufficiently compact and uniform, it protects the metal to some extent, the oxidation can then stop and the metal is "passivated"; this is particularly the case with aluminium and stainless steel at ordinary temperatures.

For other metals (copper, nickel and tin in the presence of oxygen; silver in the presence of sulphurous gases), the formation of this first layer of reaction product produced by oxidation or corrosion slows up the subsequent reaction which nevertheless continues, but more and more slowly.

For certain other metals (iron), the "oxidation" speed is more or less constant because the surface is not protected by the layer formed.

The main formulae for surface chemical reactions giving the thickness s formed as a function of time t and thermodynamic temperature T are contained in annex D for different metals.

They are derived from the general formula:

$$s = X \cdot \exp\left(-\frac{w}{2kT}\right) \cdot \sqrt{t} \quad (5)$$

If the activation energy w is expressed in electronvolts, it is necessary to multiply w by $1,6021 \times 10^{-19}$ J/eV. X is a constant and k is the Boltzmann constant.

This thin layer of oxide does not present a purely ohmic resistance to the passage of the current, such as could be evaluated by the formula:

$$\frac{\rho \times \text{length}}{\text{cross-sectional area}}$$

The electrons can in fact pass through it by a "tunnel-effect" mechanism.

The "tunnel resistivity" σ_o (*surface resistivity*), which is used to characterize the conductive properties of this layer, is expressed in Ωm^2 (see *table 1 for typical values*). *Tunnel resistivity* depends on the nature of the oxide (or other products of reaction with the atmosphere) and its thickness. Its thickness generally does not exceed 10 nm.

If the layer of "oxide" covers the actual contact area S_a uniformly, the apparent resistance R_i between the two faces is written:

$$R_i = \frac{\sigma_o}{S_a}$$

In the case of n elementary contacts of radius a , the resistance R_i , due to the layer of oxide at the interface, is expressed by the equation:

$$R_i = \frac{\sigma_o}{\text{total area in contact}} = \frac{\sigma_o}{n \pi a^2} \quad (6)$$

Table 1 ± Typical values of tunnel resistivity

Metal	State	σ_o Ωm^2
Copper	New	2×10^{-12} to 3×10^{-11}
	Oxidised	10^{-10}
	Tinned	10^{-12} to 4×10^{-11}
Silver		$4,6 \times 10^{-13}$ to 4×10^{-12} exceptionally up to $2,5 \times 10^{-11}$
Aluminium		7×10^{-11} to 10^{-9}

The values obtained are low for new contacts. The minimum value of $4,6 \times 10^{-13}$ for silver corresponds to the limit thickness of two adsorbed mono-molecular layers of oxygen, i.e. $2 \times 0,272 \text{ nm} = 0,54 \text{ nm}$.

2.3.3 Expression of the total contact resistance

The contact resistance R_c is the sum of the constriction resistance R_e (equation (4)) and the film resistance R_i (equation (6)), i.e:

$$R_c = \frac{\rho}{2na} + \frac{\sigma_0}{n\pi a^2} \quad (7)$$

If n and a in this equation are replaced by their values:

$$n = n_k H^{0,625} F^{0,2} \text{ with } n_k \approx 2,5 \times 10^{-5} \text{ (SI units)}$$

$$a = \sqrt{\frac{F}{n\pi\xi H}} \text{ with } \xi = 0,45$$

we obtain the following expression for R_c :

$$R_c = \frac{\rho}{2} \sqrt{\frac{\pi\xi}{n_k}} H^{0,1875} F^{-0,6} + \sigma_0 \xi H F^{-1}$$

This formula, applied to the different contact metals, gives the values of k_1 and k_2 shown in table 2.

If one metal is thinly plated onto another, the hardness must be taken as that of the plating and the resistivity as that of the base metal.

In the case of contacts of dissimilar metals, the overall resistance is the average of the resistance calculated using the constants for each metal.

Table 2 ± Typical values of contact resistance constants, calculated for relatively clean surfaces (For substitution in: $R_c = k_1 F^{\pm 0,6} + k_2 \sigma_0 F^{\pm 1}$)

Metal	Constriction resistance k_1 $\times 10^{\pm 6}$	Film resistance k_2 $\times 10^6$
Copper	90	247
Brass	360	450
Aluminium	130	135
Almelec	150	135
Silver	81	225
Tin	400	22,5
Nickel	420	585
Silvered copper	88	225
Tinned copper	57	22,5
Tinned aluminium	93	22,5
Silvered brass	310	225
Tinned brass	200	22,5

2.3.4 Electrical resistance of contacts when new

Tinned copper contacts theoretically show the lowest resistance compared with other kinds of contacts. However, this is only true provided two conditions are met: the layer of tin must be sufficiently thin to prevent its resistivity from being involved, and sufficiently thick for the hardness involved to actually be that of the tin. In practice, the resistivity obtained in the case of new tinned contacts is comparable with that of silvered copper and slightly less than that of copper. However, in the case of tinned contacts of the flexible type or those subject to vibration, account must be taken of "fretting corrosion" phenomena on the layer of tin, mentioned in 3.5.

Constriction resistance is particularly high in the case of tin and nickel, which rules out the use of these materials in the solid state.

Film resistance is high in the case of nickel and nickel-plated copper, which may be admissible in certain cases, bearing in mind the good corrosion resistance of nickel in corrosive atmospheres (battery rooms, atmospheres containing H₂S etc.).

