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SEPARATION OF AGEING AND MOISTURE IMPACTS ON TRANSFORMER INSULATION DEGRADATION BY POLARISATION MEASUREMENTS

by

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SUMMARY

This paper describes an accelerated ageing experiment of transformer oil/paper insulation with preset moisture levels. These samples were tested with return voltage and polarisation/depolarisation measurements. Molecular weight has also been measured with Gel Permeation Chromatography (GPC). Results suggested the impact of moisture on the ageing of oil/paper insulation. An attempt has been made regarding the separation of ageing and moisture on oil/paper insulation using the dielectric polarisation measurements.

KEYWORDS

Transformer ageing, Oil Paper Insulation, moisture and ageing, return voltage, polarisation and depolarisation current, Molecular weight measurement, GPC technique.

1. INTRODUCTION

The insulation system in a power transformer degrades under normal operating conditions, in particular with higher temperature, higher moisture and oxidation. The remnant life of a transformer is significantly influenced by the condition of solid insulation. Currently, degradation of insulation in a transformer is monitored by sampling the oil and analysing for dissolved gases, furan content and by examining the change in the degree of polymerisation (DP) of cellulosic paper. In current deregulated electricity markets, non-destructive diagnostic techniques are becoming more and more popular for condition-based maintenance of aged transformers.

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In recent years, some important works have been published in dielectric polarisation measurement by a number of teams [1] [2] [3] [4]. These studies have shown that dielectric response measurements could be used as an effective tool for transformer condition assessment.

In our past research projects, the recovery voltage (RV) measurement technique was developed and extensively used for the assessment of insulation condition in aged transformers. This technique was found to be sensitive to moisture and insulation ageing. We have also developed a technique for the measurement of molecular weight by Gel Permeation Chromatography (GPC). We investigated accelerated aged paper and pressboard insulation samples and samples from failed transformers using the RV and GPC techniques. A good correlation between the return voltage parameters and molecular weight distribution of the cellulose insulation was observed [5]. Then a number of accelerated ageing experiments were conducted at temperatures 115° to 145°C and at controlled conditions of moisture and oxygen/nitrogen. The objectives of these experiments were to study the nature of paper degradation, the deterioration of its electrical, chemical and mechanical properties. The results obtained from these measurements of controlled accelerated aged samples were published in a number of papers [6] [4]. The main question regarding the separate impact of moisture and ageing on RV results still remained unanswered.

To investigate the separation of ageing and moisture impacts on polarisation measurements we have conducted a number of accelerated ageing experiments at 115° C with known discrete moisture levels. The insulation samples were then analysed by a number of recently developed techniques. These include: RV measurements, polarisation/depolarisation current measurements and molecular weight measurements by the GPC technique. This investigation is very significant in terms of understanding the separation of ageing and moisture effects on insulation. This paper will help to understand the service ageing of transformers insulation due to moisture and high temperature. This will also emphasise changes of dielectric properties due to degradation from moisture and high temperature. We have extensively investigated these phenomena and a number of constraints encountered during these ageing experiments will be presented. Some comparison between the measured electrical and chemical properties will also be attempted in this paper.

2. EXPERIMENT

2.1 Moisture Conditioning

A method was developed to control the moisture level of insulation paper using Piper chart [7] [8] [2]. In this method, a set value of paper moisture level was achieved by controlling the pressure of water vapour and temperature inside a closed container for a long period of time. To implement the moisture conditioning process, a vessel was designed for accommodating more than thirty paper-insulated conductor samples. Figure 1 shows the glass vessel for conditioning a large number of samples.

The paper-insulated conductors (section size 12×2.5 mm) are cut into 205 mm length segments from the standard-winding conductors used for transformer manufacturing.

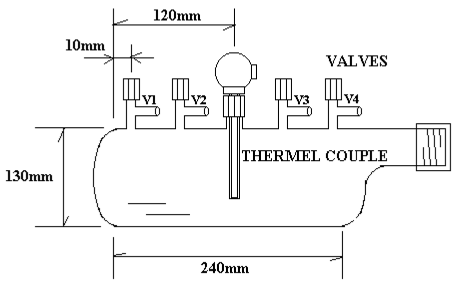

Figure 1: Moisture Conditioning Vessel

Valve connections in Figure 1: V1 is connected to water vapour supply, V2 to pressure gauge, V3 to oil supply, V4 to vacuum pump. The conditioning glass vessel was placed in a rectangular aluminum container with thermal insulation on the walls, with the bottom in direct contact with the heating block. Oil was placed between the vessel and the aluminum container to enable better heat transfer.

