
Guide to specifying permissible temperature and temperature rise for parts of electrical equipment, in particular for terminals

Guide pour la spécification des températures et des échauffements admissibles pour les parties des matériels électriques, en particulier les bornes de raccordement

Richtlinie für die Festlegung zulässiger Temperaturen und Erwärmungen für Teile elektrischer Betriebsmittel, insbesondere für Anschlüsse

National foreword

This document has been prepared under the direction of the Power Electrical Engineering Standards Policy Committee. It is identical with the English text of IEC Publication 943 'Guide for the specification of permissible temperature and temperature rise of parts of electrical equipment, in particular of terminals', first edition 1989, published by the International Electrotechnical Commission (IEC).

For the purposes of this Published Document, any references to IEC page numbers in the text should be ignored.

Cross-references

International standard	Corresponding British Standard
	BS 4727 Glossary of electrotechnical, power, telecommunication, electronics, lighting and colour terms (Technically equivalent)
*IEC 50(05) (1956)	Part 1 : Terms common to power, telecommunications and electronics Group 01 : 1983 Fundamental terminology (Technically equivalent)
IEC 50(151) (1978)	Group 02 : 1980 Electrical and magnetic devices terminology (Technically equivalent)
*IEC 50(10) (1956) } IEC 50(411) (1973) }	Part 2 Terms particular to power engineering Group 03 : 1971 (1979) Rotating machinery terminology (Technically equivalent)
IEC 50(441) (1984)	Group 06 : 1985 Switchgear and control gear terminology (including fuse terminology) (Technically equivalent)
IEC 85 (1984)	BS 2757 : 1986 Method of determining the thermal classification of electrical insulation (Identical)
IEC 216-2 (1974)	BS 5691 Guide for the determination of thermal endurance properties of electrical insulating materials Part 2 : 1979 List of materials and available tests (Identical)

The UK equivalent to IEC 364 is the *Regulations for the Electrical Installations of Buildings* published by the Institution of Electrical Engineers.

The Technical Committee has reviewed the provisions of IEC 685-2-2 (1983) IEC 157-1, IEC 157-1B, IEC 158-1B and IEC 216-1 and has decided that they are acceptable for use in conjunction with this document.

The following related British Standards also exist.

IEC 157-1 (1973) } IEC 157-1B (1979) }	BS 4752 Specification for switchgear and control gear for voltages up to and including 1000 V a.c. and 1200 V d.c. Part 1 : 1977 Circuit-breakers
IEC 158-1B (1979)	BS 5424 Specification for control gear for voltages up to and including 1000 V a.c. and 1200 V d.c. Part 1 : 1977 Contactors
IEC 216-1	BS 5691 Guide for the determination of thermal endurance properties of electrical insulating materials Part 1 : 1979 General procedures for the determination of thermal endurance properties, temperature indices and thermal endurance profiles

Compliance with a British Standard does not of itself confer immunity from legal obligations.

*These standards have been revised.

CONTENTS

	Page
National foreword	Inside front cover
Committees responsible	Back cover
Guide	2
INTRODUCTION	2
Clause	
1. General considerations	3
1.1 Scope	3
1.2 Object	3
2. General considerations concerning the nature of electric contact and the calculation of the ohmic resistance of contacts	3
2.1 Electric contacts and connection terminals	3
2.2 Calculation of contact resistance	6
3. Ageing mechanisms of contacts and connection terminals	12
3.1 General	12
3.2 Contacts of dissimilar metals	12
3.3 Oxidation ageing mechanisms	14
3.4 Results concerning ageing of contacts	16
3.5 Usage and precautions to be taken in the use of contact materials	19
4. Calculation of temperature rise of conductors, contacts and connection terminals	19
4.1 Definitions	19
4.2 Temperature rise ΔT_s of a conductor with respect to the temperature T_e of the surrounding medium	22
4.3 Temperature rise ΔT_0 in the vicinity of the contact: temperature rise of connection terminals	23
4.4 Temperature rise of the elementary contact points	28
4.5 Numerical example	28
5. Permissible temperature and temperature rise values	33
5.1 Definitions	33
5.2 Temperature and temperature rise of various equipment components	38
5.3 Temperature and temperature rise of conductors connecting electrical equipment	47
5.4 Temperature and temperature rise of connection terminals for electrical equipment — Influence on connected conductors	54
6. General procedure to be followed for determining permissible temperature and temperature rise	62
6.1 Basic parameters	62
6.2 Method to be followed for determining maximum permissible temperature and temperature rise	63
6.3 Chart for determining maximum permitted temperature or temperature rise	65
REFERENCES	66
APPENDIX A — Characteristics of selected metals and alloys	67
APPENDIX B — Physical characteristics of certain dielectrics	68
APPENDIX C — Information on the reaction of contact metals with substances in the atmosphere	69
APPENDIX D — Bolted (screwed) terminals and connections: recommended clamping torques	70
APPENDIX E — Insulation classes	71
APPENDIX F — List of letter symbols used	72
APPENDIX G — Derivation of an equation representing the temperature rise of a conductor in the vicinity of a terminal, in the case of cooling by radiation and natural convection	75

GUIDE FOR THE SPECIFICATION OF PERMISSIBLE TEMPERATURE AND TEMPERATURE RISE FOR PARTS OF ELECTRICAL EQUIPMENT, IN PARTICULAR FOR TERMINALS

INTRODUCTION

- 1) The temperature rise encountered in switchgear 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 switchgear, where numerous components dissipating energy (contactors, fuses, resistors, etc.), in particular modular devices (see Sub-clause 5.2.4.2), 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.

- 2) 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 for specifying permissible temperatures and temperature rises.
- 3) 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.
- 4) 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 cables connected 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 (Sub-clause 5.2.3.2) which specifies the values of the coefficient of filling to be used in several practical cases.

Note. — 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 values may be obtained by direct measurement on given items of electrical equipment.

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.

1. General considerations

1.1 *Scope*

This report is intended for guidance in specifying the permissible values for temperature and temperature rise of component parts of electrical equipment.

This report applies more particularly to switchgear contacts and connection terminals. It does not apply to the windings of rotating electrical machines or transformers.

1.2 *Object*

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 switchgear components, in particular the contacts, the connection terminals and the cables connected to them;
- the general procedure to be followed for specifying the permissible temperature and temperature rise.

2. General considerations concerning the nature of electric contact and the calculation 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.

2.1.1 *The 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^* , 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 Sub-clause 2.2).

