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GUIDE FOR LOADING OF OIL-IMMERSED TRANSFORMERS

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BUREAU OF INDIAN STANDARDS
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

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Indian Standard
GUIDE FOR LOADING OF OIL-IMMERSED TRANSFORMERS

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Indian Standard
GUIDE FOR LOADING OF OIL-IMMERSED TRANSFORMERS

0. FOREWORD

0.1 This Indian Standard was adopted by the Indian Standards Institution on 28 March 1972, after the draft finalized by the Transformers Sectional Committee had been approved by the Electrotechnical Division Council.

0.2 This guide covers general recommendations for loading of oil-immersed transformers conforming to IS : 2026-1962*.

0.3 In the preparation of this guide considerable assistance has been derived from IEC Document 14 (Central Office) 16 'Loading guide for oil-immersed transformers' issued by the International Electrotechnical Commission.

0.4 While it is not possible to present accurate data for all conditions of use and variations of transformer design, it is the purpose of this guide to enable the user when planning or operating, to determine the range of permissible loads under given conditions.

0.5 Modern transformers are generally designed to permit loading in line with this guide, but if there is any question as to the capability of the transformer, either old or new, to carry the desired load, the manufacturer should be consulted.

0.6 The tables given in this guide have been drawn up in a manner as to be useful to the system planner as well as the operator. Whereas a system planner may be looking for an optimum size of transformer for a given load condition, the load controller or operator may like to know what overloads can be allowed on any day on existing transformers.

0.7 In this guide the values of exponents *x* and *y* have been taken as 0·9 and 0·8 respectively on the basis of IEC document 14 (Central Office) 16 and IEC Publication 76 (1967) 'Power transformers'. These values are different from those given in IS : 2026-1962* which is at present under revision. It is expected that in the revised version of IS : 2026-1962* the values of exponents *x* and *y* will be lined up with those given in IEC Publication 76.

***Specification for power transformers. (Since revised).**

1. SCOPE

1.1 This guide is applicable to oil-immersed transformers of types ON and ON/OB complying with IS : 2026-1962*.

1.1.1 IS : 2026-1962* does not take into consideration either temperatures different from normal or variations in the load (which only exceptionally correspond to uninterrupted continuous operation at rated kVA).

1.2 This guide indicates how oil-immersed transformers may be operated for different ambients and duties without exceeding the acceptable limit of deterioration of insulation through thermal effects.

For very large transformers, for example, 100 MVA and above, the advice of the manufacturer should be followed. (For additional limitations requiring reference to the manufacturers, *see* **3**).

2. TERMINOLOGY

2.0 For the purpose of this guide, the following definitions in addition to those given in IS : 2026-1962* shall apply.

2.1 Hot-Spot Temperature — The maximum temperature that any part of the winding reaches under given load conditions and ambient.

2.2 Weighted Ambient Temperature — The temperature which, if maintained continuously during the period of time under consideration, would result in the same ageing of insulation as that occurring under the actual ambient temperature.

3. APPLICATION

3.1 This guide gives the permissible loading, under certain defined conditions, in terms of the rated kVA of the transformer, for the guidance of users and to help planners in choosing the rated kVA required for new installations. The rated kVA defined in IS : 2026-1962* is a conventional reference basis for uninterrupted continuous operation (with defined limits of cooling medium temperature) with normal expectation of life.

3.2 Basically, the cooling medium temperature is 32°C, but deviations from this are provided for, in such a way that the increased use of life when operating with a cooling medium temperature above 32°C as in summer, is balanced by the reduced use of life when it is below 32°C in winter.

3.3 Experience indicates that normal life is some tens of years. It cannot be stated more precisely, because it may vary even between units, owing in particular to operating factors which may differ from one transformer to another.

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*Specification for power transformers. (Since revised).

3.4 In practice, uninterrupted continuous operation at full rated kVA is unusual, and this guide gives recommendations for cyclic daily loads, taking into account seasonal variations of ambient temperature. The daily use of life due to thermal effects is indicated by comparison with the normal use of life corresponding to operation at rated kVA in an ambient of 32°C.

Tables 1 to 6 show the permissible load, for a normal daily use of life, in the two following sets of conditions:

a) Continuous duty, with different cooling medium temperatures; and

b) Cyclic duty, with different cooling medium temperatures.

The general method described in Appendix A is also applicable to duties with any sort of load diagram as a function of time.

NOTE — This guide is restricted to thermal considerations. Other considerations, notably economic (capitalization of losses, etc) may determine the choice of rated kVA.

4. LIMITATIONS

4.1 In preparing this guide, the following limitations on the operation of the transformer have been assumed:

a) For normal cyclic duty, the current does not exceed 1·5 times the rated value.

NOTE — If currents up to this limit and for the durations permitted by this guide are to be carried with safety, it is necessary for the terminal outlets, the tap-change device and similar attachments also to be suitable for the duty. Because IS : 2026-1962* does not define the loading possibility of these fittings, their suitability should be determined by reference to the manufacturer and, if they are found not to be suitable, lower limits of loading and duration will need to be accepted. The user shall ascertain the thermal capability of associated equipment, for example, cables, circuit-breakers and current transformers.

b) That in no case a hot-spot temperature in the windings of 140°C is exceeded.

NOTE 1 — It has been mentioned by various authors that above 140°C the Arrhenius Law is not completely in accordance with the phenomena, owing to accelerated deterioration effects, either because the formation of deterioration products is too fast for them to be taken away by the oil, or because a gaseous phase is started sufficiently rapidly to lead to over-saturation and the formation of bubbles which may endanger the electric strength.

NOTE 2 — Attention is drawn to the fact that a transformer that has been operating at loads greater than the rated kVA may not comply with the thermal requirements on short circuit specified in IS : 2026-1962*.

*Specification for power transformers. (Since revised).

5. SYMBOLS USED IN THE TABLES

5.1 Only the following four symbols are used in the tables:

K_1 = Initial load as a fraction of rated kVA;

K_2 = Permissible load as a fraction of rated kVA (may be greater than unity);

h = Duration of K_2 in hours; and

θ_a = Temperature of cooling medium (weighted average).

NOTE — $K_1 = \frac{S_1}{S_r}$ and $K_2 = \frac{S_2}{S_r}$

where

S is any value of power, and

S_r is rated kVA.

