The key concepts that this paper deals with are introduced briefly.

2.1 Transformer temperature

As mentioned, the lifetime of a transformer is tied closely to its operating temperature regime. A thorough discussion of how temperature and insulation life are linked through the Arrhenius equation is given in [1], and it is shown that (within the region of interest) for approximately every 6–8 K rise in temperature, the ageing rate of insulation materials increases twofold [2], under certain moisture, oxygen, and insulation age conditions [3].

When talking about temperature in this manner, it is referring to the HST, which can lead to evolution of bubbles. The conductor temperature can become excessively high. This is commonly due to extraordinarily high loading, but potentially for other reasons such as failed cooling systems, or possibly even the coincidence of these factors. If these high temperatures do occur and reach a certain level, then bubbles can be formed at the interface of solid and liquid insulation. The bubbles usually consist of water vapour, generated from water produced through ageing or by migration into the transformer. As water vapour has low electrical withstand strength, the bubbles generated present a risk to the transformer by introducing weaknesses to its insulation system.

Consequently, transformers must be protected against the potential for bubbles to form. There are many ways to achieve this, and one of the most crucial is to ensure that the transformer hot-spot temperature (HST) is operated below a safe limit. However this raises a question – what is that limit?

2.2 Bubble inception temperature

Bubbling in a transformer is driven by increases in energy: as the transformer load increases, so do its losses and thus its temperature, which can lead to evolution of bubbles.

The temperature at which bubbles appear is termed the bubble inception temperature (BIT). It is expected that the location of
bubbles is most likely to be at the hotspot, as this is the location which will first attain the required temperature for bubbling to occur. Note though, that the location of the HST may also be the driest part of the transformer and so wetter areas with increased temperatures could also be high risk.

2.3 Bubbles
A bubble is taken to be a gas within a liquid phase [11]. When talking about bubbles in transformers, this is a gaseous phase within the transformer insulating liquid.

It is well reported in literature that in order to generate a bubble the pressure balance equation shown in (1) must be satisfied [12–16].

\[
p_{\text{int}} = \frac{2\sigma}{r} + p_{\text{ext}}
\]

(1)

where \( p_{\text{int}} \) is the internal pressure, \( p_{\text{ext}} \) is the external pressure, \( r \) is the bubble radius, and \( \sigma \) is the surface tension of the oil–bubble interface.

In simplistic terms, (1) states that the pressure gradient between the inside of the bubble and the bulk medium is balanced by the energy requirement to maintain the surface. This is more easily seen by the rearranged version of the equation given in (2).

\[
p_{\text{int}} - p_{\text{ext}} = \Delta p = \frac{2\sigma}{r}
\]

(2)

Equations (1) and (2) provide another key clue as to how bubbles form. Noting that the denominator in the equation is \( r \); it becomes clear that a bubble cannot be formed from nothing, (the pressure gradient would need to be infinite when \( r = 0 \) ) resultantly bubbles tend not to form in the bulk oil instead they typically form at surface impurities or interfaces [11, 16, 17]. For bubbles in transformers, the solid insulation acts as a trap for released vapour phase molecules which then accumulate and are able to form a bubble [18]. Thus, bubbles are often found to form on the surface of solid insulation, and particularly at surface discontinuities [19]. The surface roughness of different solid insulation can, therefore, have an effect on formation of bubbles. An additional consideration might be the number of overlaps on paper layers. Theoretically, cellulose of greater surface roughness could decrease the energy required to overcome the free energy barrier for bubble formation by increasing the contact angle as described in [11, 20].

2.4 Paper moisture content
The moisture content of solid (paper) insulation is a factor that goes hand-in-glove with transformer bubbling. It is seen in all experimental work done to date that increasing the moisture content of paper insulation leads to a decrease in BIT. This negative correlation is very important when trying to set a correct and meaningful limitation to transformer operation.

It is important, therefore, that a definition of paper moisture content is provided. The term is usually used to mean the amount of moisture (in grams) sorbed per mass of dry, oil-free paper (also in grams), and this is the definition that is used within this report. Typical values of paper moisture content in transformers range from \( \sim 0.5\% \) (newly installed) to around 5\% (end of service age condition) [21–25].