2.3.5 Measurement of contact resistance

Contact resistance measurement is useful either for development tests or as routine tests to check production by comparison with a specimen which passed the temperature-rise test. Contact resistance is usually measured by injecting a d.c. current through the junction (so as to avoid effects of inductance), and measuring the resulting voltage drop across the junction.

For comparison purposes, it is important to measure the voltage drop at a defined location.

Measuring the contact resistance with a current much smaller than the normal current in service could give incorrect values, in particular when spring-loaded contacts have been operating on "no-load".

In addition, the voltage of the test supply should be sufficient to break down any possible surface layer, without exceeding the working voltage of the equipment under test. Care should be taken to avoid errors due to thermo-electric effects.

3 Ageing mechanisms of contacts and connection terminals

3.1 General

The ageing of closed electric contacts not subjected to arc erosion (the case with terminals in particular) is essentially due to the reaction of the metals with the surrounding environment at the contact interface.

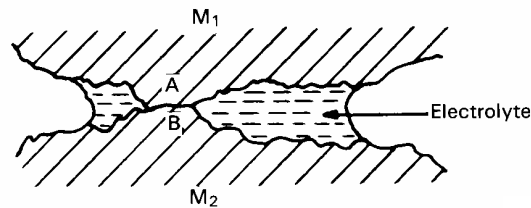
This reaction can be:

- of electrochemical origin (corrosion): as with bi-metallic contacts having incompatible electrochemical potentials in the presence of significant humidity (> 50 % r.h.);
- of chemical origin: the oxidation being due to the ambient medium (oxygen in the air, sulphurous vapours such as H₂S or SO₂).

These two aspects are covered in this report.

In addition, there are thermo-mechanical effects, involving stress relaxation, creep and dimensional variations, which are also thermally activated, and have the effect of reducing contact force and increasing contact resistance, but these are not included in this report. This complex degradation process is in principle difficult to model, because it is dependent on design and materials of manufacture. For certain devices, for example connectors, the effects are so complicated and varied, that no general simple temperature-dependent degradation curve exists.

3.2 Contacts of dissimilar metals



IEC 1 288/97

Figure 3 ± Contact between dissimilar metals in the presence of humidity (water adsorption)

Corrosion of contacts of dissimilar metals M_1 and M_2 will occur if the following conditions are met:

- different metals – The difference in electrochemical potential between terminals A and B before contact must in practice be in the order of 0,35 V or more;
- presence of an electrolyte – The film of water adsorbed on the surfaces in contact as a result of ambient humidity can play this role;
- presence of an oxidising agent – The term "oxidising" is taken here in the general sense of transfer of electrons, whose presence is necessary to depolarise the cell formed and allow the passage of current. Ambient air is sufficient;
- contact closed, in order to conduct the corrosion current.

The potential differences appearing at the contact surfaces of M_1 and M_2 in figure 3 with the contacts open are given in table 3.

Table 3 ± Voltages developed on bimetallic junction

Values in millivolts

negative pole \ positive pole	Silver	Nickel	Monel (30% Cu)	Cu-ni (70-30)	Copper	Silver solder	Bronzes*	Red bronze	Brasses*	Stainless steel*	Tin	Sn-Pb eutectic	Sn-Ag solder	Lead	Cast iron	Mild steel	Al alloys*	Aluminium	Cadmium	Galvanised Fe	Zinc alloys*	Zinc	Mg alloy*
Silver	0	150	170	190	190	210	230	250	260	330	470	480	510	560	710	720	770	770	790	1090	1100	1110	1590
Nickel		0	020	040	040	060	080	100	110	160	320	330	360	410	530	570	620	620	640	940	950	960	1440
Monel (30 % Cu)			0	020	020	040	060	080	090	160	300	310	340	390	540	550	600	600	620	920	930	940	1420
Cu/Ni (70/30)				0	0	020	040	060	070	140	280	290	320	370	520	530	580	580	600	900	910	920	1400
Copper				0	0	020	040	060	070	140	260	290	320	370	520	530	580	580	600	900	910	920	1400
Silver solder						0	020	040	050	120	260	270	300	350	500	510	560	560	580	880	890	900	1380
Bronzes*							0	020	030	100	240	250	280	330	480	490	540	540	560	860	870	880	1360
Red bronze								0	010	080	220	230	260	310	460	470	520	520	540	840	850	860	1340
Brasses*									0	070	210	220	250	300	450	460	510	510	530	830	840	850	1330
Stainless steel*										0	140	150	180	230	380	390	440	440	460	760	770	780	1280
Tin											0	010	040	090	240	250	300	300	320	620	630	640	1120
Sn-Pb eutectic												0	030	080	230	240	290	290	310	610	620	630	1110
Sn-Ag solder													0	050	200	210	260	260	280	580	590	600	1080
Lead														0	150	160	210	210	230	530	540	550	1030
Cast iron															0	010	060	060	080	380	390	400	880
Mild steel																0	050	050	070	370	380	390	870
Al alloys*																	0	0	020	320	330	340	820
Aluminium																		0	020	320	330	340	820
Cadmium																			0	300	310	320	800
Galvanised Fe																				0	010	020	500
Zinc alloys*																					0	010	490
Zinc																						0	450
Mg alloy*																							0

NOTE The above values are for guidance only. More exact values may apply for specific grades of metals and the value specified by the supplier should be used, if available. Otherwise consult specialized textbooks.

* Typical values.