INTERNATIONAL STANDARD

IEC 60354

Second edition
1991-09

The contents of the corrigendum of March 1992 has been included in this reprint

Loading guide for oil-immersed power ttransformers

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

LOADING GUIDE FOR OIL-IMMERSED POWER TRANSFORMERS

FOREWORD

1) The formal decisions or agreements of the IEC on technical matters, prepared by Technical Committees on which all the National Committees having a special interest therein are represented, express, as nearly as possible, an international consensus of opinion on the subjects dealt with.

2) They have the form of recommendations for international use and they are accepted by the National Committees in that sense.

3) In order to promote international unification, the IEC expresses the wish that all National Committees should adopt the text of the IEC recommendation for their national rules in so far as national conditions will permit. Any divergence between the IEC recommendation and the corresponding national rules should, as far as possible, be clearly indicated in the latter.

This guide has been prepared by IEC Technical Committee No. 14: Power transformers.

It forms the second edition of IEC 354 and replaces the first edition (1972).

The text of this guide is based on the following documents:

Six Months' Rule	Reports on Voting
14(CO)71	14(CO)72 and 72A

Full information on the voting for the approval of this guide can be found in the Voting Reports indicated in the above table.

The following IEC Publications are quoted in this guide:

Publications Nos. 76: Power transformers.
76-1 (1976): Part 1: General.
76-2 (1976): Part 2: Temperature rise.
76-4 (1976): Part 4: Tappings and connections.
76-5 (1976): Part 5: Ability to withstand short circuit.

LOADING GUIDE FOR OIL-IMMERSED POWER TRANSFORMERS

Section 1: General

1.1 Scope

This guide is applicable to oil-immersed transformers complying with IEC 76. It indicates how, within limits, transformers may be loaded above rated conditions. For furnace transformers, the manufacturer should be consulted in view of the peculiar loading profile.

1.2 Object

This guide provides guidance for the specification and loading of power transformers from the point of view of operating temperatures and thermal ageing. It provides recommendations for loading above the nameplate rating and guidance for the planner to choose appropriate rated quantities and loading conditions for new installations.

IEC 76-2 contains the requirements and tests relating to temperature rise figures for oil-immersed transformers during continuous rated loading. It should be noted that IEC 76-2 refers to the average winding temperature rise while the present guide refers mainly to the hot-spot temperature and the stated values are provided only for guidance.

The guide gives mathematical models for judging the consequence of different loadings, with different temperatures of the cooling medium, and with transient or cyclical variation with time. The models provide for the calculation of operating temperatures in the transformer, particularly the temperature of the hottest part of the winding. This hot-spot temperature is, in turn, used for evaluation of a relative value for the rate of thermal ageing.

The guide further presents recommendations for limitations of permissible loading according to the results of the temperature calculations. These recommendations refer to different categories of transformers by size and importance, and also to different types of loading duty – *continuous loading, normal cyclic undisturbed loading* or *temporary, emergency loading.*

For small transformers, here called *distribution transformers,* the guide provides curves which make it possible to evaluate cyclic loading at specific ambient temperatures in comparison with conditions at rated loading under normal ambient temperature, for a transformer which fulfils the requirements of IEC 76-2.

For large transformers there are differences in the temperature calculations for different methods of cooling. The category of *medium power transformers* extends up to about 100 MVA three-phase two-winding transformers or equivalent, while transformers with higher rated power are referred to as *large power transformers.* For the latter it is advisable to perform calculations using individual parameters obtained from the acceptance type test. For reasons explained in the guide, the recommended limitations for these two categories of transformers are formulated somewhat differently.

Section 1, General, contains definitions, common background information and specific recommendations for the operation of different categories of transformers.

Section 2, Temperature calculation, presents the mathematical models used.

Section 3 gives calculated results as graphs and tables for standardized conditions.

1.3 Definitions

For the purpose of this guide the following definitions apply.

1.3.1 *Distribution transformer*

A transformer with a maximum rating of 2 500 kVA three-phase or 833 kVA per limb single-phase and a high-voltage rating limited to 33 kV, i.e. a transformer with separate windings that steps down to consumer voltage, with ON cooling and without on-load tap-changing.

1.3.2 *Medium power transformer*

A transformer with separate windings having a rating not exceeding 100 MVA for three-phase transformers or 33,3 MVA per wound limb and, due to the leakage flux density restrictions, a rated short-circuit impedance z_r not exceeding the value:

$$z_r = \left(25 - 0{,}1 \frac{3\, S_r}{W} \right) \%$$

where W is the number of wound limbs and S_r the rated power in MVA.

For auto-transformers, the equivalent rating is defined in annex A.

1.3.3 *Large power transformer*

A transformer exceeding a rating of 100 MVA (three-phase) or the impedance limitation specified above.

1.3.4 *Cyclic loading*

Loading with cyclic variations (the duration of the cycle usually being one day) which is regarded in terms of the average amount of ageing that occurs during the cycle. The cyclic loading may either be a normal loading, or a long-time emergency loading.

a) Normal cyclic loading

A higher ambient temperature or a higher than rated load current is applied during part of the cycle, but, from the point of view of thermal ageing (according to the mathematical model), this loading is equivalent to the rated load at normal ambient temperature. This is achieved by taking advantage of low ambient temperatures or low-load currents during the rest of the load cycle. For planning purposes, this principle can be extended to provide for long periods of time whereby cycles with ageing rates greater than unity are compensated for by cycles with ageing rate less than unity.

b) Long-time emergency cyclic loading

Loading resulting from the prolonged outage of some system elements that will not be reconnected before a steady state temperature rise is reached in the transformer. This is not a normal operating condition and its occurrence is expected to be rare, but it may persist for weeks or even months and can lead to considerable ageing. However, it should not be the cause of breakdown due to thermal destruction or reduction of dielectric strength.

1.3.5 *Short-time emergency loading*

Unusually heavy loading due to the occurrence of one or more unlikely events which seriously disturb normal system loading, causing the conductor hot spots to reach dangerous levels and, possibly, a temporary reduction in the dielectric strength. However, acceptance of this condition for a short time may be preferable to other alternatives. This type of loading is expected to occur rarely and it must be rapidly reduced or the transformer disconnected within a short time in order to avoid its failure. The permissible duration of this load is shorter than the thermal time constant of the transformer and depends on the operating temperature before the increase in the loading; typically, it would be less than half an hour.

1.4 General limitations and effects of loading beyond nameplate rating

1.4.1 *Effect of loading beyond nameplate rating*

1.4.1.1 *Factors influencing life duration*

The actual life duration of a transformer depends to a high degree on extraordinary events, such as overvoltages, short-circuits in the system, and emergency overloading.

Decisive for the chance of survival after such events, which can occur either separately or in combination, are:

a) the severity (amplitude and duration) of the event;

b) the transformer design;

c) the temperatures of the various parts of the transformer;

d) the concentration of moisture in the insulation and in the oil;

e) the concentration of oxygen and other gases in the insulation and in the oil;

f) the number, size and type of impurity particles.

The normal life expectancy is a conventional reference basis for continuous duty under normal ambient temperature and rated operating conditions. The application of a load in excess of nameplate rating and/or an ambient temperature higher than rated involves a degree of risk and accelerated ageing. It is the purpose of this guide to identify such risks and to indicate how, within limitations, transformers may be loaded in excess of the nameplate rating.

The consequences of loading a transformer beyond its nameplate rating are as follows:

a) the temperatures of windings, cleats, leads, insulation and oil increase and can reach unacceptable levels;

b) the leakage flux density outside the core increases, causing additional eddy-current heating in metallic parts linked by the flux;

c) the combination of the main flux and increased leakage flux imposes restrictions on possible core overexcitation;

d) as the temperature changes, the moisture and gas content in the insulation and in the oil will change;

e) bushings, tap-changers, cable-end connections and current transformers will also be exposed to higher stresses which encroach upon their design and application margins.

As a consequence there will be a risk of premature failure associated with the increased currents and temperatures. This risk may be of an immediate short-term character or come from the cumulative deterioration of the transformer over many years.

1.4.1.2 *Short-term risks*

a) The main risk, for short-time failures, is the reduction in dielectric strength due to the possible presence of gas bubbles in a region of high electrical stress, i.e. the windings and leads. These bubbles may develop in the paper insulation when the hot-spot temperature rises suddenly above a critical temperature, which is about 140 °C to 160 °C for a transformer with a normal moisture content. This critical temperature decreases somewhat as the moisture concentration increases.

Gas bubbles can also develop (either in oil or in solid insulation) at the surfaces of heavy metallic parts heated by the leakage flux or be produced by supersaturation of the oil. However, such bubbles usually develop in regions of low electric stress and have to circulate in regions where the stress is higher before any significant reduction in the dielectric strength occurs.

Bare metal parts which are not in direct thermal contact with major organic insulation, but are in contact with the oil in the transformer, may rapidly rise to high temperature. 180 °C should not be exceeded.

b) Temporary deterioration of the mechanical properties at higher temperatures could reduce the short-circuit strength.

c) Pressure build-up in the bushings may result in a failure due to oil leakage. Gassing in the bushings may also occur if the temperature of the insulation exceeds about 140 °C.

d) The expansion of the oil could cause overflow of the oil in the conservator.

e) Breaking of excessively high currents in the tap-changer could be hazardous.

1.4.1.3 *Long-term risks*

a) Cumulative thermal deterioration of the mechanical properties of the conductor insulation will accelerate at higher temperatures. If this deterioration proceeds far enough, it may reduce the effective life of the transformer, particularly if the latter is subjected to system short circuits.

b) Other insulation materials, as well as structural parts and the conductors, could also suffer ageing at higher temperature.

c) The contact-resistance of the tap-changers could increase at elevated currents and temperatures and, in severe cases, thermal runaway could take place.

d) The gasket materials in the transformer may become more brittle at elevated temperatures.

The short-term risk normally disappears after the load is reduced to normal level but, from the point of view of reliability, it may have a more significant impact than long term effects.

This guide recognizes that the loading capability could be restricted both by the short-time and the long-time effects. The tables and diagrams are calculated according to the traditional methods of determining the life expectancy of the mechanical properties of the paper insulation as affected by time and temperature, while the limitations on the maximum hot-spot temperatures are based on considerations of the risk of immediate failure.

1.4.2 *Transformer size*

The sensitivity of transformers to loading beyond nameplate rating usually depends on their size. As the size increases, the tendency is that:

a) the leakage flux density will increase;
b) the short-circuit forces increase;
c) the volumes of dielectrically-stressed insulation increase;
d) the hot-spot temperatures are more difficult to determine correctly.

Thus a large transformer could be more vulnerable to loading beyond nameplate rating than a smaller one. In addition, the consequences of a transformer failure are more severe for larger sizes than for smaller units.

Therefore, in order to apply a reasonable degree of risk for the expected duties, this guide considers three categories:

a) distribution transformers, for which only the hot-spot temperature and thermal deterioration have to be considered;

b) medium power transformers where the effects of leakage flux are known not to be critical; but the variations in the cooling modes must be considered;

c) large power transformers, where the effects of stray leakage flux are significant and the consequences of failure are severe.

1.4.3 *Current and temperature limitations*

With loading values beyond the nameplate rating, it is recommended that the limits stated in table 1 are not exceeded and that account be taken of the specific limitations given in 1.5 to 1.7.

Table 1 – Current and temperature limits applicable to loading beyond nameplate rating

Types of loading		Distribution transformers	Medium power transformers	Large power transformers
Normal cyclic loading				
Current	(p.u.)	1,5	1,5	1,3
Hot-spot temperature and metallic parts in contact with insulating material	(°C)	140	140	120
Top-oil temperature	(°C)	105	105	105
Long-time emergency cyclic loading				
Current	(p.u.)	1,8	1,5	1,3
Hot-spot temperature and metallic parts in contact with insulating material	(°C)	150	140	130
Top-oil temperature	(°C)	115	115	115
Short-time emergency loading				
Current	(p.u.)	2,0	1,8	1,5
Hot-spot temperature and metallic parts in contact with insulating material	(°C)	see 1.5.2	160	160
Top-oil temperature	(°C)	see 1.5.2	115	115

1.5 Specific limitations for distribution transformers

1.5.1 *Rating limitation*

This clause covers distribution transformers up to 2 500 kVA as defined in 1.3.1.

1.5.2 *Current and temperature limitations*

The limits on load current, hot-spot temperature and top-oil temperature stated in table 1 should not be exceeded. No limit is set for the top-oil and hot-spot temperature under short-time emergency loading because it is usually impracticable to control the duration of emergency loading on distribution transformers. It should be noted that, when the hot spot reaches temperatures above 140 °C to 160 °C, gas bubbles may develop which could jeopardize the dielectric strength of the transformer (see 1.4.1.2, Short-term risks).

1.5.3 *Accessory and other considerations*

Apart from the windings, other parts of the transformer, such as bushings, cable-end connections, tap-changing devices and leads, may restrict the operation with load currents exceeding 1,5 times the rated current. Oil expansion and oil pressure could also impose restrictions.

1.5.4 *Indoor transformers*

When transformers are used indoors, a correction has to be made to the rated top-oil temperature rise to take account of the enclosure. Preferably, this extra temperature rise should be determined by a test (see 2.7.6).

1.5.5 *Outdoor ambient conditions*

Wind, sunshine and rain may have some effects on the loading capacity of distribution transformers, but their unpredictable nature makes it impracticable to take these factors into account.

1.6 Specific limitations for medium power transformers

1.6.1 *Rating limitations*

This clause covers power transformers up to 100 MVA, three-phase, having the impedance restrictions referred to in 1.3.2.

1.6.2 *Current and temperature limitations*

The limits on load current, hot-spot temperature, top-oil temperature and temperature of metallic parts other than winding and leads but nevertheless in contact with solid insulating material, stated in table 1 should not be exceeded. Moreover, it should be noted that when the hot spot reaches temperatures above 140 °C to 160 °C, gas bubbles may develop which could jeopardize the dielectric strength of the transformer (see 1.4.1.2, Short-term risks).

1.6.3 *Accessory, associated equipment and other considerations*

Apart from the windings, other parts of the transformer, such as bushings, cable-end connections, tap-changing devices and leads may restrict the operation when loaded above about 1,5 times the rated current. Oil expansion and oil pressure could also impose restrictions. Consideration may also have to be given to associated equipment such as cables, circuit-breakers, current transformers, etc.

1.6.4 *Short-circuit withstand requirements*

During or directly after operation at load beyond nameplate rating, transformers may not comply with the thermal short-circuit requirement, as specified in IEC 76-5, which is based on a short-circuit duration of 2 s. However, the duration of short-circuit currents in service is shorter than 2 s in most cases.

1.6.5 *Voltage limitations*

Unless other limitations for variable flux voltage variations are known (see IEC 76-4, clauses 3, 4 and 5) the applied voltage should not exceed 1,05 times either the rated voltage (principal tapping) or the tapping voltage (other tappings) on any winding of the transformer.

1.7 Specific limitations for large power transformers

1.7.1 *General*

For large power transformers, additional limitations, mainly associated with the leakage flux, have to be taken into consideration. It is therefore advisable in this case to specify, at the time of enquiry and order, the amount of loading capability needed in specific applications (see annex C).

As far as thermal deterioration of insulation is concerned, the same calculation method applies to all transformers. However, it is recommended that a computer calculation based on the actual thermal characteristics of the transformer under consideration be used rather than the loading tables in section 3.

According to present knowledge, the importance of the high reliability of large units in view of the consequences of a failure, together with the following considerations, make it advisable to adopt a more conservative, more individual approach here than for smaller units.

a) The combination of leakage flux and main flux in the limbs or yokes of the magnetic circuit makes large transformers more vulnerable to overexcitation than smaller transformers, especially when loaded above nameplate rating. Increased leakage flux may also cause additional eddy-current heating of other metallic parts.

b) The consequences of degradation of the mechanical properties of insulation as a function of temperature and time, including wear due to thermal expansion, may be more severe for large transformers than for smaller ones.

c) Hot-spot temperatures outside the windings cannot be obtained from a normal temperature-rise test. Even if such a test at rated current indicates no abnormalities, it is not possible to draw any conclusions for higher currents since this extrapolation may not have been taken into account at the design stage.

d) Calculation of the winding hot-spot temperature rise at higher than rated currents, based on the results of a temperature-rise test at rated current, may be less reliable for large units than for smaller ones.

1.7.2 *Current and temperature limitations*

The load current, hot-spot temperature, top-oil temperature and temperature of metallic parts other than windings and leads but nevertheless in contact with solid insulating material should not exceed the limits stated in table 1. Moreover, it should be noted that, when the hot spot reaches temperatures above 140 °C to 160 °C, gas bubbles may develop which could jeopardize the dielectric strength of the transformer (see 1.4.1.2, Short-term risks).

1.7.3 *Accessory, equipment and other considerations*

Refer to 1.6.3.

1.7.4 *Short-circuit withstand requirements*

Refer to 1.6.4.

1.7.5 *Voltage limitations*

Refer to 1.6.5.

Section 2: Determination of temperatures

2.1 Symbols

2.1.1 *Basic symbols*

A is the amplitude of yearly variation of daily mean ambient temperature in kelvins;

B is the amplitude of daily variation of ambient temperature in kelvins;

DX is the hottest day of a year;

H is the hot-spot factor;

I is the load current in amperes;

K is the load factor (load current/rated current);

L is the relative ageing over a certain period of time;

R is the ratio of load losses at rated current to no-load losses;

S is the power in MVA;

TX is the hottest hour of a day;

V is the relative ageing rate;

W is the number of wound limbs;

g is the winding to oil temperature difference in kelvins;

j is a month of a year (used in ageing and hot-spot calculations over a complete year);

t is the duration of the peak load in the rectangular load profile in hours;

z is the short-circuit impedance in per cent;

θ is the temperature in degrees Celsius;

τ is the time constant;

ON indicates either *ONAN* or *ONAF cooling;*

OF indicates either *OFAF* or *OFWF cooling;*

OD indicates either *ODAF* or *ODWF cooling.*

2.1.2 *Prefixes*

Δ indicates a temperature rise (in regard to ambient temperature).

2.1.3 *Exponents*

x is the exponential power of total losses versus oil temperature rise;

y is the exponential power of current versus winding temperature rise;

' applies to hot-spot temperature on OD cooling.

2.1.4 *Suffixes (general)*

E relates to weighted ambient temperature;
M relates to ambient temperature for hot-spot calculation;
W relates to winding;
a relates to ambient (temperature);
h relates to hot spot (temperature);
m relates to factors used to calculate maximum hot-spot temperature;

o relates to oil;
r indicates rated quantity (if used, always the last suffix);
t relates to temperature or temperature rise at time *t*;
y indicates yearly quantity.

2.1.5 *Specific suffixes relating to oil temperatures* (if used, always the first suffixes)

i relates to oil in winding, at top;
im relates to oil in winding, average;
b relates to oil in winding, in tank or in heat exchanger, at bottom;
o relates to oil in tank, at top;
om relates to oil in tank, average;
e relates to oil in heat exchanger, at top;
em relates to oil in heat exchanger, average;
bt relates to bottom oil temperature after time *t*;
bi relates to initial bottom oil temperature;
bu relates to ultimate bottom oil temperature.

2.2 Direct measurement of hot-spot temperature

The most critical limitation in the loading of a transformer is the temperature reached in the hottest area of the winding and every effort should be made to determine this temperature with accuracy. Direct measurement (with fibre-optic probes or similar devices) is now becoming available. Such measurements should improve the determination of the hot-spot temperature as compared to the calculation method outlined in 2.4.

2.3 Assumed thermal characteristics

2.3.1 *Simplifications made*

It should be borne in mind that the formulae given in this guide are based on a number of simplifications. A thermal diagram is assumed, as shown in figure 1, on the understanding that such a diagram is the simplification of a more complex distribution. The assumptions made in this simplification are as follows:

a) the oil temperature inside the windings increases linearly from bottom to top, whatever the cooling mode;

b) the temperature rise of the conductor at any position up the winding increases linearly, parallel to the oil temperature rise, with a constant difference *g* between the two straight lines (*g* being the difference between the average temperature rise by resistance and the average oil temperature rise);

c) the hot-spot temperature rise is higher than the temperature rise of the conductor at the top of the winding as shown in figure 1 because allowance has to be made for the increase in stray losses. To take account of these non-linearities, the difference in temperature between the hot-spot and the oil at the top of the winding is made equal to *Hg*. This *H* factor may vary from 1,1 to 1,5 depending on transformer size, short-circuit impedance and winding design. For the production of tables and figures in section 3, a value of 1,1 has been used for distribution transformers and 1,3 for medium and large power transformers.

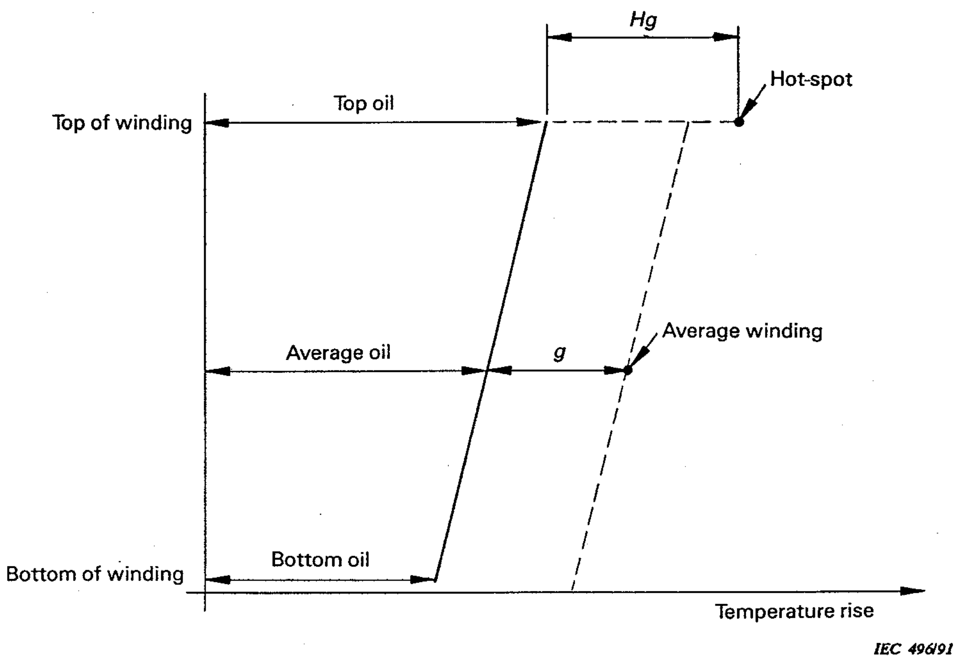


Figure 1 – Thermal diagram

2.3.2 The top-oil temperature, as measured during a temperature-rise test, differs from the temperature of the oil leaving the winding. This is especially so during the transitory period following inception of a sudden load of large magnitude. In fact, the top oil is a mixture of various oil flows which have circulated along and/or outside the various windings.

