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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 transformers

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International Electrotechnical Commission, 3, rue de Varembe, PO Box 131, CH-1211 Geneva 20, Switzerland
Telephone: +41 22 919 02 11 Telefax: +41 22 919 03 00 E-mail: inmail@iec.ch Web: www.iec.ch



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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 tapplings) 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.

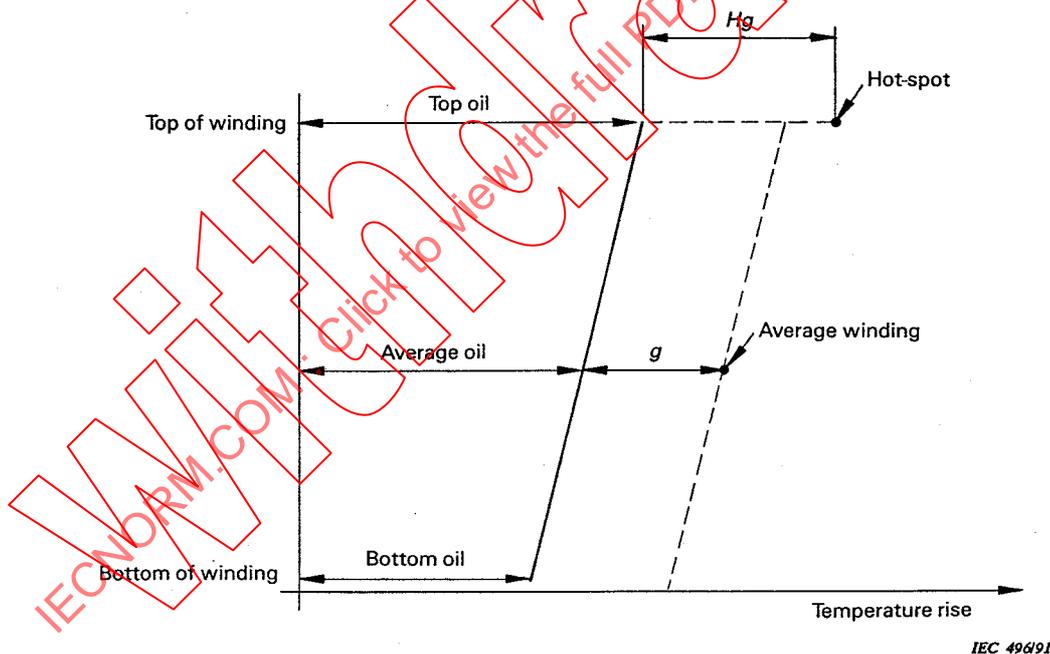


Figure 1 – Thermal diagram

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:

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

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:

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

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:

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

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:

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

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:

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

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:

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

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:

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

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:

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

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 used 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:

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

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.

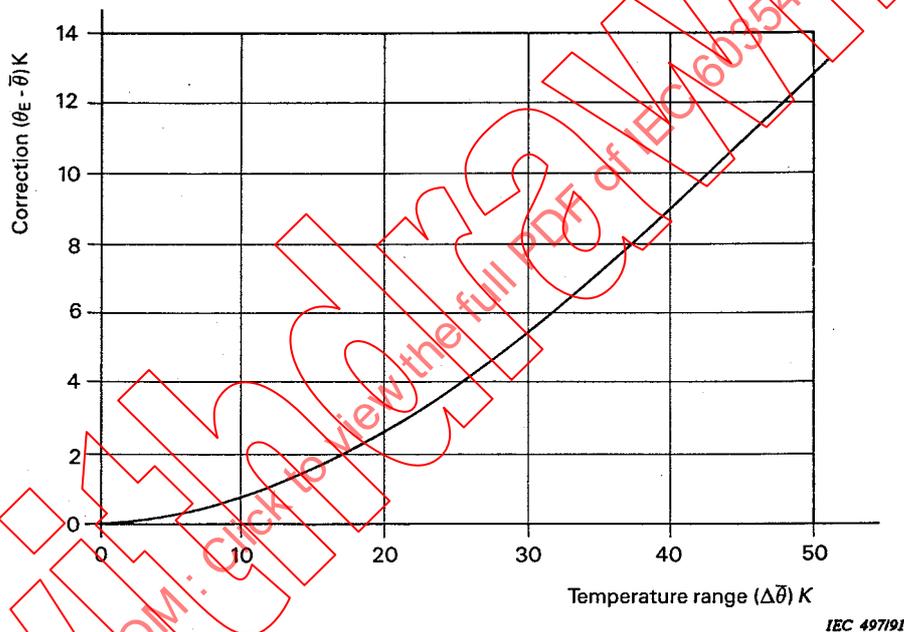


Figure 2 – Correction between weighted and average ambient temperature as a function of the temperature range

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.

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

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	11	12	13	14
	2	12	13	14	16
	3	14	17	19	22
Basements and buildings with poor natural ventilation	1	7	8	9	10
	2	8	9	10	12
	3	10	13	15	17
Buildings with good natural ventilation and underground vaults and basements with forced ventilation	1	3	4	5	6
	2	4	5	6	7
	3	6	9	10	13
Kiosks (see note 2)	1	10	15	20	—
<p>NOTES</p> <p>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.</p> <p>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.</p> <p>3 This table is an excerpt from Australian Standard AS 1078 (1984) "Guide to loading of oil-immersed transformers".</p>					

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, \dots, K_n , with the time intervals t_1, t_2, \dots, 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)

