

REPORT
to
Working Group on Revision of Loading Guide C57.91

**Comparison of Calculated Hot Spot Temperatures
Using *CLAUSE 7* Equations versus *ANNEX G* Equations**

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Summary

Comparisons are made between two methods of calculating the *hot spot temperature* in power transformers. In some cases, the results are quite different, which affects *loss of life* calculations drastically, since the equation for *Aging Rate* is very sensitive. Conclusions are not drawn at this stage.

Introduction

This working group is currently working on a revision of the C57.91-1995 IEEE Guide for Loading Mineral-Oil-Immersed Transformers.

One of the contentious issues is the method to be recommended for hot spot temperature calculations. In the current Guide, there is a long-used method described in Clause 7, and a more exhaustive method described in Annex G. These will be referred to here as the “Clause 7 method” and the “Annex G method,” respectively. The supposed advantage of the Annex G method is that it is more accurate. The advantage of the Clause 7 method is that it has been used by so many people, and for such a long time, that consistency may be more important than accuracy.

Ideally, one would compare each of these methods against actual fiber-optics-measured hot spot temperatures, in real installations; however such information does not appear to be available at this time. The Working Group might eventually collect such data, but has to balance thoroughness against getting something done in a reasonable length of time.

There seems to be some evidence that the Annex G method is more accurate than the Clause 7 method. Therefore, the assumption made here is that the Annex G results are taken as “correct” and we are looking, by comparison, at the “errors” inherent in using the Clause 7 equations. Then, perhaps we can make a judgement call as to whether to include either or both methods in the new Guide.

Firstly, three kinds of *hot spot* calculation comparisons are made:

- (1) Steady-state hot spot temperatures,
- (2) Overload (four hours) hot spot temperatures, and
- (3) Daily load curve (typical) hot spot temperatures.

Secondly, the *loss of life* is calculated for cases (2) and (3) above.

Data are from four actual transformers, one each with ONAN, ONAF, OFAF and ODAF cooling. [O=oil, A=air, N=natural-flow, F=forced/non-directed-flow, D=forced/directed-flow]

Complete data for the four transformers is listed in the Appendix. Tim Raymond programmed both sets of equations in the form of a spread sheet.

Comparison of Calculated STEADY-STATE Hot Spot Temperatures

In this comparison study, the hot spot temperature is allowed to reach its steady-state value, for each transformer, for loadings of 0.8, 1.0, 1.2, 1.4 and 1.6 per unit current.

See Fig. 1.

Comparison of Calculated FOUR-HOUR OVERLOAD Hot Spot Temperatures

The two methods are compared for a theoretical four-hour (over)loading of 1.4 per unit, with the loading before and after this period fixed at 0.7 per unit.

See Fig. 2.

Comparison of Calculated Typical DAILY LOAD CURVE Hot Spot Temperatures

The two methods are compared for a typical daily load curve, having a maximum of 1.0 per unit at around 3:00 p.m.: the 39th hour of a two-day period. The first 24 hours are used to let the calculation reach a steady-state before the loading is applied.

See Fig. 3.

