

Guide to

Loading of oil-immersed power transformers

Committees responsible for this British Standard

The preparation of this British Standard was entrusted by the Power Electrical Engineering Standards Policy Committee (PEL/-) to Technical Committee PEL/113 upon which the following bodies were represented:

- Association of Consulting Engineers
- BEAMA Ltd. (Transmission and Distribution Association)
- British Cable Makers' Confederation
- British Railways Board
- Electricity Association
- Institution of Plant Engineers
- Transmission and Distribution Association (BEAMA Ltd.)

This British Standard, having been prepared under the direction of the Power Electrical Engineering Standards Policy Committee, was published under the authority of the Standards Board and comes into effect on 15 March 1994

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The following BSI references relate to the work on this standard:
Committee reference PEL/113
Draft for comment 87/20356 DC

ISBN 0 580 22842 8

Amendments issued since publication

Amd. No.	Date	Comments

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National foreword

This British Standard has been prepared under the direction of the Power Electrical Engineering Standards Policy Committee and is identical with IEC 354:1989 *Loading guide for oil immersed power transformers* incorporating corrigendum, March 1992, published by the International Electrotechnical Commission (IEC).

The changes incorporated by the corrigendum are indicated by a single vertical line in the margin

This British Standard supersedes CP 1010:1975 which is withdrawn.

The graphics signs, symbols and letters used may be found in the following documents.

BS 3939, *Graphic symbols for electrical power, telecommunications and electronics diagrams*.

BS 3939-1:1986, *General information, general index*.

BS 3939-2:1985, *Symbol elements, qualifying symbols and other symbols having general application*.

BS 3939-3:1985, *Conductors and connecting devices*.

Cross-references

Publication referred to	Corresponding British Standard
	BS 171: <i>Power transformers</i>
IEC 76-1	Part 1:1978 <i>General</i> ^a
IEC 76-2	Part 2:1978 <i>Specification for temperature rise requirements</i> ^b
IEC 76-3	Part 3:1987 <i>Specification for insulation levels and dielectric tests</i> ^c
IEC 76-4	Part 4:1978 <i>Specification for tappings and connections</i>
IEC 76-5	Part 5:1978 <i>Specification for ability to withstand short circuit</i>

^a Implements CENELEC HD 398.1.

^b Implements CENELEC HD 398.2.

^c Implements CENELEC HD 398.3.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 70, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

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:

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

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 name plate rating.

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

- a) the temperatures of windings, cleats, leads, insulation and oil increase and can reach unacceptable levels;
- b) the leakage flux density outside the core increases, causing additional eddy-current heating in metallic parts linked by the flux;
- c) the combination of the main flux and increased leakage flux imposes restrictions on possible core overexcitation;
- d) as the temperature changes, the moisture and gas content in the insulation and in the oil will change;
- e) bushings, tap-changers, cable-end connections and current transformers will also be exposed to higher stresses which encroach upon their design and application margins.

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

1.4.1.2 Short-term risks

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

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

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

- b) Temporary deterioration of the mechanical properties at higher temperatures could reduce the short-circuit strength.
- c) Pressure build-up in the bushings may result in a failure due to oil leakage. Gassing in the bushings may also occur if the temperature of the insulation exceeds about 140 °C.
- d) The expansion of the oil could cause overflow of the oil in the conservator.
- e) Breaking of excessively high currents in the tap-changer could be hazardous.

1.4.1.3 Long-term risks

- a) Cumulative thermal deterioration of the mechanical properties of the conductor insulation will accelerate at higher temperatures. If this deterioration proceeds far enough, it may reduce the effective life of the transformer, particularly if the latter is subjected to system short circuits.
- b) Other insulation materials, as well as structural parts and the conductors, could also suffer ageing at higher temperature.
- c) The contact-resistance of the tap-changers could increase at elevated currents and temperatures and, in severe cases, thermal runaway could take place.
- d) The gasket materials in the transformer may become more brittle at elevated temperatures.