2.5 Transformer operating limits
In order to prevent bubbles forming in transformers, there are many steps that can, and many that should, be taken. One of the most obvious means of doing so (from the narrative above) is to ensure that temperatures do not reach the BIT.

In the 2018 edition of IEC standard 60076-7 [8], there is a maximum permissible temperature of 140°C to prevent formation of bubbles within transformers, and this is the value used by most people. Quoting from the standard, moreover, it should be noted that, when the hot-spot temperature exceeds 140°C, gas bubbles may develop which could jeopardize the dielectric strength of the transformer, [8]

In the previous (2005) edition of the same standard, the wording was slightly different and provided a major caveat to the temperature limit, stating that it applied only for transformers of 2% moisture, and that lower temperatures must be used for higher moisture contents [26]. The 140°C and 2% are placed 'under the microscope' herein.

3 History and development
It is important to understand the history behind the '140°C' value before determining if it is fit for purpose.

After work on bubbles by Kaufmann and colleagues in the late 1970s and early 1980s [27, 28], Heinrichs performed tests on a small scale system attempting to generate bubbles from dry oil and dry paper insulation [29]. He also provided qualitative and quantitative assessment of the contents of the bubbles. In his paper, he suggested a limit of 140°C. To the best of the authors' knowledge this was the first time this value appeared in literature. This suggested limit for temperature appears to have stood the test of time, unquestioned.

After Heinrichs, work carried out by McNutt et al. attempted to formalise the calculation of bubble formation [30], but their work focused mainly on the formation of bubbles within the bulk oil (this work was further refined by Fessler et al. in [31]). In fact, most researchers now appreciate that bubbles as a result of high overloads are generally formed at the oil–paper interface.

Concerns about bubbling seem to have then taken a back seat until around 2001 when it was revived by the work of Oommen and Lindgren [12]. Their study is the backbone of the calculations and discussions presented both in Annex A of IEEE standard C57.91 [7] and in Annex B of IEC standard 60076-14 [32]. Based on an impressive array of experiments which covered key parameters of paper moisture content, oil gas content, and system pressure, Oommen and Lindgren established a formula to calculate the BIT. Using this formula for a gas-free system at 2% moisture of paper, the inception temperature is 142.9°C (based on the pressure used in that study), with increasing gas content in oil expected to drive down the BIT. This work also began a flurry of investigations by other researchers, a timeline of which is shown in Fig. 1.

Later studies continued the initial work, looking into a variety of insulation conditions and alternative insulation materials such as high-temperature insulation.

However, as identified in [33], there is a miscalculation in [31] in the algebraic rearrangement for the vapour pressure of water, \( p_v \) (in torr), in terms of \( W \) (water content of paper in g H₂O / g dry paper), and \( \theta \) (temperature in K).

The formula as presented in [31] was adopted by Oommen and Lindgren as part of their equation for bubble formation [12]. The formula (for gas free systems) ‘as used’ is shown in (3) [32]; the corrected version is in (4).

\[
\theta = \frac{6996.7}{22.454 + 1.4495ln W - ln p_v}
\]

(3)

\[
\theta = \frac{7064.8}{22.95 + 1.4959ln W - ln p_v}
\]

(4)

Fig. 2 shows the plot of the results from (3) and (4). It can be seen that some deviation occurs between the two. At 2% moisture of paper, we see a difference of >8 K (134.5°C versus 142.9°C), and the updated model appears to suggest that limiting operational temperatures to 140°C would be insufficient to prevent bubbling.

Despite its use as a method of calculation for BIT, (4) is constructed from sorption curves and thus only really provides a calculation of the temperature at which moisture desorbs from the paper. By considering the thermodynamics at play, this is not necessarily the temperature at which desorption occurs as a bubble (rather than simply as molecular movement of water into oil) – formation of a bubble will require additional energy input above.
and beyond this, which would be indicated by a higher BIT. For bubbling, the requisite temperature is higher, representing the increased energy demand to form the bubble and maintain its surface (seen in (2)) and so an additional term should be included to achieve this increase. The current formula in [7, 32] has an additional term, as shown in (5), but this only results in reduction of the temperature estimation, and in fact is usually very small [12]. In (5), \( \gamma \) is the gas content of the oil in percentage.

\[
\theta = \frac{6996.7}{22.454 + 1.4493\ln W - \ln p_v - \gamma^{1.585} \exp(0.473 W)} \quad (5)
\]

Our recommendation, therefore, is for the formula presented in the standard to be updated. Such a formula should ideally incorporate all factors which can influence the formation of moisture bubbles from solid insulation; the most prominent factors are discussed throughout this report.