FIGURE 1. COMPARISON FOR STEADY-STATE CONDITIONS

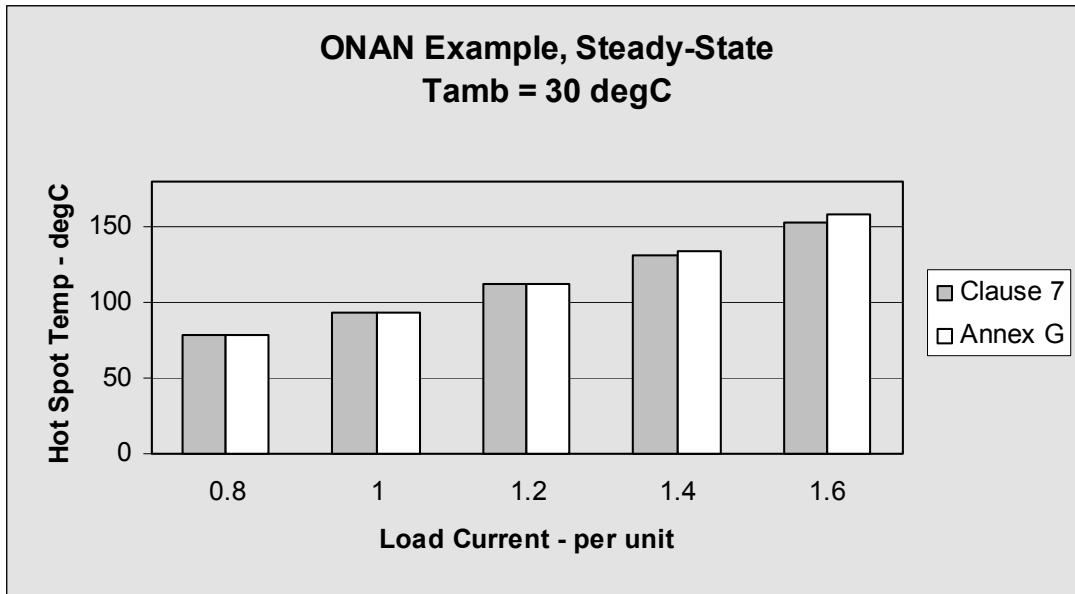


Fig. 1(a)

The largest error, at a loading of 1.6 per unit, is 6 °C.

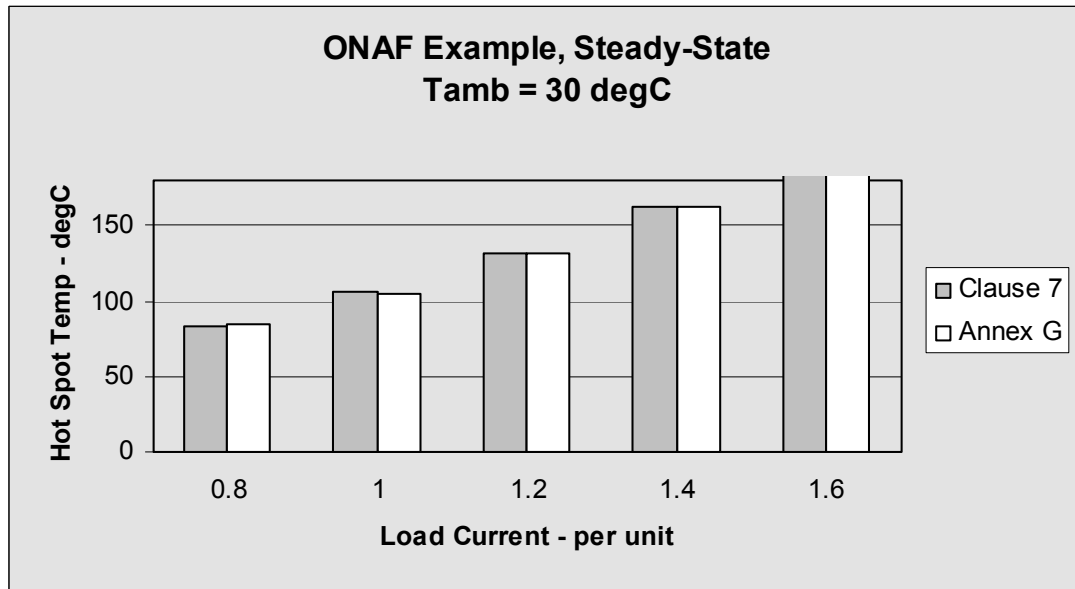


Fig. 1(b)

The two methods show good agreement up to a loading of 1.4 per unit. The graph is purposely truncated at a temperature of 180°C because tripping would certainly occur before that temperature is reached, making the accuracy irrelevant.