In the following, for ease of calculation and for a better understanding of the contact mechanisms, we make the simplifying assumption 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:

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

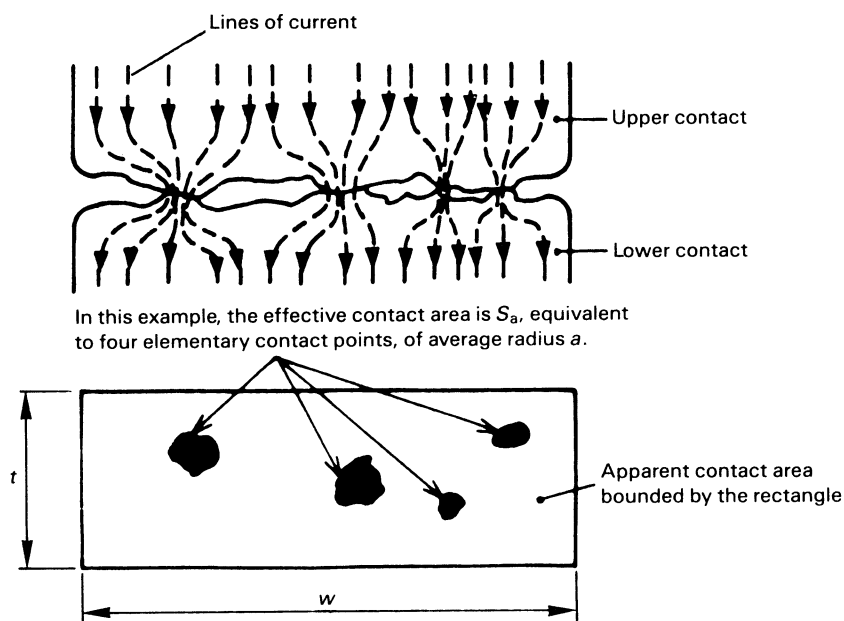


FIG. 1. — Illustration of apparent contact and effective contact areas.

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 material characterized by the “hardness” of the 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 (in the order of 1/100 mm) and are crushed even by small forces in the order of 0.1 N.

If we assume that the pressure exerted upon the contact area is equal to the contact hardness of the metal (H), we obtain:

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

* For an explanation of the symbols used in this report, see Appendix F.

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:

$$n_k \approx 2.5 \times 10^{-5} \text{ (S I)}$$

This 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 0.5×10^{-5} and 30×10^{-5} (S I).

2.1.2 Numerical example

Let us take a contact formed by the end-to-end meeting of two conductive copper bars, of square section measuring $10 \text{ mm} \times 10 \text{ mm} = 100 \text{ mm}^2$, applied with a contact force $F = 100$ N.

For copper, Appendix A gives $H = 5.5 \times 10^8$ Pa, hence:

$$n = 2.5 \times 10^{-5} \times (5.5 \times 10^8)^{0.625} \times 100^{0.2} = 18.2, \text{ i.e. } n \approx 18 \text{ points of contact.}$$

We thus obtain:

$$a = \sqrt{\frac{100}{18 \times \pi \times 0.45 \times 5.5 \times 10^8}} = 85 \times 10^{-6} \text{ m}$$

The radius of each elementary contact is thus of the order of 0.085 mm.

The contact area, taken to be equal to the area in actual physical contact, is given by:

$$S_a = \frac{F}{\xi H} = n \pi a^2 = 0.4 \text{ mm}^2$$

The active area, through which the whole of the current passes, is therefore only 4‰ of the apparent contact area; if the total current is 300 A (3 A/mm² in the conductor), the current density at the contacts is 750 A/mm².

The current density at the elementary contact points is thus very large, in the same order as that usually found in semiconductors.

Note. — The contact hardness H of a contact surface depends on the duration of a uniform contact force and also on the temperature prevailing at the contact point [1], [2]*. When calculating the rise in temperature of a contact, a *constant* contact hardness has here been assumed for simplicity.

* The figures in square brackets refer to the references given on page 137.

2.2 Calculation of contact resistance

Contact resistance is made up of two components:

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

2.2.1 Calculation of the constriction resistance

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

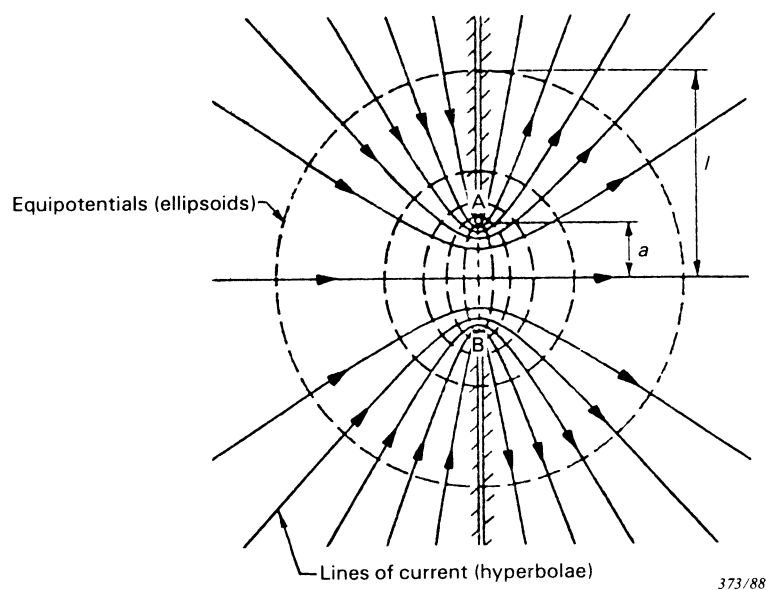


FIG. 2. — Equipotentials and lines of current at an elementary contact point.

The resistance $R_{(a,l)}$ between the point of contact AB and the semi-ellipsoid of major semi-axis l (l being the average distance between neighbouring elementary contacts) is equal to half the contact resistance, and is written:

$$R_{(a,l)} = \frac{\rho}{\pi a} \arctan \frac{\sqrt{l^2 - a^2}}{a}; (\rho = \text{resistivity of the metal})$$

i.e., if l is large compared with a , which is the more common case:

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

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

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

2.2.2 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 Appendix C 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 1.6021×10^{-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

$\frac{\rho \times \text{length}}{\text{cross-section area}}$; the electrons can in fact pass through it by a “tunnel effect” mechanism.

The “tunnel effect resistivity” σ_o which is used to characterize the conductive properties of this layer is expressed in Ωm^2 ; this depends on the nature of the oxide and its thickness (see Figure 3). It is a question in this case of “practical” thickness rather than the theoretical thickness of an ideal crystalline oxide network, for which the abscissae should be multiplied by a factor of between 0.5 and 0.1.

σ_o is also dependent on the contact force, as the crystalline oxide network may be deformed. The independence of σ_o in relation to temperature does not apply in the case of higher temperatures (for $\Theta > 30^\circ\text{C}$) which can only, for example, be produced by current heat losses in the contact. (Θ is the Celsius temperature. Note $T = \Theta + 273.15$.)