4 Later experimental work

After 2001, several studies have been carried out to develop further understanding of bubble formation in Kraft paper-mineral oil systems [18, 34–37]. A thorough comparison of the experimental conditions and foci is found in [38].

It is significant to note here that most authors do not vary gas content in oil or the system pressure in their tests. Fig. 3 shows a plot of gas-free and ‘nitrogen-saturated’ (assumed value of 8%) systems. The influence of gas content becomes more apparent with increasing moisture content in paper. From around 2% moisture, there is a noticeable difference between the two extreme cases of ‘gas-free’ and ‘gas-saturated’ scenarios. Gas content makes a significant impact only at very high moisture content, that is, at a moisture content beyond that which would reasonably be expected within a transformer (IEEE Standard 62 classified >4.5% as ‘extremely wet’ [22]).

By considering the data in Table 1, the use of 140°C as a limitation is further validated. Table 1 provides a list of the predicted BIT at 2% in each system, the majority of which are above 140°C. Note that the results from [12] are for a gas-free (best case) scenario.

The expected BIT at 1% is also shown. Here, it is seen that temperatures can be much higher than those at 2%, indicating a steep rise in BIT in this region of paper moisture. Results at 1% also seem to show higher variation among studies than at 2%
moisture. Fig. 4 shows a plot of all results from 0.5% to 7% moisture in paper.

In a study on paper ageing under overload conditions, [40] records that bubbles occurred for paper samples prepared to 2% moisture (in mineral oil), but only during tests which reached 160°C (other tests reaching 140 and 150°C were not reported to have generated bubbles).

4.1 Insulation ageing condition

The condition of the insulation is important to the study of bubble formation. Moisture content is identified as a key parameter, but other conditions also contribute to the BIT for a transformer insulation system. Heinrichs' work and the study by Oommen and Lindgren were both done on systems of new oil and paper insulation. The basis of 140°C appears to be reliant on the system having these parameters. However, a system displaying 2% paper moisture with unaged paper and oil insulation is unlikely to occur - in reality the insulation would be aged. Thermal limits on the transformer should take into account these differences as in some cases they can be large.

Przybylek considered the influence of paper ageing on bubble formation [35], and provided the results shown in Fig. 5, which suggests a clear reduction in BIT for aged paper (new paper had degree of polymerisation = 1357; aged paper was lab aged and had degree of polymerisation = 341). The reason proposed is that aged paper is less polar (so less hydrophilic) and hence less strongly binding of water molecules. This outcome accords with the finding that cellulose insulation has less strong affinity for water as it ages, as seen in [35, 41, 42].

Koch and Tenbohlen studied aged oil (the new oil had a total acid number = 0.016 mg KOH/g oil; whereas, the aged oil was aged in-service and had a total acid number = 0.48 mg KOH/g oil) and found the same trend [18], though the reduction in BIT was not as drastic as for paper ageing. Comparing between these two cases is difficult given it is hard to match paper and oil ageing degree (and also because the authors utilised different paper insulation for their studies).

It should be mentioned that the effects of paper ageing on BIT was also looked at in [18], but due to concerns over hornification of the paper (an ageing process which affects the physical structure of cellulose fibres), their results are not included for comparison herein.

From the results of [18, 35], the effect of insulation ageing on BIT at 2% may be large enough to merit reduction of the maximum allowable HST to below 140°C.

4.2 Alternative insulation materials

Kraft paper and mineral oil are not the only options for the insulation material in a transformer. Thermoally upgraded Kraft paper (TUP) and alternative liquids such as ester liquids are used for their higher thermal performance. There are other drivers for using alternative insulation, such as improved environmental performance or fire safety for ester liquids [43–45].

Unlike for Kraft paper-mineral oil systems, there is not much data available for systems of alternative insulation. The studies that are available to date are discussed next.

4.2.1 Alternative solid insulation: There are two studies found which have looked at alternative solid insulation, [18, 39]. Reference [39] looked at Aramid insulation, and [18] used TUP (with no further detail, e.g. brand or N2 content, provided). Both studies found significant difference in the BIT compared to Kraft paper when assessing them at the same moisture level.