FIGURE 1. continued

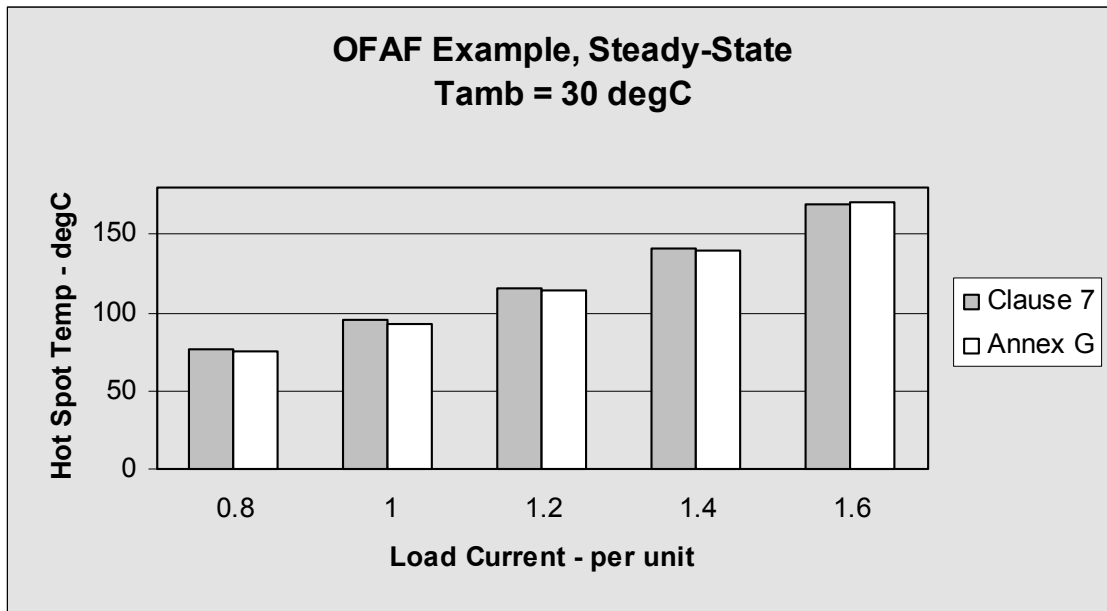


Fig. 1(c)

There is good agreement at all load levels.

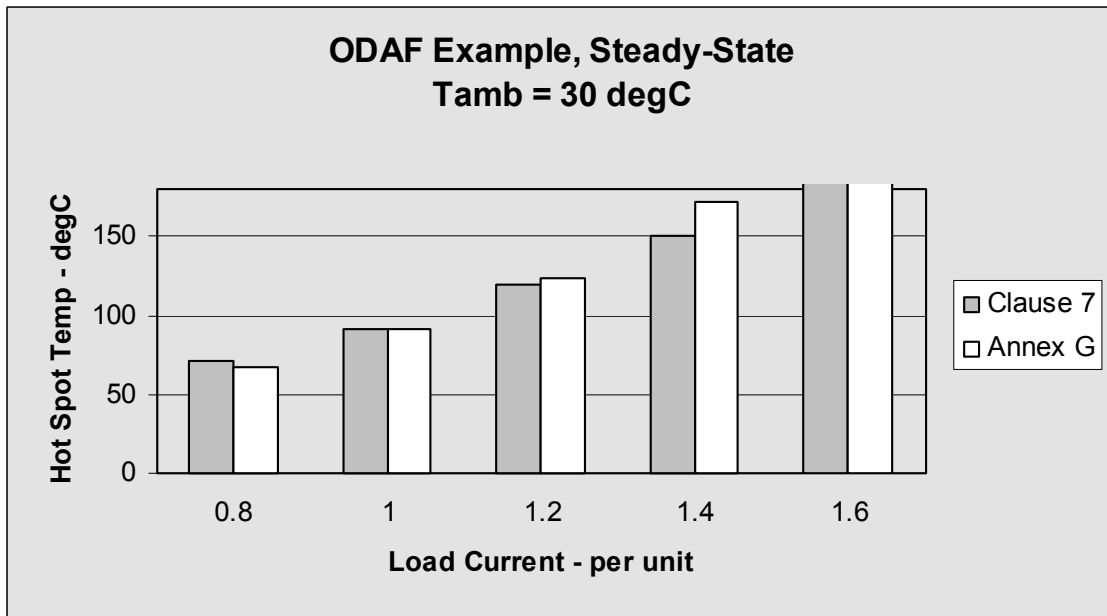


Fig. 1(d)

There is significant error at a loading of 1.4 per unit: 22°C. (Again, the graph is purposely truncated at 180°C.)