During the moisture conditioning, samples are first dried at 100°C in a vacuum of 10^{-3} Torr. After this, the temperature inside the vessel is reset to a lower value for conditioning. Then water vapour is supplied to the vessel from the water bottle that contains degassed water (while the entire system is a closed system). Great care is taken at the beginning of the water vapour supply, as the water is above its boiling point under such low pressure. The desired moisture level can be achieved by controlling the water vapour pressure and the temperature at fixed values for a sufficiently long period, for instance, more than one week. As an example, by maintaining the water vapour pressure at 6.5 Torr and the temperature at 50°C in the vessel with a sufficiently long absorption time, 2% moisture content in paper can be achieved.

After the moisture level was attained, degassed and dry transformer oil (Shell Diala B) is injected into the vessel. After the equilibrium in oil/paper is achieved (normally it requires about one week) samples were transferred to a test cell for RV and polarisation/depolarisation current measurement Measurements were performed at a temperature of 30°C and at 60% humidity in a temperature/humidity controlled cabinet.

2.2 Ageing Samples

To perform ageing experiments moisture conditioned conductor samples and oil were transferred from the conditioning vessel to the ageing ampoules after oil/paper equilibrium was achieved. The ampoules were subsequently placed in a controlled temperature oven for three selected periods of ageing: 42, 83 and 125 days. The temperature of the oven was set to 115°C during the ageing period. After completion of the ageing according to the set period, the ampoules were taken out of the oven and placed into a humidity-controlled room. After cooling down, the ageing samples and oil was transferred into the test cells for dielectric response measurement. The moisture content of paper and oil after ageing was also tested by the Karl Fischer titration method. The paper from the ageing sample was collected to perform gel permeation chromatography (GPC) measurement for molecular weight distribution of paper.

2.3 Polarisation measurement System

To perform dielectric response measurements, a new computer controlled measurement system was developed which is capable of performing RV (guarded or unguarded) and polarisation and depolarisation current measurements. The new system is equipped with a laptop computer, a GPIB Interface card, a model 6517A High Resistance Electrometer with in-built DC Voltage Source, a control 488/16 16-channel with PCAC2 Switch Module Power Control Interface, and two High Voltage Relays ES-25-DT-25-0-32-BD and E-12-DT-12-0-32-BD, etc. The software used to control this system has been designed using LabView graphical language.

3. RESULTS

The moisture conditioning experiments were performed at 2%, 4% and 5% preset levels. After the conditioning is completed, papers from conductor samples were tested with Karl Fischer titration. Due to some unknown reasons the 5% sample was corrupted during the conditioning and hence 5% samples were prepared again in a second batch. The ageing experiments with 5% samples are now in progress. The moisture measurement result is shown in Table 1. It is observed that the 2 and 5 % sample results are very close to the preset value while the 4% result is lower than the preset value and was 3%. The reason for the 4% not achieving the preset level could be due to conditioning time not being long enough. As many samples were in the conditioning vessel, the conditioning requires a relatively longer time. Hence 4% moisture preset samples will now be identified as 3% samples. In Table 1, oil test results are also reported. These oils were injected into the conditioning vessel at the end of the conditionings.

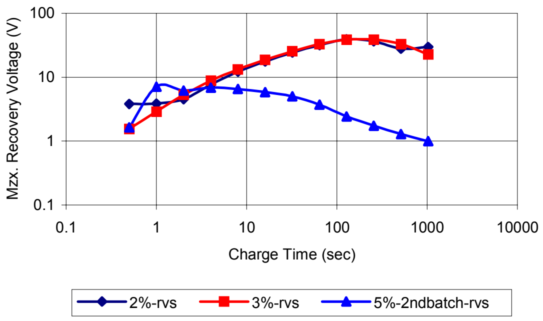

Figure 2. Max. Return Voltage Spectra of Moisture Conditioned Samples (unaged)