6. BASIS OF GUIDE

6.1 The basis for establishing the tables in this guide is as follows:

a) *Thermal Deterioration of the Insulation (Detailed in **A-2**)* — In a temperature zone extending up to 140°C, the rate at which transformer insulation deteriorates increases exponentially with temperature; it doubles for every temperature increase of 6°C.

b) *Normal Rate of Insulation Deterioration* — At a winding hot-spot temperature of 98°C, insulation deterioration is occurring at a normal rate; the rate of deterioration at other temperature is compared with this normal rate.

NOTE — This temperature of 98°C corresponds to operation in an ambient temperature of 32°C at the rated kVA of a transformer having a temperature-rise at the winding hot spot of 66°C (as detailed in A-1). The normal rate of insulation deterioration is obtained in practice, in particular, when a transformer installed in a place where the annual effective ambient temperature (weighted average according to **A-3**) is 32°C, operates continuously at rated kVA.

Periods of accelerated ageing when the ambient temperature is greater than 32°C (and the winding hot-spot temperature greater than 98°C) are then compensated for by periods of slow ageing when the ambient temperature is below 32°C (and the winding hot-spot temperature less than 98°C).

c) *Winding Hot-Spot Temperatures* — Winding hot-spot temperatures above 140°C are prohibited.

d) *Typical Load Diagram* — The basis of the tables in this guide is the simplified load diagram for cyclic daily duty shown in Fig. 1, where K_1 is the initial load, followed by K_2 for a period of h hours and returning to K_1 for the remainder of the 24 hours.

The tables give permissible cyclic duty with a normal life consumption of 24 hours per day, equal to that consumed during 24 hours at 98°C.

If there are two or more periods of high load separated by periods of low load, the high loading time *h* as represented in the diagram is the summation of the high loading times. This condition is less onerous than a single high load for the total time *h*.

To use the guide, the actual fluctuating load cycle shall be converted to thermally equivalent simple rectangular load cycle such as is represented in Fig. 1. A transformer supplying a fluctuating load generates a fluctuating loss, the effect of which is about the same as that of an intermediate load held constant for the same period of time. This is due to the heat storage characteristics of the materials in the transformer. A load which generates losses at the same rate as the average rate caused by fluctuating load, is an equivalent load from a temperature point of view.

Equivalent load for any portion of a daily-load cycle may be expressed by equation:

$$\text{Equivalent load or rms value} = \sqrt{\frac{S_1^2 t_1 + S_2^2 t_2 + S_3^2 t_3 + \ldots\ldots\ldots S_n^2 t_n}{t_1 + t_2 + t_3 + \ldots\ldots\ldots t_n}} \quad \ldots \text{(Equation 1)}$$

where

S_1, S_2, S_3, etc, are various load steps in actual kVA; and

t_1, t_2, t_3, etc, are the respective durations of these loads.

Equivalent initial load is the rms load obtained by Equation 1 over a chosen period preceding the peak load.

Experience with this method of load analysis indicates that quite satisfactory results are obtained by considering the 12-hour period preceding the peak in determination of the equivalent initial load. Time intervals (t) of 1 hour are suggested as further simplification of the equation which, for a 12-hour period, becomes:

$$\text{Equivalent initial load} = 0{\cdot}29\sqrt{S_1^2 + S_2^2 + \ldots\ldots\ldots S_{12}^2} \ldots\ldots\ldots \text{(Equation 2)}$$

where

S_1, S_2……… S_{12} is the average load by inspection for each 1-hour interval of the 12-hour period preceding peak load.

Equivalent peak load for the usual load cycle is the rms load obtained by Equation 1 for the limited period over which the major part of the actual irregular peak seems to exist. The estimated duration of the peak has considerable influence over the rms peak value. If the duration is overestimated, the rms peak value may be considerably below the maximum peak demand. To guard against overheating due to high, brief overloads during the peak period, the rms value for the peak load period should not be less than 90 percent of the integrated half-hour maximum demand.

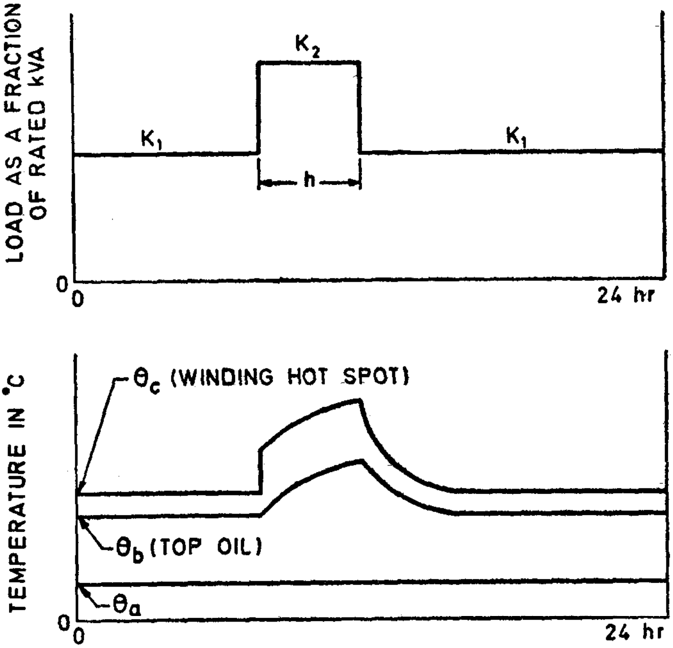


FIG. 1 SIMPLIFIED LOAD DIAGRAM FOR CYCLIC DAILY DUTY

e) *Parameters of the Tables* — The five parameters of the tables are:

1) Type of cooling: ON and ON/OB.
2) Oil-air thermal time constant: 3 hours for ON and ON/OB.
3) Temperature of cooling medium: 6 cases (0°C, 10°C, 20°C, 30°C, 32°C, 40°C).
4) Initial load (K_1): 6 values (0·25, 0·5, 0·7, 0.8, 0·9 and 1).
5) Duration of load K_2 : 8 values (0·5, 1, 2, 4, 6, 8, 12 and 24 hours).

NOTE 1 — Sufficient accuracy is obtained by having a single set of tables for ON and ON/OB types of cooling, the deviation in the value of K_2 being only of the order of 1 to 2 percent.