For ON the difference between the main windings is normally not important. The oil temperature at the top of the winding is, for all windings, taken as equal to the temperature of the mixed top oil in the tank.

For OF and OD cooling, on the other hand, the oil temperature at the top of a winding is taken to be the bottom oil temperature plus twice the difference between the average oil temperature inside that particular winding and the bottom-oil temperature.

The different types of cooling have to be treated separately because of the differences in the oil flow. For ON and OF transformers it is assumed that the oil circulation in the winding is dictated by the thermal head while for OD transformers the rate of flow of the oil is mainly governed by the pump and thus is not dependent on the oil temperature.

2.3.3 For OF and OD transformers, the average oil temperature should be determined by the best available method, since the hot-spot temperature calculation is directly dependent on it. IEC 76-2 specifies a number of acceptable methods for providing a value that is used only to derive certain corrections to be applied to the average winding temperature rise. For the purpose of this guide, the alternative method for deriving the average oil temperature from test results is preferred (see annex B).

2.3.4 As the time constant of windings is usually very short (5 min to 10 min), it has only a limited effect on the hot-spot temperature, even under short loads of high values. Since the shortest peak load duration considered in the loading tables is 30 min (section 3), the time constant is taken as equal to zero in the calculation.

2.3.5 In order to calculate the hot-spot temperature rise under continuous, cyclic or other duties, different sources of thermal characteristics can be used:

a) results of a special temperature-rise test including direct measurement of the hot-spot temperature or top-oil temperature inside the windings (in the absence of direct hot-spot measurement the hot-spot factor H can only be provided by the manufacturer);

b) results of a normal temperature rise test;

c) assumed temperature rises at rated current.

Table 2 provides examples of thermal characteristics used in the production of the loading tables in section 3. For large power transformers it should be noted that if the measured average winding temperature rise at rated current is at the limit of 65 K for ON and OF cooling, and 70 K for OD cooling, the hot-spot temperature rise at rated current may exceed 78 K, depending on the design.

Table 2 – Thermal characteristics used for the calculation of loading tables in section 3

			Distribution transformers	Medium and large power transformers		
			ONAN	ON ..	OF ..	OD ..
Oil exponent	x		0,8	0,9	1,0	1,0
Winding exponent	y		1,6	1,6	1,6	2,0
Loss ratio	R		5	6	6	6
Hot-spot factor	H		1,1	1,3	1,3	1,3
Oil time constant	τ_o	(h)	3,0	2,5	1,5	1,5
Ambient temperature	θ_a	(°C)	20	20	20	20
Hot-spot rise	$\Delta\theta_{hr}$	(K)	78	78	78	78
Average winding rise	$\Delta\theta_{Wr}$	(K)	65	63	63	68
Hot-spot to top-oil gradient	Hg_r	(K)	23	26	22	29
Average oil rise	$\Delta\theta_{imr}$	(K)	44	43	46	46
Top-of-winding oil rise[1)]	$\Delta\theta_{ir}$	(K)	55	52	56	49
Bottom-oil rise	$\Delta\theta_{br}$	(K)	33	34	36	43

1) For ON cooling, $\Delta\theta_{ir}$ is taken to be equal to $\Delta\theta_{or}$.

2.4 Steady-state temperature equations

2.4.1 *ON cooling*

For ON cooling, the ultimate hot-spot temperature under any load *K* is equal to the sum of the ambient temperature, the top-oil temperature rise and the temperature difference between the hot-spot and the top-oil:

$$\theta_h = \theta_a + \Delta\theta_{or} \left[\frac{1 + R K^2}{1 + R}\right]^x + Hg_r \, K^y \qquad (1)$$

2.4.2 *OF cooling*

For OF cooling the calculation method is based on the bottom-oil and average oil temperature for the reason explained in 2.3.2. Thus the ultimate hot-spot temperature under any load *K* is equal to the sum of the ambient temperature, the bottom-oil temperature rise, the difference between the top-oil in the winding and the bottom-oil and the difference between the hot-spot and the top-oil in the winding:

$$\theta_h = \theta_a + \Delta\theta_{br} \left[\frac{1 + R K^2}{1 + R}\right]^x + 2 \left[\Delta\theta_{imr} - \Delta\theta_{br}\right] K^y + Hg_r \, K^y \qquad (2)$$

2.4.3 *OD cooling*

For OD cooling, the calculation method is basically the same as for OF cooling except that a correction term is added to take account of the variation in the ohmic resistance of conductors with temperature:

$$\theta'_h = \theta_h + 0{,}15\ (\theta_h - \theta_{hr})\ \ (\text{for } K > 1) \tag{3}$$

where

θ_h is calculated without consideration of the influence of the ohmic-resistance variations using equation (2);

θ_{hr} is the hot-spot temperature at rated conditions.

The manufacturer may be consulted to obtain a more accurate formula.

2.4.4 *Equation corrections*

Theoretically, several corrections should be made using the foregoing equations in calculating the ultimate hot-spot temperature, such as for change with temperature in:

a) load losses;

b) relation between ohmic-resistance-dependent losses and eddy-current losses in the winding;

c) oil viscosity.

For ON and OF cooling the viscosity change with temperature counteracts the effect of the ohmic-resistance variation of the conductors. For the purpose of this guide these effects are assumed to cancel each other.

For OD cooling, the influence of the oil viscosity on temperature rises is slight. The effect of the ohmic-resistance variation has to be considered, as in the case of the correction term in equation (3).

2.5 Transient temperature equations

Any change in load conditions is treated as a step function. The rectangular load profile considered in the loading tables of section 3 consists of a single step up followed some time later by a single step down. For a continually varying load, the step function is applied over a small time interval and the hot-spot temperature calculation requires a computer program (see 2.8).

The oil temperature rise (for bottom oil, for example) after time interval *t* is given by:

$$\Delta\theta_{bt} = \Delta\theta_{bi} + (\Delta\theta_{bu} - \Delta\theta_{bi})\ (1 - e^{-t/\tau_o}) \tag{4}$$

where

$\Delta\theta_{bi}$ is the initial bottom-oil temperature rise;

$\Delta\theta_{bu}$ is the ultimate bottom-oil (steady state) temperature rise corresponding to the load applied during this time interval;

τ_o is the oil time constant.

For any increase in load the temperature difference between winding and oil will rise to a new value with a time constant characteristic of the winding. For the reason stated in 2.3.4, this time constant is neglected. The last term of equation (1) and the last two terms of equation (2) assume instantaneously the value corresponding to the new factor K^y.

2.6 Thermal ageing of transformer insulation

2.6.1 *Law of thermal ageing*

If all other influences could be disregarded, the insulation system would still undergo deterioration (ageing) of a chemical nature. This process is cumulative and leads to a point where the system is no longer acceptable, by some selected criterion. According to the Arrhenius law of chemical reaction rate, the span of time up to this end point is expressed as:

$$\text{life duration} = e^{(\alpha + \beta / T)} \qquad (5)$$

where

α and β are constants;

T is the absolute temperature.

Within a limited range of temperatures the relation can be approximated by the simpler exponential expression of Montsinger:

$$\text{life duration} = e^{-p\theta} \qquad (6)$$

where

p is a constant;

θ is the temperature in degrees Celsius.

NOTE - This guide uses the Montsinger rule of thermal degradation which, as remarked above, is a simplified version of the Arrhenius law of general chemical/thermal degradation used in some other loading guides (particularly in North America). Over the temperature range considered in the present guide, the Montsinger rule is considered sufficiently accurate and, indeed, its application results in conservative estimates of thermal degradation.

There is, however, no simple and unique end-of-life criterion that can be used for quantitative statements about the remaining life of transformer insulation, but it is possible to make meaningful comparisons based *on rate of ageing* instead. This is the inverse of the lifetime – in Montsinger's form:

$$\text{rate of ageing} = \text{constant} \times e^{p\theta}$$

The constant in the equation is dependent on many things, such as the original quality of the cellulose products (raw material composition, chemical additives) and environmental parameters (moisture content, free oxygen in the system).

However, independent of those variations, the coefficient for temperature variation, p may be taken as a constant over the actual range of temperature between 80 °C and 140 °C. Its value is such that the rate of ageing doubles for every increment of approximately 6 K; this value has been assumed as the basis of the present guide.

The rate of ageing is referred to the winding hot-spot temperature. For transformers designed in accordance with IEC 76, a usual reference value for this quantity at rated load and normal ambient temperature is 98 °C. In this guide, the relative rate of ageing at this temperature is taken as unity.

The insulation system of many transformers is provided with thermally upgraded insulation. As IEC 76-2 does not consider this class of materials for oil-immersed transformers, temperature-rise limits and improvement in thermal behaviour may be taken into account by agreement between the manufacturer and user. In many cases, transformers using this insulation have a normal life expectancy based on a hot-spot temperature of 110 °C.

2.6.2 *Relative thermal-ageing rate*

For transformers designed in accordance with IEC 76, the relative rate of thermal ageing is taken to be equal to unity for a hot-spot temperature of 98 °C, which corresponds to operation at an ambient temperature of 20 °C and a hot-spot temperature rise of 78 K. The relative ageing rate is defined as:

$$V = \frac{\text{ageing rate at } \theta_h}{\text{ageing rate at 98 °C}} = 2^{(\theta_h - 98)/6} \qquad (7)$$

This function implies that the relative ageing rate is very sensitive to the hot-spot temperature as shown below:

θ_h	Relative ageing rate
80	0,125
86	0,25
92	0,5
98	1,0
104	2,0
110	4,0
116	8,0
122	16,0
128	32,0
134	64,0
140	128,0

2.6.3 *Loss-of-life calculation*

The loss of life caused by months, days or hours of operation at a hot-spot temperature of 98 °C is expressed in normal months, days or hours.

If the load and ambient temperature are constant during a period, the relative loss of life is equal to $V \times t$, t being the period under consideration. The same applies to a constant operating condition and a variable ambient temperature if the weighted ambient is used (see 2.7).

Generally, when operating conditions and ambient temperature are changing, the relative ageing rate varies with time. The relative ageing (or relative loss of life) over a certain period of time is then equal to:

$$L = \frac{1}{t}\int_{t_1}^{t_2} V\mathrm{d}t \text{ ou } L = \frac{1}{N}\sum_{n=1}^{N} V \qquad (8)$$

where

n is the number of each time interval;

N is the total number of equal time intervals.

2.7 Ambient temperature

2.7.1 *General*

For outdoor air-cooled transformers, the actual air temperature is taken as ambient. For indoor distribution transformers, the ambient-temperature correction is given in 2.7.6. For water-cooled transformers, the ambient temperature is the temperature of the incoming water which shows less variation in time than air.

If the peak load duration is longer than a few hours, the variations of ambient temperature have to be taken into account. Depending on the user's preference these variations can be considered under either of the following methods:

a) a weighted ambient temperature can be used for the thermal ageing calculation, combined with the mean value of monthly maxima for the maximum hot-spot temperature calculation (2.7.2 and 2.7.3);

b) the actual temperature profile can be used directly (2.7.4);

c) the ambient temperature variation can be approximated by a double sinusoidal function (2.7.5).

2.7.2 *Weighted ambient temperature,* θ_E

If the ambient temperature varies appreciably during the load cycle, then a weighted value should be sued in the thermal calculation because the weighted ambient will be higher than the arithmetic average.

The weighted ambient temperature is a constant, fictitious ambient temperature which, during a specific time, causes the same ageing of the insulation as a variable ambient temperature acting during that time (which may be days, months or a year).

For the case where a temperature increase of 6 K doubles the ageing rate and the ambient temperature can be assumed to vary sinusoidally, the weighted ambient temperature is equal to:

$$\theta_E = \bar{\theta} + 0{,}01\ (\Delta\bar{\theta})^{1{,}85} \tag{9}$$

where

$\bar{\theta}$ is the mean temperature;

$\Delta\bar{\theta}$ is the temperature range for the period under consideration (mean value of maxima minus mean value of minima).

The correction factor to be applied to the average temperature can also be derived from figure 2, which is an illustration of the above formula.

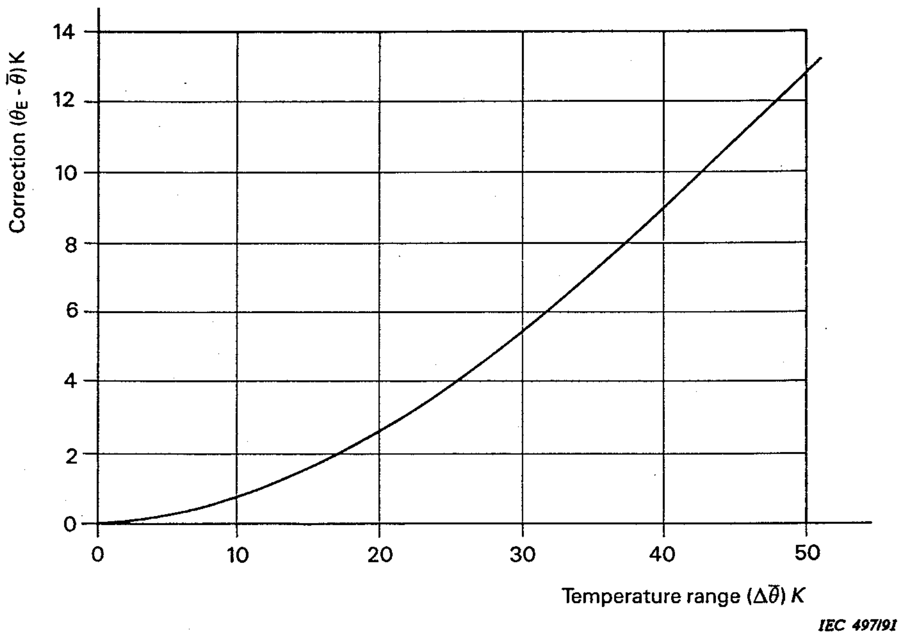


Figure 2 – Correction between weighted and average ambient temperature as a function of the temperature range

2.7.3 *Ambient temperature for hot-spot calculation,* θ_M

The weighted ambient temperature can be used for the calculation of thermal ageing but cannot be used to check the maximum hot-spot temperature reached during the peak load period. For this purpose it is recommended that the mean value of the monthly maxima be taken. Use of the absolute maximum is not considered wise in view of the low probability of occurrence of this value and the effect of the oil time constant.

2.7.4 *Continuously varying ambient temperature*

When the ageing and hot-spot temperature calculations are limited to a few days of operation with load beyond nameplate rating, it may be found more suitable to use the actual temperature variation profile that is expected for that period. The ambient temperature profile has then to be expressed in a set of discrete values corresponding to the time interval chosen to describe the load variation.

2.7.5 *Sinusoidal temperature variation*

For calculations over many days or months, it may be more convenient to consider the ambient temperature as a double sinusoidal function, the first describing the year-round temperature variation, the second the daily variation.

$$\theta_a = \theta_{ay} + A \cos \frac{2\pi}{365} (\text{day} - DX) + (B \text{ ou } B_m) \cos \frac{2\pi}{24} (\text{hour} - TX) \qquad (10)$$

where

- θ_{ay} is the yearly average ambient temperature in degrees Celsius;
- A is the amplitude of yearly variation of daily mean ambient temperature in kelvins;
- B is the amplitude of daily variation for ageing-rate calculation in kelvins;
- B_m is the amplitude of daily variation for calculation of maximum hot-spot temperature in kelvins;
- DX is the hottest day of a year;
- TX is the hottest hour of a day;
- day is the day number, for example 1st February = 32;
- hour is the hour of the day, for example 1.15 p.m. = 13,25.

Calculation of these parameters implies the use of a separate computer program, as shown in annex D, with the input of four characteristic temperatures for each month of the year.

2.7.6 *Correction of ambient temperature for transformer enclosure*

A transformer operating in an enclosure experiences an extra temperature rise which is about half the temperature rise of the air in that enclosure. Tests have shown that the top-oil extra temperature rise varies with the load current more or less as the top-oil temperature rise would do.

For transformers installed in a metal or concrete enclosure, $\Delta\theta_{or}$ in equation 1 should therefore be replaced by $\Delta\theta'_{or}$ as follows:

$$\Delta\theta'_{or} = \Delta\theta_{or} + \Delta(\Delta\theta_{or})$$

where

$\Delta(\Delta\theta_{or})$ is the extra top-oil temperature rise under rated load. It is recommended that this extra temperature rise be determined by tests, but when such test results are not available, the values given in table 3 for different types of enclosure may be used as a guide. These values should be divided by two to obtain the approximate extra top-oil temperature rise.

Table 3 – Correction for increase in ambient temperature due to enclosure

1	2	3	4	5	6
Type of enclosure	Number of transformers installed	Correction (to be added to weighted ambient temperature) °C Transformer size kVA			
		250	500	750	1 000
Underground vaults with natural ventilation	1 2 3	11 12 14	12 13 17	13 14 19	14 16 22
Basements and buildings with poor natural ventilation	1 2 3	7 8 10	8 9 13	9 10 15	10 12 17
Buildings with good natural ventilation and underground vaults and basements with forced ventilation	1 2 3	3 4 6	4 5 9	5 6 10	6 7 13
Kiosks (see note 2)	1	10	15	20	—

NOTES

1 The above temperature correction figures have been estimated for typical substation loading conditions using representative values of transformer losses. They are based on the results of a series of natural and forced-cooling tests in underground vaults and substations and on random measurements in substations and kiosks.

2 This correction for enclosures in kiosks is not necessary when the temperature-rise test has been carried out on the transformer in the kiosk as one complete unit.

3 This table is an excerpt from Australian Standard AS 1078 (1984) "Guide to loading of oil-immersed transformers".

2.8 Computer program

2.8.1 *Logic diagram*

The determination of the load factor applicable to a given transformer under a given load profile, a specific ambient-temperature variation and a preset limit on hot-spot temperature and ageing is an iterative procedure that requires computer calculations. A basic logic diagram of such an iterative procedure incorporating the fundamental ideas expressed in this guide is shown in figure 3.

A similar iterative procedure is used if the objective is to help the system planner to choose appropriate rated quantities for a new installation where the loading and ambient temperature conditions are known.

The program should be designed in such a way that the user has to enter the transformer thermal characteristics, the load profile for the period under study and the ambient temperature conditions for the same period, as well as the specific limitations on temperature and ageing that he judges applicable.

The maximum hot-spot temperature and relative ageing are calculated with the initial load diagram. If the limit temperature is not exceeded and the ageing is below the accepted value, the calculation is then repeated with a multiplying factor F applied to each discrete load K_1, K_2, ... K_n, with the time intervals t_1, t_2, ...t_n remaining unchanged. The multiplying factor F is increased in steps of 1 % at each pass until one of the limits is reached. If, in the initial calculation, the relative ageing is greater than the selected value, the calculation is repeated with a value of F reduced by 2 %.

The increment on the load multiplier and the tolerances on limiting temperatures may be chosen differently depending on the transformer and load parameters. The program designer has to consider that, for a hot-spot temperature between 100 °C and 140 °C, an increase of 2 % on the load factor will increase the maximum hot-spot temperature by more than 2 K and the relative ageing by approximately 25 %.

Allowances should be adjusted to avoid hunting while giving sufficient accuracy. For the purpose of checking the program with the examples given in tables 4 and 5, higher accuracy by reducing these allowances is advisable.

2.8.2 *Example of calculation*

Examples of calculation are given in tables 4 and 5 to illustrate the extent of input and output formats, and to allow the user to verify his program.

The first example (table 4) illustrates a simple calculation over one day, with a constant ambient temperature and a simple load profile.

The second example (table 5) applies to calculations over a full year with three different load profiles during the year and an ambient temperature considered as a double sinusoidal function.