FIGURE 2. COMPARISON FOR A FOUR-HOUR OVERLOAD CONDITION

ONAN COOLING

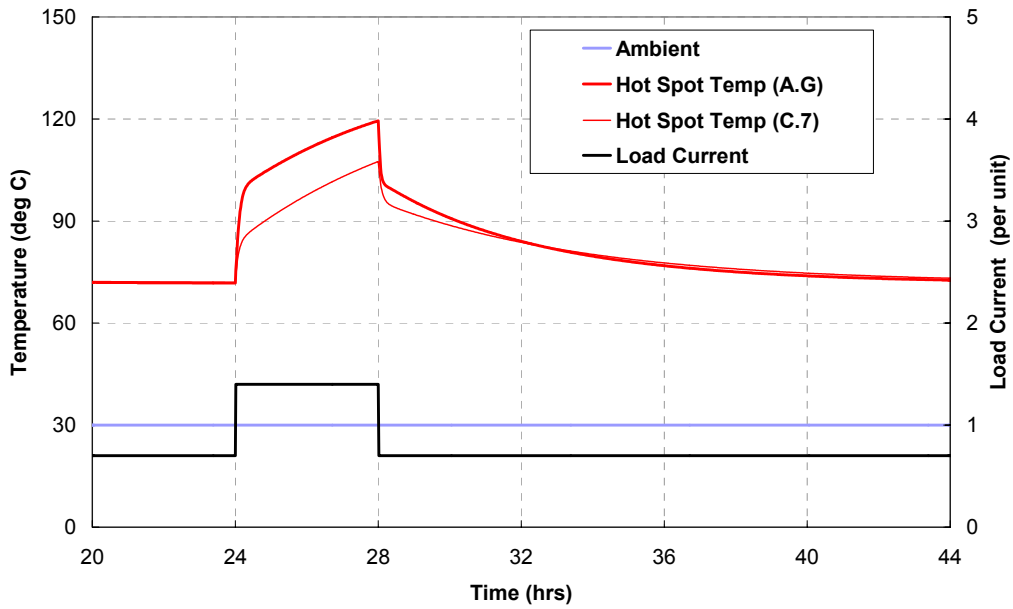


Fig. 2(a)

The error here is significant: about 10°C.

ONAF COOLING

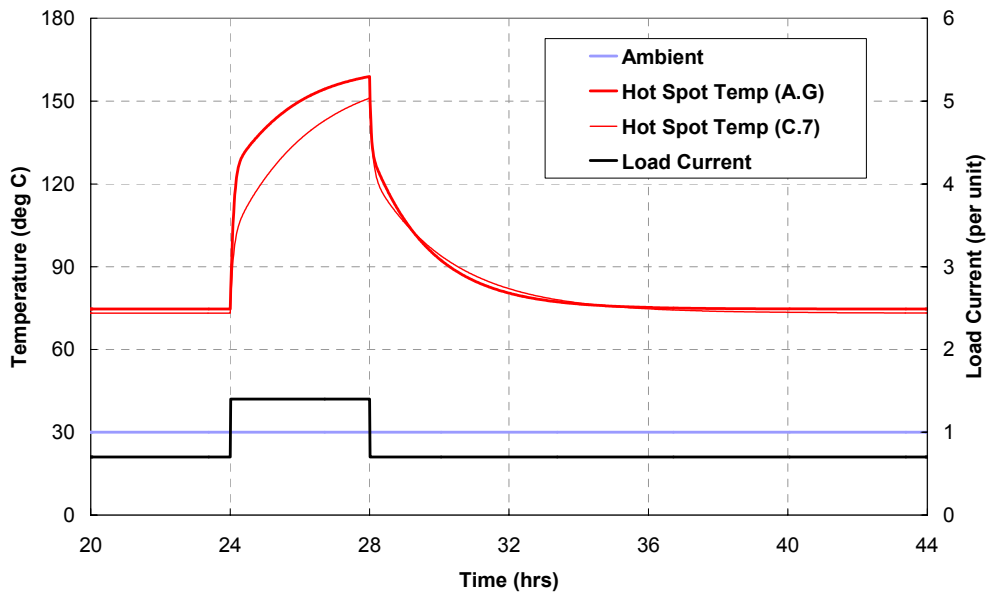


Fig. 2(b)

The error here is, again, around 10°C.

