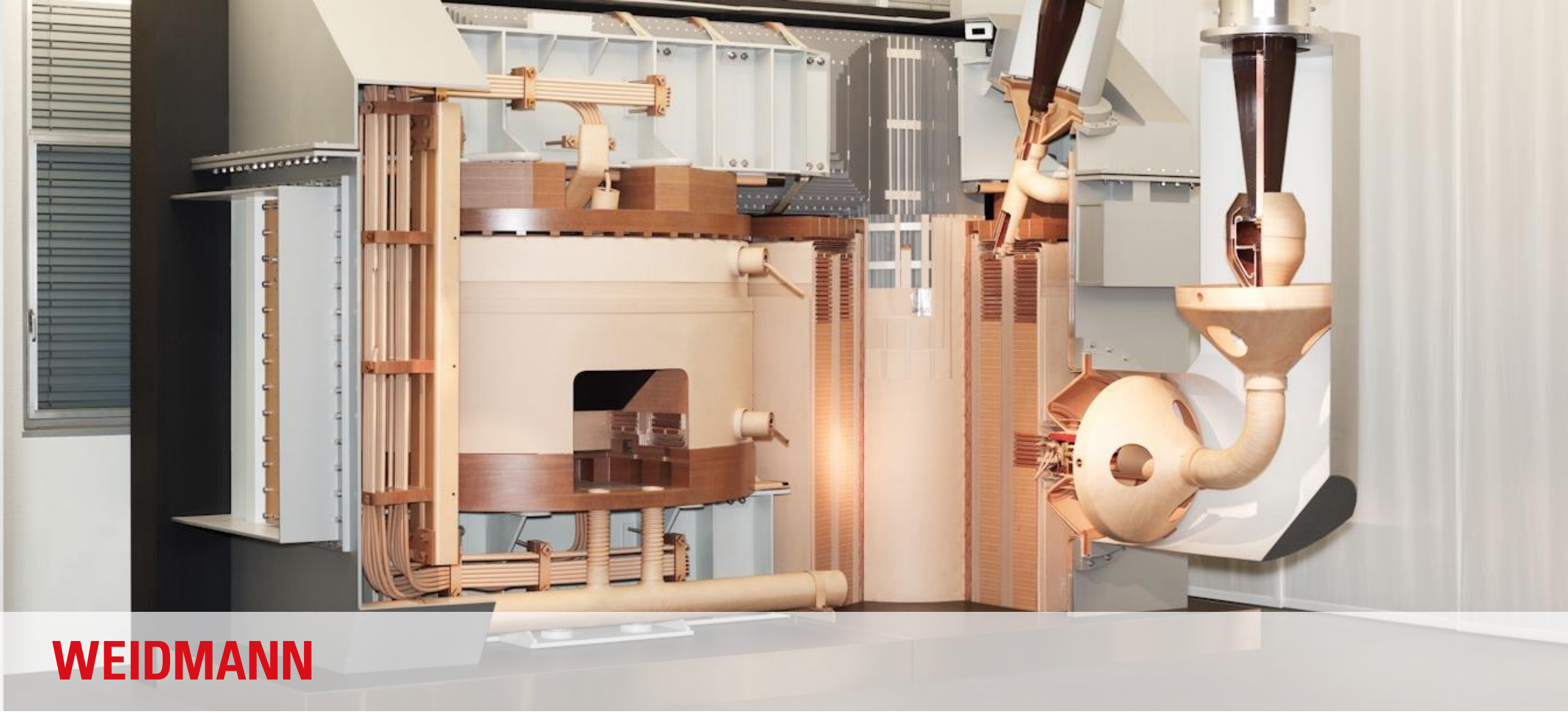

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TOM PREVOST- TRANSFORMER INSULATION THROUGH THE YEARS

WEIDMANN WEBINAR SERIES APRIL 8, 2025

IEEE C57.91

For loading purposes, IEEE Std C57.91 uses a per-unit life equation to develop the loading guide, in the form of Equation (2).

$$\text{PER UNIT LIFE} = Ae^{\left[\frac{B}{T+273}\right]} \tag{2}$$

where

T is the winding hottest spot temperature, °C
A is a constant
B is a constant
e is the base of the natural logarithm

Converting Equation (1) to Equation (3) requires the use of 180 000 h as the normal insulation life. This equation then becomes the following in per unit life form:

$$\text{PER UNIT LIFE} = 9.8\times10^{-18}e^{\left[\frac{B}{T+273}\right]} \tag{3}$$

where

T is the winding hottest spot temperature, °C
e is the base of the natural logarithm