NOTE 2 — The effect of oil-air thermal time constant is negligible for long-time loads. Even for short-time loads the effect is only ± 2 percent between 2·5 and 3·5 hours.

f) *Determination of the Rated kVA* (S_r) *of a Transformer for a Given Service* — The curves given with each table can be used for determining the rated kVA of a transformer (with normal life duration) for a load defined according to Fig. 1 for $S_1 = K_1 S_r$ of duration ($24 - h$) and $S_2 = K_2 S_r$ of duration h. It is only necessary to find the intersection of the curve with the line of constant slope:

$$\frac{K_2}{K_1} = \frac{S_2}{S_1} \text{ which defines } K_1 \text{ and } K_2 \text{ whence } S_r.$$

In order to find this line, corresponding points should be marked on ordinate $K_1 : 1$ and abscissa $K_2 : 1$ and these points should be connected.

7. SELECTION OF APPROPRIATE TABLES AND EXAMPLES OF CALCULATION

7.1 Select the table for the value of θ_a. If the value of θ_a lies between two tables, either select the nearest one above or interpolate between the nearest two tables.

7.2 For transformers rated for both ON and ON/OB cooling, use tables in terms of the rated kVA for ON cooling if the fans are not brought into operation and in terms of the rated kVA for ON/OB if the fans are brought into operation.

These tables can also be used for ON cooling if the oil pumps are not brought into operation.

The fans and oil pumps are normally put into service by a temperature sensitive device (thermal image corresponding to winding hot-spot temperature or thermometer corresponding to top oil temperature). It is recommended that pumps and fans (where their use is not restricted by other considerations, such as noise) are put into service before the high loading occurs, in order to have the hot-spot temperature of the winding low enough to slow down the ageing process. The power taken by these auxiliaries is at least partially compensated for by the decrease in load loss resulting from a lower temperature.

NOTE 1 — Loading the transformer on the basis of the annual weighted average ambient temperature permits the transformer to be loaded to the same extent allowing for variations of K_1 and K_2 (*see* Tables 1 to 6) in such a way that the increased use of life when operating with cooling medium temperatures above θ_a (as in summer) is balanced by the reduced use of life when it is below θ_a (as in winter).

NOTE 2 — If the load cycle demands higher loading during winter than in summer this can be achieved by finding the daily or monthly permissible loading cycles from tables corresponding to daily or monthly values of θ_a respectively. In such a case it is essential that the loading cycle for each day or month has to be ascertained from the tables cerresponding to θ_a for the day or month in question and followed for the entire year.

Example 1:

To determine rating of a transformer for a known load cycle at a location where the weighted average annual ambient temperature of cooling medium is 32°C.

An ON transformer is required to carry a load of 1 400 kVA for six hours and 800 kVA for the remaining 18 hours each day.

$$\theta_a = 32°C, \frac{S_2}{S_1} = \frac{1\,400}{800} = 1{\cdot}75$$

$$\text{therefore } \frac{K_2}{K_1} = \frac{S_2/S_r}{S_1/S_r} = \frac{S_2}{S_1} = 1{\cdot}75$$

Line of slope $K_2/K_1 = 1{\cdot}75$ is shown dotted on curves for Table 5 for $\theta_a = 32°C$, at the intersection of this line with $h = 6$ curve, the value of K_2 is 1·14 and that of K_1 is 0·65. Therefore $S_r = S_2/1{\cdot}14 = 1\,400/1{\cdot}14 = 1\,228$ kVA.

Example 2:

To determine rating of a transformer for a known load cycle at a location where the weighted average annual ambient temperature of cooling medium is lower than 32°C.

An ON transformer is required to carry a load of 1 400 kVA continuously for 24 hours each day at a location where the weighted average annual ambient temperature is 20°C.

$\theta_a = 20°C$, $h = 24$ hours, $S_2 = 1\,400$ kVA

Therefore from Table 3, $K_2 = 1{\cdot}11$

$$\text{Therefore } S_r = \frac{S_2}{K_2} = \frac{1\,400}{1{\cdot}11} = 1\,261 \text{ kVA.}$$

Example 3:

To determine rating of a transformer for a known load cycle at a location where the weighted average annual ambient temperature of cooling medium is higher than 32°C.

An ON transformer is required to carry a load of 1 400 kVA continuously for 24 hours each day at a location where the weighted average annual ambient temperature is 40°C.

$\theta_a = 40°C$, $h = 24$ hours, $S_2 = 1\,400$ kVA

Therefore from Table 6, $K_2 = 0{\cdot}92$

$$\text{Therefore } S_r = \frac{S_2}{K_2} = \frac{1\,400}{0{\cdot}92} = 1\,521 \text{ kVA.}$$

NOTE — The above examples illustrate as to how the rating of an ON transformer having a temperature-rise of 45 to 55°C at rated load is selected when the ambient temperature is different from the standard temperature of 32°C.

This method of selecting the rating of a transformer having the temperature-rise of 45 to 55°C at rated load is preferable to selecting a transformer rating with different temperature-rise varying with ambient temperature. The loading of such transformer cannot be determined from this guide.

Example 4:

To calculate overload capacity of an existing transformer at a location where the weighted average annual ambient temperature of cooling medium is 32°C.

A 1 000 kVA ON transformer has a load of 500 kVA throughout the day except for a period of 2 hours. What is the permissible overload for a duration of two hours?

$$\theta_a = 32°C,\ K_1 = \frac{500}{1\ 000} = 0{\cdot}5,\ h = 2 \text{ hours}$$

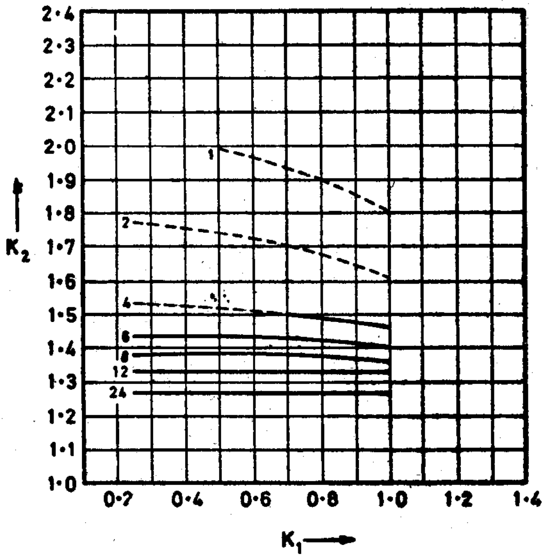
From Table 5 for $\theta_a = 32°C$ gives $K_2 = 1{\cdot}43$

Therefore, the permissible overload for 2 hours is

$1{\cdot}43 \times 1\ 000 = 1\ 430$ kVA.