START

READ INPUT:

Transformer characteristics

Cooling method: ONAN, ONAF, OF or OD

$\Delta\theta_{or}$: top-oil temperature rise at rated current for ONAN and ONAF cooling

$\Delta\theta_{br}$: bottom-oil temperature rise at rated current for OF and OD cooling

$\Delta\theta_{imr}$: average oil temperature rise at rated current

Hg_r : hot-spot to top-oil temperature difference at rated current

x : oil-temperature exponent

y : winding-temperature exponent

R : ratio of load losses to no-load losses at rated current

τ_o : oil time constant (hours)

θ_{hr} : nominal hot-spot temperature for unity ageing rate (98 °C, 110 °C or any other suitable reference temperature, see 2.6.1)

Load cycle

Cycle time, number of intervals in the load cycle, p.u. loading for each interval

Ambient temperature

Weighted ambient temperature and maximum daily temperature (θ_E, θ_M)

or Ambient temperature for each interval of the load cycle

or Parameters for the double-sinusoidal variation (θ_{ay}, A, B, B_m, DX, TX)

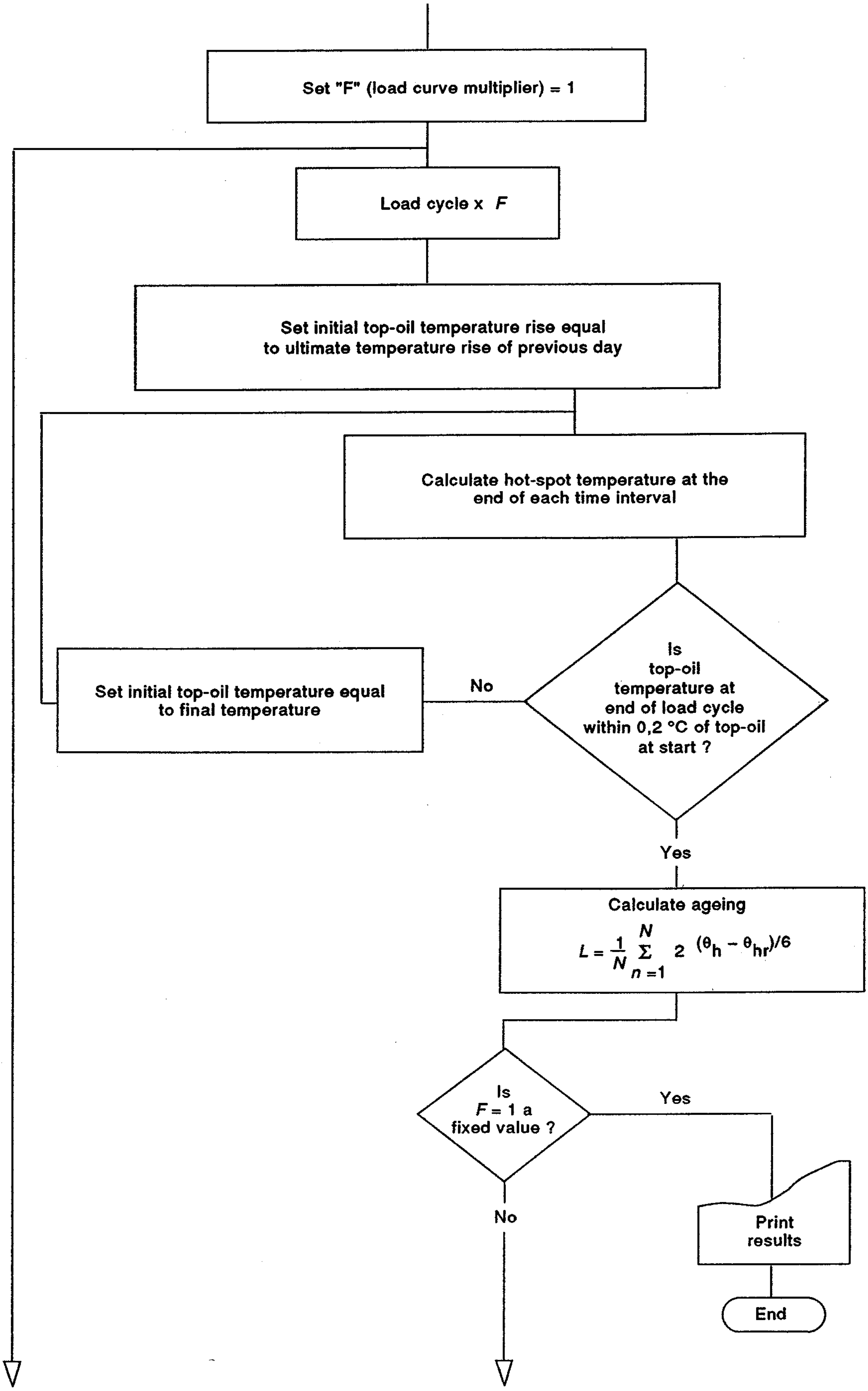
Limitations

θ_{hmax} : maximum acceptable hot-spot temperature

θ_{omax} : maximum acceptable top-oil temperature

L_{max} : maximum acceptable relative ageing

F : state if load curve multiplier is fixed at $F = 1$



Set "F" (load curve multiplier) = 1
Load cycle x F
Set initial top-oil temperature rise equal to ultimate temperature rise of previous day
Calculate hot-spot temperature at the end of each time interval
Is top-oil temperature at end of load cycle within 0,2 °C of top-oil at start ?
No
Set initial top-oil temperature equal to final temperature
Yes
Calculate ageing
$L = \frac{1}{N} \sum_{n=1}^{N} 2^{(\theta_h - \theta_{hr})/6}$
Is F = 1 a fixed value ?
Yes
No
Print results
End

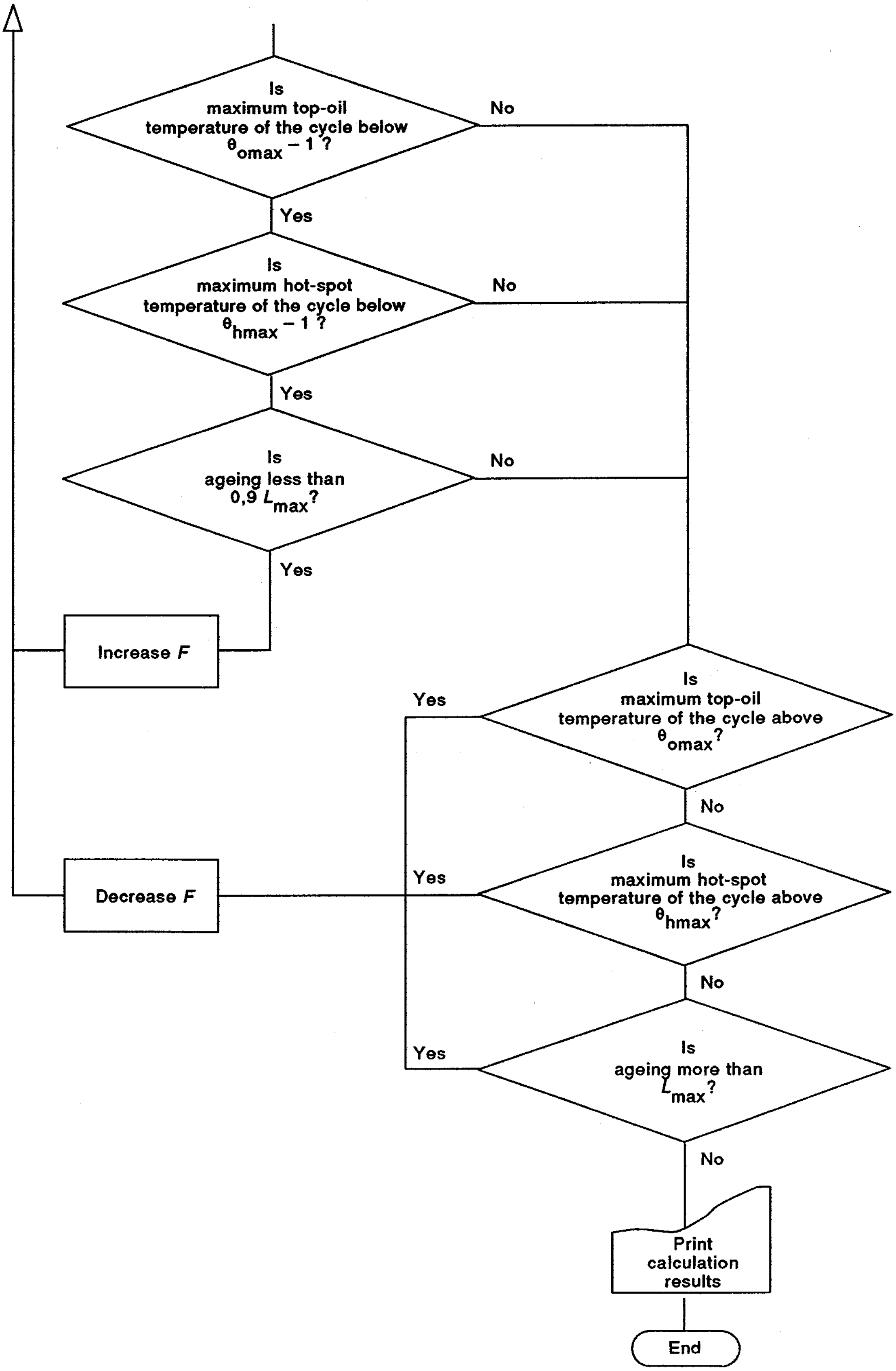


Figure 3 – Logic diagram of a computer program for calculation of an acceptable loading factor

Table 4 – Data relating to calculation over a single day with a constant weighted ambient temperature

*** Input (1) *** transformer rating and characteristics

kind of transformer: DISTRIBUTION
cooling method: ONAN

$\Delta\theta_{or}$	: top oil temperature rise [K]	55,00
$\Delta\theta_{imr}$	: average oil temperature rise [K]	44,00
Hg_r	: hot-spot to top-oil temperature rise [K]	23,00
x	: oil temperature exponent	0,80
y	: winding temperature exponent	1,60
R	: ratio of load loss to no-load loss	5,00
τ_o	: oil time constant [h]	3,00
θ_{hr}	: hot-spot temperature for normal ageing [°C]	98,00

*** Input (2) *** required load diagram

	start	end	duration [h]	load [p.u.]
1	0: 00	12: 00	12,00	0,700
2	12: 00	14: 00	2,00	1,340
3	14: 00	24: 00	10,00	0,700

*** Input (3) *** ambient temperature data

θ_E	: weighted ambient temperature [°C]	30,00
θ_{amax}	: maximum daily temperature [°C]	40,00

*** Input (4) *** temperature and operation limitations

θ_{omax}	: limitation of top oil temperature [°C]	115,00
θ_{hmax}	: limitation of hot spot temperature [°C]	140,00
L_{max}	: limitation on relative ageing	1,00
F	: load profile multiplier – fixed or variable	FIX

*** Output ***

top-oil max. [°C]	hot-spot max. [°C]	relative ageing over a day [p.u.]
98,35	135,08	0,935

	top-oil temperature [°C]	hot-spot temperature [°C]
1	75,34	88,34
2	98,35	135,08
3	76,15	89,15

Table 5 – Data relating to calculation over a full year with double sinusoidal variation of ambient temperature and three different load profiles

*** Input (1) *** transformer rating and characteristics

kind of transformer: DISTRIBUTION
cooling method: ONAN

$\Delta\theta_{or}$	: top-oil temperature rise [K]	55,00
$\Delta\theta_{imr}$	: average oil temperature rise [K]	44,00
Hg_r	: hot-spot to top-oil temperature rise [K]	23,00
x	: oil temperature exponent	0,80
y	: winding temperature exponent	1,60
R	: ratio of load loss to no-load loss	5,00
τ_o	: oil time constant [h]	3,00
θ_{hr}	: hot-spot temperature for normal ageing [°C]	98,00

*** Input (2) *** required load diagram

Period 1	1/1	17/4*	DURATION [days]:	107
	start	end	duration [h]	load [p.u.]
1	0:00	8:00	8,00	0,700
2	8:00	11:00	3,00	1,000
3	11:00	14:00	3,00	0,800
4	14:00	16.00	2,00	1,360
5	16:00	19:30	3,50	0,850
6	19:30	24:00	4,50	0,700
Period 2	18/4	17/10	DURATION [days]:	183
	start	end	duration [h]	load [p.u.]
1	0:00	10:00	10,00	0,700
2	10:00	13:00	3,00	1,000
3	13:00	15:00	2,00	1,360
4	15:00	20:00	5,00	0,900
5	20:00	24:00	4,00	0,700
Period 3	18/10	31/12	DURATION [days]:	75
	start	end	duration [h]	load [p.u.]
1	0:00	8:00	8,00	0,700
2	8:00	11:00	3,00	1,000
3	11:00	14:00	3,00	0,800
4	14:00	16.00	2,00	1,360
5	16:00	19:30	3,50	0,850
6	19:30	24:00	4,50	0,700

*** Input (3) *** ambient-temperature data

θ_{ay}	: yearly average ambient temperature [°C]	11,47
A	: yearly variation [K]	8,05
B	: daily variation for ageing [K]	5,10
B_m	: daily variation for temperature limit [K]	11,45
DX	: hottest day of the year	199
TX	: hottest hour of the day	14:00

* 17/4 = 17 April for example.

Table 5 *(continued)*

*** Input (4) *** temperature and operation limitations

θ_{omax}:	limitation of top oil temperature [°C]	115,00
θ_{hmax}:	limitation of hot-spot temperature [°C]	140,00
L_{max} :	limitation on relative ageing [p.u.]	1,00
F :	load profile multiplier – fixed or variable	FIX

*** Output ***

Period	start	end	top-oil max. [°C]	hot-spot max. [°C]	relative ageing [p.u.]
1	1 / 1	17 / 4	84,77	122,39	0,237
2	18 / 4	17 / 10	96,20	133,82	1,160
3	18 / 10	31 / 12	84,84	122,46	0,266

Relative ageing over a year L = 0,706 p.u.

Period 1	top-oil temperature [°C]	hot-spot temperature [°C]
1	46,89	59,89
2	67,28	90,28
3	66,52	82,61
4	84,77	122,39
5	63,29	81,03
6	40,12	53,12

Relative ageing for the period L (1) = 0,237 p.u.

Period 2	top-oil temperature [°C]	hot-spot temperature [°C]
1	60,72	73,72
2	78,40	101,40
3	96,20	133,82
4	70,78	90,21
5	49,13	62,13

Relative ageing for the period L (2) = 1,160 p.u.

Period 3	top-oil temperature [°C]	hot-spot temperature [°C]
1	46,96	59,96
2	67,34	90,34
3	66,59	82,68
4	84,84	122,46
5	63,36	81,10
6	40,19	53,19

Relative ageing for the period L (3) = 0,266 p.u.

Section 3: Loading tables

3.1 Limitations applicable to loading tables

This section provides readily available loading allowances for the different types of transformer. The information presented in the tables and figures of 3.2 to 3.4 was obtained using the equations given in 2.4 to 2.6 and the transformer thermal characteristics in table 2.

A high degree of accuracy is not to be expected from these curves and tables because of the required approximations:

a) The daily load variation is represented by a simplified two-step load cycle (see figure 4).

b) The thermal characteristics used in the calculation (as shown in table 2) may not correspond to those of the transformer under study.

c) The ambient temperature is considered constant throughout the 24-hour duty cycle.

d) It is not practical to take into account the winding correction factor (2.4.3) in tables that are independent of ambient temperature. Instead, the following correction factor has been used for OD transformers:

$$\Delta\theta'_h = \Delta\theta_h + 0,15\ (\Delta\theta_h - \Delta\theta_{hr}) \qquad (12)$$

Users are strongly encouraged to make their own calculations based on a more accurate set of thermal characteristics for the transformers and taking account of a more realistic load profile.

3.2 Method of representing an actual load cycle by an equivalent two-step rectangular load cycle

3.2.1 *Use of guide*

To use the figures and tables of 3.4 and 3.5, the daily load cycle has to be represented by a simplified two-step load cycle as shown in figure 4. The load steps shall be K_1 and K_2, where K_2 is the peak load. The duration of the peak load is t hours. The methods of determining this duration in the rectangular load profile depend upon a number of factors, and 3.2.2, 3.2.3 and 3.2.4 describe recommended methods for various shapes of actual load cycles.

In case of doubt regarding the suitability of the equivalent two-step load cycle, several approximations should be made and the most conservative profile adopted.

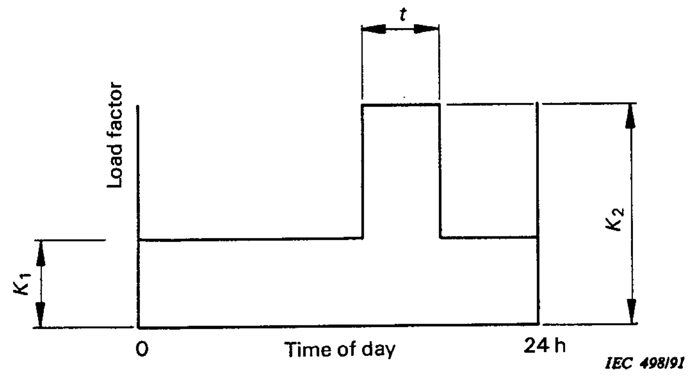


Figure 4 – Equivalent two-step load cycle

3.2.2 *Load cycle with one peak*

In this case, the value of t should be selected on an area basis as indicated in figure 5.

For the off-peak portion of the load cycle, the value of K_1 is selected to correspond to the average off-peak load.

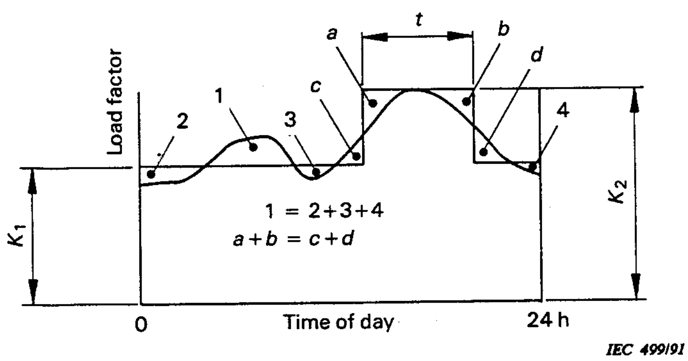


Figure 5 – Load cycle with one peak

3.2.3 *Load cycle with two peaks of equal amplitude and different duration*

In the case where there are two peaks of nearly equal amplitude but different duration, the value of t is determined for the peak of longer duration and the value of K_1 is selected to correspond to the average of the remaining load. A typical load cycle is shown in figure 6.

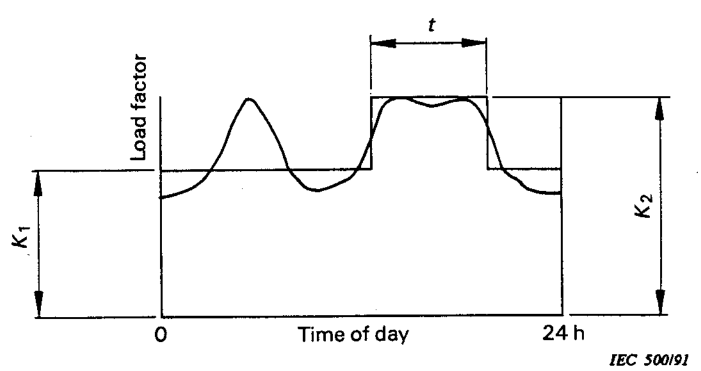


Figure 6 – Load cycle with two peaks of equal amplitude and different duration

3.2.4 *Load cycles with peaks in close succession*

In the case where there are peaks in close succession, the value of t is made long enough to enclose both peaks and K_1 is selected to correspond to the average of the remaining load, as shown in figure 7.

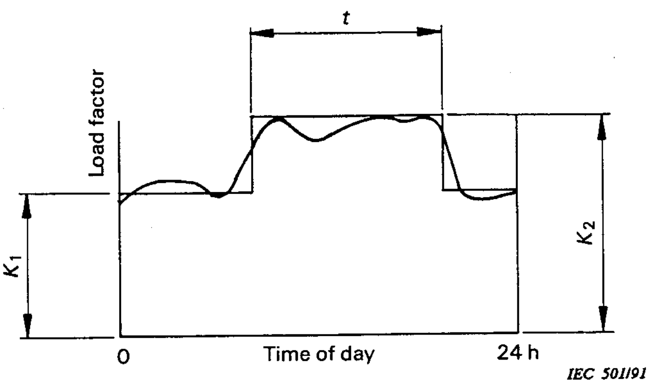


Figure 7 – Load cycle with peaks in close succession

3.3 Normal continuous loading

If the load current over a certain period of time shows no pronounced variation, a constant equivalent load current may be used. Table 6 gives an acceptable load factor $K = K_{24}$ for continuous duty for different ambient temperatures.

Table 6 – Acceptable load factor for continuous duty K_{24} at different ambient temperatures (ON, OF and OD cooling)

Ambient temperature °C			–25	–20	–10	0	10	20	30	40
Hot-spot temperature rise K			123	118	108	98	88	78	68	58
K_{24}	Distribution	ONAN	1,37	1,33	1,25	1,17	1,09	1,00	0,91	0,81
	Power transformer	ON	1,33	1,30	1,22	1,15	1,08	1,00	0,92	0,82
		OF	1,31	1,28	1,21	1,14	1,08	1,00	0,92	0,83
		OD	1,24	1,22	1,17	1,11	1,06	1,00	0,94	0,87

3.4 Normal cyclic loading

The information is presented in the following figures, corresponding to the four types of transformer as below and eight different ambient temperatures:

ONAN distribution transformers - figure 9
ON medium and large power transformers - figure 10
OF medium and large power transformers - figure 11
OD medium and large power transformers - figure 12

If the ambient temperature value falls between two figures, select the next highest or interpolate between the two nearest figures.

The curves can be used to determine the permissible peak load K_2 for a given duration t and a given initial load K_1. Assuming that the applied voltage remains constant, they can also be used for determining the rated power of a transformer (with normal life duration) for a given rectangular load profile defined as the ratio K_2/K_1. All that is necessary is to find the intersection of the curve corresponding to the duration of the load K_2 with the line of constant slope K_2/K_1, which can be found by marking corresponding points on ordinate $K_2 = 1$ and abscissa $K_1 = 1$, and joining them (see example 2 below and the appropriate figure 8).

Example 1: 2 MVA ONAN distribution transformer, initial load of 1 MVA. To find the pemissible load for 2 h at an ambient temperature of 20 °C, assuming constant voltage:

$$\theta_a = 20\ °C \qquad K_1 = 0{,}5 \qquad t = 2\ h$$

Figure 9 gives K_2 = 1,56, but the guide limit is 1,5.

Therefore, the permissible load for 2 h is 3 MVA (then returning to 1 MVA).