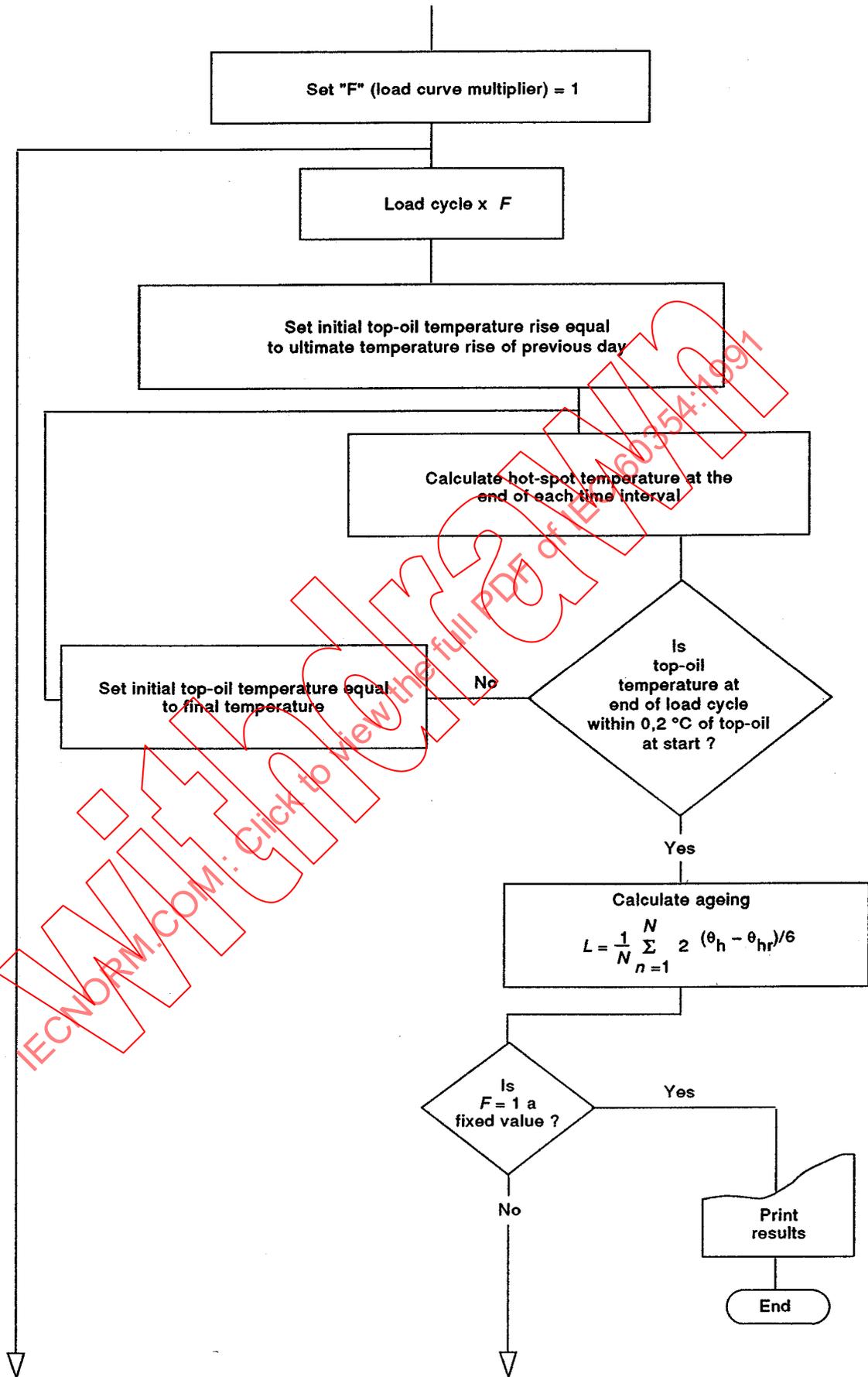
Limitations

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 $F=1$



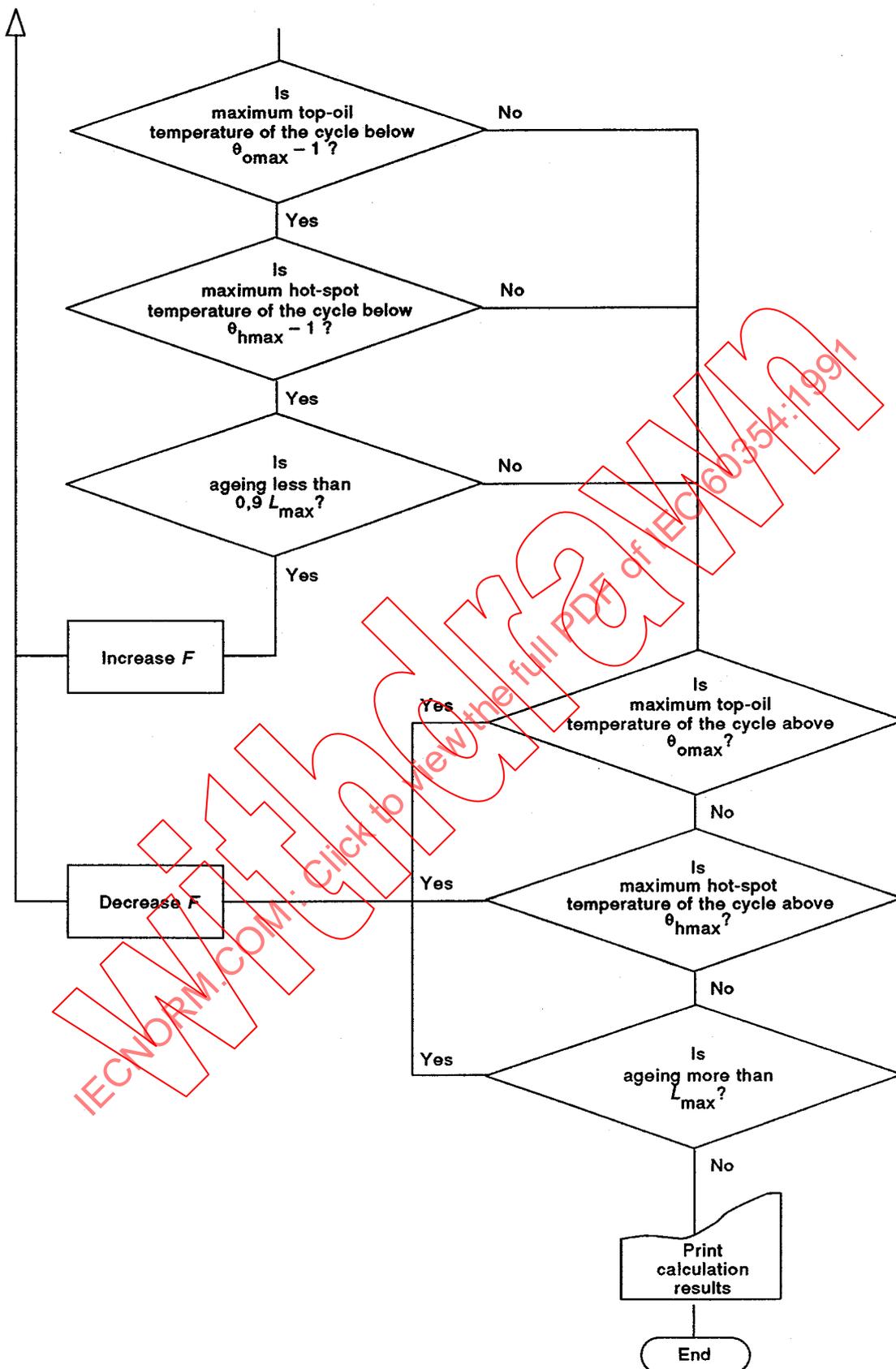


Figure 3 – Logic diagram of a computer program for calculation of an acceptable loading factor

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 start	17/4* end	DURATION [days]: duration [h]	107 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 start	17/10 end	DURATION [days]: duration [h]	183 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 start	31/12 end	DURATION [days]: duration [h]	75 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:

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

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.

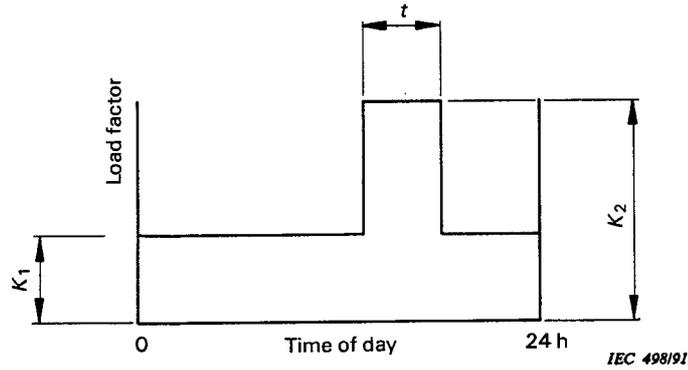


Figure 4 – Equivalent two-step load cycle

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.

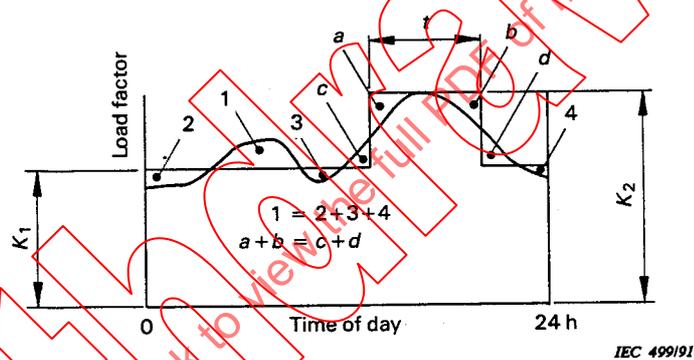


Figure 5 – Load cycle with one peak

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.