FIGURE 2. continued

OFAF COOLING

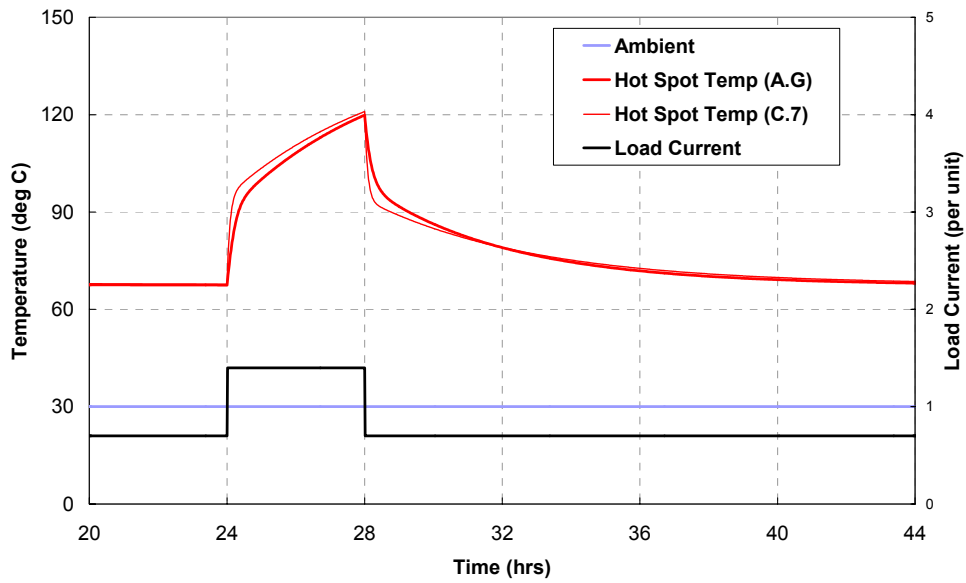


Fig. 2(c)

Here, the error is not significant.

ODAF COOLING

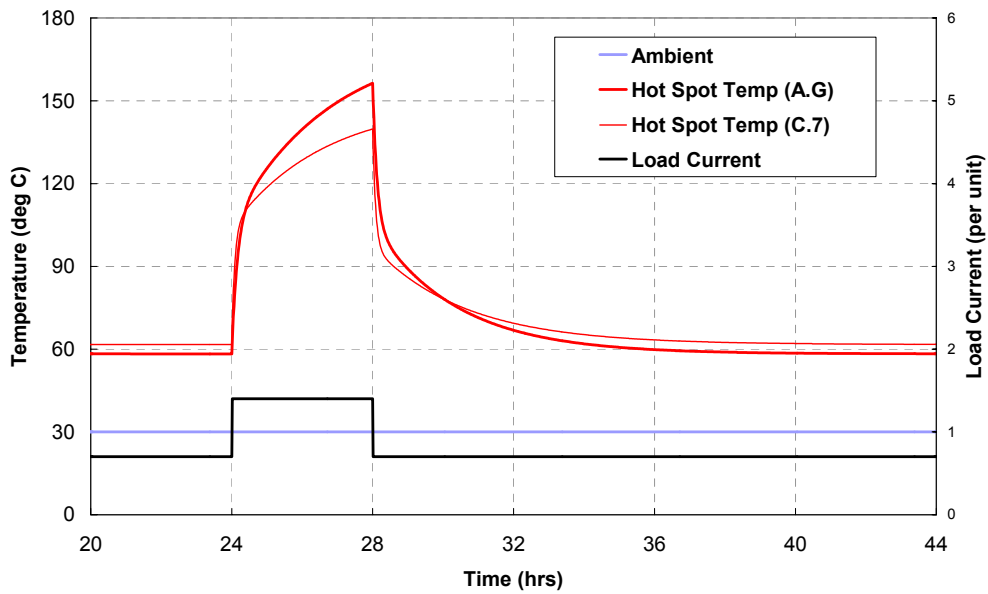


Fig. 2(d)

Again, a significant error of from zero to 15° during the rising transient period.