Example 2: With θ_a = 20 °C, an ONAN distribution transformer is required to carry 1 750 kVA for 8 h and 1 000 kVA for the remaining 16 h each day. Assuming constant voltage, we have:

$$\frac{K_2}{K_1} = \frac{1\ 750}{1\ 000} = 1{,}75$$

From the curve of figure 9, on the line t = 8, the values of K_1 and K_2 giving K_2/K_1 = 1,75 are K_2 = 1,15 and K_1 = 0,66 (see figure 8) so that the rated power is:

$$S_r = \frac{1\ 750}{1{,}15} = \frac{1\ 000}{0{,}66} = 1\ 520\ kVA$$

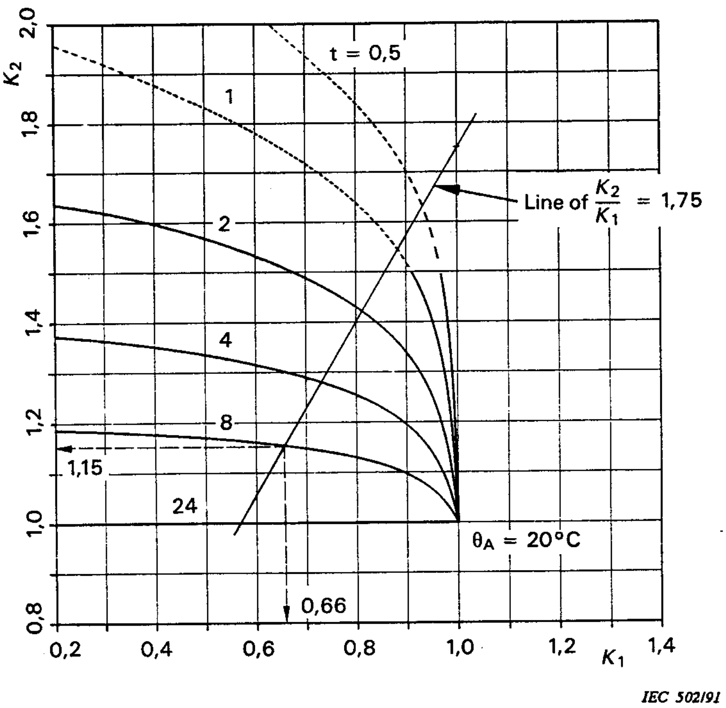


Figure 8 – Illustration of example 2

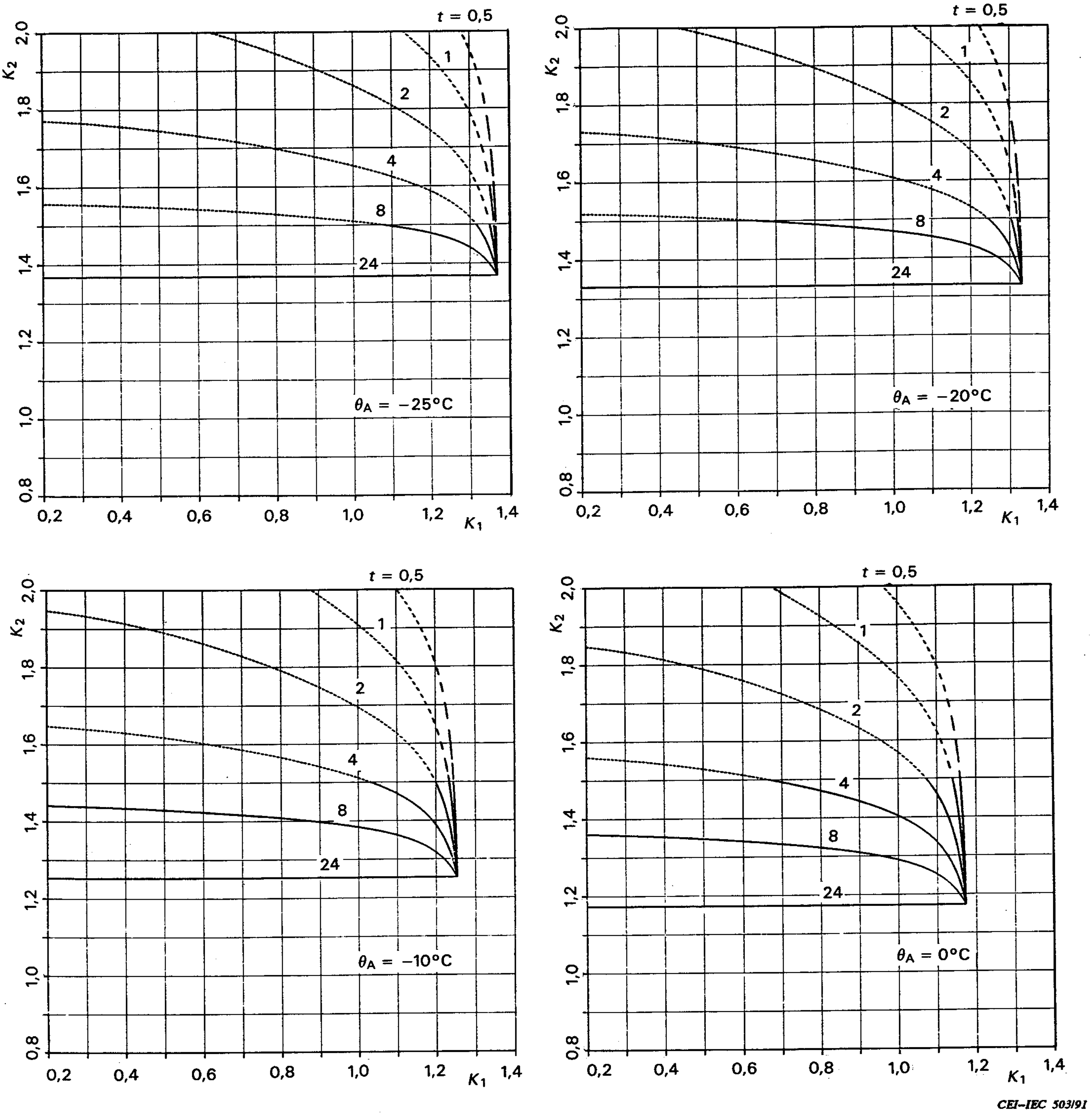
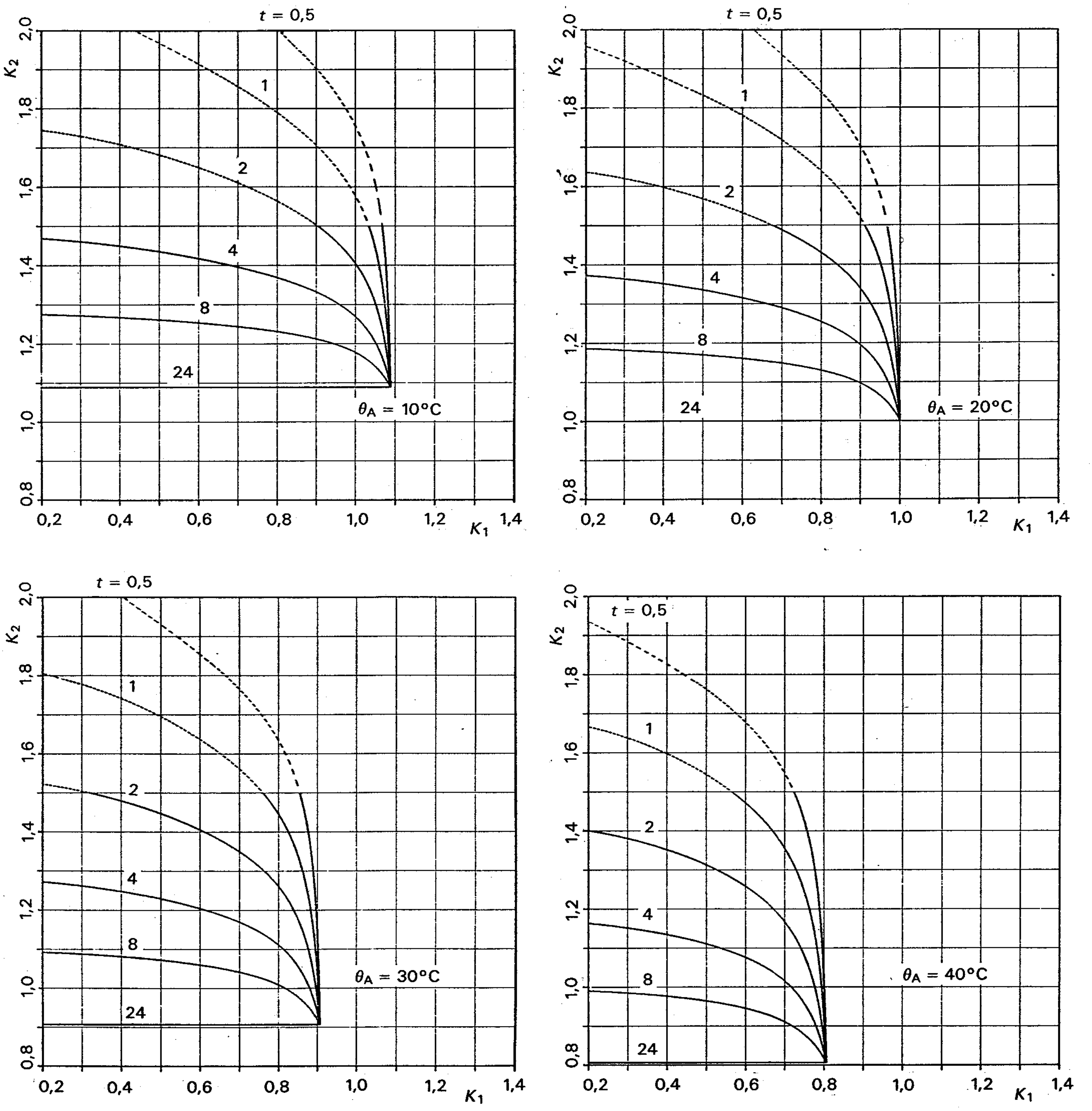


Figure 9

ONAN distribution transformers – Permissible duties for normal loss of life



CEI-IEC 504/91

Figure 9

ONAN distribution transformers –
Permissible duties for normal loss of life (continued)

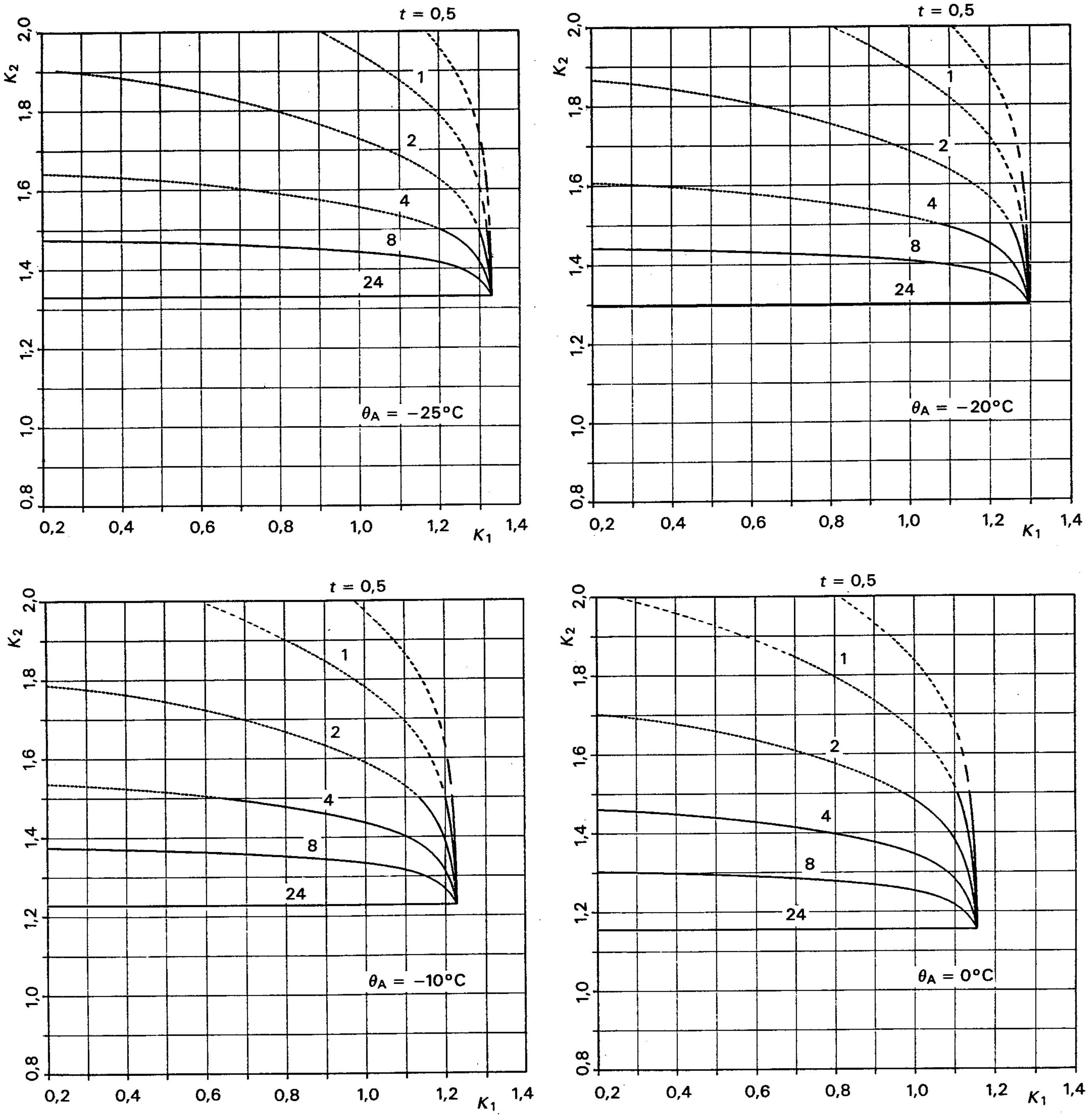


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Figure 10

ON medium and large power transformers –
Permissible duties for normal loss of life

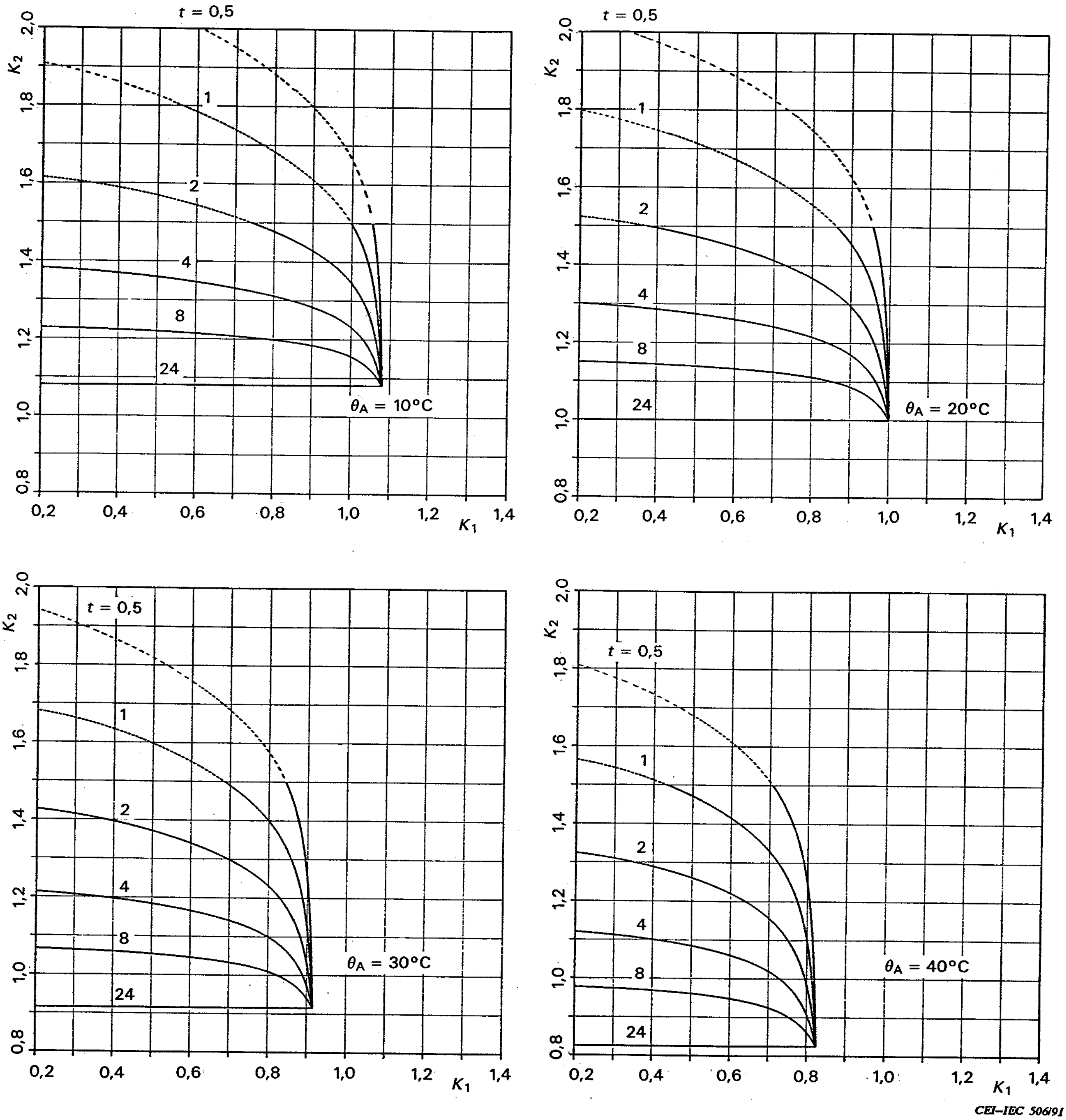
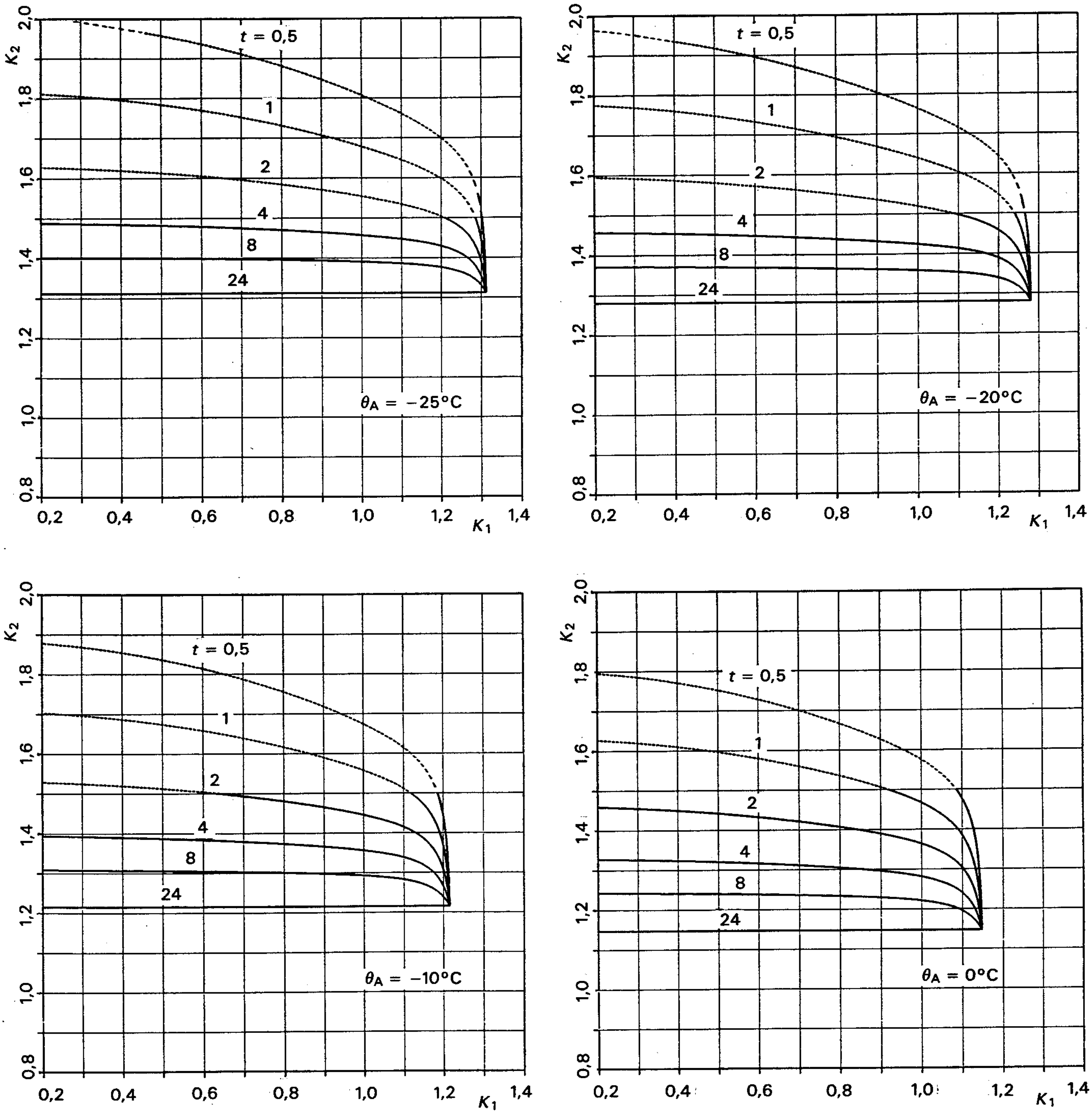


Figure 10

ON medium and large power transformers – Permissible duties for normal loss of life (continued)



CEI–IEC 507/91

Figure 11

OF medium and large power transformers – Permissible duties for normal loss of life

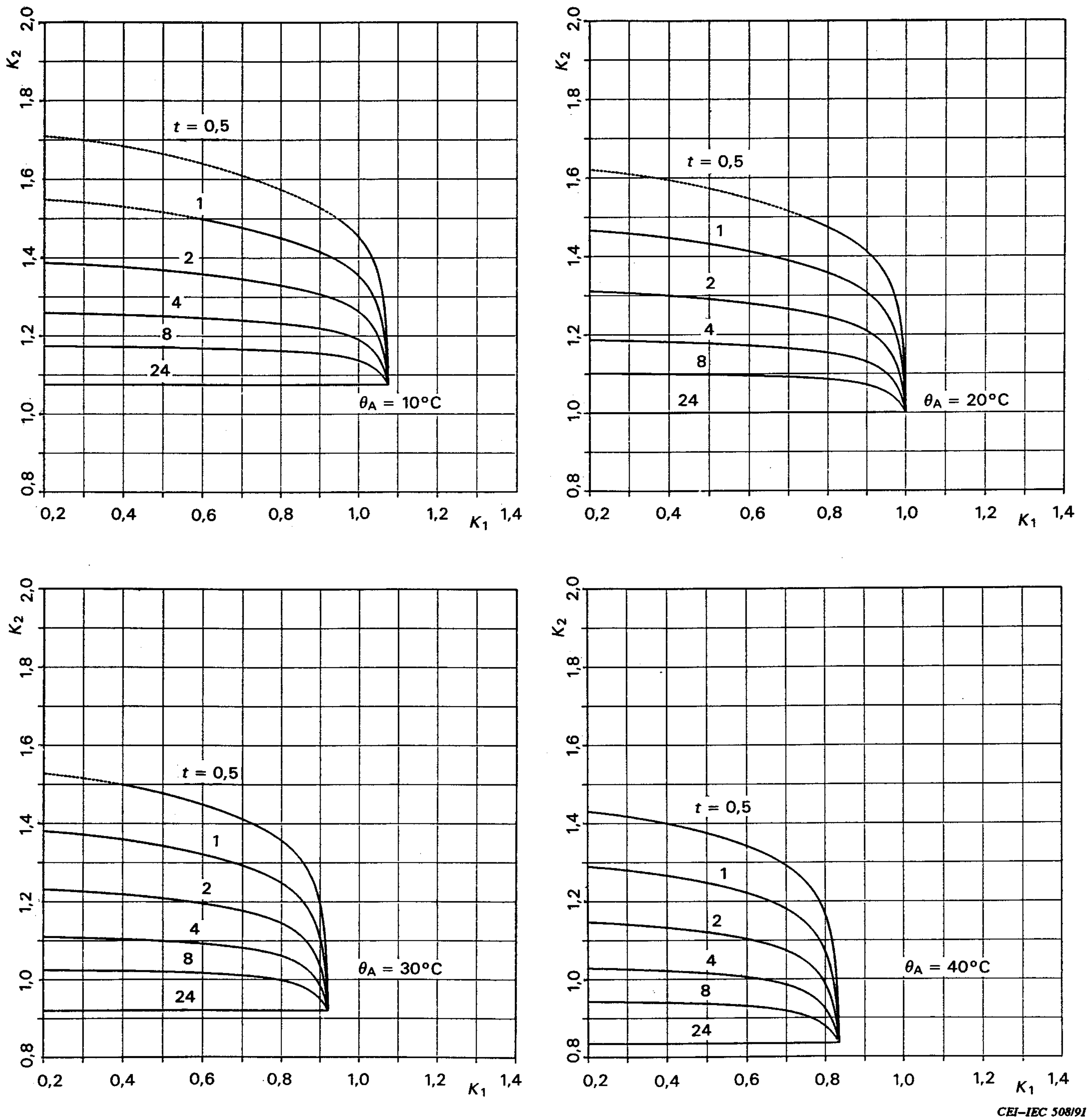


Figure 11

OF medium and large power transformers –
Permissible duties for normal loss of life (continued)