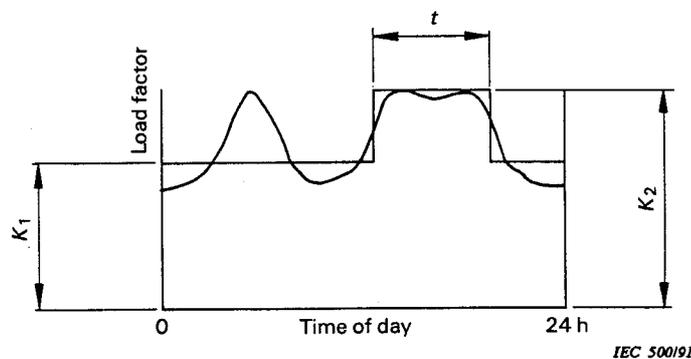


Figure 6 – Load cycle with two peaks of equal amplitude and different duration

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.

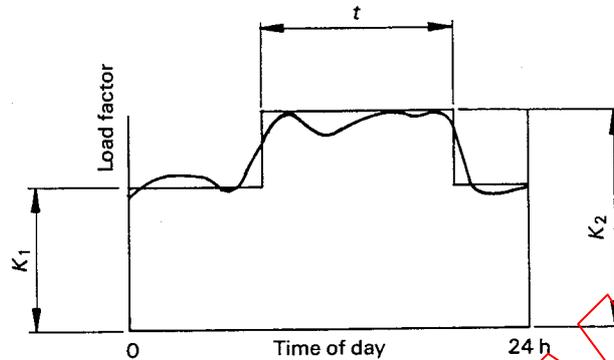


Figure 7 – Load cycle with peaks in close succession

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
		ON	1,33	1,30	1,22	1,15	1,08	1,00	0,92	0,82
	Power transformer	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 permissible load for 2 h at an ambient temperature of 20 °C, assuming constant voltage:

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

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

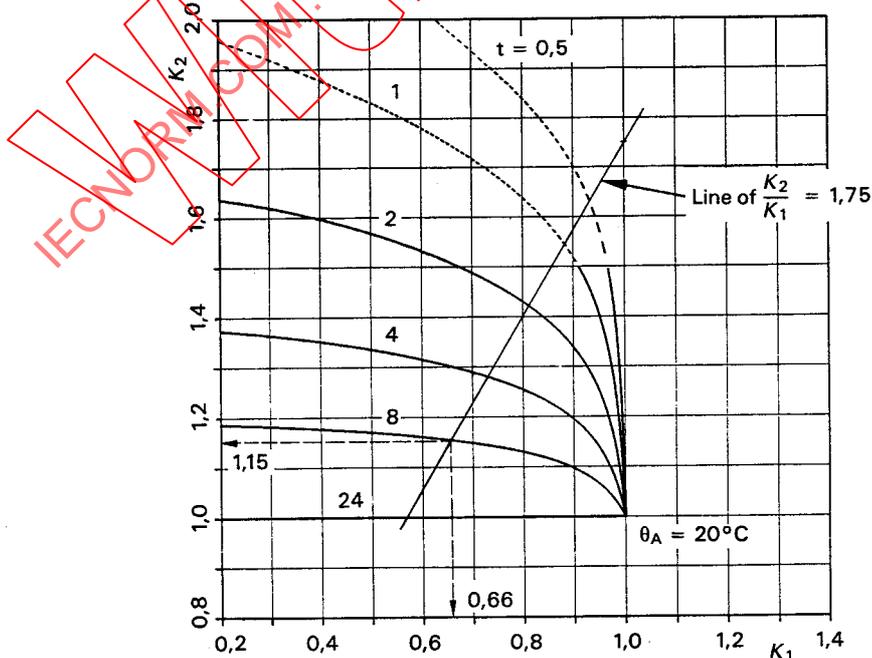
Therefore, the permissible load for 2 h is 3 MVA (then returning to 1 MVA).

Example 2: With $\theta_a = 20 \text{ °C}$, 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:

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



IEC 502/91

Figure 8 – Illustration of example 2

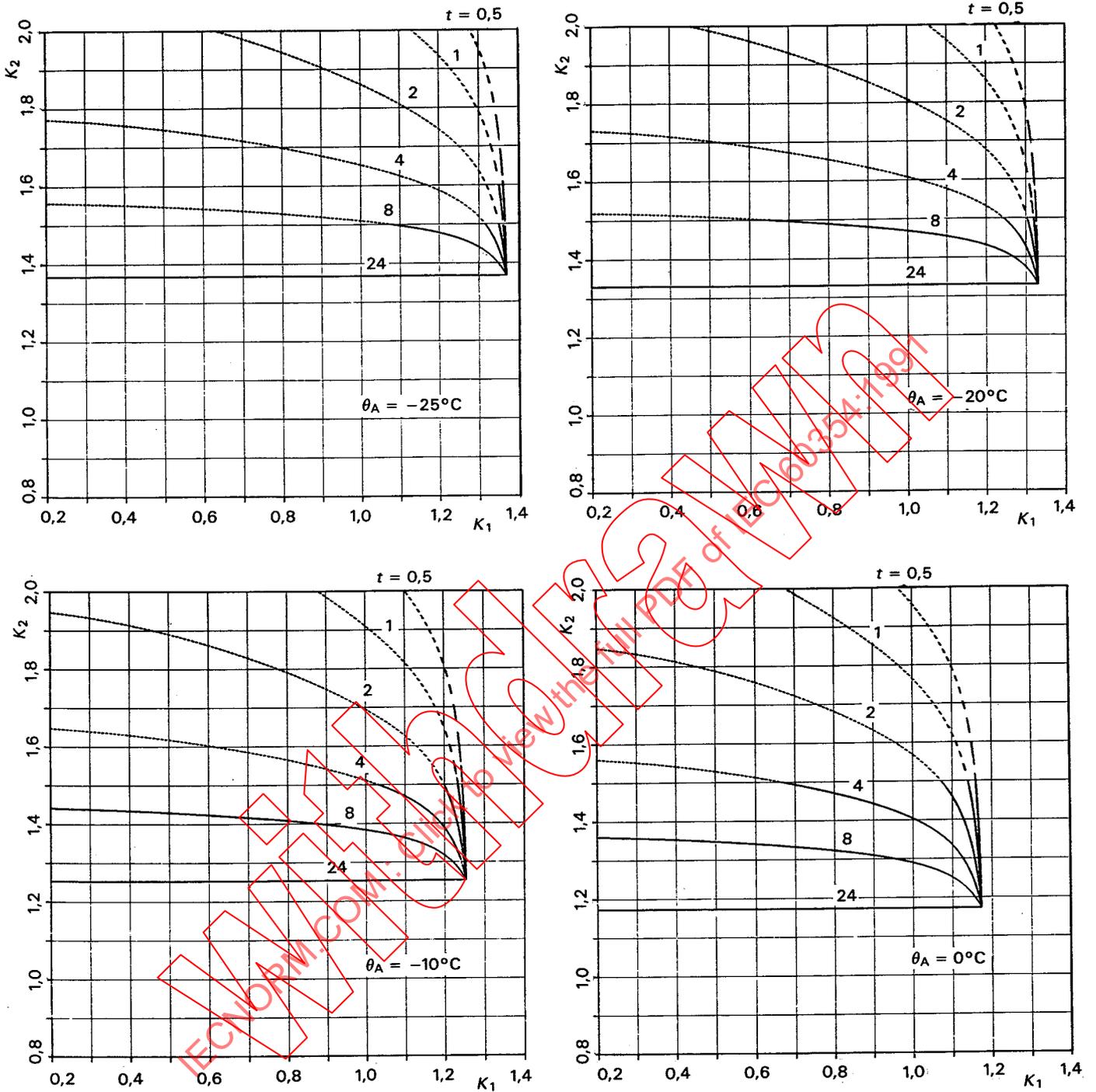