TABLE 1 PERMISSIBLE VALUES OF K_2 AT $\theta_a = 0°C$

(*Clauses* 3.4 *and* 7.2)

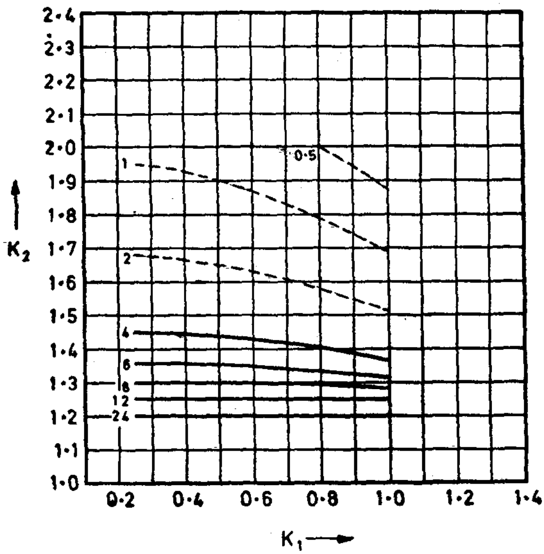


k \ K_1	0·25	0·5	0·7	0·8	0·9	1·0
	Values of K_2					
0·5	+	+	+	+	+	1·99
1	+	1·99	1·93	1·90	1·85	1·80
2	1·77	1·74	1·70	1·67	1·65	1·61
4	1·53	1·52	1·50	1·49	1·48	1·46
6	1·43	1·43	1·42	1·41	1·40	1·40
8	1·38	1·38	1·37	1·37	1·37	1·36
12	1·33	1·33	1·33	1·33	1·33	1·33
24	1·28	1·28	1·28	1·28	1·28	1·28

NOTE — In normal cyclic duty the values of K_2 should not be greater than 1·5. The sign '+' indicates that K_2 is higher than 2·0. The values of K_2 greater than 1·5 are underlined.

TABLE 2 PERMISSIBLE VALUES OF K_2 AT $\theta_a = 10°C$

(*Clauses* 3.4 *and* 7.2)

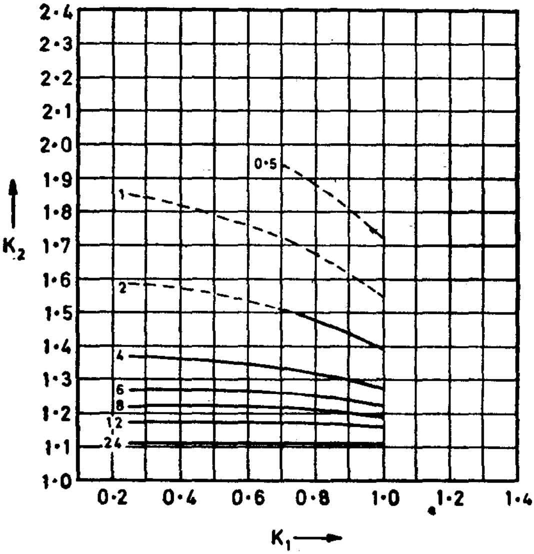


h \ K_1	0·25	0·5	0·7	0·8	0·9	1·0
			Values of K_2			
0·5	+	+	+	2·00	1·94	1·87
1	1·95	1·90	1·83	1·79	1·74	1·69
2	1·68	1·65	1·61	1·58	1·55	1·51
4	1·45	1·44	1·42	1·41	1·39	1·37
6	1·36	1·35	1·34	1·33	1·32	1·32
8	1·30	1·30	1·30	1·29	1·29	1·28
12	1·25	1·25	1·25	1·25	1·25	1·25
24	1·20	1·20	1·20	1·20	1·20	1·20

NOTE — In normal cyclic duty the values of K_2 should not be greater than 1·5. The sign '+' indicates that K_2 is higher than 2·0. The values of K_2 greater than 1·5 are underlined.

TABLE 3 PERMISSIBLE VALUES OF K_2 AT $\theta_a = 20°C$

(*Clauses* 3.4 *and* 7.2)

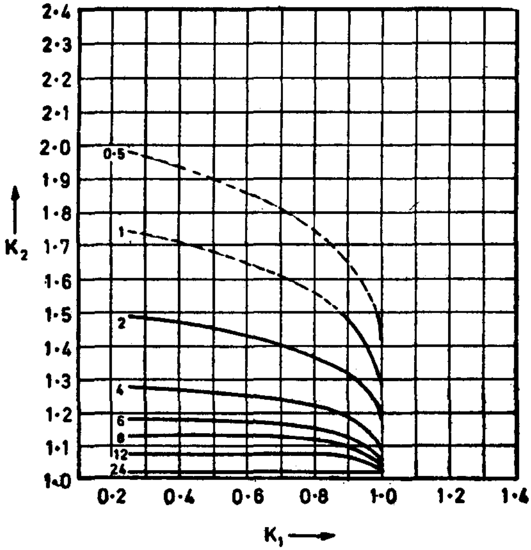


K_1 / h	0·25	0·5	0·7	0·8	0·9	1·0
			Values of K_2			
0·5	+	+	1·94	1·88	1·81	1·72
1	1·85	1·79	1·72	1·68	1·63	1·55
2	1·59	1·55	1·51	1·48	1·44	1·39
4	1·37	1·35	1·33	1·32	1·30	1·27
6	1·27	1·26	1·25	1·25	1·24	1·22
8	1·22	1·22	1·21	1·21	1·20	1·19
12	1·17	1·17	1·17	1·17	1·16	1·16
24	1·11	1·11	1·11	1·11	1·11	1·11

NOTE — In normal cyclic duty the values of K_2 should not be greater than 1·5. The sign ' + ' indicates that K_2 is higher than 2·0. The values of K_2 greater than 1·5 are underlined.