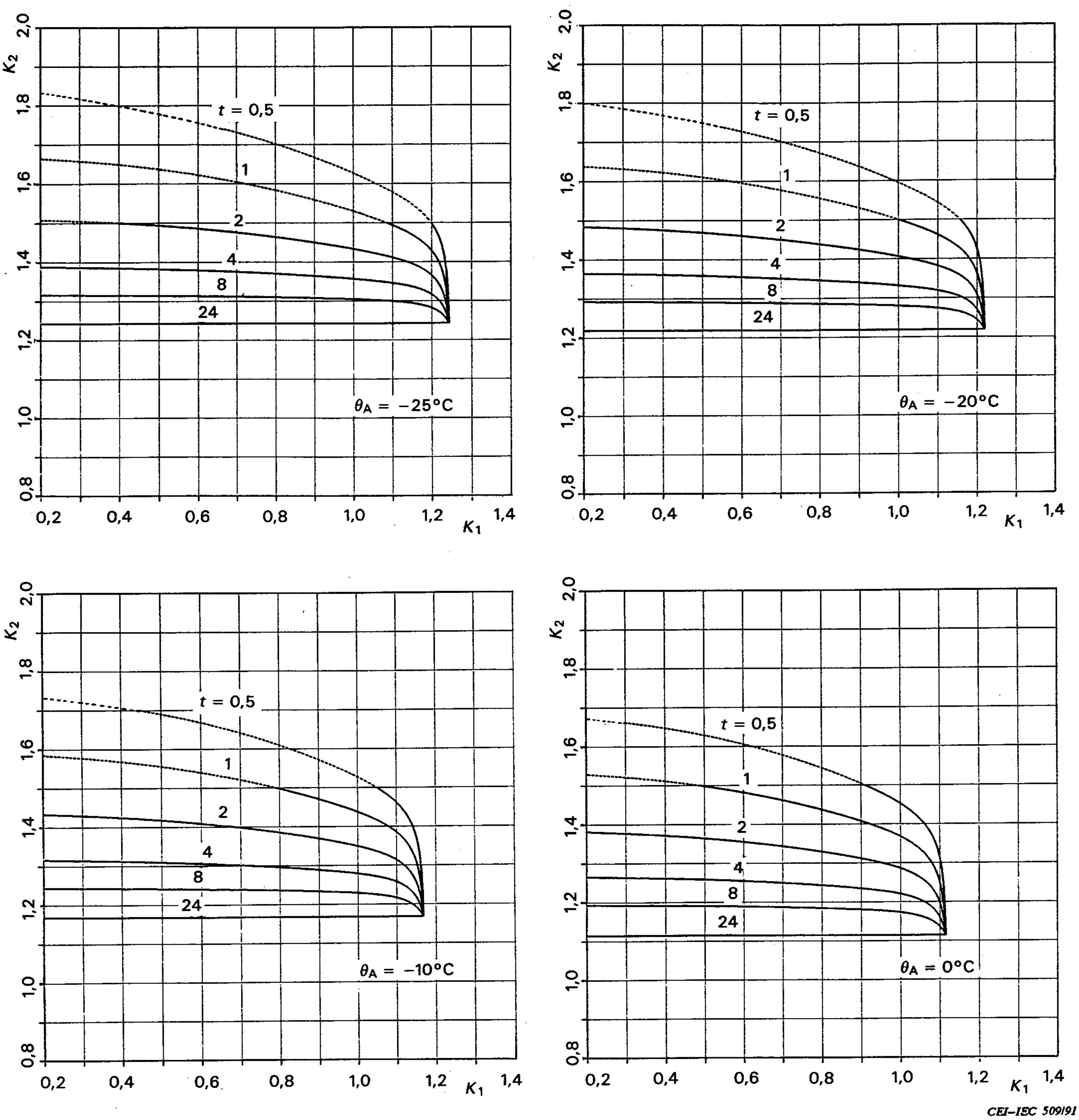


Figure 12

OD medium and large power transformers – Permissible duties for normal loss of life

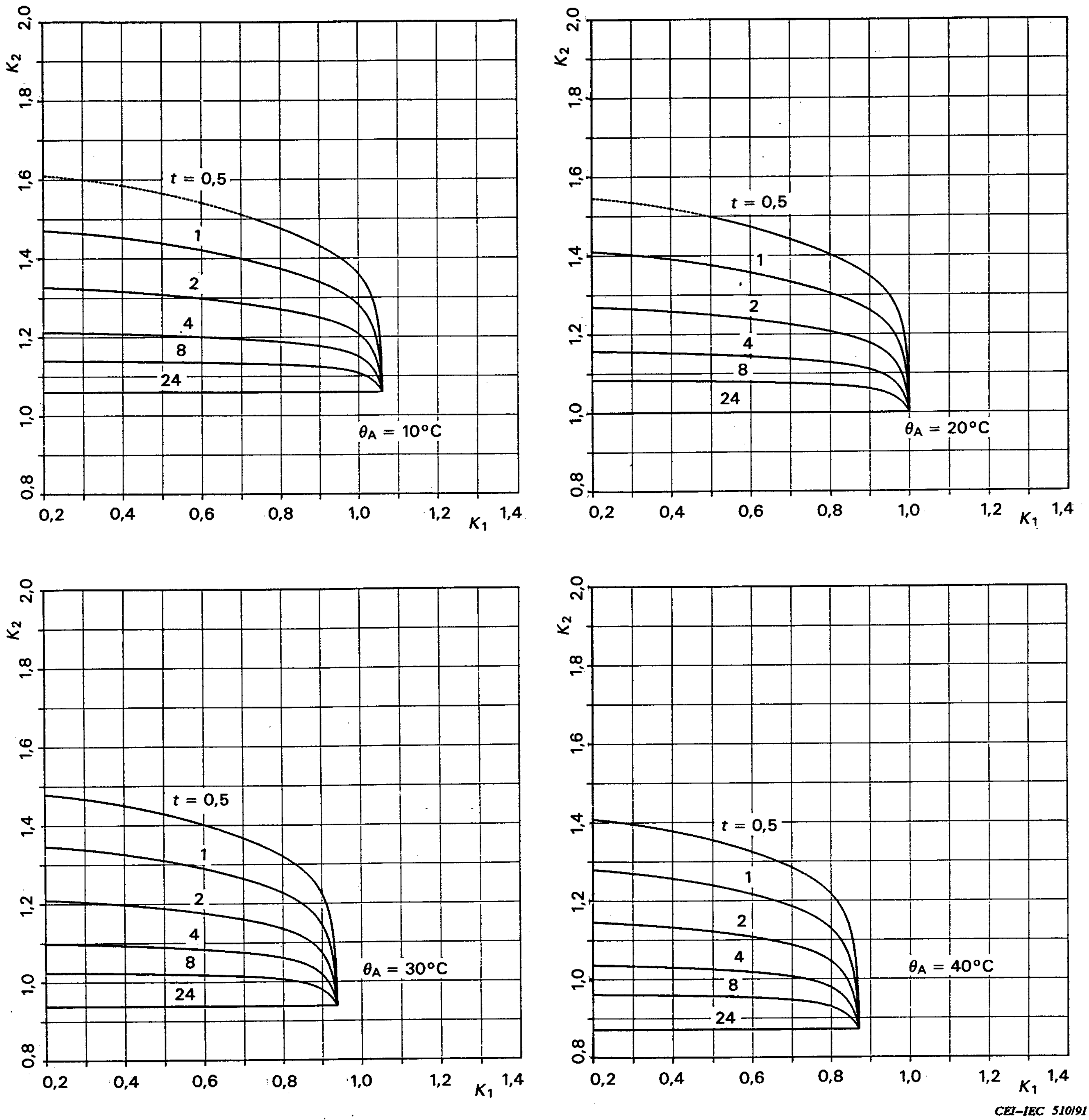


Figure 12

OD medium and large power transformers –
Permissible duties for normal loss of life (continued)

3.5 Emergency cyclic loading

The following tables are intended to give the user an indication of the loads that can be carried by a transformer without exceeding the winding hot-spot temperature limit stated in table 1 and, also, of the loss of life entailed, assuming that the thermal characteristics of the transformer under consideration are similar to those listed in table 2. The information is presented in 24 tables corresponding to the following four types of transformers and six values of t (from 0,5 h to 24 h).

ONAN	distribution transformers	- Tables 7 to 12
ON	medium and large power transformers	- Tables 13 to 18
OF	medium and large power transformers	- Tables 19 to 24
OD	medium and large power transformers	- Tables 25 to 30

With the aid of these tables it can be ascertained whether a load diagram characterized by particular values of K_1 and K_2 is permissible for a given ambient temperature and, if so, what daily loss of life it will entail (expressed in "normal" days, i.e. equivalent days of operation at rated power and at an ambient temperature of 20 °C).

The temperature and daily loss of life for these emergency duties have been calculated on the basis of cyclic duty. If the actual situation requires a single day of emergency duty, preceded and followed by days at lower loads, the calculated values of loss of life are greater than those that would actually occur, and will thus include a safety margin.

The relative loss of life is given in the tables to three significant figures. Such precision, which may appear unjustifiable, makes it easy to draw curves and make interpolations, on the understanding that the values obtained will be rounded off at the end of the calculations.

Example 1: What is the daily loss of life and the hot-spot temperature under the following conditions applied to a medium power transformer ?

OF cooling, $K_1 = 0,8$, $K_2 = 1,3$, $t = 8$ h, $\theta_a = 30$ °C

Table 23 shows that $V = 31,8$, $\Delta\theta_h = 121$ K for an ambient temperature of 20 °C. Taking account of the actual ambient temperature of 30 °C we find:

$L = 31,8 \times 3,2 = 101,8$ "normal" days

$\theta_h = 121 + 30 = 151$ °C

Thus the hot-spot temperature exceeds the recommended limit of 140 °C and this loading condition should be avoided.

Table 7 – ONAN distribution transformers: t = 0,5 h Permissible duties and corresponding daily loss of life (in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,001 32	0,006 40	0,032 48								
0,8	0,001 36	0,006 44	0,033 52	0,093 57							
0,9	0,001 41	0,006 48	0,034 57	0,095 62	0,292 67						
1,0	0,002 45	0,006 53	0,036 61	0,099 66	0,301 72	1,00 78					
1,1	0,002 50	0,007 58	0,038 66	0,104 71	0,312 77	1,03 83	3,72 89				
1,2	0,002 55	0,008 63	0,042 72	0,112 77	0,330 82	1,08 88	3,84 95	14,9 101			
1,3	0,003 61	0,011 68	0,049 77	0,125 82	0,359 88	1,14 94	4,02 100	15,5 107	64,7 114		
1,4	0,005 67	0,014 74	0,061 83	0,148 88	0,407 93	1,25 99	4,30 106	16,2 113	67,2 120	302 127	
1,5	0,007 73	0,022 80	0,083 89	0,191 94	0,495 100	1,45 106	4,77 112	17,5 119	70,8 126	314 133	1 510 141
1,6	0,013 79	0,036 86	0,126 95	0,273 100	0,662 106	1,81 112	5,61 118	19,6 125	76,6 132	332 140	1 570 148
1,7	0,025 86	0,066 93	0,213 102	0,437 107	0,992 112	2,52 118	7,21 125	23,5 132	86,9 139	361 146	1 670 154
1,8	0,050 92	0,129 100	0,394 108	0,778 114	1,67 119	3,95 125	10,4 131	31,2 138	107 145	415 153	1 830 161
1,9	0,104 99	0,263 107	0,782 115	1,50 121	3,11 126	6,98 132	17,2 138	47,0 145	146 152	520 160	2 130 168
2,0	0,224 107	0,559 114	1,64 123	3,10 128	6,26 133	13,6 139	31,7 146	80,9 153	229 160	737 167	2 730 175

Table 8 – ONAN distribution transformers: t = 1 h
Permissible duties and corresponding daily loss of life
(in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,001 35	0,006 41	0,032 48								
0,8	0,002 40	0,006 46	0,034 53	0,093 57							
0,9	0,002 45	0,007 51	0,037 58	0,098 63	0,292 67						
1,0	0,002 50	0,008 57	0,040 64	0,106 68	0,310 73	1,00 78					
1,1	0,003 56	0,010 63	0,047 70	0,118 74	0,337 79	1,07 84	3,72 89				
1,2	0,005 62	0,014 69	0,058 76	0,140 80	0,382 85	1,17 90	3,98 96	14,9 101			
1,3	0,008 69	0,022 75	0,080 83	0,180 87	0,461 92	1,34 97	4,39 102	16,0 108	64,7 114		
1,4	0,015 76	0,038 82	0,123 90	0,258 94	0,612 99	1,66 104	5,11 109	17,9 115	69,8 121	302 127	
1,5	0,031 83	0,073 90	0,214 97	0,419 101	0,918 106	2,28 111	6,46 116	21,1 122	78,3 128	327 135	1 510 141
1,6	0,065 91	0,150 97	0,413 104	0,771 109	1,57 113	3,58 119	9,22 124	27,3 130	93,9 136	370 142	1 640 149
1,7	0,146 99	0,329 105	0,871 112	1,57 117	3,05 121	6,46 126	15,2 132	40,5 138	125 144	450 150	1 870 157
1,8	0,340 107	0,760 113	1,96 120	3,46 125	6,52 129	13,2 135	28,8 140	69,9 146	192 152	615 158	2 310 165
1,9	0,826 115	1,83 122	4,66 129	8,12 133	15,0 138	29,4 143	61,5 148	139 154	347 160	983 167	3 250 173
2,0	2,08 124	4,58 130	11,5 138	20,0 142	36,4 147	70,2 152	143 157	311 163	725 169	1 860 175	5 410 182

Table 9 – ONAN distribution transformers: t = 2 h
Permissible duties and corresponding daily loss of life
(in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,002 39	0,006 43	0,032 48								
0,8	0,002 45	0,008 49	0,036 54	0,093 57							
0,9	0,003 51	0,010 56	0,042 61	0,104 64	0,292 67						
1,0	0,005 58	0,014 63	0,053 68	0,123 71	0,330 74	1,00 78					
1,1	0,010 66	0,023 70	0,074 75	0,159 78	0,398 82	1,14 85	3,72 89				
1,2	0,020 74	0,043 78	0,118 83	0,234 86	0,531 90	1,40 93	4,28 97	14,9 101			
1,3	0,045 82	0,090 86	0,221 92	0,399 95	0,814 98	1,93 102	5,35 106	17,4 110	64,7 114		
1,4	0,108 91	0,208 95	0,470 100	0,792 103	1,47 107	3,10 110	7,60 114	22,1 118	76,0 123	302 127	
1,5	0,275 100	0,518 104	1,12 110	1,80 113	3,11 116	5,93 120	12,8 124	32,5 128	98,5 132	357 137	1 510 141
1,6	0,745 109	1,38 114	2,88 119	4,51 122	7,48 126	13,3 129	26,0 133	57,4 137	150 142	472 146	1 800 151
1,7	2,13 119	3,89 124	7,96 129	12,2 132	19,8 135	33,8 139	61,7 143	123 147	278 151	742 156	2 430 161
1,8	6,36 129	11,5 134	23,3 139	35,4 142	56,3 146	93,9 149	165 153	308 157	628 162	1 450 166	3 950 171
1,9	19,9 140	35,9 145	71,8 150	108 153	170 156	280 160	480 164	866 168	1 660 172	3 440 177	8 070 182
2,0	65,3 151	117 156	232 161	348 164	544 167	884 171	1 500 175	2 640 179	4 880 183	+ +	+ +

Table 10 – ONAN distribution transformers: $t = 4$ h
Permissible duties and corresponding daily loss of life
(in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,003 43	0,008 46	0,032 48								
0,8	0,005 51	0,012 53	0,040 56	0,093 57							
0,9	0,010 59	0,020 61	0,056 64	0,117 66	0,292 67						
1,0	0,023 68	0,039 70	0,091 73	0,170 74	0,377 76	1,00 78					
1,1	0,056 77	0,091 79	0,178 82	0,294 84	0,566 86	1,32 87	3,72 89				
1,2	0,154 87	0,236 89	0,417 92	0,621 94	1,04 95	2,06 97	5,00 99	14,9 101			
1,3	0,455 98	0,677 100	1,12 103	1,56 104	2,36 106	4,02 108	8,13 110	20,5 112	64,7 114		
1,4	1,45 109	2,11 111	3,36 114	4,50 115	6,38 117	9,76 119	16,8 121	34,7 123	90,6 125	302 127	
1,5	4,94 120	7,09 122	11,0 125	14,4 127	19,7 128	28,2 130	43,7 132	76,1 134	160 137	431 139	1 510 141
1,6	17,9 132	25,5 134	38,8 137	50,1 139	66,8 140	92,7 142	135 144	211 146	371 149	790 151	2 200 153
1,7	69,0 144	97,3 147	146 149	187 151	246 153	334 155	470 157	694 159	1 100 161	1 950 163	4 190 166
1,8	282 157	394 160	587 162	745 164	971 166	1 300 167	1 790 169	2 560 172	3 830 174	6 110 176	+ 179
1,9	1 220 171	1 690 173	2 500 176	3 150 177	4 080 179	5 410 181	7 370 183	+ +	+ +	+ +	+ +
2,0	5 540 184	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +

Table 11 – ONAN distribution transformers: t = 8 h Permissible duties and corresponding daily loss of life (in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	-25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,007 47	0,012 48	0,032 48								
0,8	0,016 56	0,023 56	0,049 57	0,093 57							
0,9	0,040 65	0,054 66	0,092 66	0,148 67	0,292 67						
1,0	0,114 75	0,144 76	0,212 77	0,295 77	0,485 78	1,00 78					
1,1	0,356 86	0,436 87	0,584 87	0,735 88	1,03 88	1,73 89	3,72 89				
1,2	1,22 98	1,46 98	1,85 99	2,20 99	2,78 100	3,92 100	6,68 101	14,9 101			
1,3	4,53 110	5,33 110	6,57 111	7,55 111	9,01 112	11,4 112	16,2 113	27,9 114	64,7 114		
1,4	18,1 122	21,1 123	25,5 124	28,8 124	33,3 125	39,9 125	50,7 126	71,9 126	126 127	302 127	
1,5	78,1 136	90,0 136	107 137	120 137	136 138	158 138	190 139	242 140	345 140	609 141	1 510 141
1,6	360 150	412 150	486 151	538 151	604 152	690 152	807 153	974 153	1 240 154	1 770 155	3 160 155
1,7	1 770 164	2 020 165	2 360 165	2 600 166	2 890 166	3 270 167	3 760 167	4 410 168	5 350 168	6 840 169	9 770 170
1,8	9 320 179	+ 180	+ 180	+ 181	+ 181	+ 182	+ 182	+ 183	+ 183	+ 184	+ +

Table 12 – ONAN distribution transformers: t = 24 h
Permissible duties and corresponding daily loss of life
(in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2	
0,7	0,032 48
0,8	0,093 57
0,9	0,292 67
1,0	1,00 78
1,1	3,72 89
1,2	14,9 101
1,3	64,7 114
1,4	302 127
1,5	1 510 141
1,6	8 080 156
1,7	+ 171

Table 13 – ON medium and large power transformers: t = 0,5 h
Permissible duties and corresponding daily loss of life
(in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,001 30	0,004 37	0,024 46								
0,8	0,001 35	0,004 42	0,025 50	0,074 55							
0,9	0,001 40	0,004 47	0,026 55	0,077 61	0,258 66						
1,0	0,001 45	0,005 52	0,027 61	0,080 66	0,267 72	1,00 78					
1,1	0,001 51	0,005 58	0,029 67	0,085 72	0,279 78	1,04 84	4,30 91				
1,2	0,002 57	0,007 64	0,034 73	0,094 78	0,300 84	1,09 90	4,47 97	20,5 104			
1,3	0,003 64	0,009 71	0,042 79	0,111 84	0,338 90	1,18 96	4,73 103	21,4 111	108 119		
1,4	0,005 71	0,015 78	0,059 86	0,144 91	0,409 97	1,35 103	5,18 110	22,8 118	113 125	631 134	
1,5	0,010 78	0,027 85	0,095 93	0,213 98	0,554 104	1,69 110	6,03 117	25,2 125	121 133	661 141	4 040 150
1,6	0,022 85	0,054 92	0,174 101	0,365 106	0,868 112	2,39 118	7,76 125	29,9 132	135 140	710 148	4 250 157
1,7	0,048 93	0,118 100	0,356 109	0,712 114	1,58 119	3,98 126	11,6 133	39,8 140	164 148	802 156	4 590 165
1,8	0,113 101	0,271 108	0,794 117	1,54 122	3,28 128	7,69 134	20,4 141	62,3 148	226 156	994 164	5 250 173
1,9	0,275 110	0,652 117	1,88 125	3,60 130	7,45 136	16,8 142	41,7 149	116 157	373 164	1 430 173	6 650 182
2,0	0,695 118	1,64 125	4,69 134	8,88 139	18,1 145	40,0 151	95,8 158	251 165	736 173	2 480 182	+ +