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

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

1.4.2 Transformer size

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

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

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

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

- a) distribution transformers, for which only the hot-spot temperature and thermal deterioration have to be considered;
- b) medium power transformers where the effects of leakage flux are known not to be critical; but the variations in the cooling modes must be considered;
- c) large power transformers, where the effects of stray leakage flux are significant and the consequences of failure are severe.

1.4.3 Current and temperature limitations

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

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

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

1.5 Specific limitations for distribution transformers

1.5.1 Rating limitation

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

1.5.2 Current and temperature limitations

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

1.5.3 Accessory and other considerations

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

1.5.4 Indoor transformers

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

1.5.5 Outdoor ambient conditions

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

1.6 Specific limitations for medium power transformers

1.6.1 Rating limitations

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

1.6.2 Current and temperature limitations

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

1.6.3 Accessory, associated equipment and other considerations

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

1.6.4 Short-circuit withstand requirements

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

1.6.5 Voltage limitations

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

1.7 Specific limitations for large power transformers

1.7.1 General

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

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

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

- a) The combination of leakage flux and main flux in the limbs or yokes of the magnetic circuit makes large transformers more vulnerable to overexcitation than smaller transformers, especially when loaded above nameplate rating. Increased leakage flux may also cause additional eddy-current heating of other metallic parts.
- b) The consequences of degradation of the mechanical properties of insulation as a function of temperature and time, including wear due to thermal expansion, may be more severe for large transformers than for smaller ones.
- c) Hot-spot temperatures outside the windings cannot be obtained from a normal temperature-rise test. Even if such a test at rated current indicates no abnormalities, it is not possible to draw any conclusions for higher currents since this extrapolation may not have been taken into account at the design stage.
- d) Calculation of the winding hot-spot temperature rise at higher than rated currents, based on the results of a temperature-rise test at rated current, may be less reliable for large units than for smaller ones.

1.7.2 Current and temperature limitations

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

1.7.3 Accessory, equipment and other considerations

Refer to 1.6.3.

1.7.4 Short-circuit withstand requirements

Refer to 1.6.4.

1.7.5 Voltage limitations

Refer to 1.6.5.

Section 2. Determination of temperatures

2.1 Symbols

2.1.1 Basic symbols

- A is the amplitude of yearly variation of daily mean ambient temperature in kelvins;
 B is the amplitude of daily variation of ambient temperature in kelvins;
 DX is the hottest day of a year;
 H is the hot-spot factor;
 I is the load current in amperes;
 K is the load factor (load current/rated current);
 L is the relative ageing over a certain period of time;
 R is the ratio of load losses at rated current to no-load losses;
 S is the power in MVA;
 TX is the hottest hour of a day;
 V is the relative ageing rate;
 W is the number of wound limbs;
 g is the winding to oil temperature difference in kelvins;
 j is a month of a year (used in ageing and hot-spot calculations over a complete year);
 t is the duration of the peak load in the rectangular load profile in hours;
 z is the short-circuit impedance in per cent;
 θ is the temperature in degrees Celsius;
 τ is the time constant;
 ON indicates either *ONAN* or *ONAF* cooling;
 OF indicates either *OFAF* or *OFWF* cooling;
 OD indicates either *ODAF* or *ODWF* cooling.

2.1.2 Prefixes

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

2.1.3 Exponents

- x is the exponential power of total losses versus oil temperature rise;
 y is the exponential power of current versus winding temperature rise;
 $'$ applies to hot-spot temperature on OD cooling.

2.1.4 Suffixes (general)

- E relates to weighted ambient temperature;
- M relates to ambient temperature for hot-spot calculation;
- W relates to winding;
- a relates to ambient (temperature);
- h relates to hot spot (temperature);
- m relates to factors used to calculate maximum hot-spot temperature;
- o relates to oil;
- r indicates rated quantity (if used, always the last suffix);
- t relates to temperature or temperature rise at time t ;
- y indicates yearly quantity.