Table 1. Paper and Oil Moisture Content Test Results for unaged samples

Sample's Preset Moisture Content (%)	Paper Moisture from KFT (%)	Oil Moisture Content from KFT (PPM)
2	2	< 10
4	3	< 10
5 (2nd batch)	5.3	6

RV and polarisation/depolarisation current measurements on 2%, 3% and 5% unaged samples have been carried out, where samples (with two paper wrapped conductors placed side by side to form the specimen) are placed in individual test cell with the same oil/paper ratios. The charging (polarisation) voltage used in these measurements was 500 volt DC. Return voltage spectra are presented in Figure 2. The important values from the RVM are shown in Table 2. From Figure 2 and Table 2, we can see for the 5% sample, the Central time constant is located in the smaller time range; on the other hand 2% and 3% moisture level sample's Central time constants are located in the larger time range. It is very interesting to see that there was little difference in the results for the 2% and 3% samples.

The 10,000-second polarisation current measurement results on moisture-conditioned samples are presented in Figure 3. From Figure 3 it can be seen that the amplitude of long term DC polarisation current is very sensitive to the moisture content in paper insulation. This demonstrates that polarisation current measurement can be used for assessing the paper insulation moisture level.

After the ageing is completed, paper from samples is tested with Karl Fischer titration (KFT). Table 3 presents the KFT results for 2% unaged and aged samples.

Table 2: RVM Results of Moisture Conditioned unaged Samples

Sample's Moisture Content (%)	Peak Max. Return Voltage (V)	Central Time Constant (sec)	Initial Slope (V/s)
2	39.0	262	0.46
3	38.9	266	0.44
5	7.1	21	3.37

The moisture content of paper is increased after ageing. The increasing moisture may come from the thermal degradation of cellulose, formation of acids, and oxidised products from the oilpaper system.

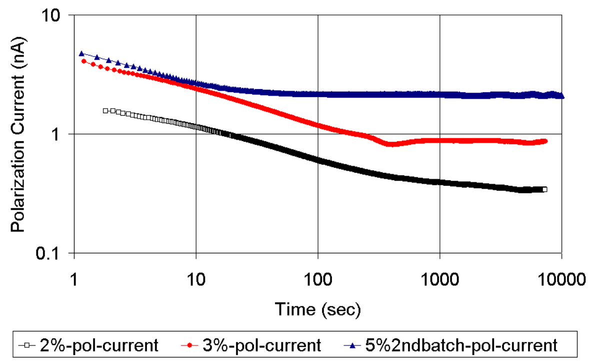

Figure 3. Polarisation Curves of Moisture Conditioned Samples

Table 3: Paper Moisture Content Test Results from Unaged and Aged Samples

Sample's Preset Moisture Content & Days of Ageing at 115 °C	Paper Moisture from KFT (%)
2%-unaged	2
2%--42days	4.7
2%--83days	4.7
2%--125days	6.8

Figure 4 shows the Max. Return Voltage spectra from the aged samples together with the unaged moisture sample. The important values from the RVM are also summarized in Table 4. From the spectra in Figure 4, it can be seen that the time to peak for the maximum return voltage of all the samples are in a similar time range. From Table 4, it can be seen that the central time constant of 2%-42 days sample is 242 sec which is very close to the 2% sample's central time constant 262 sec.

From the same table it also can be seen that the central time constant of 2%-83 days is 89 sec and 2%-125 days is 121 sec. These values are 50% reduced from the 2% unaged samples. The above results seem to suggest that the condition of insulation of 2%-42 days ageing is not much different compared to the unaged 2% sample, while the condition of the 2%-83 days is closer to the 2%--125 days one. As the moisture of the paper sample after 42 days was close to that of 83 days, one would expect similar central time constants. However the results show a significant difference. We find it very difficult to explain.

The 10,000-second polarisation current measurement results on 2% aged samples together with the 2% un-aged sample's current (as reference) are presented in Figure 5. From the currents in Figure 5, we can see that the charging currents for ageing samples are significantly higher than the unaged 2% moisture sample. This indicates that the polarisation current can provide better indication at the ageing of the paper insulation. However, the difference in long term DC current among the aged samples of different ageing periods was not as significant as would have been expected.