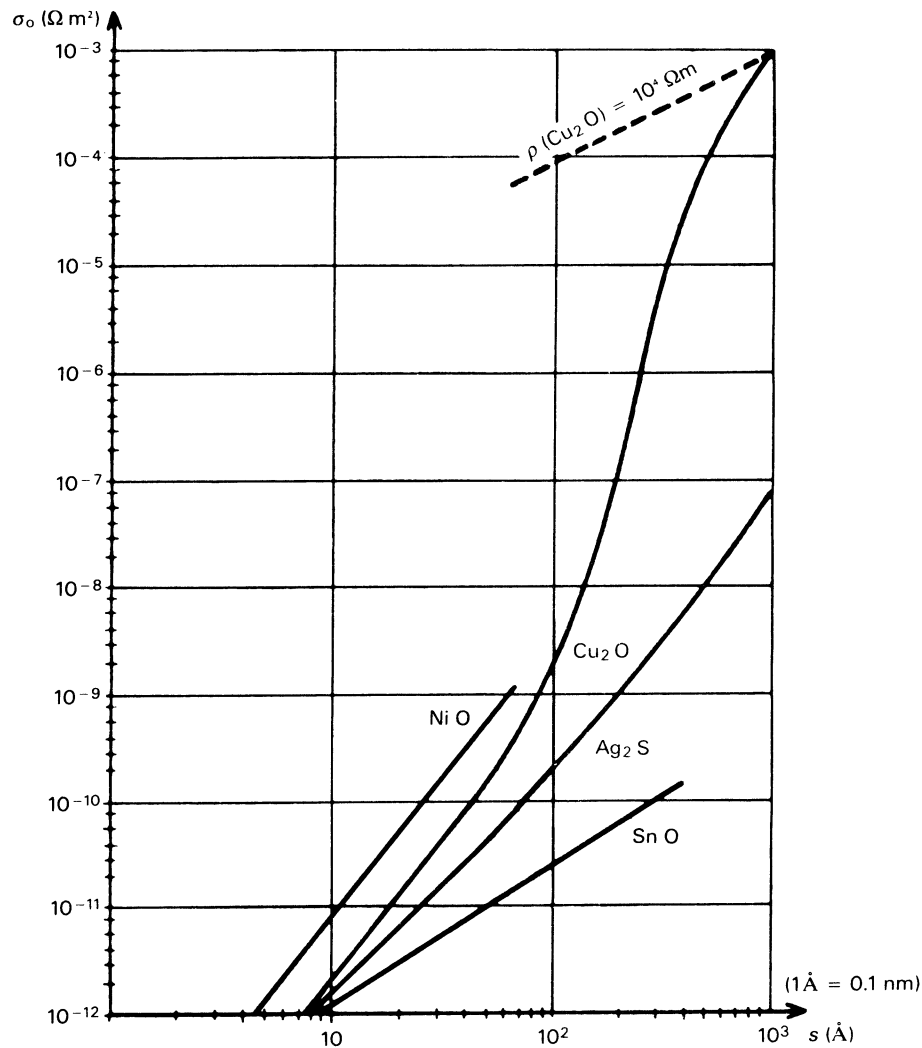


FIG. 3. — Surface resistivity σ_0 as a function of the thickness s of the layer of oxide.

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

$$R_i = \frac{\sigma_0}{S_a}$$

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:

$$R_i = \frac{\sigma_0}{\text{total area in contact}} = \frac{\sigma_0}{n \pi a^2} \quad (6)$$

2.2.3 Expression of the total contact resistance

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

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

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

$$n = n_k H^{0.625} F^{0.2} \quad \text{with } n_k \approx 2.5 \times 10^{-5} \text{ (S I)}$$

$$a = \sqrt{\frac{F}{n \pi \xi H}} \quad \text{with } \xi \approx 0.45$$

we obtain the following expression for R_c :

$$R_c = \frac{\rho}{2} \sqrt{\frac{\pi \xi}{n_k}} H^{0.1875} F^{-0.6} + \sigma_o \xi H F^{-1} \quad (8)$$

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

TABLE I
Typical values of contact resistance constants, calculated for relatively clean surfaces

Metal	Contact resistance $R_c = k_1 F^{-0.6} + k_2 \sigma_o F^{-1}$	
	Constriction resistance k_1 $\times 10^{-5}$	Film resistance k_2 $\times 10^6$
Copper	9	247
Brass	36	450
Aluminium (A5L)	13	135
Almelec	15	135
Silver	8.1	225
Tin	40	22.5
Nickel	42	585
Silvered copper	8.8	225
Tinned copper	5.7	22.5
Tinned aluminium	9.3	22.5
Silvered brass	31	225
Tinned brass	20	22.5

2.2.4 Comparison with experimental results

Experimental results taken from the work of various authors are given in Figure 4, page 27, for copper, tinned copper, silver and aluminium. The corresponding references are:

- 1: new copper
- 2: oxidized copper
- 3: cleaned copper
- 4: tinned copper (direct and inverse characteristics)
- 5: silvered copper
- 6: silver contacts in air (end contact)
- 7: silver contacts in vacuum (the direct and inverse characteristics are mixed; end contact)
- 8: end contacts of aluminium, covered with contact grease (direct and inverse characteristics)
- 9: aluminium contact (direct and inverse characteristics)

The values obtained in practice for σ_o in the case of these data are those given in Table II.

- Notes 1.* — 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.
- 2.* — In the case of contacts of dissimilar metals, the overall resistance is half the sum of the resistance of each member of the contact pair.

TABLE II
Typical values of the tunnel effect surface resistivity

Metal	State	$\sigma_o (\Omega m^2)$
Copper	New	2×10^{-12} to 3×10^{-11}
	Oxidized	10^{-10}
	Tinned	10^{-12} to 4×10^{-11}
Silver		4.6×10^{-13} to 4×10^{-12} and up to 2.5×10^{-11}
Aluminium		7×10^{-11} to 10^{-9}

The values obtained are low for new contacts. The minimum value of 4.6×10^{-13} for silver corresponds to the limit thickness of two adsorbed mono-molecular layers of oxygen, i.e. $2 \times 2.72 \text{ \AA} = 5.4 \text{ \AA}$.

The maximum values obtained for σ_o are $10^{-10} \Omega m^2$ for oxidized copper and 7×10^{-11} to $10^{-9} \Omega m^2$ for aluminium, the latter being due to the considerable thickness of the layer of alumina ($40 \text{ \AA}$) always existing on the surface of this metal after exposure to air.

In general, the theoretical curves drawn with these σ_o values coincide closely with experimental results.