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

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

2.2 Direct measurement of hot-spot temperature

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

2.3 Assumed thermal characteristics

2.3.1 Simplifications made

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

- a) the oil temperature inside the windings increases linearly from bottom to top, whatever the cooling mode;
- b) the temperature rise of the conductor at any position up the winding increases linearly, parallel to the oil temperature rise, with a constant difference g between the two straight lines (g being the difference between the average temperature rise by resistance and the average oil temperature rise);
- c) the hot-spot temperature rise is higher than the temperature rise of the conductor at the top of the winding as shown in Figure 1 because allowance has to be made for the increase in stray losses. To take account of these non-linearities, the difference in temperature between the hot-spot and the oil at the top of the winding is made equal to Hg . This H factor may vary from 1,1 to 1,5 depending on transformer size, short-circuit impedance and winding design. For the production of tables and figures in section 3, a value of 1,1 has been used for distribution transformers and 1,3 for medium and large power transformers.

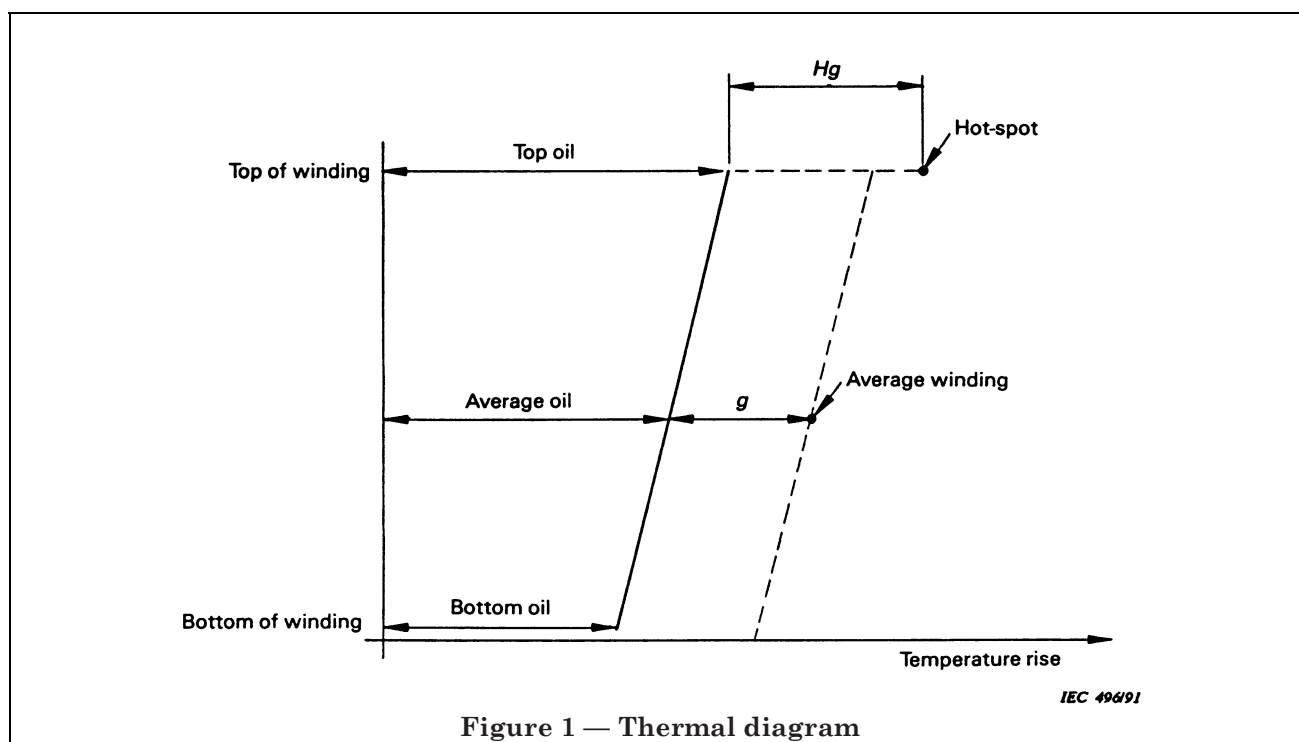


Figure 1 — Thermal diagram

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

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

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

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

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

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

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

- a) results of a special temperature-rise test including direct measurement of the hot-spot temperature or top-oil temperature inside the windings (in the absence of direct hot-spot measurement the hot-spot factor H can only be provided by the manufacturer);
- b) results of a normal temperature rise test;
- c) assumed temperature rises at rated current.