Table 14 – ON medium and large power transformers: $t = 1$ h
Permissible duties and corresponding daily loss of life
(in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,001 33	0,004 39	0,024 46								
0,8	0,001 39	0,004 44	0,025 51	0,074 55							
0,9	0,001 45	0,005 50	0,027 57	0,079 62	0,258 66						
1,0	0,002 51	0,006 57	0,031 64	0,087 68	0,276 73	1,00 78					
1,1	0,003 58	0,009 64	0,038 71	0,100 75	0,306 80	1,08 85	4,30 91				
1,2	0,005 66	0,014 71	0,053 78	0,128 83	0,363 87	1,21 93	4,66 98	20,5 104			
1,3	0,011 74	0,026 79	0,084 86	0,185 91	0,477 95	1,46 100	5,29 106	22,4 112	108 119		
1,4	0,024 82	0,055 88	0,158 95	0,317 99	0,733 104	2,00 109	6,56 114	25,7 120	119 127	631 134	
1,5	0,059 91	0,128 97	0,342 104	0,641 108	1,35 112	3,25 118	9,36 123	32,7 129	138 136	695 143	4 040 150
1,6	0,153 100	0,324 106	0,827 113	1,48 117	2,92 122	6,40 127	16,2 132	48,7 138	180 145	821 152	4 480 159
1,7	0,418 110	0,875 115	2,17 122	3,81 127	7,20 131	14,8 136	34,0 142	89,4 148	281 155	1 100 161	5 360 169
1,8	1,21 120	2,50 125	6,11 132	10,6 137	19,5 141	38,9 146	84,0 152	201 158	549 165	1 800 171	7 400 179
1,9	3,65 130	7,52 136	18,2 143	31,2 147	57,0 152	111 157	233 162	527 168	1 310 175	3 730 182	+ +
2,0	11,6 141	23,8 147	57,1 154	97,3 158	176 162	341 168	701 173	1 540 179	+ +	+ +	+ +

Table 15 – ON medium and large power transformers: $t = 2$ h
Permissible duties and corresponding daily loss of life
(in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,001 37	0,004 41	0,024 46								
0,8	0,002 44	0,005 48	0,027 53	0,074 55							
0,9	0,003 52	0,008 56	0,032 60	0,084 63	0,258 66						
1,0	0,005 60	0,013 64	0,044 69	0,104 71	0,297 75	1,00 78					
1,1	0,012 69	0,025 73	0,070 77	0,148 80	0,377 83	1,17 87	4,30 91				
1,2	0,030 78	0,057 82	0,136 87	0,254 90	0,563 93	1,53 96	5,09 100	20,5 104			
1,3	0,083 88	0,148 92	0,321 97	0,542 100	1,04 103	2,40 106	6,86 110	24,6 114	108 119		
1,4	0,248 99	0,432 103	0,879 108	1,39 110	2,42 114	4,79 117	11,4 121	34,2 125	132 129	631 134	
1,5	0,803 110	1,37 114	2,70 119	4,12 122	6,74 125	12,1 128	24,6 132	60,2 136	189 140	778 145	4 040 150
1,6	2,80 122	4,73 126	9,07 131	13,6 133	21,5 137	36,4 140	67,1 144	140 148	352 152	1 150 157	5 060 162
1,7	10,4 134	17,5 138	33,0 143	48,8 146	75,9 149	125 152	218 156	414 160	885 164	2 280 169	7 760 174
1,8	41,6 147	69,2 151	129 156	190 158	291 162	470 165	800 169	1 450 173	2 820 177	6 190 182	+ +
1,9	177 160	293 164	542 169	790 172	1 200 175	1 920 178	3 210 182	+ +	+ +	+ +	+ +
2,0	803 174	1 320 178	2 430 183	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +

Table 16 – ON medium and large power transformers: t = 4 h Permissible duties and corresponding daily loss of life (in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,002 42	0,006 44	0,024 46								
0,8	0,004 50	0,009 52	0,030 54	0,074 55							
0,9	0,010 60	0,018 61	0,045 64	0,097 65	0,258 66						
1,0	0,027 70	0,042 72	0,085 74	0,154 75	0,347 76	1,00 78					
1,1	0,082 81	0,118 83	0,205 85	0,316 86	0,585 87	1,39 89	4,30 91				
1,2	0,277 93	0,386 94	0,608 96	0,844 98	1,32 99	2,48 101	6,15 102	20,5 104			
1,3	1,04 105	1,41 107	2,11 109	2,76 110	3,88 112	6,12 113	11,7 115	30,2 117	108 119		
1,4	4,26 118	5,70 120	8,27 122	10,5 123	14,0 125	19,9 126	31,7 128	61,6 130	164 132	631 134	
1,5	19,1 132	25,3 134	36,0 136	44,9 137	58,2 139	78,7 140	113 142	182 144	358 146	987 148	4 040 150
1,6	93,7 147	123 148	172 151	213 152	271 153	356 155	490 156	715 158	1 160 160	2 300 162	6 530 164
1,7	499 162	649 164	901 166	1 100 167	1 390 168	1 800 170	2 410 172	3 360 174	4 980 175	8 140 178	+ 180
1,8	2 880 178	3 730 180	5 130 182	6 240 183	7 790 184	+ +	+ +	+ +	+ +	+ +	+ +

Table 17 – ON medium and large power transformers: t = 8 h Permissible duties and corresponding daily loss of life (in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,005 45	0,009 45	0,024 46								
0,8	0,014 54	0,019 55	0,038 55	0,074 55							
0,9	0,040 65	0,051 65	0,080 66	0,126 66	0,258 66						
1,0	0,135 76	0,160 77	0,216 77	0,287 77	0,463 78	1,00 78					
1,1	0,506 89	0,584 89	0,726 89	0,871 90	1,16 90	1,90 90	4,30 91				
1,2	2,12 102	2,40 102	2,86 103	3,26 103	3,91 103	5,22 103	8,64 104	20,5 104			
1,3	9,84 116	11,0 116	12,8 117	14,2 117	16,3 117	19,6 117	26,1 118	43,6 118	108 119		
1,4	50,5 131	56,1 131	64,3 131	70,4 132	78,5 132	90,1 132	108 133	145 133	244 133	631 134	
1,5	286 146	315 147	358 147	388 147	427 148	478 148	551 148	665 149	886 149	1 500 149	4 040 150
1,6	1 780 163	1 950 163	2 200 164	2 370 164	2 580 164	2 850 164	3 220 165	3 720 165	4 500 165	5 990 166	+ 166
1,7	+ 180	+ 180	+ 181	+ 181	+ 181	+ 182	+ 182	+ 182	+ 183	+ 183	+ 184

Table 18 – ON medium and large power transformers: t = 24 h Permissible duties and corresponding daily loss of life (in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2	
0,7	0,024 46
0,8	0,074 55
0,9	0,258 66
1,0	1,00 78
1,1	4,30 91
1,2	20,5 104
1,3	108 119
1,4	631 134
1,5	4 040 150
1,6	+ 167

Table 19 – OF medium and large power transformers: t = 0,5 h Permissible duties and corresponding daily loss of life (in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,001 35	0,003 39	0,020 44								
0,8	0,001 42	0,003 46	0,020 51	0,065 54							
0,9	0,001 49	0,004 53	0,022 59	0,067 62	0,239 66						
1,0	0,002 57	0,005 61	0,024 67	0,072 70	0,249 74	1,00 78					
1,1	0,004 66	0,008 70	0,032 75	0,084 79	0,270 83	1,05 87	4,70 91				
1,2	0,009 75	0,018 79	0,051 85	0,114 88	0,323 92	1,15 96	4,93 101	24,8 106			
1,3	0,025 85	0,045 89	0,107 95	0,202 98	0,471 102	1,42 106	5,49 111	26,2 116	147 121		
1,4	0,075 96	0,131 100	0,280 105	0,470 108	0,915 112	2,21 116	7,02 121	29,5 126	156 132	975 138	
1,5	0,241 107	0,415 111	0,846 116	1,35 119	2,35 123	4,73 127	11,8 132	39,2 137	178 143	1 040 149	7 230 155
1,6	0,823 118	1,41 122	2,82 127	4,38 131	7,30 135	13,3 139	27,7 143	70,8 148	246 154	1 200 160	7 730 166
1,7	2,99 130	5,08 134	10,1 139	15,5 143	25,4 146	44,6 151	85,0 155	183 160	482 166	1 740 172	9 120 178
1,8	11,5 142	19,5 147	38,4 152	58,8 155	95,5 159	165 163	305 168	609 173	1 360 178	3 700 184	+ +
1,9	46,9 155	79,1 160	155 165	237 168	383 172	657 176	1 200 181	+ +	+ +	+ +	+ +
2,0	203 169	341 173	666 178	1 010 182	+ +	+ +	+ +	+ +	+ +	+ +	+ +

Table 20 – OF medium and large power transformers: t = 1 h Permissible duties and corresponding daily loss of life (in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,001 37	0,003 40	0,020 44								
0,8	0,001 45	0,004 48	0,021 52	0,065 54							
0,9	0,002 54	0,005 57	0,024 61	0,070 63	0,239 66						
1,0	0,005 63	0,009 66	0,032 70	0,081 72	0,260 75	1,00 78					
1,1	0,012 73	0,021 76	0,053 80	0,113 82	0,312 85	1,10 88	4,70 91				
1,2	0,036 84	0,058 87	0,119 91	0,209 93	0,462 96	1,35 99	5,21 102	24,8 106			
1,3	0,120 95	0,186 98	0,342 102	0,528 105	0,945 107	2,14 110	6,62 114	27,8 117	147 121		
1,4	0,431 108	0,659 110	1,16 114	1,68 117	2,66 119	4,85 122	11,2 126	36,4 129	166 133	975 138	
1,5	1,68 120	2,55 123	4,37 127	6,18 129	9,30 132	15,2 135	28,3 138	66,7 142	225 146	1 110 150	7 230 155
1,6	7,09 134	10,7 137	18,1 140	25,3 143	37,2 146	58,0 149	97,6 152	186 155	446 159	1 570 164	8 340 168
1,7	32,3 148	48,3 151	81,0 154	112 157	164 160	250 163	406 166	706 170	1 380 173	3 370 178	+ 182
1,8	159 162	236 165	393 169	543 171	784 174	1 190 177	1 890 181	3 180 184	+ +	+ +	+ +
1,9	842 178	1 250 181	2 060 184	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +

Table 21 – OF medium and large power transformers: t = 2 h Permissible duties and corresponding daily loss of life (in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,001 41	0,004 42	0,020 44								
0,8	0,002 50	0,005 51	0,023 53	0,065 54							
0,9	0,006 60	0,010 61	0,030 63	0,076 64	0,239 66						
1,0	0,017 70	0,025 72	0,053 74	0,107 75	0,286 76	1,00 78					
1,1	0,056 82	0,077 84	0,130 86	0,207 87	0,426 88	1,22 90	4,70 91				
1,2	0,211 95	0,280 96	0,421 98	0,577 99	0,922 101	1,93 102	5,85 104	24,8 106			
1,3	0,877 108	1,14 109	1,64 111	2,10 113	2,91 114	4,66 116	9,90 117	31,6 119	147 121		
1,4	4,03 122	5,20 124	7,27 126	9,07 127	11,8 128	16,6 130	26,7 131	57,2 133	191 135	975 138	
1,5	20,5 137	26,1 139	36,0 141	44,3 142	56,4 143	75,1 145	107 146	173 148	372 150	1 300 153	7 230 155
1,6	114 153	145 154	198 156	241 158	303 159	394 161	536 162	774 164	1 260 166	2 730 168	9 870 171
1,7	703 169	886 171	1 200 173	1 450 174	1 800 176	2 320 177	3 090 179	4 280 181	6 290 183	+ +	+ +

Table 22 – OF medium and large power transformers: t = 4 h Permissible duties and corresponding daily loss of life (in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,003 43	0,005 43	0,020 44								
0,8	0,006 53	0,010 53	0,026 54	0,065 54							
0,9	0,019 64	0,025 64	0,046 65	0,089 65	0,239 66						
1,0	0,069 76	0,082 76	0,117 77	0,172 77	0,344 78	1,00 78					
1,1	0,278 89	0,320 89	0,403 90	0,499 90	0,734 91	1,50 91	4,70 91				
1,2	1,26 103	1,43 103	1,71 104	1,96 104	2,42 104	3,54 105	7,37 105	24,8 106			
1,3	6,40 118	7,18 118	8,40 119	9,37 119	10,8 119	13,3 120	19,3 120	40,7 121	147 121		
1,4	36,4 134	40,5 134	46,7 134	51,4 135	57,8 135	67,0 136	82,6 136	119 136	252 137	975 138	
1,5	231 150	256 151	292 151	319 151	353 152	400 152	467 153	576 153	823 154	1 760 154	7 230 155
1,6	1 640 168	1 800 168	2 040 169	2 210 169	2 430 169	2 720 170	3 100 170	3 640 171	4 500 171	6 400 172	+ 173

Table 23 – OF medium and large power transformers: t = 8 h Permissible duties and corresponding daily loss of life (in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,006 44	0,008 44	0,020 44								
0,8	0,017 54	0,020 54	0,034 54	0,065 54							
0,9	0,057 66	0,063 66	0,082 66	0,118 66	0,239 66						
1,0	0,223 78	0,238 78	0,273 78	0,324 78	0,469 78	1,00 78					
1,1	0,989 91	1,04 91	1,14 91	1,24 91	1,45 91	2,11 91	4,70 91				
1,2	4,95 106	5,17 106	5,53 106	5,82 106	6,31 106	7,37 106	10,7 106	24,8 106			
1,3	27,8 121	28,9 121	30,6 121	31,8 121	33,5 121	36,3 121	42,1 1121	60,7 121	147 121		
1,4	175 137	181 137	190 137	197 137	205 137	217 137	235 137	271 137	388 138	975 138	
1,5	1 240 155	1 280 155	1 330 155	1 370 155	1 420 155	1 490 155	1 570 155	1 700 155	1 950 155	2 780 155	7 230 155
1,6	9 790 173	+ 173	+ 173	+ 173	+ 173	+ 173	+ 173	+ 173	+ 173	+ 173	+ 173

Table 24 – OF medium and large power transformers: t = 24 h
Permissible duties and corresponding daily loss of life
(in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2	
0,7	0,020 44
0,8	0,065 54
0,9	0,239 66
1,0	1,00 78
1,1	4,70 91
1,2	24,8 106
1,3	147 121
1,4	975 138
1,5	7 230 155
1,6	+ 173

Table 25 – OD medium and large power transformers: t = 0,5 h Permissible duties and corresponding daily loss of life (in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,000 23	0,001 29	0,008 36								
0,8	0,000 31	0,001 36	0,008 44	0,032 48							
0,9	0,000 40	0,001 45	0,009 53	0,034 57	0,163 62						
1,0	0,001 50	0,002 55	0,010 63	0,037 67	0,172 72	1,00 78					
1,1	0,002 61	0,004 66	0,016 73	0,048 78	0,196 83	1,06 89	7,42 95				
1,2	0,005 73	0,012 78	0,037 86	0,087 90	0,275 95	1,25 101	7,97 107	66,7 114			
1,3	0,021 86	0,045 91	0,123 99	0,244 103	0,589 108	1,94 114	9,73 120	72,3 127	726 135		
1,4	0,096 100	0,201 105	0,524 113	0,970 117	2,02 122	5,03 128	17,1 135	92,3 142	794 149	9 550 157	
1,5	0,497 115	1,03 121	2,63 128	4,77 132	9,43 138	20,8 143	53,7 150	186 157	1 070 164	+ 172	+ 181
1,6	2,90 131	5,97 137	15,1 144	27,1 149	52,8 154	112 160	263 166	711 173	2 520 180	+ +	+ +
1,7	19,1 148	39,2 154	98,5 161	176 166	339 171	712 177	1 630 183	+ +	+ +	+ +	+ +
1,8	143 167	291 172	727 180	1 290 184	+ +	+ +	+ +	+ +	+ +	+ +	+ +

Table 26 – OD medium and large power transformers: t = 1 h
Permissible duties and corresponding daily loss of life
(in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,000 27	0,001 31	0,008 36								
0,8	0,000 36	0,001 40	0,008 45	0,032 48							
0,9	0,001 46	0,002 50	0,010 55	0,035 59	0,163 62						
1,0	0,002 58	0,004 62	0,015 67	0,045 70	0,183 74	1,00 78					
1,1	0,007 70	0,013 74	0,035 80	0,078 83	0,246 87	1,14 91	7,42 95				
1,2	0,030 84	0,054 88	0,123 94	0,221 97	0,500 101	1,65 105	8,65 109	66,7 114			
1,3	0,152 100	0,269 104	0,571 109	0,939 112	1,74 116	3,98 120	13,6 125	79,4 130	726 135		
1,4	0,893 116	1,56 120	3,23 125	5,14 129	8,85 132	17,0 136	39,4 141	137 146	884 151	9 550 157	
1,5	6,08 134	10,5 138	21,4 143	33,6 146	56,4 150	102 154	204 159	483 164	1 700 169	+ 175	+ 181
1,6	48,0 153	82,3 157	165 162	257 165	426 169	754 173	1 440 178	3 000 183	+ +	+ +	+ +
1,7	438 173	745 177	1 480 182	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +

Table 27 – OD medium and large power transformers: t = 2 h Permissible duties and corresponding daily loss of life (in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,000 31	0,001 33	0,008 36								
0,8	0,001 42	0,002 44	0,009 47	0,032 48							
0,9	0,002 54	0,004 56	0,014 59	0,040 60	0,163 62						
1,0	0,010 68	0,015 70	0,032 72	0,067 74	0,209 76	1,00 78					
1,1	0,048 83	0,070 85	0,122 87	0,192 89	0,398 91	1,33 93	7,42 95				
1,2	0,278 99	0,395 101	0,639 104	0,894 105	1,41 107	2,93 109	10,4 112	66,7 114			
1,3	1,93 117	2,70 119	4,22 122	5,66 123	8,09 125	12,9 127	26,6 130	97,7 132	726 135		
1,4	15,9 136	22,0 138	33,7 141	44,3 143	61,1 144	89,6 147	145 149	297 152	1 120 154	9 550 157	
1,5	156 157	213 159	321 162	418 163	566 165	805 167	1 210 170	1 990 172	4 070 175	+ 178	+ 181
1,6	1 800 179	2 450 181	3 650 184	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ +

Table 28 – OD medium and large power transformers: t = 4 h Permissible duties and corresponding daily loss of life (in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,001 35	0,002 35	0,008 36								
0,8	0,003 47	0,004 47	0,011 48	0,032 48							
0,9	0,011 60	0,014 61	0,024 61	0,049 62	0,163 62						
1,0	0,054 75	0,065 76	0,091 76	0,130 77	0,271 77	1,00 78					
1,1	0,334 92	0,392 93	0,500 93	0,610 94	0,863 94	1,80 95	7,42 95				
1,2	2,50 110	2,90 111	3,56 112	4,12 112	5,03 113	7,01 113	14,6 114	66,7 114			
1,3	22,7 130	26,0 131	31,2 131	35,4 132	41,3 132	50,6 133	69,9 134	145 134	726 135		
1,4	248 152	281 152	334 153	374 153	429 154	505 155	622 155	853 156	1 740 157	9 550 157	
1,5	3 270 175	3 690 175	4 330 176	4 810 177	5 440 177	6 300 178	7 490 178	9 300 179	+ 180	+ 180	+ 181

Table 29 – OD medium and large power transformers: t = 8 h Permissible duties and corresponding daily loss of life (in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2 \ K_1	0,25	0,50	0,70	0,80	0,90	1,00	1,10	1,20	1,30	1,40	1,50
0,7	0,002 36	0,003 36	0,008 36								
0,8	0,008 48	0,009 48	0,015 48	0,032 48							
0,9	0,036 62	0,039 62	0,049 62	0,071 62	0,163 62						
1,0	0,204 78	0,218 78	0,247 78	0,285 78	0,407 78	1,00 78					
1,1	1,42 95	1,50 95	1,64 95	1,76 95	2,02 95	2,85 95	7,42 95				
1,2	12,0 114	12,6 114	13,5 114	14,3 114	15,3 114	17,4 114	24,3 114	66,7 114			
1,3	123 135	129 135	137 135	143 135	151 135	162 135	183 135	252 135	726 135		
1,4	1 540 157	1 590 157	1 680 157	1 740 157	1 820 157	1 930 157	2 080 157	2 340 157	3 170 157	9 550 157	
1,5	+ 181	+ 181	+ 181	+ 181	+ 181	+ 181	+ 181	+ 181	+ 181	+ 181	+ 181

Table 30 – OD medium and large power transformers: t = 24 h
Permissible duties and corresponding daily loss of life
(in "normal" days)

To determine whether a daily load diagram characterized by particular values of K_1 and K_2 is permissible and to evaluate the daily loss of life entailed, proceed as follows:

Ambient temperature	40 °C	30 °C	20 °C	10 °C	0 °C	–10 °C	–20 °C	–25 °C
Daily loss of life: Multiply the value given in the table below by the factor given here, then round off the result	10	3,2	1	0,32	0,1	0,032	0,01	0,0055
Hot-spot temperature: Add the hot-spot temperature rise given in the table to the ambient temperature. If the resulting hot-spot temperature exceeds the limit stated in table 1, the duty is not permissible.								

K_2	
0,7	0,008 36
0,8	0,032 48
0,9	0,163 62
1,0	1,00 78
1,1	7,42 95
1,2	66,7 114
1,3	726 135
1,4	9 550 157
1,5	+ 181

Annex A

Equivalent rating for auto-transformers

For three-phase auto-transformers, the limits in short-circuit impedance and rated power apply to the equivalent double-wound rated power S_t = 100 MVA, and the corresponding short-circuit impedance z_t between 0 – 100 MVA decreasing linearly from 25 % to 15 % and a maximum rated power S_r = 200 MVA.

For auto-transformers other than three-phase transformers, the limits of equivalent rated power and rated power are 33,3 MVA/wound limb and 66,6 MVA/wound limb, respectively.

Three-phase auto-transformers

$$S_t = S_r \frac{U_1 - U_2}{U_1} \leq 100 \text{ MVA}$$

$$z_t = z_r \frac{U_1}{U_1 - U_2} \leq 25 - \frac{S_t}{10}$$

Auto-transformers with the limitation in rated power per limb

$$S_t = \frac{S_r}{W} \frac{U_1 - U_2}{U_1} \leq 33{,}3 \text{ MVA}$$

$$z_t = z_r \frac{U_1}{U_1 - U_2} \leq 25 - \frac{3S_t}{10\,W}$$

For a nomogram to these formulae with examples, see figure A.1.