IEEE 1276-2020 GUIDE FOR APPLICATION OF HIGH TEMPERATURE MATERIALS

Table 5—Examples of per-unit life equation constants

		Per-unit life equation constants							
Insulation system temperature	Rated hottest spot winding temperature	Same HIC[a] (6.9°C) as the industry proven insulation system		Slope equal to industry proven insulation system		Slope equal to 20% lower than industry proven insulation system		Slope equal to 20% higher than industry proven insulation system	
°C	°C	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*
120	110	9.80E-18	15 000	9.80E-18	15 000	2.47E-14	12 000	3.88E-21	18 000
130	120	3.59E-18	15 786	2.65E-17	15 000	5.48E-14	12 000	1.28E-20	18 000
140	130	1.31E-18	16 593	6.84E-17	15 000	1.17E-13	12 000	4.00E-20	18 000
155	145	2.91E-19	17 840	2.60E-16	15 000	3.41E-13	12 000	1.99E-19	18 000
180	170	2.36E-20	20 020	1.97E-15	15 000	1.72E-12	12 000	2.26E-18	18 000

[a]HIC = halving interval constant.

IEEE 1276-2020

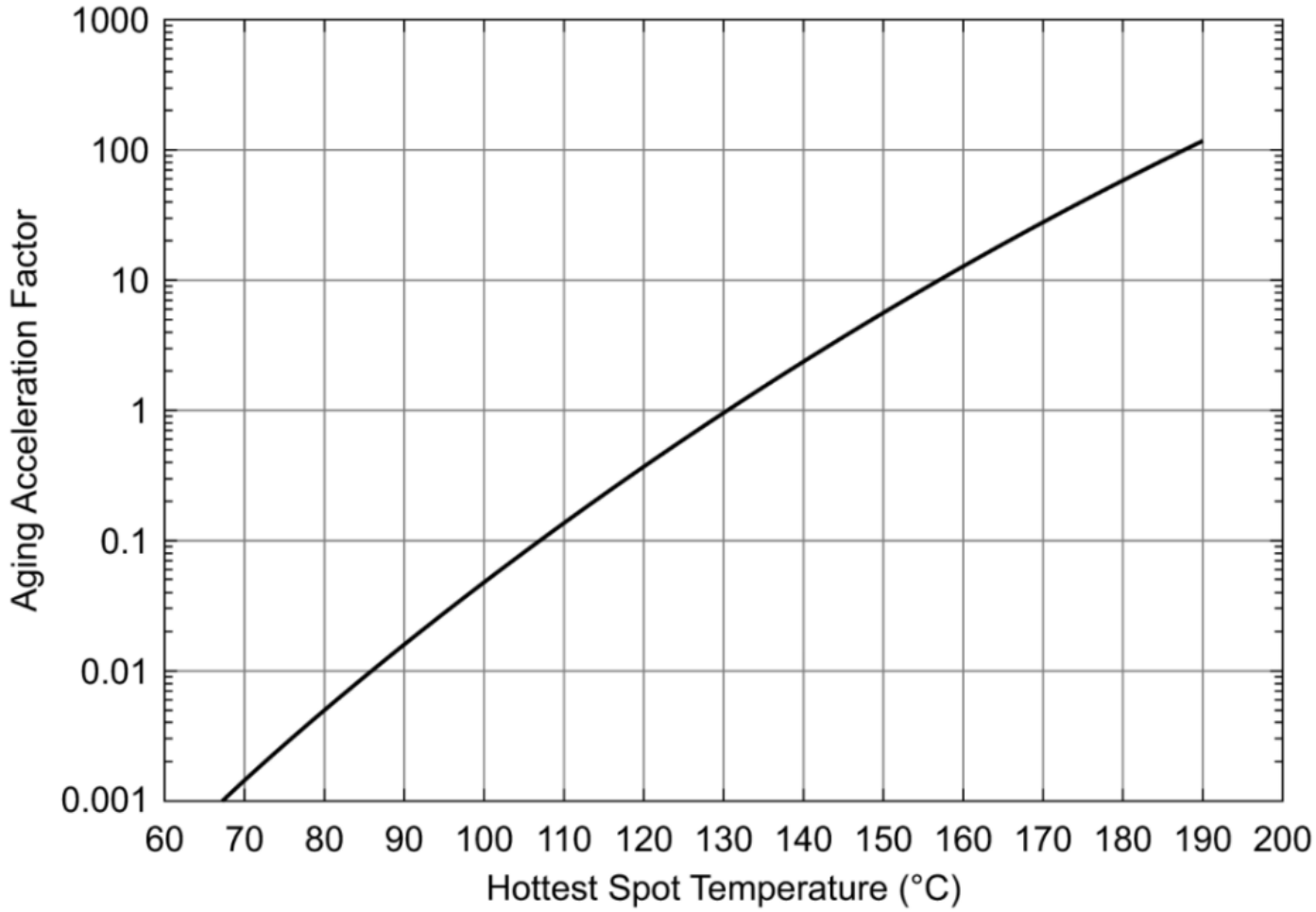
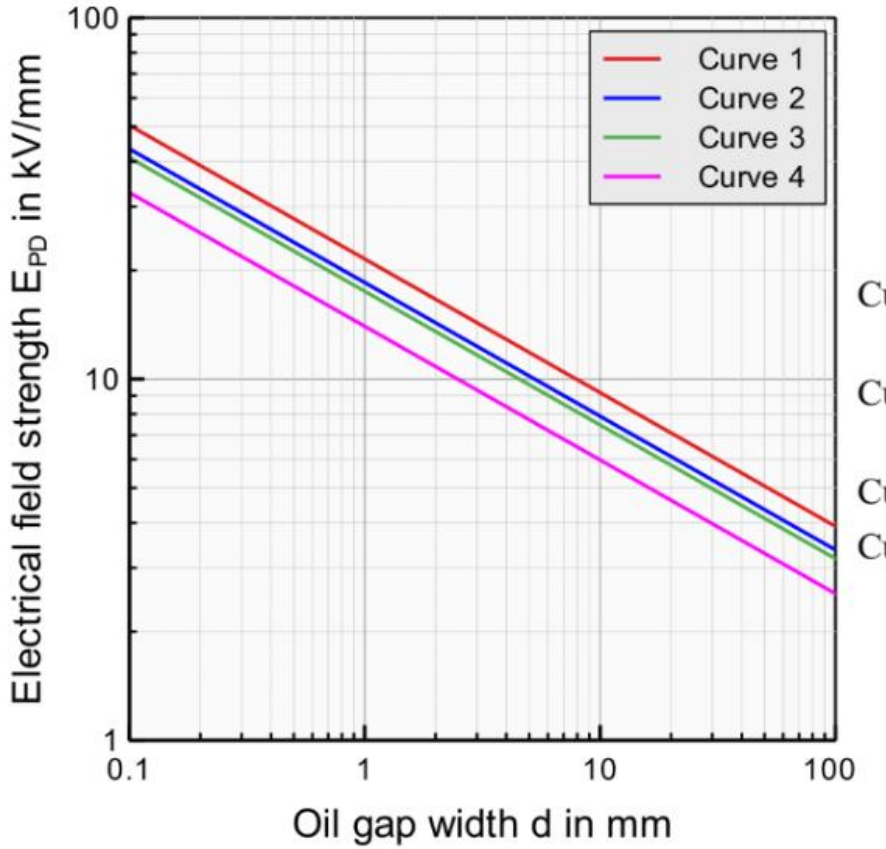