FIGURE 3. COMPARISON FOR A TYPICAL DAILY LOAD CURVE CONDITION

ONAN COOLING

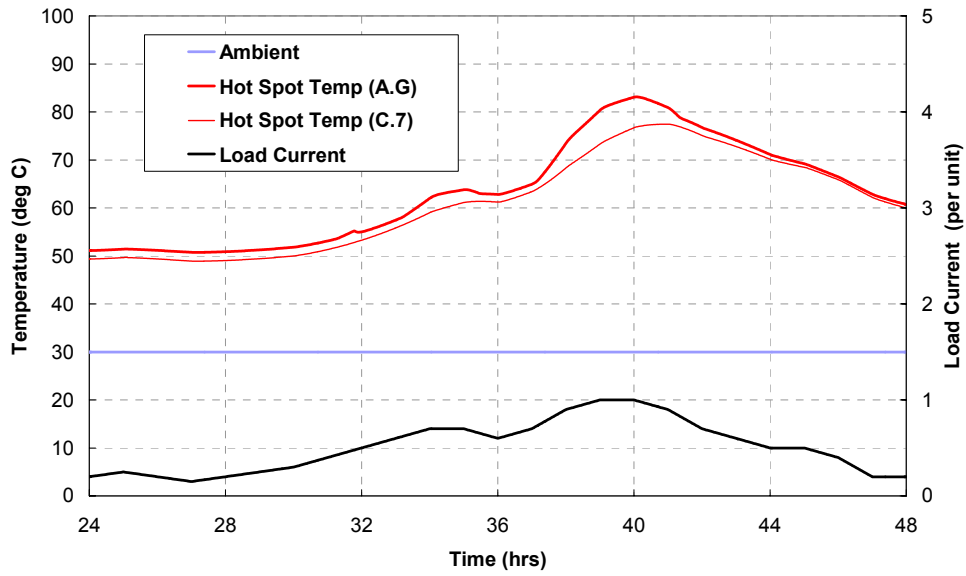


Fig. 3(a)

The maximum error is about 6°C.

ONAF COOLING

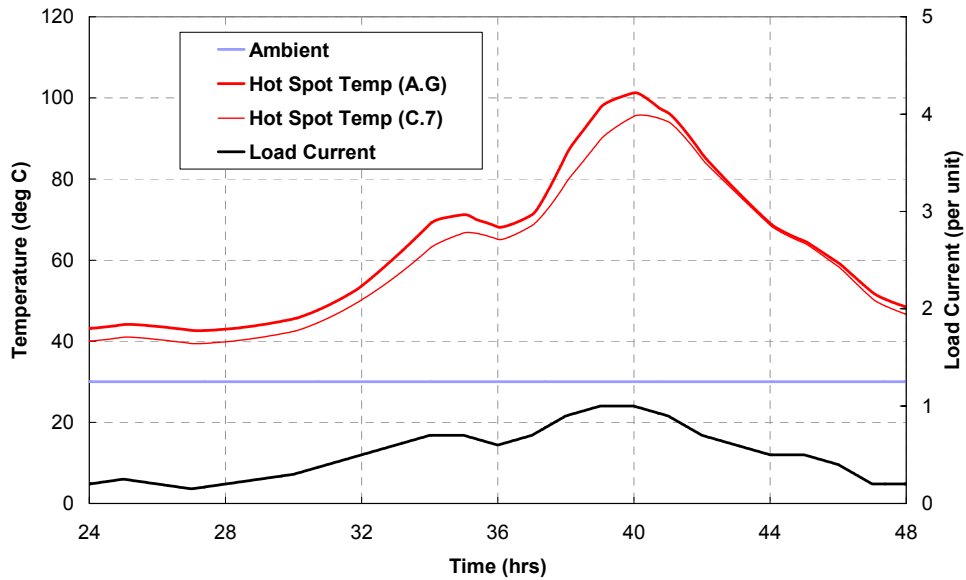


Fig. 3(b)

The maximum error is about 5°C.