Table 2 summarises the BIT at 2% and at 1% moisture from both studies. There is a divergence in the results, however, with [39] witnessing a decrease in BIT for Aramid, whereas [18] see a large increase in BIT for TUP. While it is not necessarily expected that the two different materials (Aramid and TUP) would perform similarly compared to standard Kraft paper, it clearly indicates that more investigation is needed into alternative solid insulation material in order to establish the impact of material selection on BIT and the reasons behind deviations in BIT.

4.2.2 Alternative liquid insulation: Regarding alternative insulating liquids, [36] studied a natural ester in comparison with mineral oil and [46] studied a synthetic ester in comparison with mineral oil. The results show that there is only little deviation in BIT among liquid types. For both natural and synthetic esters, a slightly higher BIT is apparent (~5–6 K).

The results of 1% and 2% moisture are summarised in Table 3 (results from [46] are not shown as the moisture content tested is limited to higher values only).

There are currently no published results that the authors are aware of for bubbling within other liquid insulation types, such as gas-to-liquid oils or silicone oils. As these liquids contribute to the transformer fleet, investigation into these materials should be considered by researchers for future studies.

5 Discussion

With all of this data in hand, the question turns to how to set appropriate limits on transformer HST so as to hinder formation of bubbles and prevent failures.

Based on Table 1, it can be said with a degree of confidence that operating below 140°C will mean that bubbles are not likely to form in the transformer when the paper insulation is at 2% moisture, if it is new. Only two of the numerous studies show a temperature at or below 140°C. Some studies show that 140°C could be setting the limitation overly conservatively, but the two results that are the lowest did allow food for thought. However, as these results are done on ‘new’ insulating paper yet in reality paper may be more aged, there is a need to reduce the temperature limit down from 140°C according to the insulation ageing conditions. In most developed nations, a considerable number of transformers have been in service for many decades [47, 48]; that aged insulation appears to have a lower BIT should, therefore, be of high importance.

It is seen that all results at 1% moisture are certainly far from 140°C, all sitting well above the limit for 2% moisture. The implication here is that a new transformer is safe from bubbling at these conditions. Adoption of a higher limit could even be considered if desirable to release transformer capacity. Here, it is also noted that the IEC loading guide [8] provides thermal limits for a variety of situations. Some of these temperatures are allowed to exceed 140°C; this includes the winding HST and any metallic parts in contact with cellulose insulation material which is allowed to reach 160°C during a short-term emergency loading scenario (for medium / large transformers). This is an obvious contradiction in the operational capability of the asset.

The results of Table 3 indicate that the BIT is slightly elevated in the system when using natural ester compared to the system using mineral oil; however, there is currently an insufficient amount of experimental data available for alternative insulating liquids to assuredly merit the setting of a temperature limitation higher than 140°C. More experiments must be conducted to provide a better picture of the bubbling behaviour within transformers which make use of alternative insulating liquids. The studies conducted to date where different insulating liquids have been considered have discussed the different BIT seen between them. This follows from earlier studies which focussed on the BIT for systems of Kraft paper with mineral oil. However, noting that the thermo-physical properties of the different liquids are dissimilar means that temperature will vary among them for the same energy input. It, therefore, might be more prudent to analyse the energy input to the insulation rather than temperature required to generate bubbles, being more directly comparable.

When considering alternative paper insulation though, the waters are muddy. The main advantage of TUP is that it has a higher rated temperature than standard Kraft paper. However, from the results shown, these alternative solid insulation materials may generate bubbles at temperatures lower than 140°C, although results available are not conclusive. Importantly, the moisture content of different paper insulation differs when exposed to the
same environmental moisture conditions. This means that while at 2% paper moisture content, the limitation for TUP or Aramid may need to be distinct from the 140°C as used for standard Kraft paper. Thus, it is probable that for different paper insulation types, an explicit definition of transformer temperature limits may be needed. Certainly, more work is required to develop a fuller understanding of how to set the threshold temperature values for different insulation materials.

Notably, there is difficulty in comparing different experimental systems (and hence even greater difficulty in translating the results of these experiments to transformers in the field). This is exemplified by considering this statement from [18]:

> The temperature rise is of crucial importance for bubble emission. For low rise rates (<3 K/min), water diffuses into the oil without bubble formation.