TABLE 4 PERMISSIBLE VALUES OF K_2 AT $\theta_a = 30°C$

(*Clauses* 3.4 *and* 7.2)

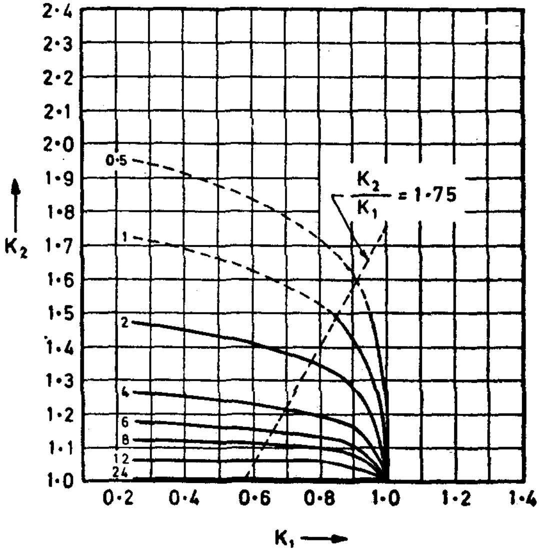


K_1 / h	0·25	0·5	0·7	0·8	0·9	1·0
			Values of K_2			
0·5	1·98	1·90	1·81	1·75	1·66	1·42
1	1·74	1·68	1·61	1·56	1·48	1·28
2	1·49	1·45	1·40	1·37	1·32	1·17
4	1·28	1·26	1·24	1·22	1·19	1·09
6	1·18	1·18	1·16	1·15	1·13	1·06
8	1·13	1·13	1·12	1·12	1·10	1·05
12	1·08	1·08	1·08	1·08	1·07	1·04
24	1·02	1·02	1·02	1·02	1·02	1·02

NOTE — In normal cyclic duty the values of K_2 should not be greater than 1·5. The values of K_2 greater than 1·5 are underlined.

TABLE 5 PERMISSIBLE VALUES OF K_2 AT $\theta_a = 32°C$

(*Clauses* 3.4 *and* 7.2)

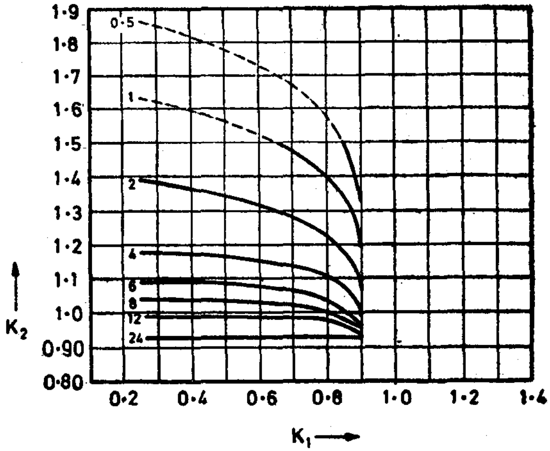


h \ K_1	0·25	0·5	0·7	0·8	0·9	1·0
			Values of K_2			
0·5	1·95	1·88	1·78	1·72	1·62	1·00
1	1·72	1·66	1·58	1·53	1·45	1·00
2	1·47	1·43	1·38	1·34	1·29	1·00
4	1·26	1·24	1·22	1·20	1·16	1·00
6	1·17	1·16	1·14	1·13	1·11	1·00
8	1·12	1·11	1·10	1·10	1·08	1·00
12	1·06	1·06	1·06	1·06	1·04	1·00
24	1·00	1·00	1·00	1·00	1·00	1·00

NOTE — In normal cyclic duty the values of K_2 should not be greater than 1·5. The values of K_2 greater than 1·5 are underlined.

TABLE 6 PERMISSIBLE VALUES OF K_2 AT $\theta_a = 40°C$

(*Clauses* 3.4 *and* 7.2)



h \ K_1	0·25	0·5	0·7	0·8	0·9
	Values of K_2				
0·5	1·86	1·78	1·67	1·58	1·33
1	1·63	1·56	1·48	1·40	1·19
2	1·39	1·34	1·28	1·23	1·07
4	1·18	1·16	1·13	1·10	0·99
6	1·09	1·08	1·06	1·04	0·96
8	1·04	1·03	1·02	1·00	0·95
12	0·99	0·98	0·98	0·97	0·93
24	0·92	0·92	0·92	0·92	0·92

NOTE — In normal cyclic duty the values of K_2 should not be greater than 1·5. The values of K_2 greater than 1·5 are underlined.

APPENDIX A

(*Clause* 3.4)

METHOD FOLLOWED IN PREPARING THE GUIDE

A-0. SYMBOLS USED

A-0.1 The following is a list of the symbols used in this appendix:

θ = Temperature in °C.

$\Delta\theta$ = Temperature-rise in °C.

θ_a = Weight ambient temperature.

a = Subscript representing 'ambient' (cooling medium).

b = Subscript representing 'top oil'.

c = Subscript representing 'hot spot of winding'

d = Ratio $\dfrac{\text{Load loss at rated kVA}}{\text{No-load loss}}$.

g = Difference between average winding temperature-rise and average oil temperature-rise.

h = Time duration in hours of any load kVA.

K = Load kVA as a fraction of rated kVA = $\dfrac{S}{S_r}$.

K_1 = Initial load kVA as a fraction of rated kVA = $\dfrac{S_1}{S_r}$.

K_2 = Permissible load kVA as a fraction of rated kVA = $\dfrac{S_2}{S_r}$

x = Exponent of $\dfrac{\text{Total losses}}{\text{Rated losses}}$ used in oil temperature-rise calculations.

y = Exponent of $\dfrac{\text{(Hot-spot temperature-rise — top oil temperature-rise) at kVA } S}{\text{(Hot-spot temperature-rise — top oil temperature-rise) at rated kVA } S_r}$ used in hot-spot temperature-rise calculations.

N = Number of equal intervals constituting period h.

o = Subscript representing start of period h.

p = Exponent (constant) used only in Montsinger relation.

r = Subscript representing rated value.

S = kVA (any value); S_r = rated kVA.

t = Variable time during the period h.

T = Absolute temperature, used only in Arrhenius Law.

V = Relative rate of using life.

τ = Oil-air thermal time constant at rated load in hours.

Examples:

Temperature in °C

θ_a = Weighted ambient (cooling medium) temperature.

θ_b = Top oil temperature = $\theta_a + \Delta\theta_b$.

θ_c = Winding hot-spot temperature = $\theta_a + \Delta\theta_c$.

Temperature-rises in °C

$\Delta\theta_b$ = Oil temperature-rise (top).

$\Delta\theta_{br}$ = Oil temperature-rise (top) at rated kVA.

$\Delta\theta_c$ = Winding temperature-rise (hot spot).