U_1 = high voltage (principal tapping)

U_2 = low voltage (principal tapping)

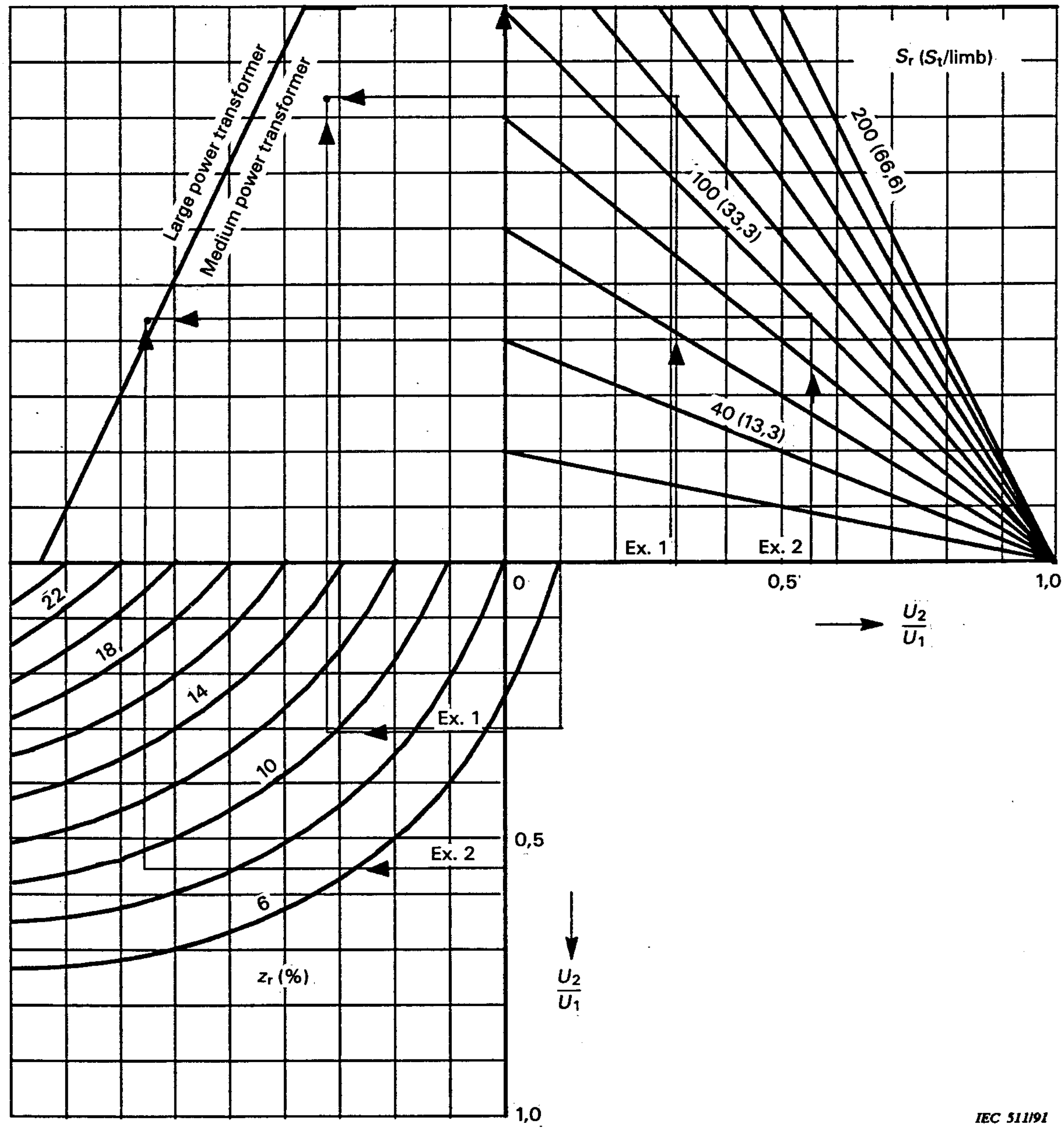
S_r = rated power (MVA)

S_t = equivalent double-wound power (MVA) (transformed power)

z_r = short-circuit impedance corresponding to S_r (%)

z_t = short-circuit impedance corresponding to S_t (%)

W = number of wound limbs



Examples for three-phase auto-transformers:

Example 1 S_r = 120 MVA, U_1 = 525 kV, U_2 = 161 kV, z_r = 10 %:
S_t = 83,2 MVA (< 100), z_t = 14,42 % (< 16,68)

Example 2 S_r = 100 MVA, U_1 = 400 kV, U_2 = 220 kV, z_r = 9,5 %:
S_t = 45,0 MVA (< 100), z_t = 21,11 % (> 20,50)

Figure A.1 – Auto-transformers: Limitations in rated power S_r and short-circuit impedance z_r

Annex B

Alternative method for determining the winding oil average temperature rise from temperature-rise test measurements (see 2.3.3)

B.1 For ONAN and OFAN cooling, satisfactory cooling curves may be attainable. Where there is forced air or water cooling, the requirement of 3.9.1 of IEC 76-2 is that "when the supply to the transformer is switched off, the fans and water pumps shall be stopped but the oil pumps shall remain running". This may cause thermal transients that distort the cooling curve from its expected characteristic having two exponentials, thus making it difficult to extrapolate to the "zero" and "infinity" times to obtain R_2 and R' (see IEC 76-2, figure 2).

In order to minimize these thermal transient distortions of the temperature (resistance) cooling curve for any type of cooling, it is necessary to maintain, during the cooling period, the same cooling conditions that prevail during the temperature rise test. Each test reading has then to be adjusted to allow for the cooling of the transformer after switch off, as follows:

Using the transformer (oil) time constant derived from B.2 below, the average temperature rise of the winding at each measured resistance point is given as:

$$\Delta\theta_{Rt} = \mathrm{Exp}\ \frac{t}{\tau_o}\left[\frac{R_t}{R_c}(235 + \theta_{Rc}) - (235 + \theta_a)\right] \text{ for copper} \qquad (1)$$

$$\Delta\theta_{Rt} = \mathrm{Exp}\ \frac{t}{\tau_o}\left[\frac{R_t}{R_c}(225 + \theta_{Rc}) - (225 + \theta_a)\right] \text{ for aluminium} \qquad (2)$$

where

R_t is the winding resistance measured at time t after switch-off;

R_c is the winding resistance (cold) measured at temperature θ_{Rc} (°C);

θ_{Rc} is the temperature of the winding during R_c measurement (°C);

θ_a is the ambient temperature at switch-off (°C);

t is the time (minutes) from switch-off;

τ_o is the transformer (oil) time constant derived from formula (3a), (3b) or (3c) (preferred) or (5);

τ_w is the winding time constant.

The winding average temperature rise and the winding oil average temperature rise at switch-off are derived from $\Delta\theta_{Rt}$ and t by either graphical construction in a similar manner to figure 2 of IEC 76-2 (points equivalent to R_2 and R' respectively), or the function $\Delta\theta_{Rt} = A + B\ \mathrm{Exp}\ (-t/\tau_w)$ from regression analysis (for $t = 0$ and $t =$ infinity respectively). This construction is illustrated in figure B.1.

B.2 For each condition of cooling, the transformer oil time constant is derived by maintaining the cooling unaltered for t minutes (where $t \geq 30$ min) and recording the oil temperature rise (either $t\,\Delta\theta_o$, $\Delta\theta_e$ or $\Delta\theta_b$) at the instant of switch-off (t = o) and again at time t after switch-off. The transformer oil time constant is then derived from:

$$\tau_o = \frac{t}{\ln \Delta\theta_{e0} - \ln \Delta\theta_{et}} \text{ minutes} \qquad (3a)$$

ou

$$\tau_o = \frac{t}{\ln \Delta\theta_{b0} - \ln \Delta\theta_{bt}} \text{ minutes} \qquad (3b)$$

ou

$$\tau_o = \frac{t}{\ln \Delta\theta_{o0} - \ln \Delta\theta_{ot}} \text{ minutes} \qquad (3c)$$

Should it not be possible to maintain the cooling for at least 30 min after switch-off, the transformer (oil) time constant may be derived from the oil heating curve provided that, for the heating period, a constant input of loss has been maintained and no change has been made to the cooling conditions. The procedure illustrated in figure B.2 is as follows:

Plot the curve for the top oil temperature rise from switch-on ($\Delta\theta_o$) against time (t). From the curve, note the actual values of $\Delta\theta_o$ and t for points approximately 0,6 p.u. and 0,95 p.u. of the last measured point to give t_1, $\Delta\theta_{o1}$ and t_3, $\Delta\theta_{o3}$ respectively. A third point, t_2, $\Delta\theta_{o2}$ is determined from the curve where $(t_2 - t_1) = (t_3 - t_2)$.

The final top oil temperature rise is given by:

$$\Delta\theta_{ou} = \frac{\Delta\theta_{o1} \times \Delta\theta_{o3} - \Delta\theta_{o2}^2}{\Delta\theta_{o1} + \Delta\theta_{o3} - 2.\Delta\theta_{o2}} \qquad (4)$$

and the time constant (minutes) by:

$$\tau_o = (t_3 - t_1) / \ln \frac{\Delta\theta_{ou} - \Delta\theta_{o1}}{\Delta\theta_{ou} - \Delta\theta_{o3}} \qquad (5)$$

B.3 Illustration of the derivation of average winding temperature and average oil temperature is provided in figures B.1 and B.2.

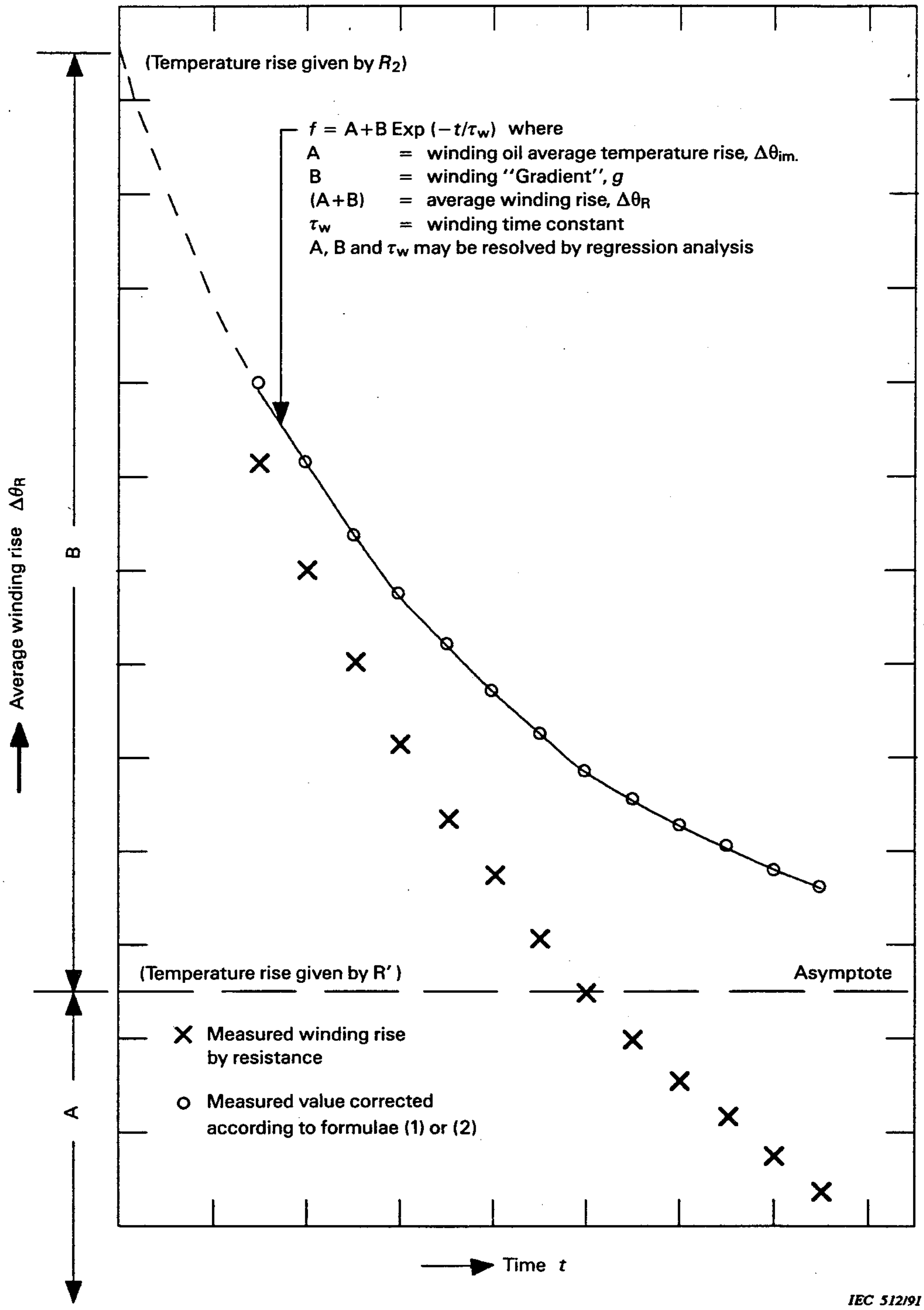


Figure B.1 – Determination of average winding rise, gradient and winding time constant from resistance cooling curve

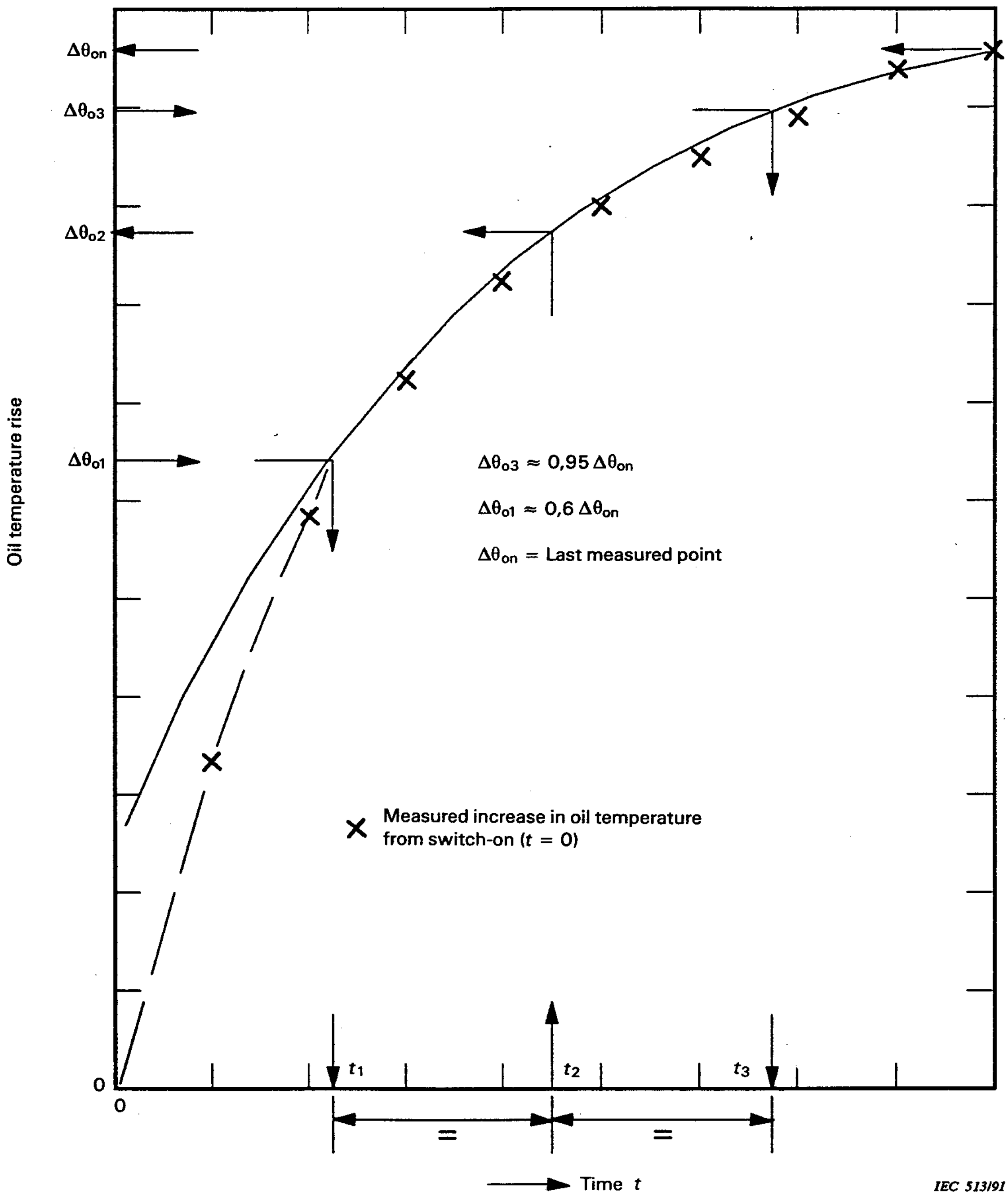


Figure B.2 – Determination of effective oil time constant, τ_o, from oil heating curve

Annex C

Information to be supplied with enquiry and order

Appendix A of IEC 76-1 specifies the information to be given in all cases and additional information which may need to be given:

- special cooling conditions, for example temperature of cooling medium if above or below the limits specified under service conditions or restrictions to circulation of cooling air.
- details of intended loading (loading in excess of nameplate rating).

Loading of transformers beyond nameplate rating may be restricted (apart from bushings, leads, tap-changers and other associated equipment) by the winding hottest temperature as well as the hottest temperature of parts having low thermal time constants outside windings.

For load currents exceeding the rated value, special provisions may be necessary in the design to prevent overheating, for example, special dimensioning of conductors at the ends of windings or of electromagnetic screens. Also, dimensioning of magnetic screens may require attention in order to avoid saturation.

Large transformers need a more individual approach than smaller units in order to obtain reliable service when loaded beyond nameplate rating. Therefore a set (or sets) of intended load conditions should be supplied by the user, giving:

- operating conditions, for example the maximum or equivalent load current and its duration or the cyclic duties, a load diagram or a simplified load diagram (initial load current and peak current with its duration);
- the weighted ambient temperature or the mean temperature and its range, corresponding to the operating conditions;
- the acceptable relative rate of loss of life corresponding to the various operating conditions.

Annex D

Calculation of parameters for sinusoidal variation of ambient temperature

Generally the ambient temperature varies over the year and, further, over the day. If the meteorological data accumulated for many years throughout the world are carefully examined, the variation in ambient temperatures is found to change almost in a sinusoidal mode. Therefore, when calculating annual loss of life, ambient temperatures can be taken as having a double-sinusoidal function based on the parameters shown in figure D.1. The maximum *B* should be chosen from the *B* values of every month in the year (generally the maximum *B* is obtainable from the hottest month) and regarded as a constant. Based on this assumption, annual ambient temperatures can be adopted as the double sinusoidal function for the calculation of loss of life.

If it is possible to assume the respective values of θ_{ay}, *A*, *B*, B_m, *DX* and *TX* in a region where the transformer in question is to be installed, then these values can be used. If meteorological data accumulated for many years (for example, those of the British Meteorological Office, London) are available, then these data should be used to determine the values θ_{ay}, *A*, *B*, B_m, and *DX* with the aid of the program shown in figure D.2. If the value *TX* is then specified, the ambient temperature in that region for every calendar day throughout the year can be set as a double sinusoidal function. An example of sinusoidal parameters calculation is given in table D.1.

A simplified procedure for the calculation of the values *A* and *B* can be used by considering that with ascending temperature the ageing increases exponentially and therefore it is only the temperature in the hottest month that is significant. The procedure is as follows:

Calculate the daily average temperature of the hottest month:

$$\theta_{ad(h)} = \frac{1}{2}\,(\theta_{adm(h)} + \theta_{adn(h)})$$

Calculate the yearly average temperature:

$$\theta_{ay} = \frac{1}{24}\sum_{j=1}^{12}(\theta_{adm(j)} + \theta_{adn(j)})$$

Calculate *A*, *B* and B_m as follows:

$$A = \theta_{ad(h)} - \theta_{ay}$$

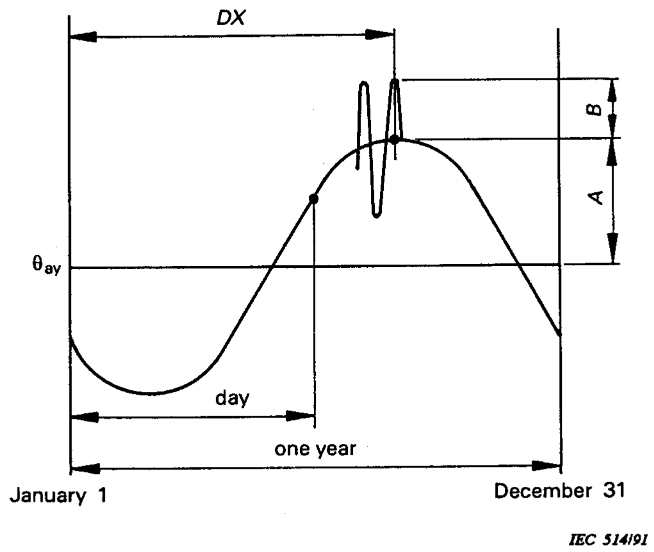
$$B = \theta_{adm(h)} - \theta_{ad(h)}$$

$$B_m = \theta_{ahm(h)} - \theta_{ad(h)}$$

An example of this simplified calculation is given in table D.2.

θ_{ad} is the daily average ambient temperature in degrees Celsius.

The other symbols have the meanings given in 2.7.5.