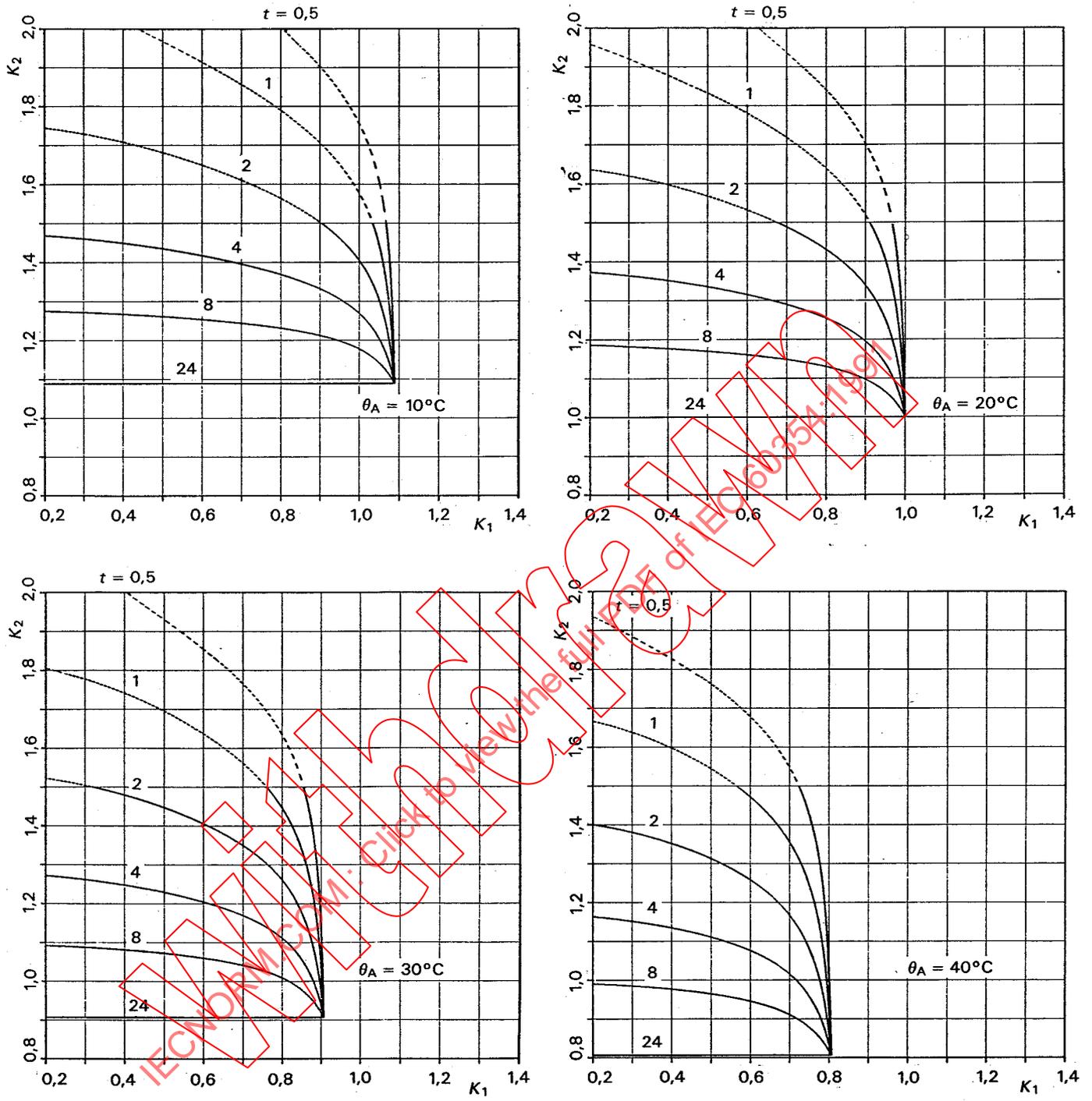


Figure 9

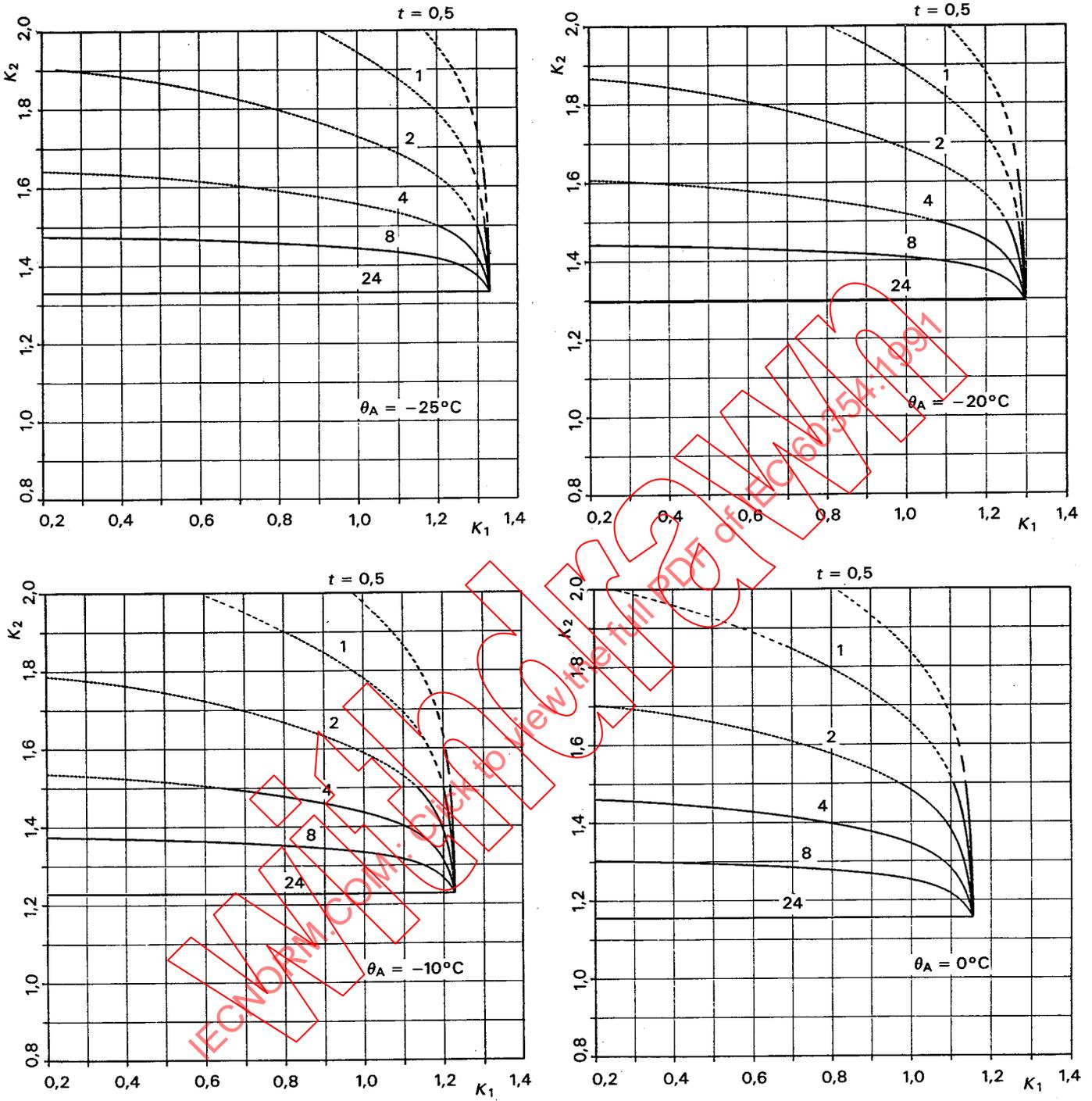
ONAN distribution transformers –
Permissible duties for normal loss of life