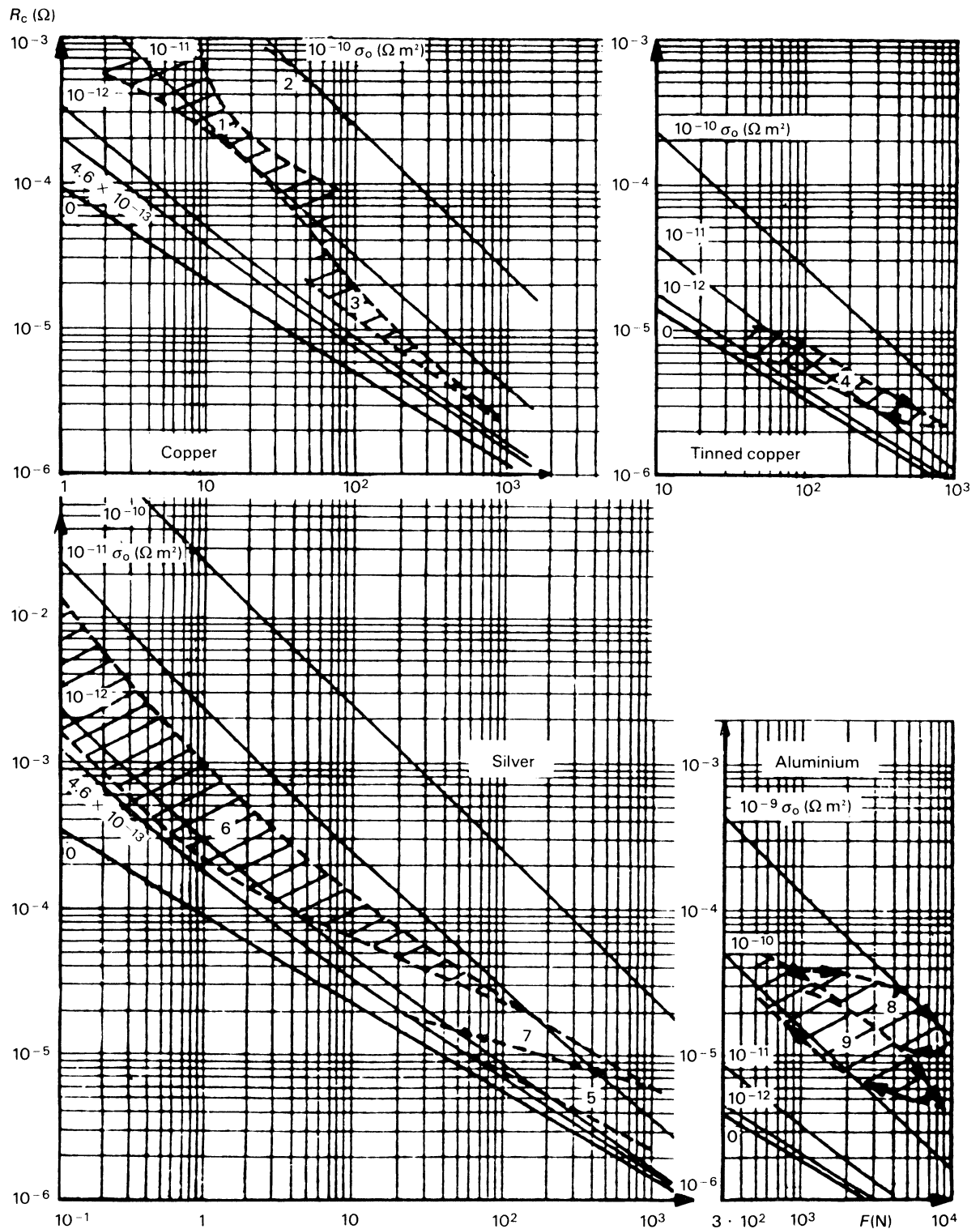


FIG. 4. — Comparison of the theoretical curves of contact resistance (R_c) as a function of applied force (F) (continuous line for various values of the superficial resistivity σ_o (from 4.6×10^{-13} to 10^{-9})) with experimental results (broken line, curves showing resistance as a function of applied force for copper, tinned copper, silver and aluminium). (Numbers 1 to 9 on the graphs refer to the materials enumerated in the first paragraph of Sub-clause 2.2.4.)

The hysteresis phenomenon to which the contact resistance is subject will be noted when the contact is made to undergo increasing and decreasing cyclic loading, care being taken to prevent the two faces of the contact from sliding against each other when cycling the mechanical load.

2.2.5 *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 subject to vibration, account must be taken of “fretting corrosion” phenomena on the layer of tin, mentioned in Sub-clause 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, etc.).

2.2.6 *Numerical example*

Refer to the example in Sub-clause 4.5 which deals fully with the problem of the contact formed by the end-to-end meeting of two conductive copper bars.

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 oxidation of the metals at the contact interface.

This oxidation can be:

- of electrochemical origin: 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 H_2S or SO_2).

3.2 *Contacts of dissimilar metals*

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

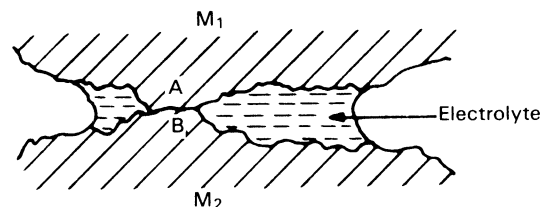


FIG. 5. — Contact between dissimilar metals in the presence of humidity (water adsorption).

- a) Different metals — The difference in electrochemical potential between terminals A and B before contact must in practice be in the order of 0.5 V or more.
- b) Presence of an electrolyte — The film of water adsorbed on the surfaces in contact as a result of ambient humidity can play this role.
- c) Presence of an oxidizing agent — The term “oxidizing” is taken here in the general sense of giving up electrons, whose presence is necessary to depolarize the cell formed and allow the passage of current. Ambient air is sufficient.
- d) Contact closed, in order to conduct the corrosion current.

The potential differences appearing at surfaces A and B in open circuit (contact not yet made) are given in Table III.

TABLE III
Voltages in 10^{-2} V developed on bi-metallic contacts

Anode (–) Cathode (+)	Silver	Nickel	Monel (30% Cu)	Cupro-nickel (70-30)	Copper	Silver solder	Bronzes*	Red bronze	Brasses*	Stainless steels*	Tin	Tin-lead solder	Tin-silver solder	Lead	Cast-iron	Steels	Aluminium alloys*	Aluminium	Cadmium	Galvanized iron or steel	Zinc alloys*	Zinc	Magnesium alloy*
Silver	0	15	17	19	19	21	23	25	26	33	47	48	51	56	71	72	77	77	79	109	110	111	159
Nickel		0	02	04	04	06	08	10	11	16	32	33	36	41	53	57	62	62	64	94	95	96	144
Monel (30% Cu)			0	02	02	04	06	08	09	16	30	31	34	39	54	55	60	60	62	92	93	94	142
Cupro-nickel (70-30)				0	0	02	04	06	07	14	28	29	32	37	52	53	58	58	60	90	91	92	140
Copper					0	02	04	06	07	14	28	29	32	37	52	53	58	58	60	90	91	92	140
Silver solder						0	02	04	05	12	26	27	30	35	50	51	56	56	58	88	89	90	138
Bronzes*							0	02	03	10	24	25	28	33	48	49	54	54	56	86	87	88	136
Red bronze								0	01	06	22	23	26	31	46	47	52	52	54	84	85	86	134
Brasses*									0	07	21	22	25	30	45	46	51	51	53	83	84	85	133
Stainless steels*										0	14	15	18	23	38	39	44	44	46	76	77	78	128
Tin											0	01	04	09	24	25	30	30	32	62	63	64	112
Tin-lead solder												0	03	08	23	24	29	29	31	61	62	63	111
Tin-silver solder													0	05	20	21	26	26	28	58	59	60	108
Lead														0	15	16	21	21	23	53	54	55	103
Cast-iron															0	01	06	06	08	38	39	40	88
Steels																0	05	05	07	37	38	39	87
Aluminium alloys*																	0	0	02	32	33	34	82
Aluminium																		0	02	32	33	34	82
Cadmium																			0	30	31	32	80
Galvanized iron or steel																				0	01	02	50
Zinc alloys*																					0	01	49
Zinc																						0	45
Magnesium alloy*																							0

*Characteristic values.