FIGURE 3 continued

OFAP COOLING

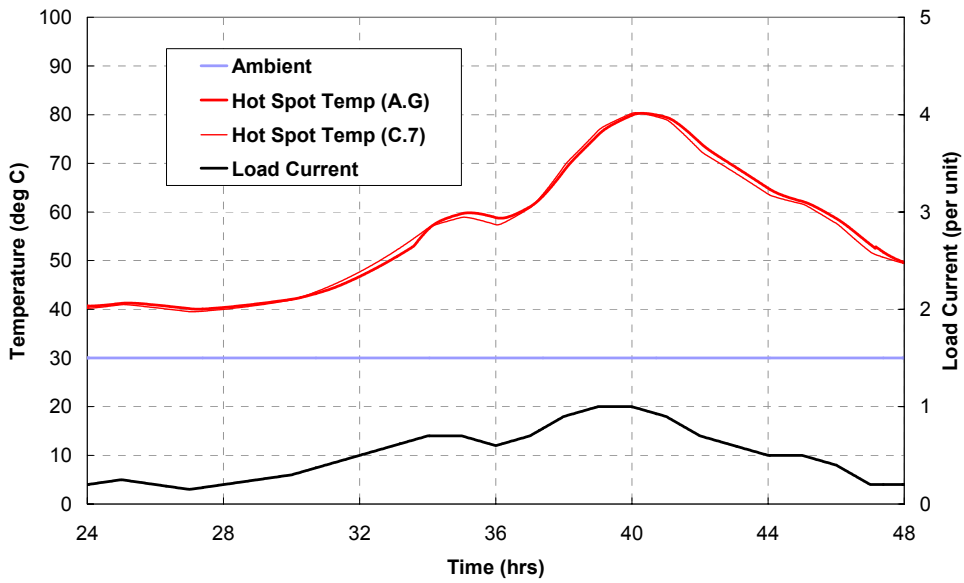


Fig. 3(c)

The error here is negligible.

ODAF COOLING

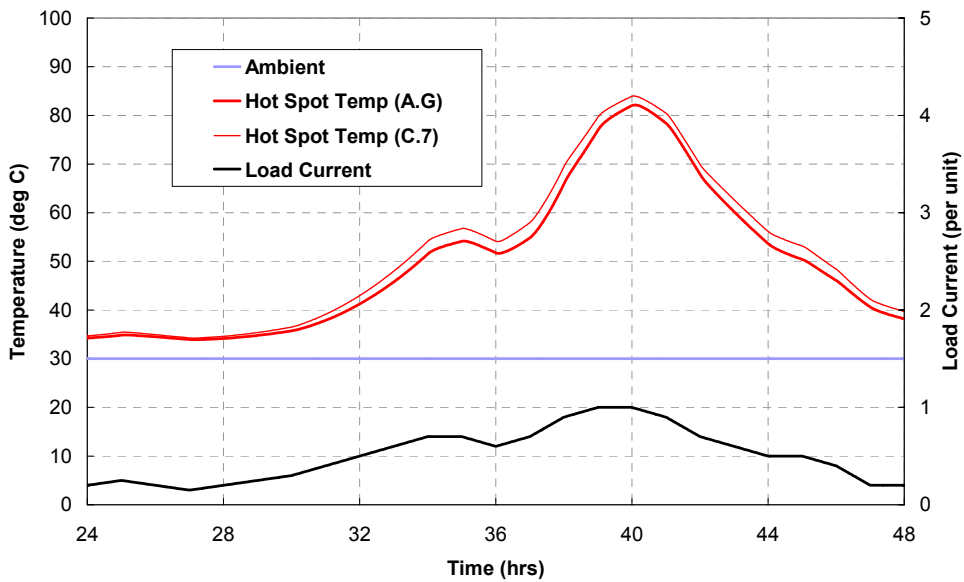


Fig. 3(d)

The error here is probably negligible: around 2°C.