CEI-IEC 504191

Figure 9

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



CEI-IEC 505191

Figure 10

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

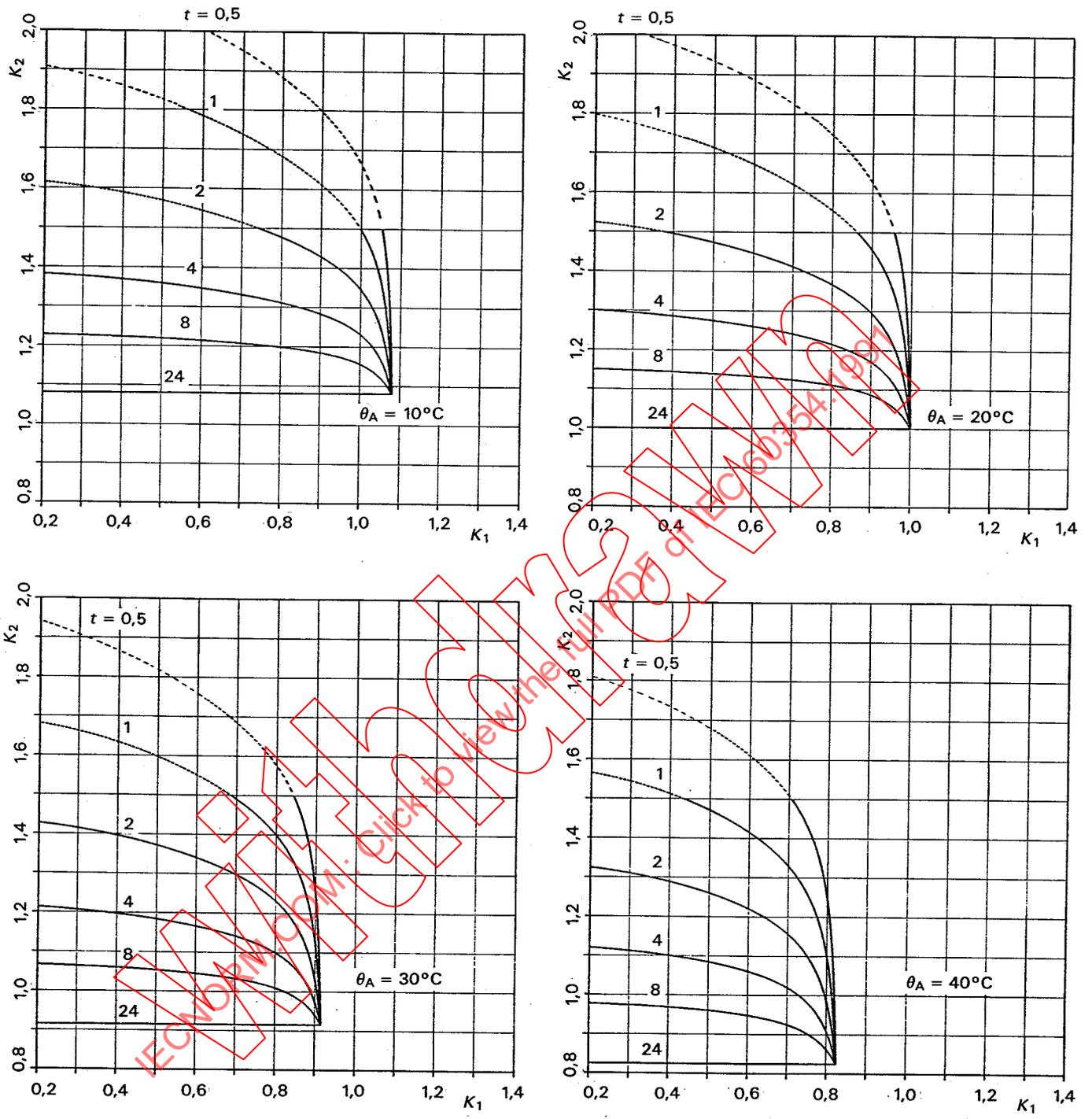


Figure 10

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

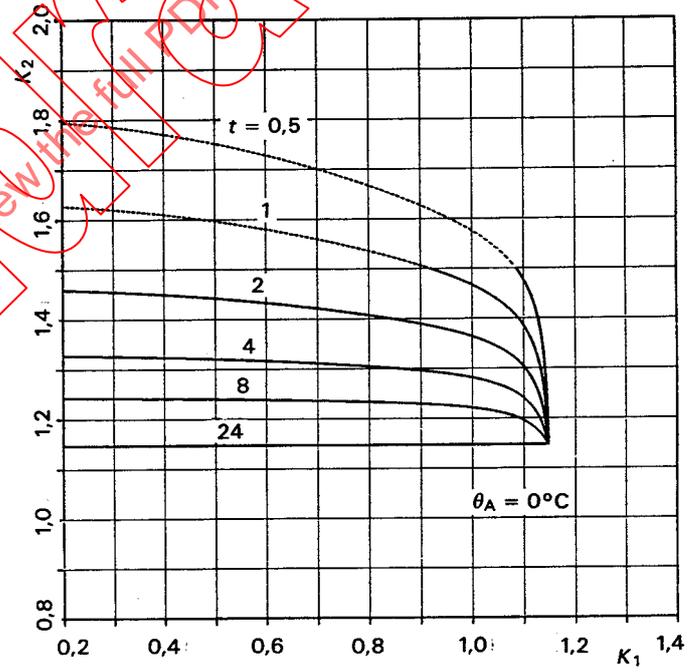
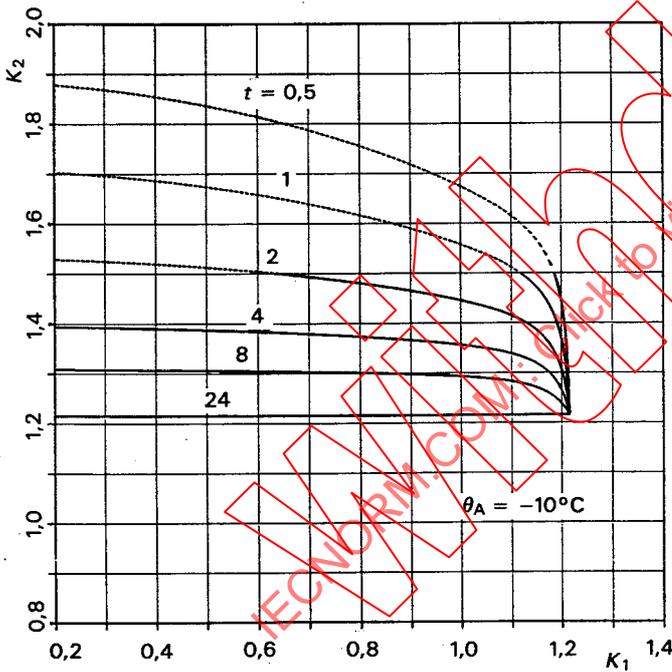
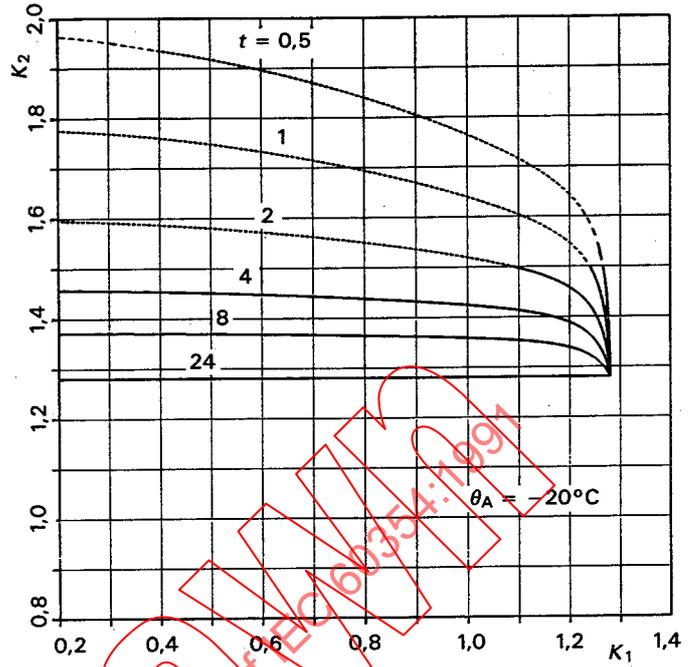
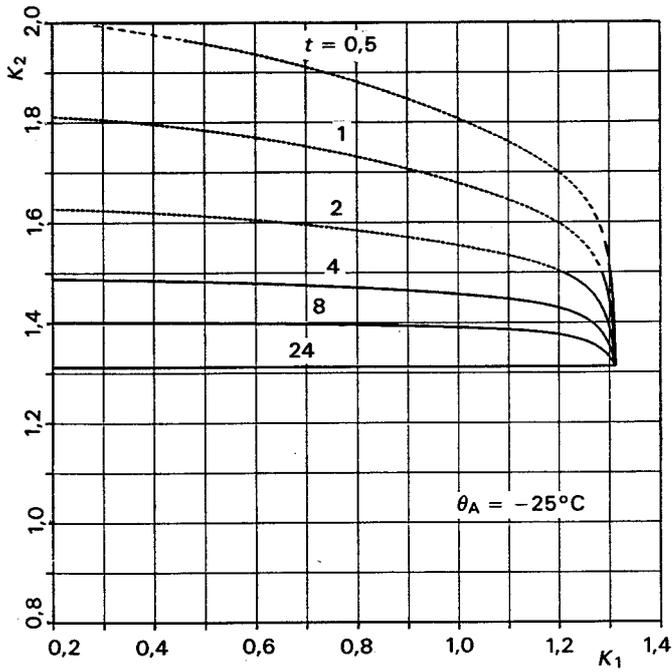