$\Delta\theta_{cr}$ = Winding temperature-rise (hot spot) at rated kVA.

A-1. DETERMINATION OF TEMPERATURE-RISE

A-1.1 Assumed Thermal Diagram — A simple thermal diagram, is assumed, as shown in Fig. 2, it being understood that such a diagram is the simplification of a more complex distribution.

The top oil temperature-rise, as measured during a temperature-rise test, differs from that of the oil leaving the winding, because this oil is a mixture of partial oil flows which have circulated along the various windings, but these differences are not considered sufficiently significant to invalidate the method.

Between the bottom of the cooling means and the bottom of the winding, the difference is even less.

The following simplified assumptions are made for the purpose of the guide and Fig. 2:

a) The oil temperature increases linearly up the winding.

b) The average oil temperature-rise is the same for all the windings of the same column.

c) The difference of temperature between the oil at the top of the winding (assumed equal to that of the top oil) and the oil at the bottom of the winding (assumed equal to that at the bottom of the cooler) is the same for all the windings.

d) The average temperature-rise of the copper 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 average rise by resistance and mean oil rise).

e) The average temperature-rise of the top coil is the top oil temperature-rise plus g.

f) The hot-spot temperature-rise is higher than the average rise of the top coil. To take account of the difference between maximum and average in the top coil, a value of 0·1 g is assumed for natural oil circulation. Thus, the temperature-rise of the hot spot is equal to the top oil temperature-rise plus 1·1 g.

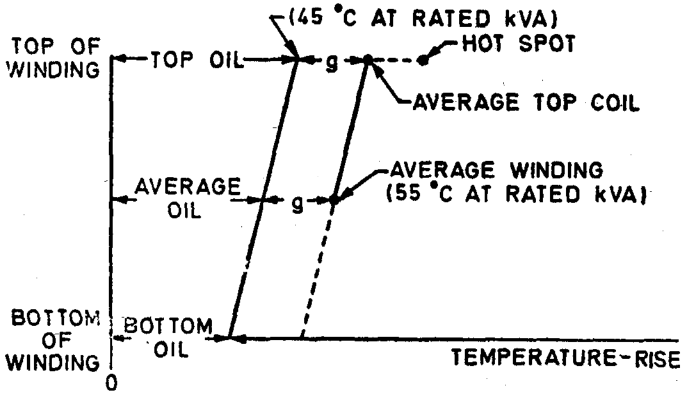


FIG. 2 THERMAL DIAGRAM

A-1.2 Conditions for Rated Power

A-1.2.1 *Natural Oil Circulation*

Average copper temperature-rise (measured by resistance) = 55°C

Top oil temperature-rise = 45°C

Mean oil temperature-rise = 36°C

g_r = 19°C

Hot-spot temperature-rise = Top oil temperature-rise plus 1·1 g_r = 45 + 21 = 66°C

NOTE — Higher or lower oil temperature-rises are offset by the correspondingly lower or higher values for g_r necessary to keep the mean temperature-rise of the windings within 55°C. Appreciable differences in the assumed values only slightly influence the permissible loading given in the tables. Greater accuracy is not required, because there is, in practice, inevitable inaccuracy in the appreciation of the ambient, in the variability of the load (current and voltage), etc.

A-1.3 Values for Any Thermally Stabilized Condition

A-1.3.1 *Top Oil Temperature-Rise* $\Delta\theta_b$ *at Any Load* kVA S — This is equal to the top oil temperature-rise at rated kVA multiplied by the ratio of total losses with exponent x:

$$\Delta\theta_b = \Delta\theta_{br}\left[\frac{(1 + d K^2)}{1 + d}\right]^x$$

For this guide d is assumed to be equal to 5.

x is assumed to be equal to 0·9 for ON and OB*.

$\Delta\theta_{br}$ is assumed to be equal to 45°C for ON, as given in **A-1.2.**

The value of d is relatively unimportant at high loading, giving only marginally higher or lower oil temperature-rises in practice. Even this is compensated for to some extent by the correspondingly lower or higher oil temperature-rises at low loads.

A-1.3.2 *Hot-Spot Temperature-Rise* $\Delta\theta_c$ *at Any Load* kVA S

This is equal to:

Top oil temperature-rise $\Delta\theta_b$ (as calculated in **A-1.3.1**) plus $(\Delta\theta_{cr} - \Delta\theta_{br})\,K^{2y}$

For this guide $\Delta\theta_{cr}$ is assumed to be equal to 66°C as given in **A-1.2.**

$\Delta\theta_{br}$ is assumed to be equal to 45°C for ON, as given in **A-1.2.**

y is assumed to be equal to 0·8 for ON and OB.

A-1.4 Values for Any Transient Condition

A-1.4.1 The top oil temperature-rise $\Delta\theta_{bt}$ at any time h after the application of a given load is very close to the exponential rise given by:

$$\Delta\theta_{bt} = \Delta\theta_{bo} + (\Delta\theta_b - \Delta\theta_{bo})\,(1 - e^{-h/\tau})$$

where

$\Delta\theta_{bo}$ is the initial oil temperature-rise; and

$\Delta\theta_b$ would be the final stabilized oil temperature-rise corresponding to the load considered, as calculated in **A-1.3.1.**

For the tables of the guide, τ is assumed equal to 3 hours.

*This value of 0·9 has been taken both for ON and OB because it allows single set of tables to be used for both kinds of cooling, with errors only of the order of ± 2 percent.

A-1.4.2 The hot-spot temperature-rise at any time before stabilized conditions are reached is approximated by assuming that the hot-spot temperature-rise above the top oil temperature-rise is established immediately.

The temperature-rise of the hot spot at any time is thus equal to the top oil temperature-rise (as calculated in **A-1.4.1**) plus $(\Delta\theta_{cr} - \Delta\theta_{br})\ K^{2y}$.