Acceptable combinations give potential differences generally significantly less than 50×10^{-2} V; the lower the better.

It can be seen that the potential differences developed between dissimilar contacts of the principal contact materials are low, apart from silver-tin and silver-aluminium combinations which should be avoided, particularly in corrosive atmospheres.

3.3 Oxidation ageing mechanisms

Since each terminal or contact in fact consists of the joining of numerous small elementary contact points, it is here that the corrosion mechanisms operate. There are two processes of oxidation, both of which may take place simultaneously:

- the side surfaces of the elementary contact points are progressively attacked, reducing the cross-section of the conducting area;
- the layer of oxide of surface resistivity σ_o gradually thickens.

These two mechanisms are considered below:

3.3.1 Reduction in cross-section of the elementary contacts

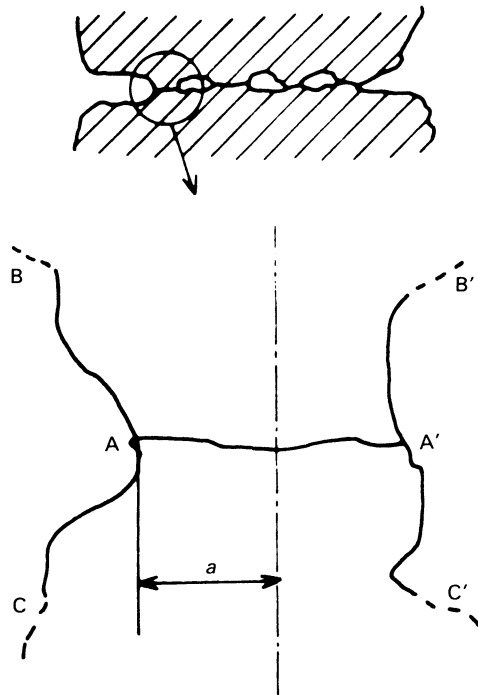


FIG. 6. — Elementary contact point of radius a .

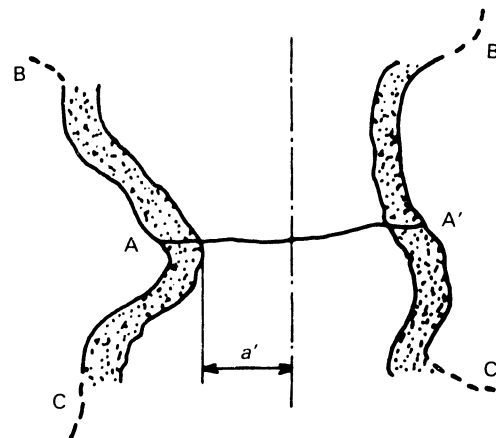


FIG. 7. — Oxidation of an elementary contact point.

On a non-oxidized contact an elementary contact point of radius a is considered (see Figure 6).

The contact surface AA' contains relatively little air, which is partly expelled by the closure of the contact, and is sufficient only to produce slight oxidation.

By contrast, the side surfaces such as BC and B'C' are exposed to the air and are subject to progressive oxidation.

As a result, the elementary contact radius gradually decreases and the contact resistance rises (see Figure 7, page 33).

In fact, the reduction in cross-section to which this type of oxidation leads is so slow that several decades would be needed to bring about a major deterioration of the contact, even at high temperatures. However, experience shows that this is not so in practice and that another physical phenomenon must be involved; in fact, it is frequently found that contacts subjected to current cycles deteriorate more quickly than those carrying a constant current. These cycles result in differential thermal expansion at the contact area which lead to micro-movements of the faces in contact with each other.

Because of these small relative movements which may also be caused by electrodynamic vibrations or mechanical shock, the contact width AA' shown in Figure 7 may be reduced to DD' (see Figure 8). The surfaces EF and $E'F'$ (initially protected) are now exposed to corrosion and, when the contacts return to their initial position, the non-oxidized region in contact is very small.

This apparently causes a considerable increase in the effect of oxidation at the point of contact. The effects of micro-movement are thus equivalent in this case to an acceleration of the oxidation.

This phenomenon is obviously more serious on electrically closed contacts than on tightened-down connection terminals.

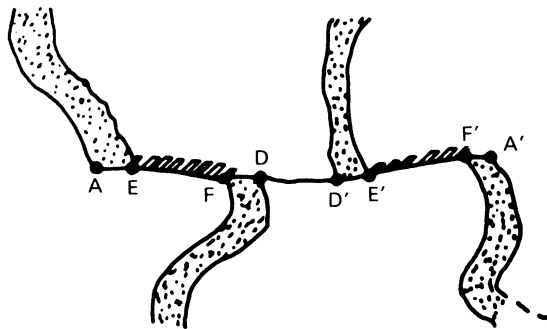


FIG. 8. — Influence of a relative micro-movement on the oxidation of an elementary contact.

3.3.2 Growth in the layer of oxide at the contact interface

The second ageing mechanism is as follows (see Figure 9, page 37):

It is assumed that, as a result of the contact movements (stress, vibration, shock) and through diffusion through the interstices of the two surfaces ① and ②, the oxygen has partial access to these surfaces and creates an additional film of oxide between the two parts in contact which increases the surface resistivity of the layer of oxide at the interface and, consequently, increases the contact resistance.

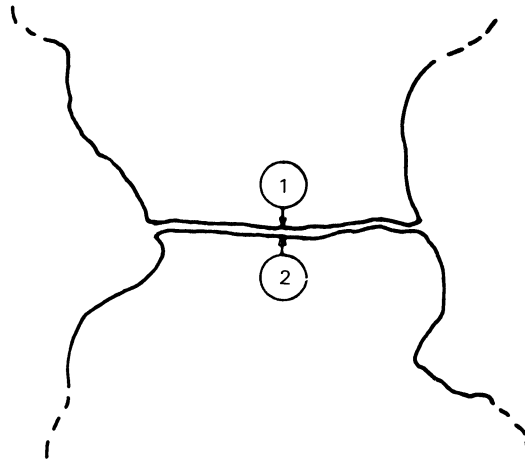


FIG. 9. — Oxidation of the opposite faces of a contact.

If the contact surfaces were assumed to be freely exposed to the ambient air, the contact resistance would very quickly (in a few hours) reach prohibitive values even at very low contact temperatures. It is clear that the surfaces in contact offer each other mutual protection which slows down the oxidation speed, the molecules of oxygen in this case only being able to diffuse very slowly.

3.3.3 Discussion and synthesis of these two ageing processes

The reduction of the area in electric contact and the increase in surface resistivity are two ageing phenomena which may occur simultaneously.

They depend:

- in general, upon the structure of the contact and the nature of its atmosphere;
- more particularly:
 - upon the intensity of the stresses leading to micro-movements, such as thermal stresses due to the current cycles or to electrodynamic variations and vibrations;
 - upon the concentration of the oxidizing element in the contact atmosphere.