Figure B.9—Aging acceleration factor (relative to 130 °C) versus hottest spot temperatu



Curve 1: degassed mineral oil between Transformerboard barriers

Curve 2: gas-saturated mineral oil between Transformerboard barriers

Curve 3: degassed mineral oil adjacent to winding

Curve 4: gas saturated mineral oil adjacent to winding.

Fig. 4-45 Weidmann design curves as lines of electric field strength in mineral oil gaps with uniform electric field under AC voltage (1 min, 50/60 Hz, RMS value) with a low discharge probability

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Tab. 2-16 Thermal rating of DPE paper (based on IEC standard requirements).

Insulation System	Insulation Material and Liquid	Transformer Average Winding Temperature Rise (AWR), K	Transformer Hot-Spot Temperature Rise, K	System Thermal Class, °C
Industry Proven System	Kraft in mineral oil	65 / 70	78	105
	TUK in mineral oil	75	90	120
DPE System	DPE in mineral oil	85	100	130
	DPE in ester liquid	95	110	140

Tab. 2-17 Thermal rating of DPE paper (based on IEEE standard requirements).

Insulation System	Insulation Material and Liquid	Transformer Average Winding Temperature Rise (AWR), °C	Transformer Hottest Spot Temperature (Thermal Index), °C	System Thermal Class, °C
Industry Proven System	Kraft in mineral oil	55	95	105
	TUK in mineral oil	65	110	120
DPE System	DPE in mineral oil	75	120	130
	DPE in ester liquid	85	130	140

WEIDMANN TRANSFORMERBOARD III

Fig. 2-10 Weidmann's and other manufacturer's paper formation (paper 0.76 mm, 0.75 g/cm³).

Fig. 2-11 Weidmann state-of-the-art paper machine in Urbana, OH, USA.