This can be simplified for loading K_2 lasting for h hours and loading K_1 lasting for the remainder of the 24 hours as follows:

$$\Delta\theta_c K_2 = \Delta\theta_{bo} + (\Delta\theta_b - \Delta\theta_{bo})(1 - e^{-h/T}) + (\Delta\theta_{cr} - \Delta\theta_{br})\ K_2^{2y}$$

where

$$\Delta\theta_{bo} = \Delta\theta_b K_1 = \Delta\theta_{br}\left[\frac{1 + dK_1^2}{1 + d}\right]^x$$

$$\Delta\theta_b = \Delta\theta_b K_2 = \Delta\theta_{br}\left[\frac{1 + dK_2^2}{1 + d}\right]^x$$

$$\therefore\ \Delta\theta_c K_2 = \Delta\theta_{br}\left[\frac{1 + dK_1^2}{1 + d}\right]^x + \left[\Delta\theta_{br}\left\{\frac{1 + dK_2^2}{1 + d}\right\}^x - \Delta\theta_{br}\left\{\frac{1 + dK_1^2}{1 + d}\right\}^x\right](1 - e^{-h/T}) + (\Delta\theta_{cr} - \Delta\theta_{br})\ K_2^{2y}$$

$$\therefore\ \Delta\theta_c K_2 - \Delta\theta_{br}\left[\frac{1 + dK_1^2}{1 + d}\right]^x + \Delta\theta_{br}\left[\frac{1 + dK_1^2}{1 + d}\right]^x (1 - e^{-h/T})$$

$$= \Delta\theta_{br}\left[\frac{1 + dK_2^2}{1 + d}\right]^x (1 - e^{-h/T}) + (\Delta\theta_{cr} - \Delta\theta_{br})\ K_2^{2y}$$

Approximating $\left[\frac{1 + dK_2^2}{1 + d}\right]^x = 1 - x + \frac{x}{1 + d} + \frac{xdK_2^2}{1 + d}$, and

$$K_2^{2y} = \left[1 - (1 - K_2^2)\right]^y = 1 - y + yK_2^2,$$

$$\Delta\theta_c K_2 - \Delta\theta_{br}\left[\frac{1 + dK_1^2}{1 + d}\right]^x e^{-h/T} = \Delta\theta_{br}(1 - e^{-h/T})\left[\left(1 - x + \frac{x}{1 + d}\right) + \left\{\frac{xdK_2^2}{1 + d}\right\}\right] + (\Delta\theta_{cr} - \Delta\theta_{br})(1 - y + yK_2^2)$$

$$\therefore \Delta\theta_c K_2 - \Delta\theta_{br}\left[\left(\frac{1+dK_1^2}{1+d}\right)^r . e^{-h/T} + (1 - e^{-h/T})\left(1 - x + \frac{x}{1+d}\right)\right] - (\Delta\theta_{cr} - \Delta\theta_{br})(1-y)$$

$$= \left[\Delta\theta_{br}\ (1 - e^{-h/T}).\frac{xd}{1+d} + (\Delta\theta_{cr} - \Delta\theta_{br}).y\right]K_2^2$$

$$\therefore K_2 = \sqrt{\frac{\Delta\theta_c K_2 - \Delta\theta_{br}\left[\left(\frac{1+dK_1^2}{1+d}\right)^x . e^{-h/T} + (1 - e^{-h/T})\left(1 - x + \frac{x}{1+d}\right)\right] - (\Delta\theta_{cr} - \Delta\theta_{br})(1-y)}{\Delta\theta_{br}\ (1 - e^{-h/T}).\frac{xd}{1+d} + (\Delta\theta_{cr} - \Delta\theta_{br}).y}}$$

A-2. RELATIVE RATE OF THERMAL DETERIORATION OF THE INSULATION

A-2.1 Law of Deterioration — The life of insulation, as affected by deterioration due to temperature and time, is given by the law of Arrhenius as:

$$\text{Life} = e^{\left(A + \frac{B}{T}\right)}$$

where A and B are constants (derived by experiment for any given insulating material) and T is the absolute temperature. In the range 80 to 140°C this law can be expressed in the more convenient Montsinger relation as:

$$\text{Life} = e^{-p\theta}$$

where p is a constant and θ is the temperature in °C.

Various investigators have not always agreed on the length of life at any given temperature. They do agree reasonably well, however, that over the range 80 to 140°C the rate of using life in transformers is doubled for every temperature increase of approximately 6°C, and this value is used as the basis for this guide.

A-2.2 Relative Rate of Using Life (*V*) — The Montsinger relation can now be used to obtain the relative rate of using life at any temperature θ_c compared with the normal rate of using life at temperature θ_{cr}, and is given by:

$$V = \frac{\text{Rate of using life at } \theta_c}{\text{Rate of using life at } \theta_{cr}} = 2^{\left(\frac{\theta_c - \theta_{cr}}{6}\right)} = e^{0{\cdot}693\left(\frac{\theta_c - \theta_{cr}}{6}\right)} \qquad \text{(Formula 1)}$$

The value of θ_{cr} for a transformer is taken to be 98°C.

This temperature corresponds to operation in an ambient temperature of 32°C at the rated kVA of a transformer having a temperature-rise at the hot spot of 66°C, that is, 11°C above the average temperature-rise (measured by resistance) of 55°C. Such temperature conditions correspond to normal ageing of the insulation.

Using Formula 1 and θ_{cr} = 98°C, the following formula in terms of $\log_{10}$ is derived:

$$V = \text{Relative rate of using life} = 10^{\left(\frac{\theta_c - 98}{19{\cdot}93}\right)} \qquad \text{(Formula 2)}$$

This is represented in Fig. 3 and by the following table:

θ_c °C	*Relative Rate of Using Life*
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

Example:

10 hours at 104°C and 14 hours at 86°C would use (10 × 2) plus (14 × 0·25) = 23·5 hours life in 24 hours operation.

It may be noted that below 80°C the use of life can be considered negligible.

A-2.3 Equivalent Life Loss Diagrams in a 24-Hour Period

A-2.3.1 *Operation at Constant Temperature* — Consider a rectangular diagram of temperatures in a 24-hour period corresponding to *h* hours at a constant temperature θ, with the complement to 24 hours corresponding to a sufficiently low temperature for negligible life loss; then the hours of life used are given by hV.

A-2.3.2 *Operation at Variable Temperature* — In the case of a varying temperature θ_c = function of h, an integration is necessary with the preceding relations. The hours of life used are then given by:

$$\int_a^h V dh$$

An example at the end of the preceding table shows how this can be summated for a few values of θ_c and h.

A-2.3.3 *Permissible Duration h hours of Operation at θ_c to Use One-Day's Life*

From Formula 2, $\theta_c = 98 + 19{\cdot}93 \log_{10} V$ (Formula 3)

Also, hours of life used $= hV = h \times 10^{\left(\frac{\theta_c - 98}{19{\cdot}95}\right)}$ (Formula 4)

for hV to equal 24, $h = \frac{24}{V} = 24 \times 10^{\left(\frac{98 - \theta_c}{19{\cdot}93}\right)}$ (Formula 5).