In practice, it is somewhat difficult to identify the part played by each of these two phenomena, and the analysis can only take into account one mechanism at a time. However, the results are so close for each of the hypotheses that it is possible to draw a common conclusion, whatever the manner in which the ageing of the contact or terminal occurs.

3.4 Results concerning ageing of contacts

Starting from ageing hypotheses, it is possible to construct a mathematical model representing the behaviour of the contacts as a function of time; a model which can be validated by short duration experimental tests. The main results which can be drawn from this analysis are given below; in general, it is possible to separate the influence of the temperature rise due to the actual current flowing between the contacts from the influence of the ambient temperature (temperature of the fluid surrounding the contact).

3.4.1 Influence of temperature rise

All other things being equal, a contact or a terminal will have its life reduced by one half if its temperature rise increases by $\Delta_i(K)$, Δ_i being given as a function of the initial temperature rise (see Figure 10, page 39). ΔT_i is the temperature rise of the component relative to the surrounding fluid.

In general, when the temperature rise of a contact or terminal passes from a value ΔT_{i1} to a value ΔT_{i2} , the life is multiplied by an ageing factor K_i which for moderate differences between ΔT_{i1} and ΔT_{i2} is expressed as:

$$K_i = 2^{\frac{\Delta T_{i1} - \Delta T_{i2}}{\Delta_i}}$$

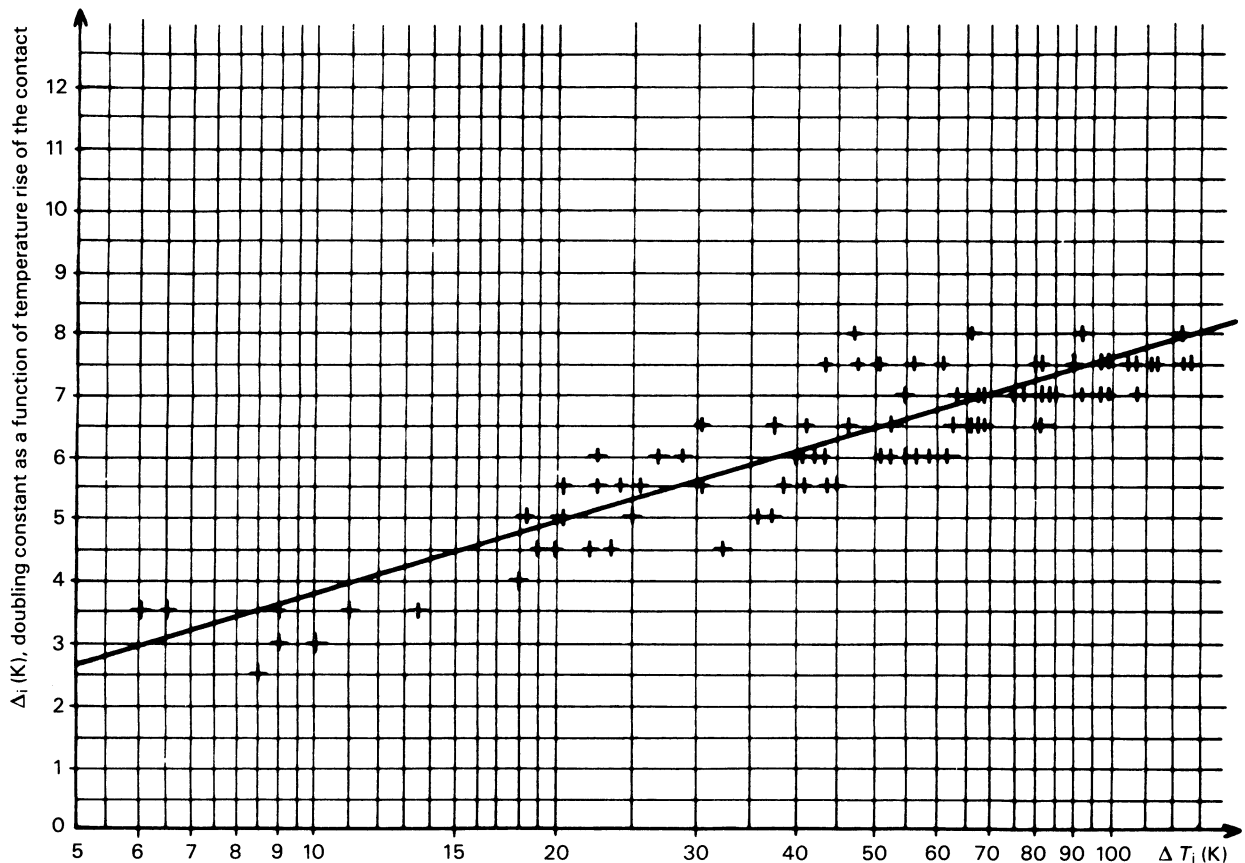


FIG. 10. — Doubling constant Δ_i as a function of temperature rise (for copper contacts).

Example: Consider, for example, a copper electrical contact in air having an initial temperature rise of 35 K. The doubling constant Δ_i is approximately 6 K. If we wish to overload this contact so that its initial temperature rise is 45 K, all other things being equal, its life will be reduced by a factor

$$2^{\left(\frac{35 - 45}{6}\right)} = 0.315$$

i.e. its life is divided by approximately 3.2.

Note. — It is unreliable to make calculations based upon an extrapolation of these results outside the region of experimental values.

3.4.2 Influence of ambient temperature

All other things being equal, a contact or terminal will have its life reduced by half if the temperature of the ambient medium surrounding it increases by Δ_e (K), Δ_e being given in Figure 11 as a function of the initial temperature rise.

In general, when the temperature of the fluid surrounding a contact or a terminal passes from value T_{e1} to value T_{e2} , the life is multiplied by an ageing factor K_e which is expressed as:

$$K_e = 2^{\frac{T_{e1} - T_{e2}}{\Delta_e}}$$

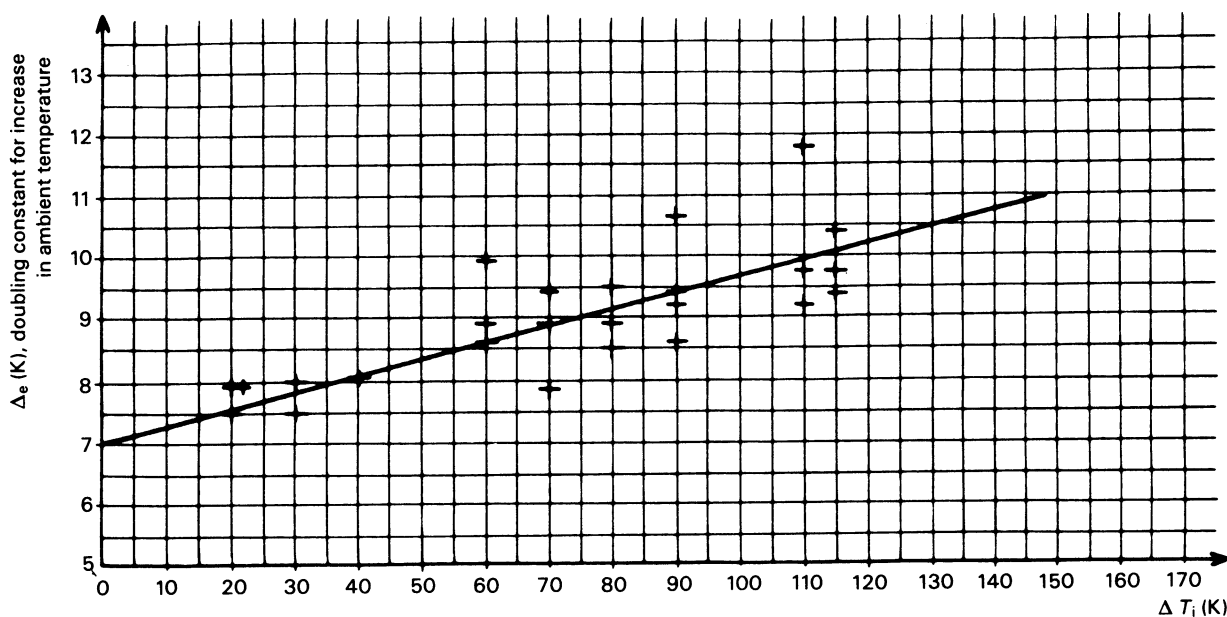


FIG. 11. — Doubling constant Δ_e expressed as the required temperature rise of the surrounding fluid, as a function of the temperature rise ΔT_i of the contact (contact material: copper, fluid: air).

Note. — It is unreliable to make calculations based upon extrapolation of these results outside the region of experimental values.

Thus, for a copper electrical contact with a temperature rise ΔT_i of 35 K an increase of $\Delta_e = 8$ K in the temperature of the surrounding air will reduce its life by half.

3.4.3 Combined influence of the temperature rise of the contact and the temperature rise of the surrounding fluid

When the temperature rise of a contact or terminal and the temperature of the surrounding medium vary simultaneously, the two effects combine and the overall ageing factor K is expressed as follows:

$$K = 2^{\left[\frac{(\Delta T_{i1} - \Delta T_{i2})}{\Delta_i} + \frac{(T_{e1} - T_{e2})}{\Delta_e} \right]} \quad (9)$$

3.5 Usage and precautions to be taken in the use of contact materials

Copper tends to deteriorate considerably with time and temperature. It is unwise to exceed 60°C to 85°C (value to be determined according to the use of the metal in the contacts and according to the nature of the atmosphere), and to use this material for contacts remaining closed for long periods at their rated thermal current (as on incomer circuit-breakers). In this latter case, silvered copper, the ageing of which is slow in non-sulphurous atmospheres, is to be preferred.

As an interesting example, we may calculate the resistance of copper and of nickel-plated, tinned and silver-plated copper contacts for a contact force of 10 N and after 1 000 h exposure to ambient air (see Appendix C).

The following values are obtained:

Bare copper	20 mΩ
Nickel-plated copper	35 mΩ
Tinned copper	6.8 mΩ
Silver-plated copper	0.3 mΩ

The advantages of tinning or silver plating are clear. Nickel only appears interesting for polluted atmospheres where silver could be unsuitable; nickel-plated copper is suitable in the case of corrosive atmospheres or high temperature contacts, a frequent situation in certain power stations or in railway transport.

Tinned copper and aluminium are the preferred materials for low voltages. The low hardness of tin is interesting in so far as it gives low contact resistances. By contrast, it is not possible to carry out frequent openings and closures on such contacts for fear of damaging the tin plating. A standard use of tinned metal is found in the contacts of fuses, the fuse-links which are replaced (to restore the supply after the fuse has operated) creating a new contact surface. The temperature should not exceed 105°C for tin, because of the creep phenomena which occur above this level.

Moreover, for flexible or bolted tinned contacts subject to vibration, a “fretting corrosion” phenomenon may occur on the tin plating, rapidly leading to the destruction of the contact, even in the case of low currents compared with the rated current; it may be preferable in this case to use bare, silver-plated or nickel-plated contacts.

Silver is an excellent contact material which ages slowly except in atmospheres with sulphurous fumes.

Aluminium cannot be used unless its layer of insulating alumina is removed by brushing with grease or by other special treatment recommended by the manufacturer.

4. Calculation of temperature rise of conductors, contacts and connection terminals

4.1 Definitions

Figure 12, page 45, represents, as a theoretical example, the temperature variation along two conductors forming an end-to-end contact.

In the case of real contacts (e.g. a conductor leading to a terminal), the temperature variation along the cable is generally not symmetrical.

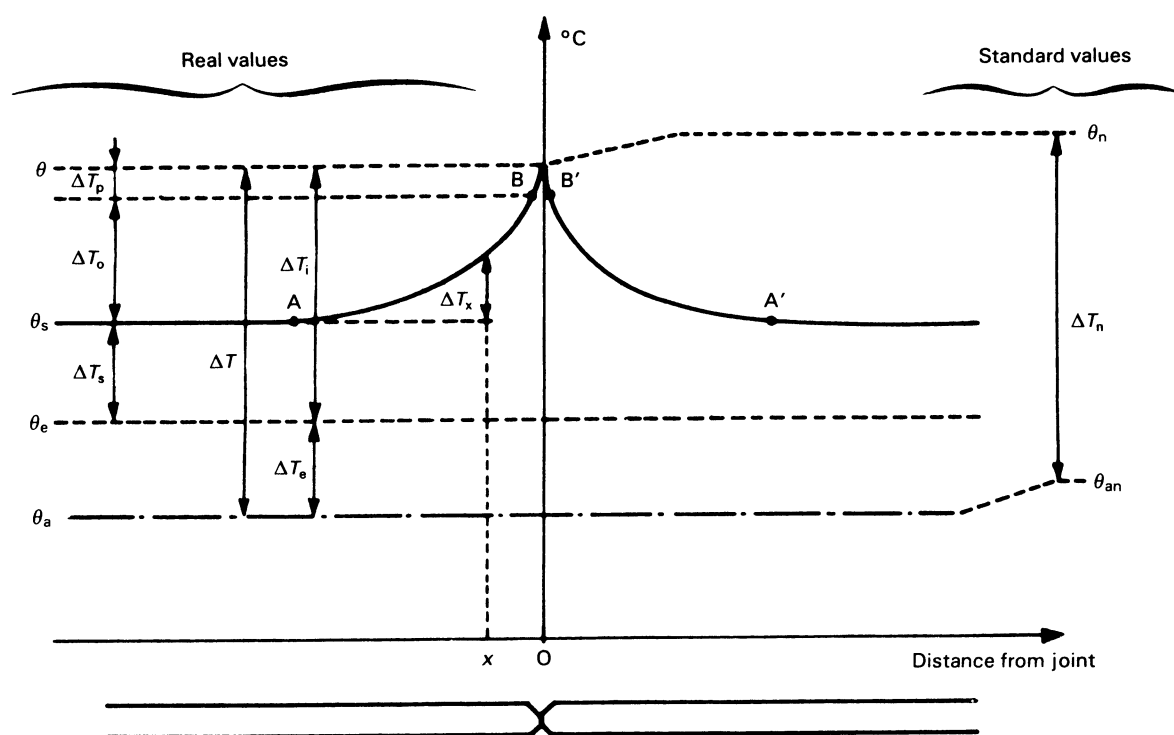


FIG. 12. — Symbols used for the definition of temperatures and temperature rises; example chosen: end-to-end contacts.