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

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

			Distribution transformers	Medium and large power transformers		
			ONAN	ON..	OF..	OD..
Oil exponent	x		0,8	0,9	1,0	1,0
Winding exponent	y		1,6	1,6	1,6	2,0
Loss ratio	R		5	6	6	6
Hot-spot factor	H		1,1	1,3	1,3	1,3
Oil time constant	τ_o	(h)	3,0	2,5	1,5	1,5
Ambient temperature	θ_a	(°C)	20	20	20	20
Hot-spot rise	$\Delta\theta_{hr}$	(K)	78	78	78	78
Average oil 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-spot-winding oil rise ^a	$\Delta\theta_{ir}$	(K)	55	52	56	49
Bottom-oil rise	$\Delta\theta_{br}$	(K)	33	34	36	43
^a 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:

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

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:

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

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.

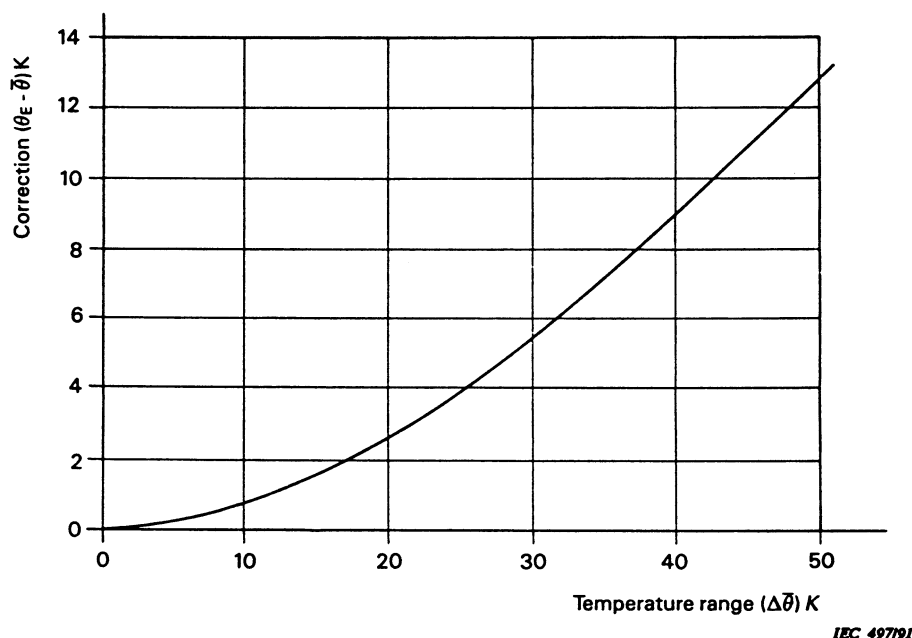


Figure 2 — Correction between weighted and average ambient temperature as a function of the temperature range

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	—

NOTE 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.

NOTE 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.

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

2.8 Computer program

2.8.1 Logic diagram

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

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

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

The maximum hot-spot temperature and relative ageing are calculated with the initial load diagram. If the limit temperature is not exceeded and the ageing is below the accepted value, the calculation is then repeated with a multiplying factor F applied to each discrete load $K_1, K_2, \dots K_n$, 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 Table 4 and Table 5, higher accuracy by reducing these allowances is advisable.

2.8.2 Example of calculation

Examples of calculation are given in Table 4 and Table 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.