Formula 5 gives the number of hours per day of operation at any given value of θ_c that will use one-day's life per day. The following table gives values of h for various values of θ_c:

Hours Per Day	θ_c °C
24	98
16	101·5
12	104
8	107·5
6	110
4	113·5
3	116
2	119·5
1·5	122
1·0	125·5
0·75	128
0·5	131·5
0·375	134
0·25	137·5
0·188	140

A-2.4 Method of Calculating K_2

A-2.4.1 *Example*

Given $\theta_a = 30°C$, $K_1 = 0{\cdot}9$, $h = 6$

To determine K_2.

Duration of $K_1 = 24 - 6 = 18$

From **A-1.3.1**

$$\Delta\, \theta_b K_1 = 45 \left[\frac{1 + 5\,(0{\cdot}9)^2}{1 + 5} \right]^{0\cdot9} = 38{\cdot}47$$

From **A-1.3.2**

$$\Delta\, \theta_c K_1 = 38{\cdot}47 + (66 - 45)\,(0{\cdot}9)^{2 \times 0\cdot8} = 56{\cdot}2$$

$\therefore\ \theta_c K_1 = 30 + 56{\cdot}2 = 86{\cdot}2$

Corresponding to $\theta_c K_1 = 86{\cdot}2$, relative rate of using life VK_1 (from Fig. 3) $= 0{\cdot}25$

Life lost during 18 hours $= 0{\cdot}25 \times 18 = 4{\cdot}5$

Remaining hours of life per day $= 24 - 4{\cdot}5 = 19{\cdot}5$

Permissible relative rate of using life VK_2 corresponding to K_2, for 6 hours $= \frac{19{\cdot}5}{6} = 3{\cdot}25$

$\theta_c K_2$ corresponding to $VK_2 = 3{\cdot}25$ from **A-2.3.3** or Fig. 3,

$\theta_c K_2 = 98 + 19{\cdot}93 \log 10^{3\cdot25} = 108{\cdot}2$

Permissible hot-spot temperature-rise $\Delta\, \theta_c K_2 = 108{\cdot}2 - 30 = 78{\cdot}2$.

Substituting the values in the formula for K_2 given in **A-1.4.2**

$K_2 = 1{\cdot}13$

Also from Table 4, for $K_1 = 0{\cdot}9$ and $h = 6$

$K_2 = 1{\cdot}13$

A-3. AMBIENT TEMPERATURE TO BE CONSIDERED IN THE TABLES OF THE LOADING GUIDE DETERMINATION OF THE EFFECTIVE VALUE OF θ_a

A-3.1 If θ_a varies appreciably during the high loading time h, then a weighted value of θ_a should be used, because the weighted ambient temperature will be higher than the arithmetic average.

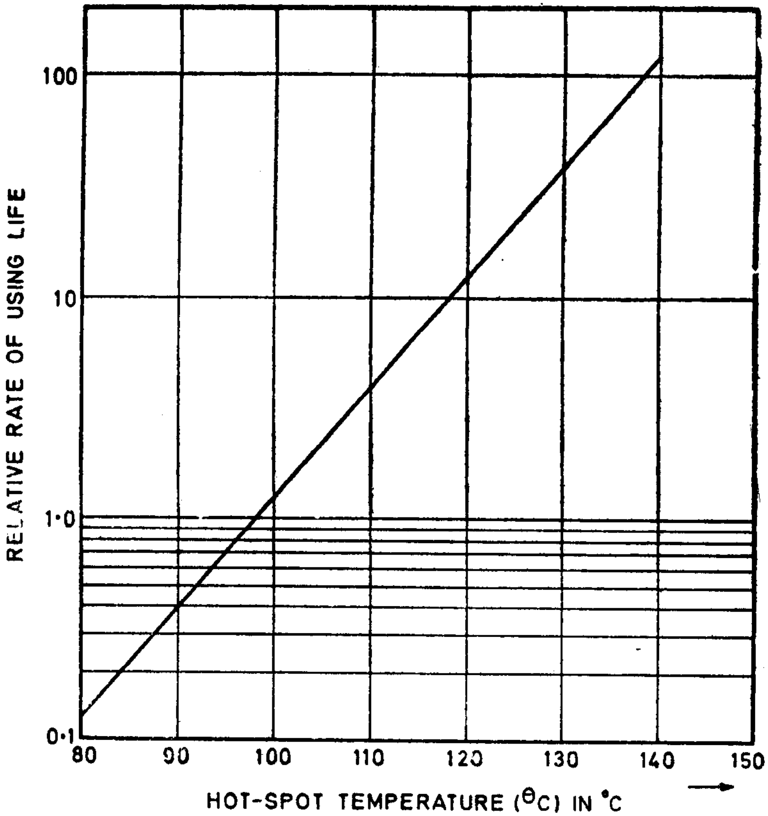


FIG. 3 LIFE LINE

Consider operation at constant load with a varying ambient temperature θ_a for a given period h. The weighted ambient temperature X during that period is given by the formula:

$$2^{\frac{X}{6}} = \frac{1}{h} \int_0^h 2^{\frac{\theta_a}{6}} \, dh$$

If the time h is divided into N equal intervals, the preceding formula becomes:

$$2^{\frac{X}{6}} = \frac{1}{N} \sum_{1}^{N} 2^{\frac{\theta_a}{6}}$$

From this, the weighted ambient temperature

$$X = 6 \log_2 \left[\frac{1}{N} \sum_{1}^{N} 2^{\frac{\theta_a}{6}} \right]$$ which is practically equal to

$$20 \log_{10} \left(\frac{1}{N} \sum_{1}^{N} 10^{\frac{\theta_a}{20}} \right)$$

Example:

The average temperature for the several months of the year for a city are as follows:

Month	θ_a	*Month*	θ_a	*Month*	θ_a
January	17·4°C	May	38·0°C	September	31·9°C
February	22·2°C	June	37·8°C	October	29·8°C
March	29·3°C	July	33·5°C	November	23·2°C
April	33·4°C	August	32·4°C	December	19·4°C

The average for the year would work out to 29·0°C.

Using the above formula, the weighted ambient average works out to 31·2°C.

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