Figure 13 illustrates a practical case of fuses inside a junction box.

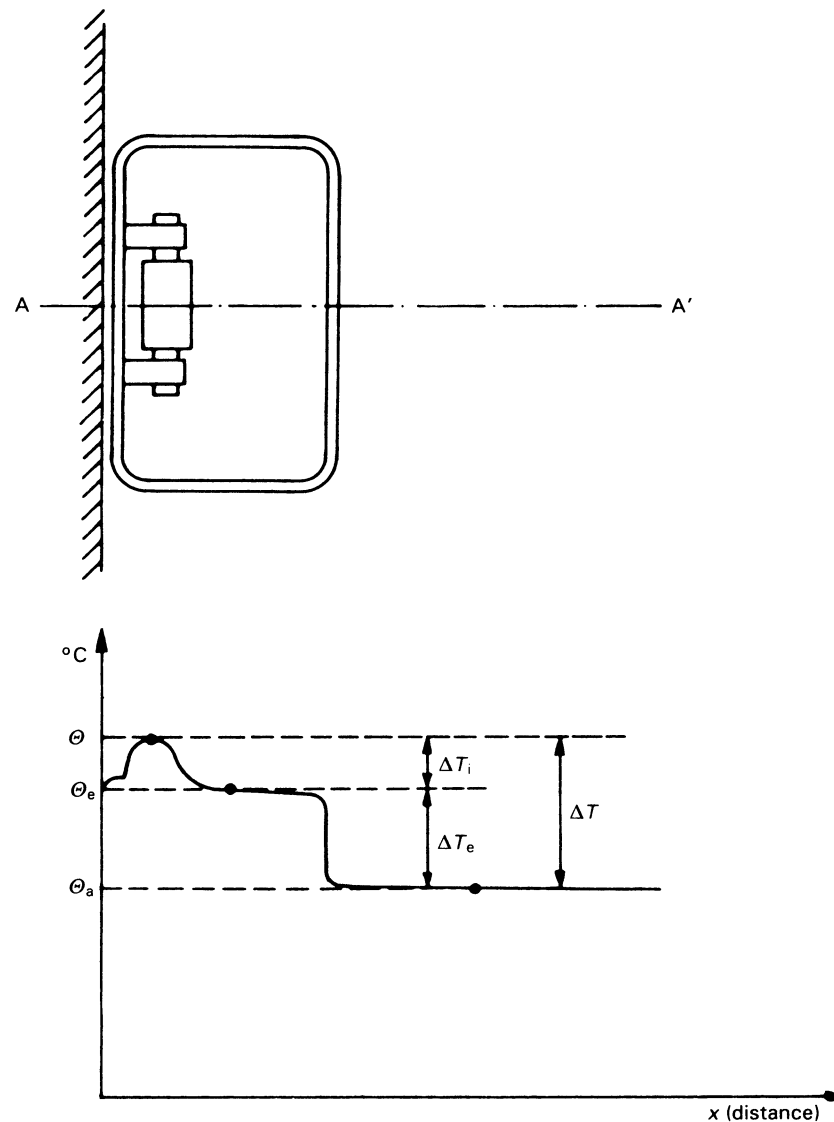


FIG. 13. — Temperature and temperature rise along the axis AA', in a junction box containing a fuse.

Let us now consider the definition of the main parameters contributing to the maximum temperature Θ of the contact or the component concerned.

This maximum temperature Θ is the sum of the following terms:

$$\Theta = \Theta_a + \Delta T_e + \Delta T_s + \Delta T_0 + \Delta T_p$$

where:

Θ_a is the external ambient temperature, the standard definition of which is given in Sub-clause 5.1.1.

ΔT_e is the temperature rise of the air surrounding the contact or component considered, in relation to the ambient temperature Θ_a ; if the component is inside an enclosure, the temperature of the air surrounding the component will thus be $\Theta_e = \Theta_a + \Delta T_e$.

- ΔT_s is the actual temperature rise of the conductor (temperature Θ_s (°C) or T_s (K)) in the absence of the contact. Electrical contacts and conductors are, in the majority of cases, cooled by radiation and natural convection, and sometimes by forced convection (air speed over about 0.3 m/s to 0.4 m/s, as in the case of overhead lines or conductors installed out of doors).
- ΔT_0 is the temperature rise in the vicinity of the contact; in fact, the heat in joules produced by Joule effect in the contact resistance is dissipated along the periphery of the conductor, giving a decreasing temperature distribution as shown in segments BA and B'A' of the curve in Figure 12, page 45. The maximum temperature rise occurs when x approaches zero.
- ΔT_p represents a supplementary temperature rise at the elementary contact points, due to the opening out of the thermal flux lines from the interfaces between the elementary contact points. The magnitude of this item is generally small compared with the previous ones.

The formulae for these items are given below.

4.2 Temperature rise ΔT_s of a conductor with respect to the temperature T_e of the surrounding medium

The temperature rise of a conductor in relation to the ambient temperature is expressed by the general relationship:

$$\Delta T_s = \frac{[(T_e + \Delta T_s - 273.15) \alpha + 1] R_0 I^2 + r \phi_s S_r}{Bl \left[\sigma \varepsilon \frac{(T_e + \Delta T_s)^4 - T_e^4}{\Delta T_s} + \frac{\lambda}{D_h} N_u \right]} \quad (10)$$

Note. — All these temperatures T are expressed on the Kelvin scale.

The dimensionless Nusselt number N_u used in the above formula depends upon the method of cooling.

With radiation and natural convection, for the general case of indoor contacts and terminals, we have:

$$N_u = 0.8 (G_r P_r)^{0.05} + 0.35 (G_r P_r)^{0.27} \quad (11)$$

where:

$$G_r P_r = \frac{M^2 \mu g C_p D_h^3 \Delta T}{\mu_d \lambda}$$

In general, the temperature rises calculated from equation (10) are roughly proportional to the power 1.67 of the current intensity.

With radiation and forced convection, which is the case with outdoor type contacts and terminals such as line or sub-station connections, we must use:

$$N_u = 0.65 R_e^{0.2} + 0.23 R_e^{0.61} \quad (12)$$

where:

$$R_e = \frac{M v D_h}{\mu_d} \text{ (Reynolds number)}$$

The temperature rises are then proportional to the square of the current. For the numerical calculation of ΔT_s , it is noted that this term is also in both sides of the equation; its solution is achieved by successive approximations from any value taken for ΔT_s . The convergence is very rapid and a few repetitions are generally sufficient to obtain ΔT_s to within at least 1 K.

The numerical values to be used in the calculations are shown in Appendices A and B.