Figure 11

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

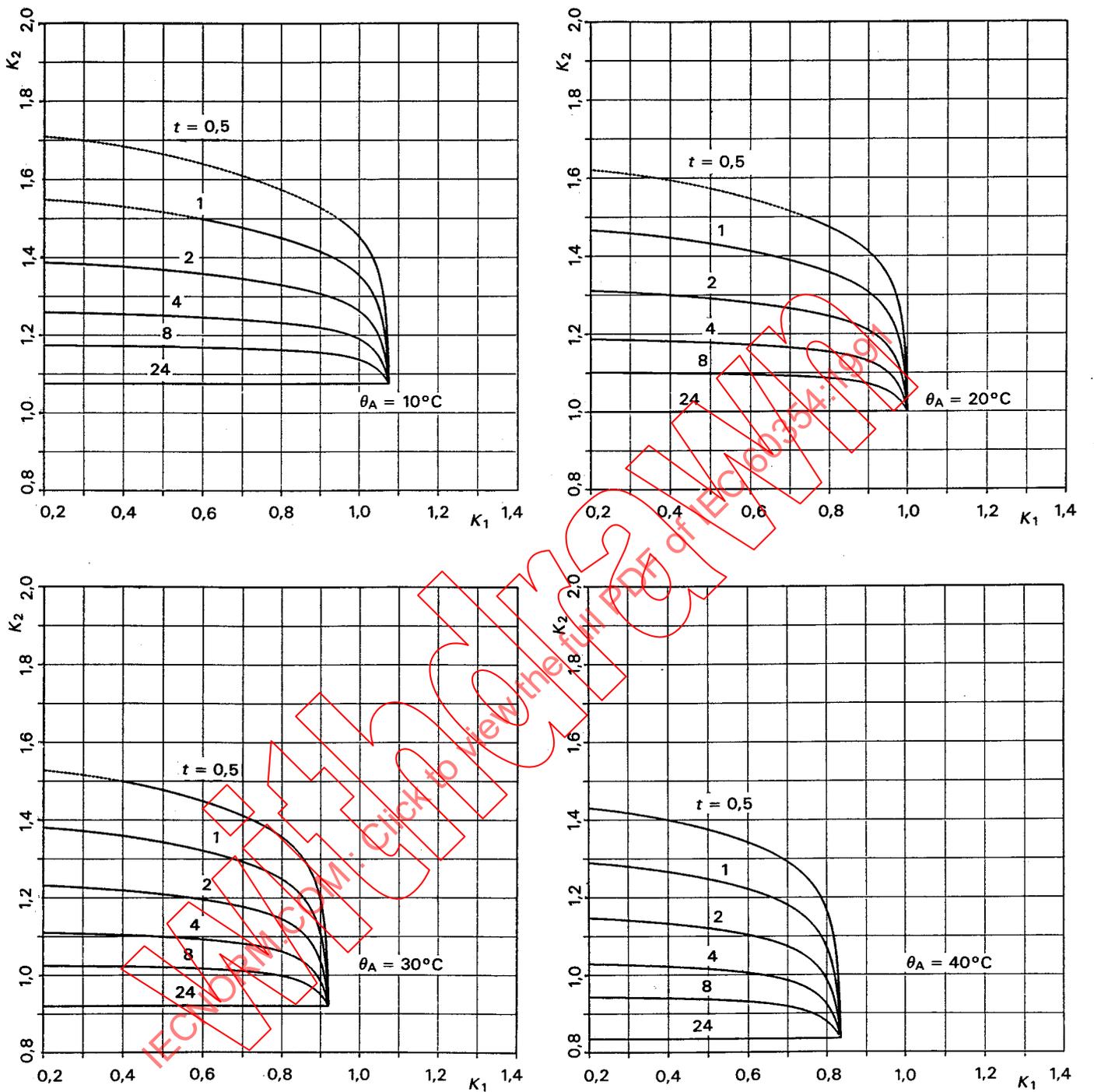
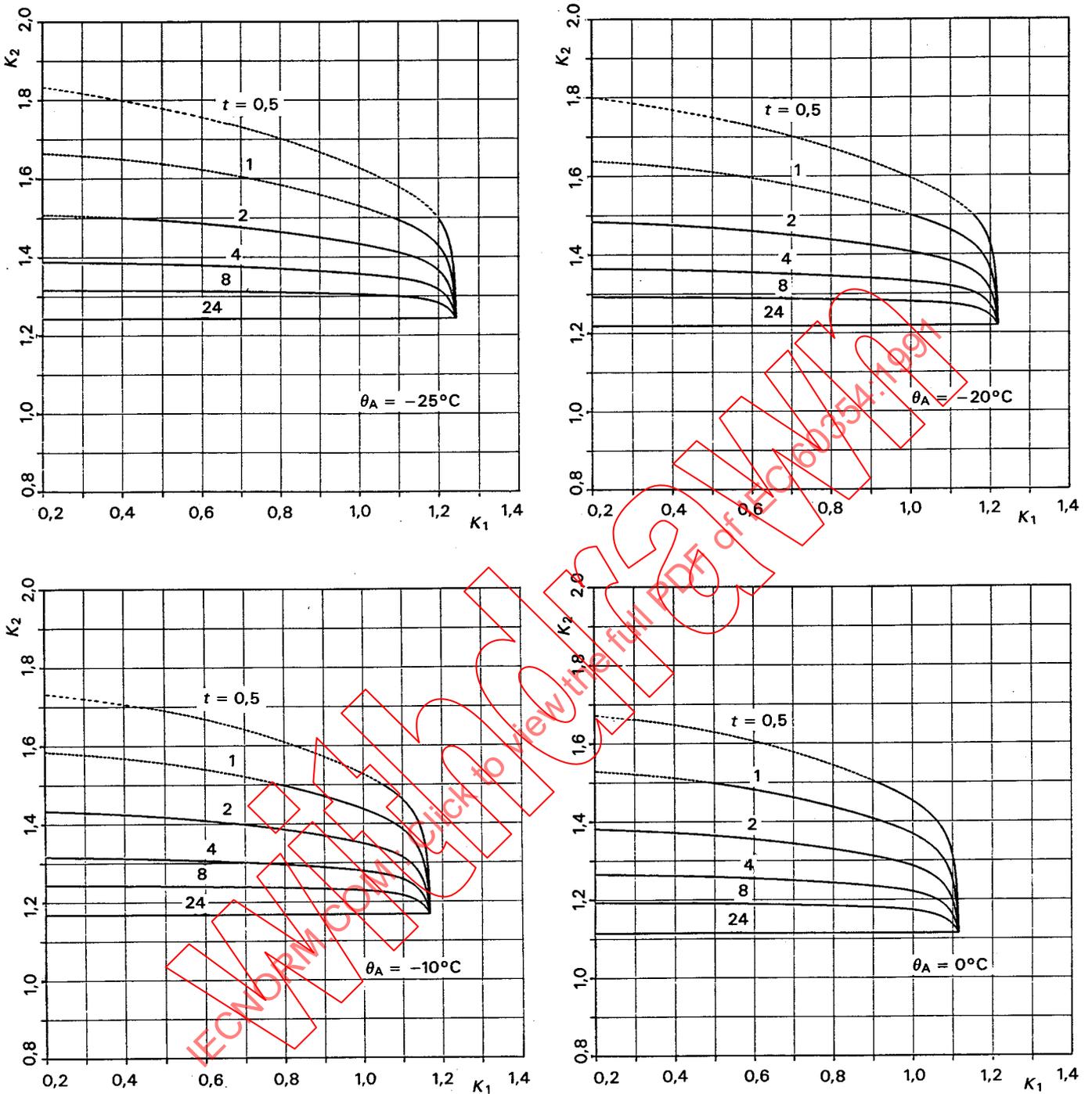


Figure 11

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



CEI-IEC 509191

Figure 12

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

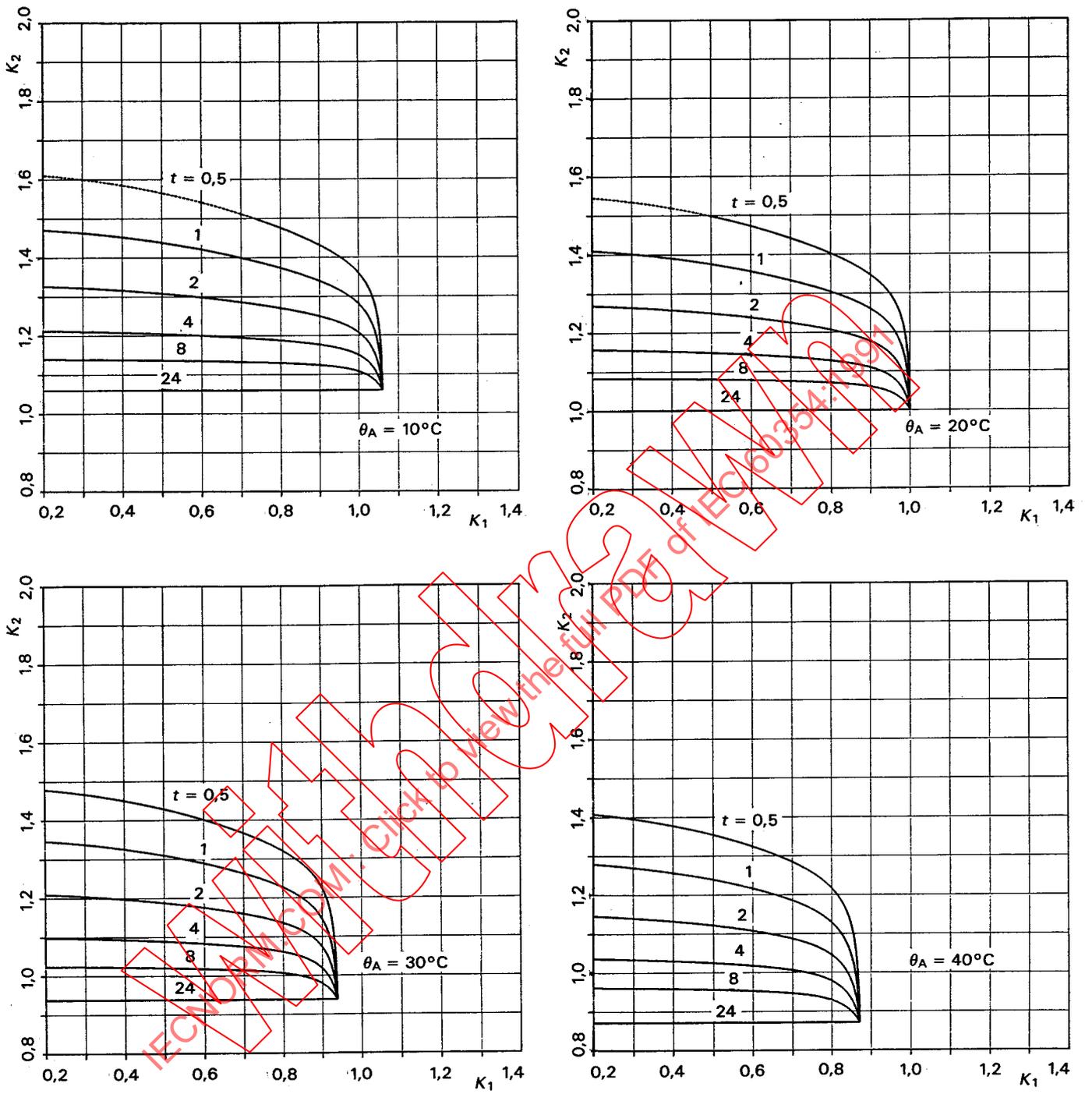


Figure 12

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:

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

$$\theta_h = 121 + 30 = 151 \text{ °C}$$

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

$K_2 \backslash K_1$	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 57						
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	0,116 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 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	0,012	0,032								
		47	48	48								
0,8		0,016	0,023	0,049	0,093							
		56	56	57	57							
0,9		0,040	0,054	0,092	0,148	0,292						
		65	66	66	67	67						
1,0		0,114	0,144	0,212	0,295	0,485	1,00					
		75	76	77	77	78	78					
1,1		0,356	0,436	0,584	0,735	1,03	1,73	3,72				
		86	87	87	88	88	89	89				
1,2		1,22	1,46	1,85	2,20	2,78	3,92	6,68	14,9			
		98	98	99	99	100	100	101	101			
1,3		4,53	5,33	6,57	7,55	9,01	11,4	16,2	27,9	64,7		
		110	110	111	111	112	112	113	114	114		
1,4		18,1	21,1	25,5	28,8	33,3	39,9	50,7	71,9	126	302	
		122	123	124	124	125	125	126	126	127	127	
1,5		78,1	90,0	107	120	136	158	190	242	345	609	1 510
		136	136	137	137	138	138	139	140	140	141	141
1,6		360	412	486	538	604	690	807	974	1 240	1 770	3 160
		150	150	151	151	152	152	153	153	154	155	155
1,7		1 770	2 020	2 360	2 600	2 890	3 270	3 760	4 410	5 350	6 840	9 770
		164	165	165	166	166	167	167	168	168	169	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 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	0,006	0,024								
		42	44	46								
0,8		0,004	0,009	0,030	0,074							
		50	52	54	55							
0,9		0,010	0,018	0,045	0,097	0,258						
		60	61	64	65	66						
1,0		0,027	0,042	0,085	0,154	0,347	1,00					
		70	72	74	75	76	78					
1,1		0,082	0,118	0,205	0,316	0,585	1,39	4,30				
		81	83	85	86	87	89	91				
1,2		0,277	0,386	0,608	0,844	1,32	2,48	6,15	20,5			
		93	94	96	98	99	101	102	104			
1,3		1,04	1,41	2,11	2,76	3,88	6,12	11,7	30,2	108		
		105	107	109	110	112	113	115	117	119		
1,4		4,26	5,70	8,27	10,5	14,0	19,9	31,7	61,6	164	631	
		118	120	122	123	125	126	128	130	132	134	
1,5		19,1	25,3	36,0	44,9	58,2	78,7	113	182	358	987	4 040
		132	134	136	137	139	140	142	144	146	148	150
1,6		93,7	123	172	213	271	356	490	715	1 160	2 300	6 530
		147	148	151	152	153	155	156	158	160	162	164
1,7		499	649	901	1 100	1 390	1 800	2 410	3 360	4 980	8 140	+
		162	164	166	167	168	170	172	174	175	178	180
1,8		2 880	3 730	5 130	6 240	7 790	+	+	+	+	+	+
		178	180	182	183	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 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.								

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

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

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

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

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

U_1 = high voltage (principal tapping)

U_2 = low voltage (principal tapping)

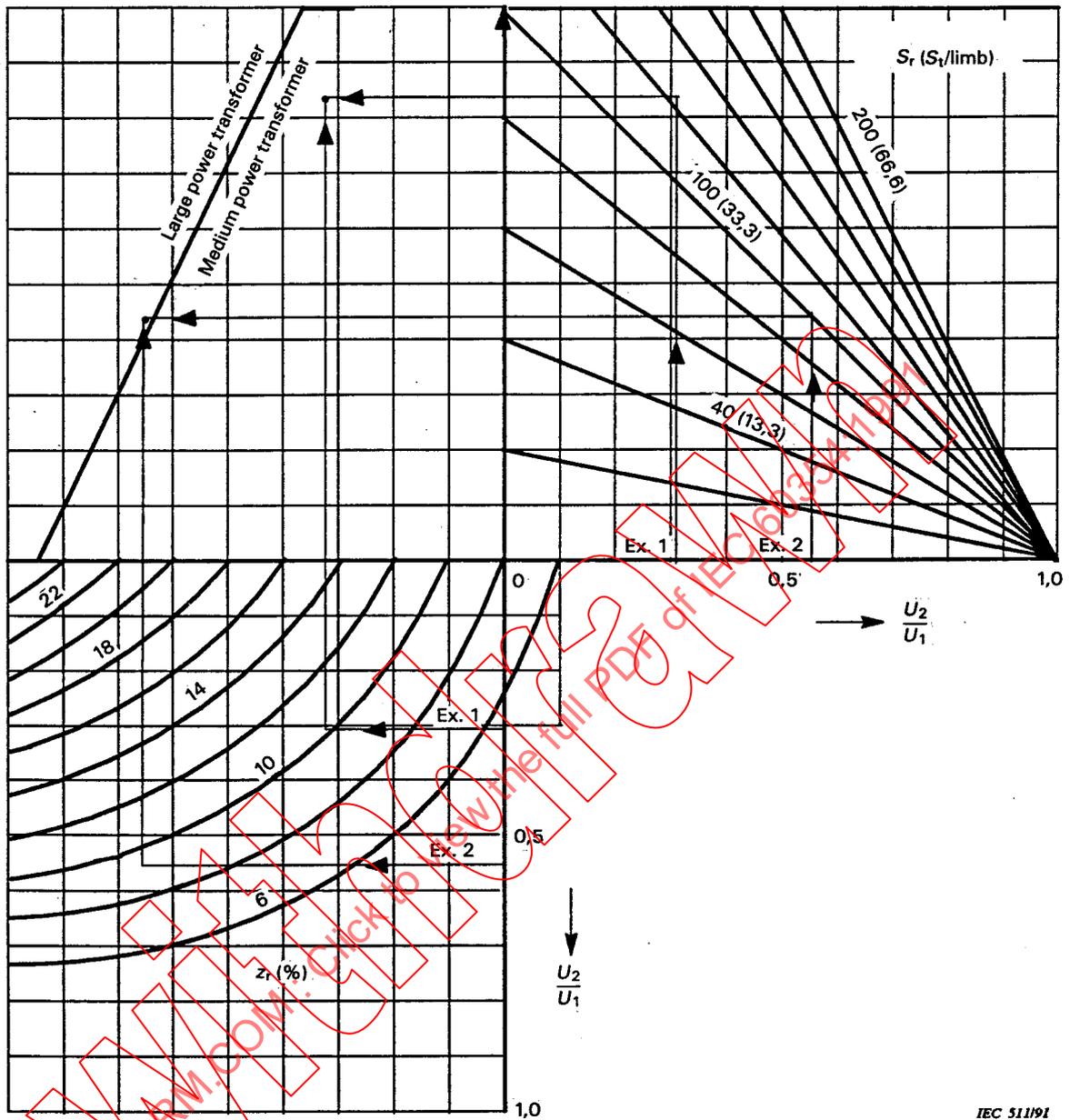
S_r = rated power (MVA)

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



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Examples for three-phase auto-transformers:

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

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

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