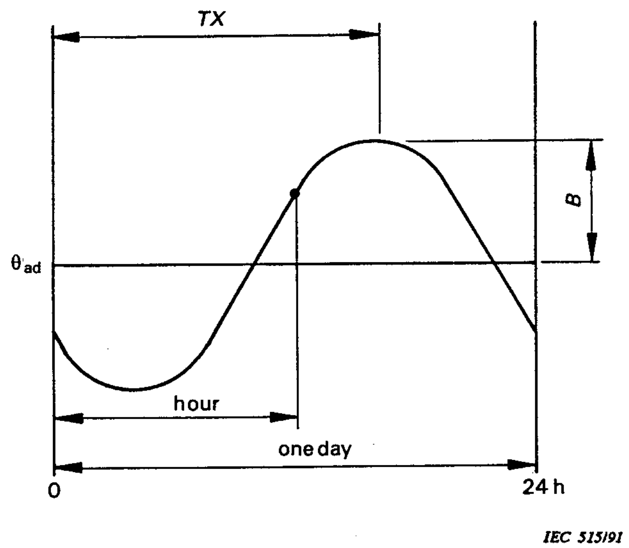
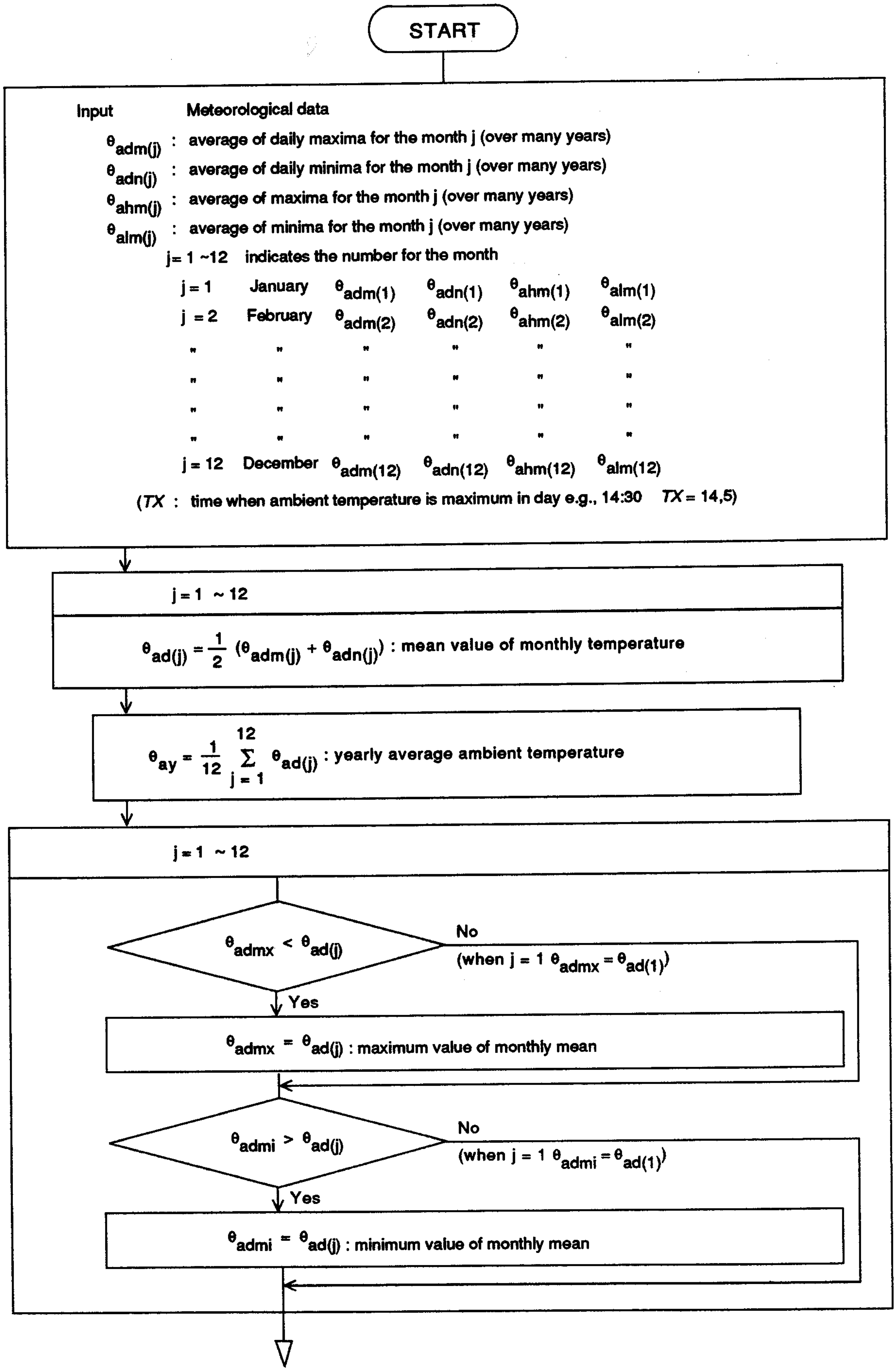
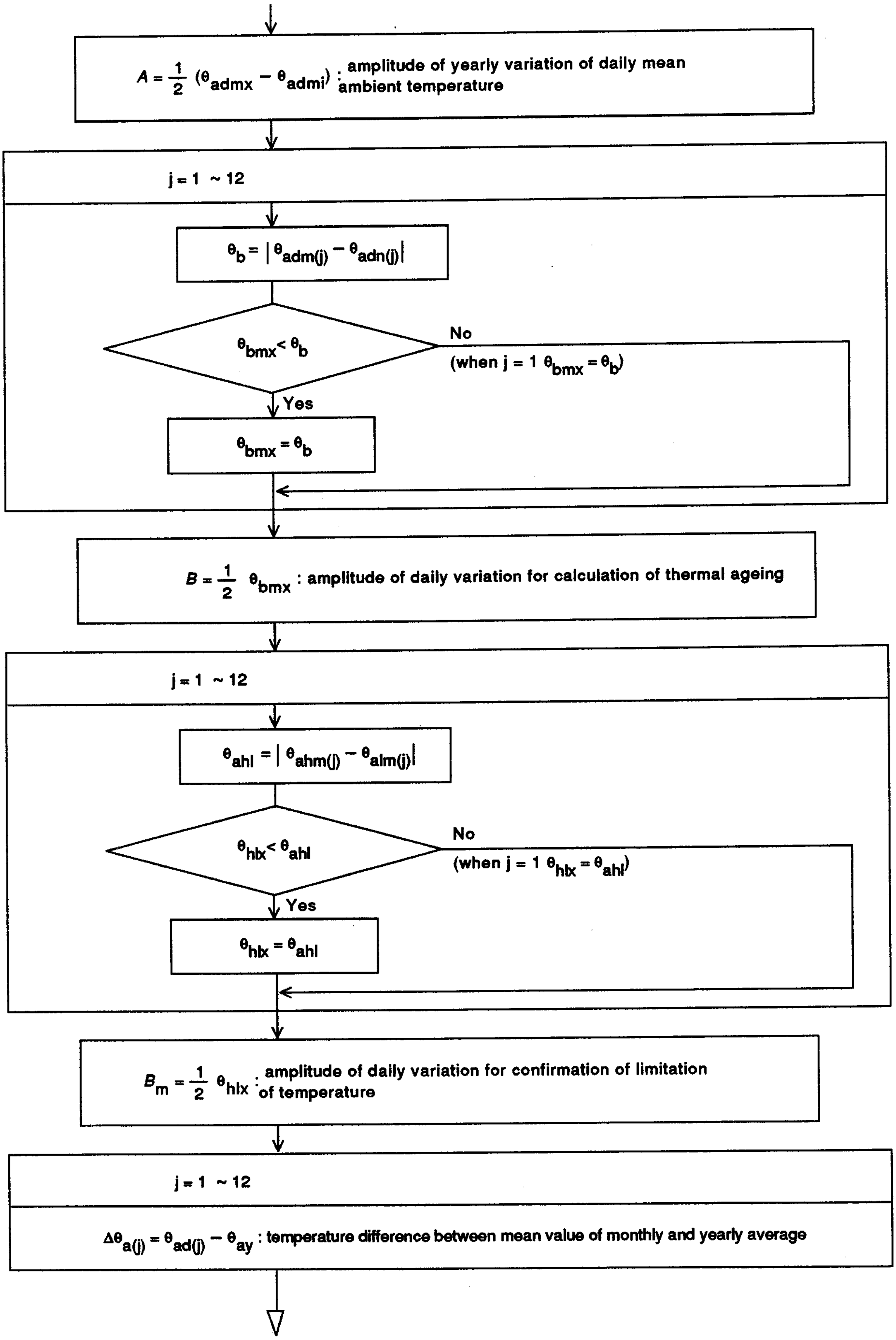


Figure D.1 – Definition of the parameters for sinusoidal variation of ambient temperature


START
Input Meteorological data
$\theta_{adm(j)}$: average of daily maxima for the month j (over many years)
$\theta_{adn(j)}$: average of daily minima for the month j (over many years)
$\theta_{ahm(j)}$: average of maxima for the month j (over many years)
$\theta_{alm(j)}$: average of minima for the month j (over many years)
j= 1 ~12 indicates the number for the month
j = 1 January $\theta_{adm(1)}$ $\theta_{adn(1)}$ $\theta_{ahm(1)}$ $\theta_{alm(1)}$
j = 2 February $\theta_{adm(2)}$ $\theta_{adn(2)}$ $\theta_{ahm(2)}$ $\theta_{alm(2)}$
" " " " " "
" " " " " "
" " " " " "
" " " " " "
j = 12 December $\theta_{adm(12)}$ $\theta_{adn(12)}$ $\theta_{ahm(12)}$ $\theta_{alm(12)}$
(*TX* : time when ambient temperature is maximum in day e.g., 14:30 *TX* = 14,5)
j = 1 ~ 12
$\theta_{ad(j)} = \frac{1}{2} (\theta_{adm(j)} + \theta_{adn(j)})$: mean value of monthly temperature
$\theta_{ay} = \frac{1}{12} \sum_{j=1}^{12} \theta_{ad(j)}$: yearly average ambient temperature
j = 1 ~ 12
$\theta_{admx} < \theta_{ad(j)}$
No
(when j = 1 $\theta_{admx} = \theta_{ad(1)}$)
Yes
$\theta_{admx} = \theta_{ad(j)}$: maximum value of monthly mean
$\theta_{admi} > \theta_{ad(j)}$
No
(when j = 1 $\theta_{admi} = \theta_{ad(1)}$)
Yes
$\theta_{admi} = \theta_{ad(j)}$: minimum value of monthly mean


$A = \frac{1}{2}(\theta_{admx} - \theta_{admi})$: amplitude of yearly variation of daily mean ambient temperature
j = 1 ~ 12
$\theta_b = |\theta_{adm(j)} - \theta_{adn(j)}|$
$\theta_{bmx} < \theta_b$
No
(when j = 1 $\theta_{bmx} = \theta_b$)
Yes
$\theta_{bmx} = \theta_b$
$B = \frac{1}{2}\theta_{bmx}$: amplitude of daily variation for calculation of thermal ageing
j = 1 ~ 12
$\theta_{ahl} = |\theta_{ahm(j)} - \theta_{alm(j)}|$
$\theta_{hlx} < \theta_{ahl}$
No
(when j = 1 $\theta_{hlx} = \theta_{ahl}$)
Yes
$\theta_{hlx} = \theta_{ahl}$
$B_m = \frac{1}{2}\theta_{hlx}$: amplitude of daily variation for confirmation of limitation of temperature
j = 1 ~ 12
$\Delta\theta_{a(j)} = \theta_{ad(j)} - \theta_{ay}$: temperature difference between mean value of monthly and yearly average

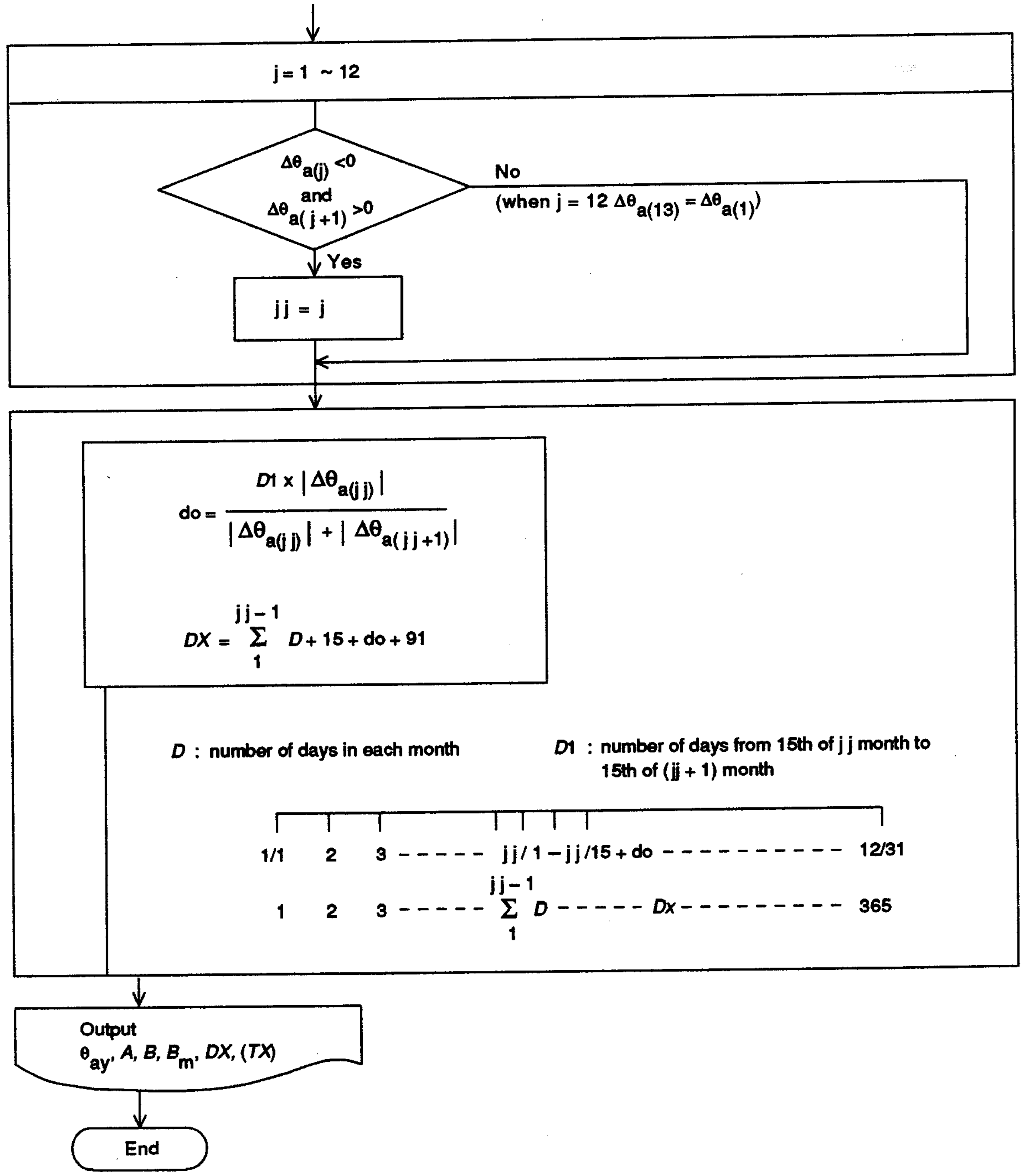


Figure D.2 – Logic diagram of a computer program for the calculation of parameters for sinusoidal variation of ambient temperature

Table D.1 – Data relating to calculation for sinusoidal parameters

*** Input data *** Meteorological data

month	θ_{adm}	θ_{adn}	θ_{ahm}	θ_{alm}
1	6,00	0,90	13,30	–5,80
2	7,40	1,30	15,10	–5,20
3	12,20	3,60	20,50	–1,40
4	15,80	6,30	24,30	1,40
5	19,70	9,50	27,40	4,50
6	22,90	12,70	31,10	8,20
7	24,60	14,50	33,20	10,60
8	24,00	14,30	31,10	9,60
9	21,10	11,90	28,60	7,10
10	15,60	7,90	23,90	1,40
11	10,00	4,50	16,50	–1,70
12	6,60	2,00	13,30	–3,80

TX (time when ambient temperature is maximum on day) = 14:00

*** Output data ***

θ_{ay}	: yearly average ambient temperature [°C]	11,47
A	: ambient yearly variation	8,05
B	: ambient daily variation for calculating life	5,10
B_m	: ambient daily variation for temperature limit	11,45
DX	: the day when [daily average] = [$\theta_{ay} + A$]	199,00

Table D.2 – Simplified calculation for sinusoidal parameters

Meteorological data: same as table D.1

Hottest month of the year: month 7

$$\theta_{ad(h)} = \frac{1}{2}\ (24{,}60 + 14{,}50) = 19{,}55\ °C$$

$$\theta_{ay} = \frac{1}{24} \sum_{j=1}^{12} (\theta_{adm(j)} + \theta_{adn(j)}) = 11{,}47\ °C$$

$$A = 19{,}55 - 11{,}47 = 8{,}08\ °C$$
$$B = 24{,}60 - 19{,}55 = 5{,}05\ °C$$
$$B_m = 33{,}20 - 19{,}55 = 13{,}65\ °C$$

Annex E

Example of simplified application of the guide

From the information given in this guide, the user can calculate loading capacity for a specific transformer or a group of transformers having similar characteristics. From these calculations, a simplified loading instruction can be issued to the network operator provided that the utility staff have agreed on a certain number of criteria.

For instance, assume that a utility has a number of ONAN power transformers with thermal characteristics similar to those stated in table 2 and that it has been agreed to accept a hot-spot temperature of 120 °C for base load emergency conditions and 140 °C under a short duration additional loading. If the ageing concern is disregarded, the instructions to the network operator can be issued in the form of two simple charts and notes as shown in figure E.1.

In figure E.1a, a curve shows the permissible continuous loading in emergency conditions (in percent of the rated current) as a function of ambient temperature. A second curve shows the permissible top-oil temperature for the corresponding loading condition.

In figure E.1b, the curves show the additional loading capacity permissible during the peak-load period as a function of the peak-load duration. This additional loading capacity is given in percent of the above mentioned continuous loading in regard to the permissible continuous loading given in figure E.1a. The curves shown in figure E.1b are only slightly sensitive to ambient temperature; in this case they have been calculated for an ambient temperature of 20 °C.

For new transformers, the manufacturer could be asked to provide sufficient information so that these curves could be submitted with the tender. Information could also be requested about the loading capacity on the extreme tappings.

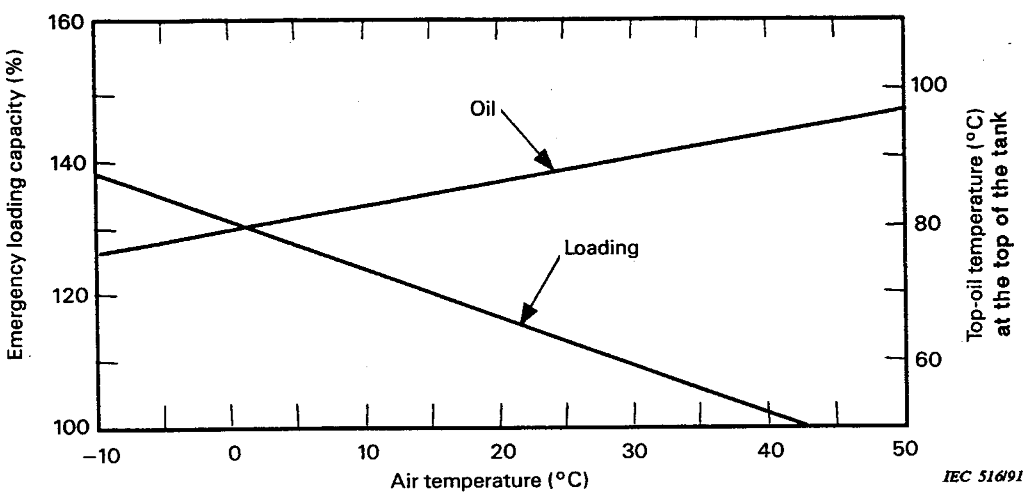


Figure E.1a – Emergency loading capacity on the principal tapping in steady-state condition in per cent of rated current, and permissible top-oil temperature at the loading in question

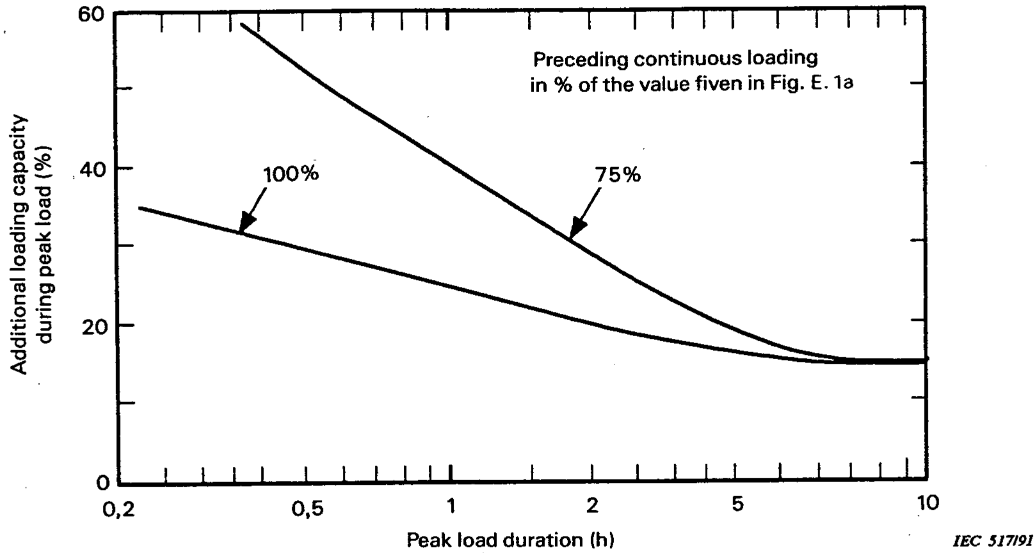


Figure E.1b – Additional short-time loading capacity in percent of the loading capacity in steady-state condition according to figure E.1a

NOTES

1 The loading must be limited to 1,5 times the rated current irrespective of figures E.1a and E.1b.

2 Operation of the tap-changer to be blocked at currents above 200 A. The tap-changer does not tolerate a higher loading than 250 A even when blocked.

3 Figure E.1a is based on a winding hot-spot temperature of +120 °C and figure E.1b on that of +140 °C.

4 The curves in figure E.1b are calculated for a cooling air temperature of +20 °C, but they are sufficiently accurate within the range of –10 °C to +50 °C.

5 The loading capacity on tapping 1 (126,5 kV) is 102 % and on tapping 19 (93,5 kV) 98 % of the corresponding loading capacity on the principal tapping 10 (110 kV).

6 The curves are derived from a temperature rise test made on transformer No.123456

EMERGENCY LOADING CAPACITY OF TRANSFORMERS NOS. 123456 AND 123457
(ONAN, 25 MVA, 110 ± 9 x 1,67 %/21 kV, 114 – 131 – 154/687 A)

Figure E.1 – Example of simplified instructions for loading beyond nameplate rating

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