Hitachi Energy's answer to Question 2.5 is that the experiences of our application of the alternative transformer technology at higher temperatures are very good and transformer standards (IEC 60076-14 / IEEE PC57/144/D7) are still conventional than at upper limits regarding true thermal performance especially when using synthetic ester liquid. We agree to statement of the need to further develope standards for transformer accessories to to have clear rules for their applications along with elevated liquid temperatures.

Hitachi Energy factory in Finland have produced ca. 1000 transformers for windturbines up to 16.7 MVA and 72.5 kV) and tens of offshore transformers for platforms and floaters up to 75 MVA and 145 kV. These transformers have been based on the combination « Aramid insulation + synthetic ester liquid » and designed with conventional liquid temperature and elevated winding hot-spot temperature. Many of these transformers have been equipped with fiber optic sensors and all respective types heat run tested. The experieneces yielded by these transformers (e.g. gassing) are fully in line with the results shown below for a 50 MVA transformer, extra thermally tested during 7 long days.

To further analyze the thermal performance at elevated temperatures, a 3-phase, 50 MVA transformer designed for KFWF-cooling was temporarily equipped with radiators for extra thermal testing at different load currents at KNAN- and KNAF-cooling. The transformer was of semi-hybrid design with Aramid conductor insulation and filled with synthetic ester. It was designed for conventional liquid temperature limits and for winding hot-spot temperatures beyond conventional cellulose temperature limits. The reason for the selection of conventional liquid temperature limits was the limitations of the accessories.

The transformer was equipped with totally 51 thermal sensors (40 fiber optic sensors). The test series comprised 7 days of the length of 16 h. The maximum temperatures obtained during each testing day are shown in Table 1. The limit for hot spot according to IEC 60076-14 for semihybrid design (130 °C in normal cyclic loading and 160 °C for short term emergency loading) were purposely exceeded.

Table 1 – Maximum recorded temperatures during the extra thermal tests.

Testing day	Temperature / °C	
	Top liquid	Winding hot-spot
1	102.8	150.2
2	107.6	172.6
3	106.6	159.1
4	105.6	151.4
5	110.0	172.6
6	68.9	128.3
7	106.0	172.4

Liquid samples were taken at the top of the transformer in the morning of each testing day before the current supply started for the next test. The results are in Table 2.

Table 2 – Dissolved gas-in-liquid during the 7 testing days, µl/l.

Day, at 07:00	Hydrog. H_2	Meth. CH_4	Ethyl. C_2H_4	Ethane C_2H_6	Acetyl. C_2H_2	Carbon Monox. CO	Carbon Diox. CO_2	Total Combust. TCG
1	0.0	0.2	0.3	0.0	0.2	4.2	100	5
2	2.4	0.4	0.3	0.0	0.2	20.0	247	23
3	3.8	0.5	0.4	0.0	0.2	32.1	325	37
4	3.8	1.0	0.5	0.0	0.2	49.5	617	55
5	7.1	1.1	0.6	0.0	0.2	66.8	676	76
6	7.4	1.3	0.6	0.0	0.2	80.3	812	90
7	8.5	1.4	0.6	0.0	0.2	84.7	839	95
8	**8.9**	**1.4**	**0.6**	**0.0**	**0.2**	**95.3**	**883**	**106**
Typical values IEC	≤ 150	≤ 130	≤ 280	≤ 90	≤ 20	≤ 600	≤14000	-
Tresh. Values IEEE	≤ 64	≤ 104	≤ 150	≤ 124	≤ 13	≤ 1344	-	-

It should be noted that the IEC-.typical values in Table 2 are valid for mineral oil (IEC 60599) and the IEEE threshold values are valid for synthetic ester (Table 1 in IEEE Std C57.155-2014).

The test series was made during 3 successive days (11+12+ 13 of May 2021) + 4 successive days (17 + 18 + 19 + 20 of May 2021). The last liquid sample was taken after the whole test series, i.e. in the morning of May 21 (the row Day 8 in Table 2) and then all gas concentrations were farly below the IEC and IEEE values.