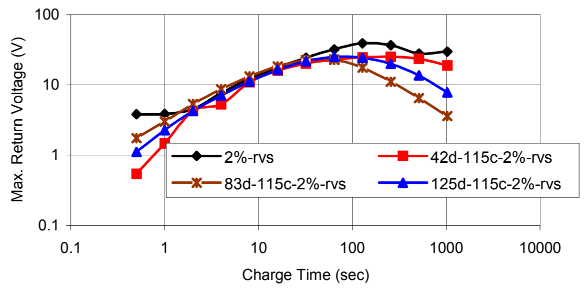

Figure 4. Max. Return Voltage Spectra of 2% Moisture Conditioned Samples

The 3% ageing samples' KFT results are shown in Table 5 together with the 3% moisture conditioned one. It can be seen again that the moisture content of paper increased after ageing. However, the increase in moisture after 83 and 125 days was lower than that of 42 days ageing sample. This appears to be unusual and hence all possible problems were investigated very carefully. It was found that the temperature inside the oven was dependent on the location.

At some locations, the difference was ±5°C from the set point 115 °C. Due to this uneven temperature distribution inside the ageing oven, the samples' ageing progress was affected. This caused some unexpected results as shown from the KFT, RV and polarisation current measurement. RVM was performed on these aged samples and Figure 6 shows the Max. Return Voltage spectra from the aged samples together with the unaged moisture sample.

The important values from the RVM are also summarized in Table 6. From Figure 6 and Table 6, we can see that the time constant of unaged sample and aged samples are significantly different, where 3% unaged sample's central time constant was 266 sec compared to 53.3 sec for 3%--42 days.

Table 4: RVM Results of 2% Moisture Conditioned Sample and Aged Samples

Sample's Moisture Content & Days of Ageing at 115 °C	Peak Max. Return Voltage (V)	Central Time Constant (sec)	Initial Slope (V/s)
2%	39.0	262	0.46
2%--42days	25.1	242	0.20
2%--83days	22.8	89	0.45
2%--125days	25.0	121	0.35

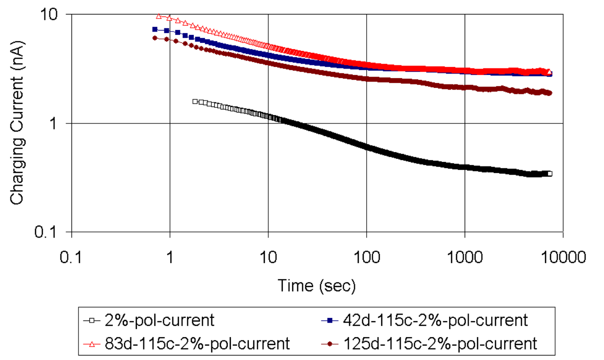

Figure 5. Polarisation Curves of 2% Aged and Moisture Conditioned Samples

The 3%--83 days and 3%--125 days had central time constants 115 sec and 112 sec respectively, which was higher than the 3%--42 days. This might be due to the uneven temperature distribution in the ageing oven, which suggested that the ageing ampoules for these two ageing periods was placed in low temperature zone compared to 42 days. In general the RV results of 3% unaged and aged samples showed better separation between ageing and moisture than the 2% samples.

The 10,000-second polarisation current measurement results are presented in Figure 7. From the Figure, it can be seen that the long-term DC current amplitude of the 3% unaged samples is significantly different than that of the 3%-42 days aged sample. The long-term DC Charging Current for the 3%--83 days and 3%--125 days are lower than that for the 3%--42 days. This is possibly because of the uneven temperature distribution in the ageing oven, which produces a lower moisture level than the 42 days ageing sample. This group of experiments also proves how difficult it is to separate the impacts of ageing and moisture on polarisation parameters.

Table 5: Paper Moisture Content Test Results from Unaged and Aged Samples

Sample's Preset Moisture Content & Days of Ageing at 115 °C	Paper Moisture from KFT (%)
3%	3
3%--42days	4.5
3%--83days	3.7
3%--125days	3.3

4. DISCUSSION OF RESULTS

One would expect that increasing moisture would be produced after longer periods of ageing at the same temperature. The uneven distribution of temperature in the ageing oven has produced some anomaly in this moisture production.