IEC 60076-7 : 2018

ANNEX A - INSULATION LIFE EXPECTANCY AND RELATIVE AGEING RATE CONSIDERING OXYGEN AND WATER EFFECT

$$\frac{1}{DP_{end}} - \frac{1}{DP_{start}} = A \times t \times e^{-\frac{E_A}{R \times (\theta_h + 273)}} \qquad (A.1)$$

where

DP_{end} is the insulation DP value at the moment of the sampling or the end of life criterion;

DP_{start} is the initial insulation DP value;

A is the pre-exponential factor in 1/h;

E_A is the activation energy in kJ/mol;

t is the life time of a transformer in h;

R is the gas constant in J/(K·mol);

θ_h is the hot-spot temperature, °C.

Table A.1 – Activation energy (E_A) and environment factor (A) for oxidation, hydrolysis

Paper type/ageing parameters		Free from air and 0,5 % moisture	Free from air and 1,5 % moisture	Free from air and 3,5 % moisture	With air and 0,5 % moisture
Non-thermally upgraded paper	A (h^{-1})	$4{,}1 \times 10^{10}$	$1{,}5 \times 10^{11}$	$4{,}5 \times 10^{11}$	$4{,}6 \times 10^{5}$
	E_A (kJ/mol)	128	128	128	89
Thermally upgraded paper	A (h^{-1})	$1{,}6 \times 10^{4}$	$3{,}0 \times 10^{4}$	$6{,}1 \times 10^{4}$	$3{,}2 \times 10^{4}$
	E_A (kJ/mol)	86	86	86	82

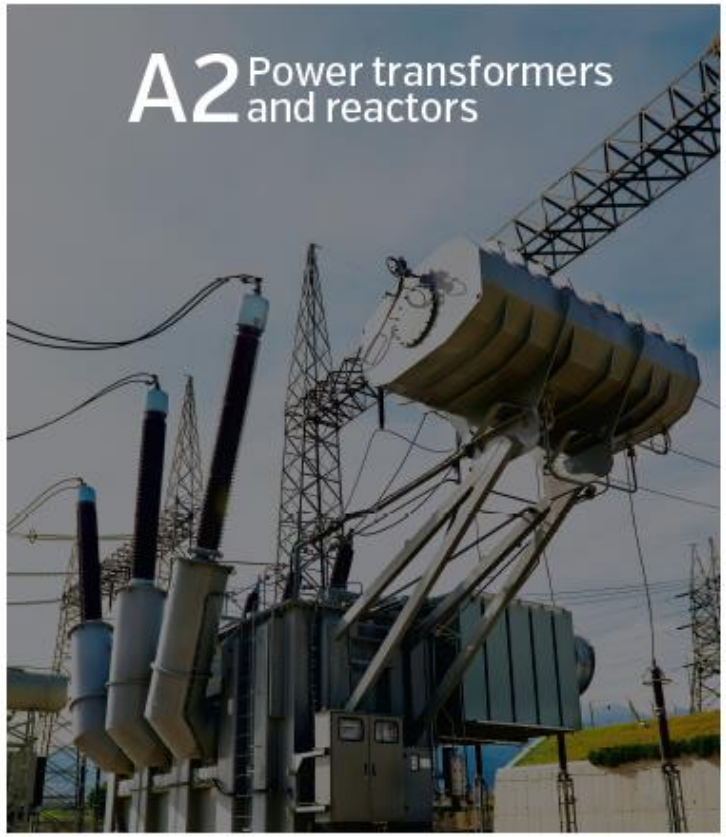
IEC 60076-7 : 2018

ANNEX A - INSULATION LIFE EXPECTANCY AND RELATIVE AGEING RATE CONSIDERING OXYGEN AND WATER EFFECT

Temperature °C	Relative ageing rate, V				
	Table 1	Free from air and 0,5 % moisture	Free from air and 1,5 % moisture	Free from air and 3,5 % moisture	With air and 0,5 % moisture
80	0,036	0,10	0,19	0,38	0,79
86	0,073	0,16	0,31	0,63	1,25
92	0,145	0,26	0,5	1,00	1,97
98	0,282	0,42	0,78	1,59	3,05
104	0,536	0,65	1,22	2,48	4,66
110	**1,00**	**1,00**	**1,88**	**3,81**	**7,02**
116	1,83	1,52	2,84	5,78	10,45
122	3,29	2,27	4,26	8,66	15,36
128	5,8	3,36	6,30	12,82	22,32
134	10,07	4,91	9,22	18,74	32,07
140	17,2	7,11	13,33	27,12	45,60

The relative ageing rates, V, for different ageing factors at temperature of 110 °C are indicated to be compared to the rated insulation condition, i.e. where the relative ageing rate is 1.

CIGRE TECHNICAL BROCHURE 937



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