Comparison of Calculated LOSS OF LIFE

Loss of Life during 4-hour Overload

	<u>ONAN</u>	<u>ONAF</u>	<u>OFAF</u>	<u>ODAF</u>
Annex G	4.8 hrs	164.8 hrs	4.0 hrs	91.3 hrs
Clause 7	1.3 hrs	63.7 hrs	4.9 hrs	27.7 hrs

Loss of Life over One Day of Typical Daily Load

	<u>ONAN</u>	<u>ONAF</u>	<u>OFAF</u>	<u>ODAF</u>
Annex G	0.25 hrs	1.11 Hrs	0.15 hrs	0.12 hrs
Clause 7	0.16 hrs	0.66 hrs	0.15 hrs	0.16 hrs

In most cases the two calculation methods yield quite different results, because the equation for *Aging Rate* is very sensitive to the hot spot temperature, *Ths*:

$$\text{Aging Rate} = e^{[15,000/(110+273) - 15,000/(Ths+273)]} \quad [= 1.0 \text{ per unit for } Ths = 110 \text{ }^\circ\text{C}]$$

For every 7 degrees difference in *Ths* the *Aging Rate* doubles (approximately).

Conclusions

At this time, this report is presented for information only. Conclusions will have to be drawn eventually, as to the appropriateness of what direction to take regarding the two methods of calculation.

For the majority of cases, it appears as though the “errors” in using the Clause 7 method are negligible. However, for short duration overloads (<4-6 hours) the differences can be appreciable. In addition, even at steady-state, the Clause 7 method significantly underestimates the temperature rises for ODAF (directed forced oil) cooled transformers.

The Clause 7 method, beginning with its earliest incarnations, neglected the increase in winding resistance with temperature and the decrease in oil viscosity with temperature. This was done to reduce computational effort. It was assumed that the effects of these two components would offset. However, this is not true in directed forced oil situations, as the velocity of oil is dictated mostly by pumping force. Therefore, for ODAF transformers, the increase in winding losses with increased temperatures is not offset by the increase in heat transfer due to the decreased viscosity. The temperature of the winding is therefore higher than would be predicted by the Clause 7 method.

There are two approaches that could be taken:

- 1) Utilize the Annex G method, with some simplifications and a provision for users that do not have a measured bottom oil rise -or-
- 2) Introduce a viscosity and resistance corrections into the Clause 7 method.

Appendix

Transformer Data

	ONAN	ONAF	OFAP	ODAF	
MVA Base for Loss Data	300	300	240	200	MVA
Temperature Base for Loss Data	85	85	75	75	C
Winding I ² R Losses	337560	337560	408871	525072	W
Winding Eddy Losses	0	0	0	0	W
Stray Losses	0	0	0	0	W
Core Losses	102690	102690	67500	54560	W
Cooling Mode Type	1	2	3	4	
Nameplate MVA	300	500	240	224	MVA
Gauranteed Average Winding Rise	65	65	65	65	C
Rated Average Winding Rise	55.4	62.2	49.66	50.6	C
Rated Hot Spot Rise	63.9	75.7	64.66	62.2	C
Rated Top Oil Rise	53.1	50.1	40.32	32.2	C
Rated Bottom Oil Rise	27.5	16.6	37.28	29.2	C
Rated Ambient Temperature	30	30	30	30	C
Winding Conductor	2	2	2	2	
Per Unit Eddy Loss at Winding Hot Spot	0	0	0	0	
Winding Time Constant	5	5	5	5	min
Per Unit Winding Height to Hot Spot	1	1	1	1	
Weight of Core & Coils	286000	286000	291010	225500	lbs
Weight of Tank & Fittings	119000	119000	143300	102600	lbs
Fluid Type	1	1	1	1	
Oil Volume	20200	20200	17708	21696	gals