The first sentence from the quote seems to be valid, with [37] also finding that when running at a higher rate of change of temperature (RoCoT) the BIT is reduced. However in contradiction of the above, [35] states that a 2 K/min RoCoT was used, yet bubbles were witnessed at temperatures lower than in [18] across the full moisture range. Of course, there are many reasons that could account for this, but all of them come down to the specificity of the different systems. Examples of these reasons are the oil:paper ratio, the paper thickness and paper surface condition, and heater surface area:oil ratio. System pressure (liquid head and any overage from the blanketing system for example) also has influence, as shown by [12]. A further reason could be the oil flow regime: faster oil flow may carry away the moisture more effectively and thus limit bubble forming potential; there could also be differences between laminar and turbulent flow in the effectiveness of local moisture removal (this question was asked of work done in [49], but appears to have gone unanswered since). It is easy to see how this situation becomes even more complex when considering in-service transformers.

The implications from this are not limited to cross-comparison of experimental systems. It follows that the load profile of the transformer is crucial to understanding of bubbling behaviour. High loads may bring about high temperatures, but the rate at which those temperatures are approached can play a part in the likelihood of formation of bubbling. This means that different overload scenarios need to be taken into account when considering the limitations necessary for bubble formation.

Fig. 6 shows the results mentioned from [18] (3 K/min) and [35] (2 K/min), as well as results from [39] (6 K/min). It can be seen that there is no trend between systems for BIT and RoCoT. Increasing the load from one step to another more rapidly causes the temperature to rise more quickly. However for different systems (and for different transformers), the manner of this response is specific to that system. Stated otherwise, within a single system, changing the rate of energy input is equivalent to changing the RoCoT. Across systems, however, the temperature dependence on energy input differs, and as the energy inputs are not stated, a comparison between systems is not possible.

Table 2 Summary comparison of BIT for different solid insulating materials from two experimental datasets

| Dataset       | Kraft paper BIT at 2% (°C) | TUP BIT at 2% (°C) | Kraft paper BIT at 1% (°C) | TUP BIT at 1% (°C) |
|---------------|-----------------------------|-------------------|-----------------------------|-------------------|
| Przybylek [39]| 144.6                       | 125.8             | 174.0                       | 147.9             |
| Koch & Tenbohlen [18] | 156.3                     | 180.7             | 174.8                       | 207.2             |

Table 3 Summary comparison of BIT for different liquid insulation

| Dataset      | Mineral oil BIT at 2% (°C) | Natural ester BIT at 2% (°C) | Mineral oil BIT at 1% (°C) | Natural ester BIT at 1% (°C) |
|--------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Perkasa [36] | 140.0                       | 146.7                       | 161.4                       | 166.0                       |
6 Conclusions

From the above assessment, it is clear that setting of temperature limits on transformer operation is a necessary but complex task. The conclusions of the work done in this area so far suggest the following two main outcomes:

i. Introduction of condition-based limitations appears to be necessary. Here, ‘condition’ relates to solid and liquid insulation age, paper moisture content, and insulation material type (of solid and liquid) as a minimum. Working from one temperature value for all transformers and overall stages of transformer lifetime will result in periods of over-caution (resulting in reduced operational efficiency) and periods of under-caution (potentially leading to scenarios dangerous to the transformer).

ii. There is not enough data available within the literature to make a sound judgement about the temperature limitation which would be suitable for alternative liquids. It has been shown in the handful of studies published to date that there are some situations where the BIT is different between insulation types. However, the results are not yet conclusive.

Further investigation into alternative material types of both solid and liquid insulation is needed. The transformer industry is seeing uptake of alternative insulation materials but it is currently unknown if the existing guidance is suitable for materials which do not fit the ‘normal’ conditions of new Kraft paper and new mineral oil insulation. Likewise, the 140°C is challenged here even for the base scenario of Kraft paper and mineral oil systems, with requirement to establish a better picture of how loading, temperature rise, and transformer condition may affect this value. Finally, it seems prudent to investigate further the idea that a limit based on the energy required to form a bubble in place of or in addition to temperature required could bring about a significant improvement in prevention of bubbles in transformers, while opening up their loading capacity.

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