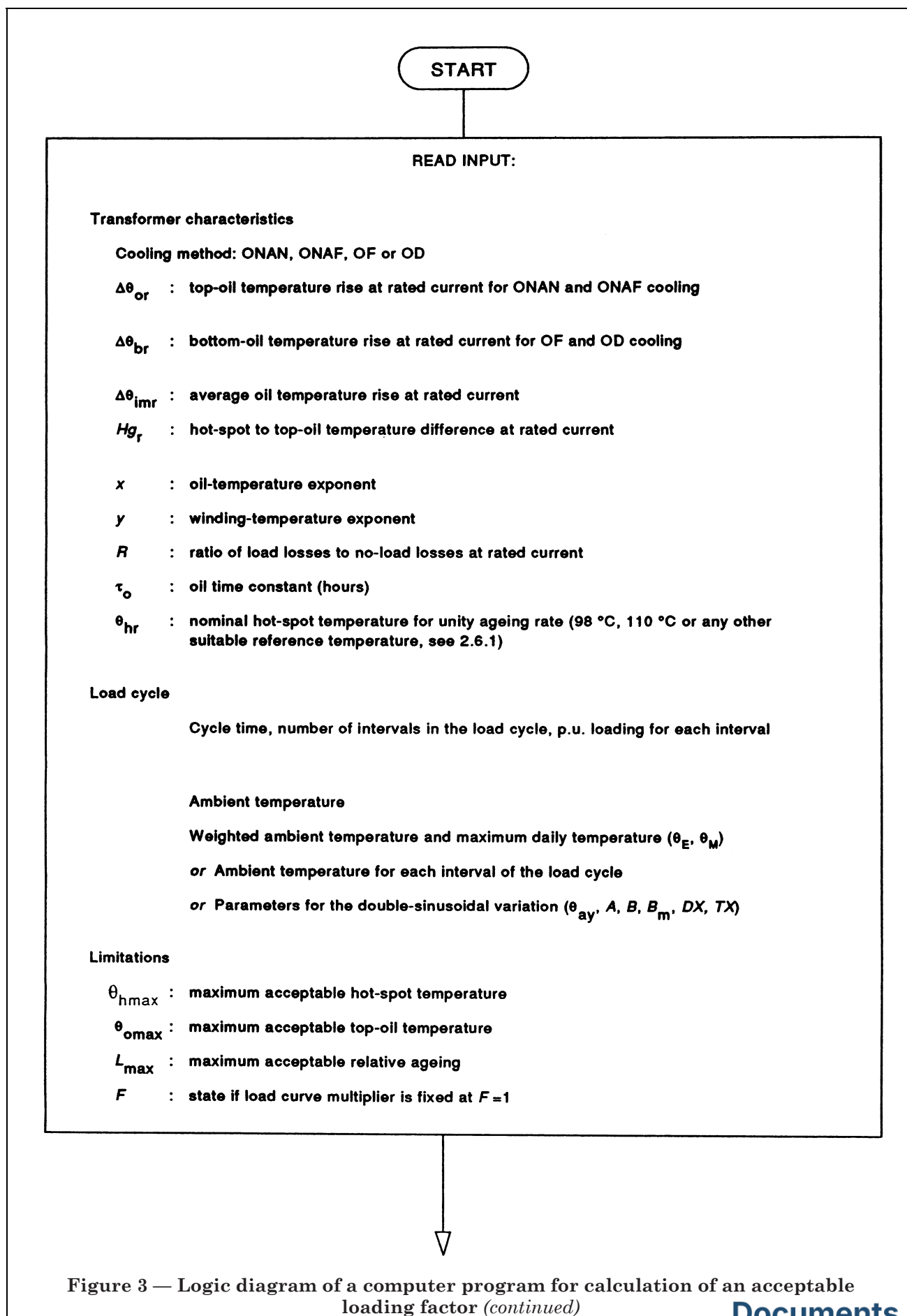


Figure 3 — Logic diagram of a computer program for calculation of an acceptable loading factor (*continued*)