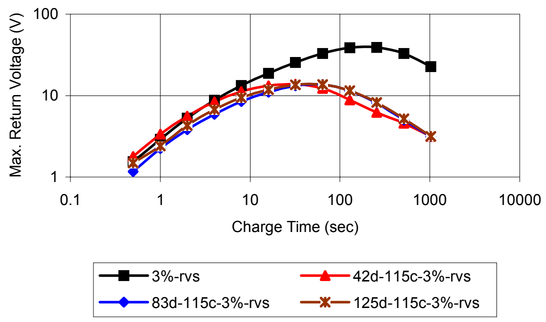

Figure 6. Max. Return Voltage Spectra of 3% Moisture Conditioned Samples

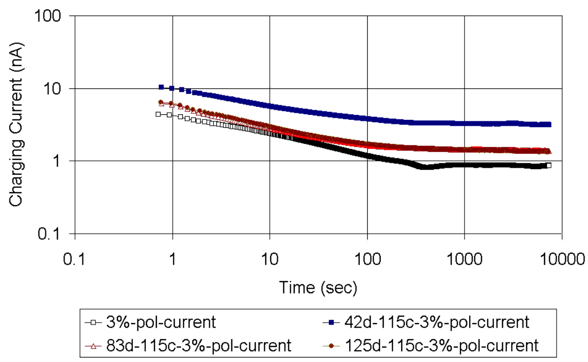

Figure 7. Polarisation Curves of 3% Aged and Moisture Conditioned Samples

Table 6: RVM Results of 3% Moisture Conditioned Sample and Aged Samples

Sample's Moisture Content & Days of Ageing at 115 °C	Peak Max. Return Voltage (V)	Central Time Constant (sec)	Initial Slope (V/s)
3%	38.9	266	0.44
3%--42 days	13.8	53.3	0.47
3%--83 days	13.7	115	0.22
3%--125 days	13.7	112	0.23

The dielectric measurement results are influenced by the oil conductivity, dielectric response function and the paper conductivity. The long term DC conduction current from the polarisation measurement normally relates to the paper conductivity, while the short term current magnitude relates to the oil conductivity. To explain this, polarisation current from short charging times may provide a better indication of the oil condition. Figure 8 provides the 4 seconds charging cycle polarisation current measurement.

From the above figure, we can see that the Charging Currents for all the aged samples are located above or close to the unaged 5% current curve. Figure 8 is a bit difficult to read. To present a trend of the differences between the Charging Currents of the unaged and aged samples, Figure 9 is presented with some selected current measurements.

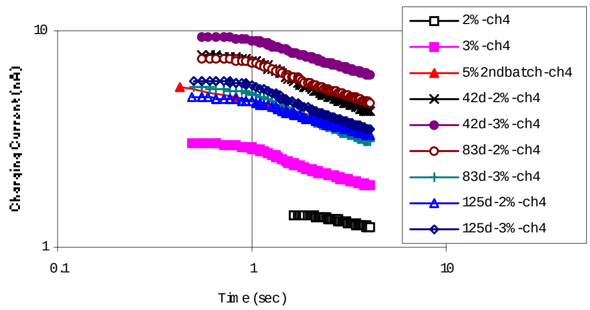

Figure 8. Comparison of Charging Currents (from 4 sec charging) on Unaged and Aged Samples

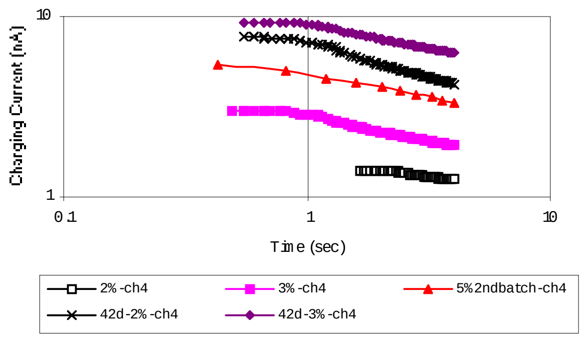

Figure 9. Comparison of 4 sec Charging Current (from 4 sec charging cycle of RVM) on Unaged and Aged Samples—A Trend from Figure 8

Figure 9 clearly shows that the oil conductivity of the 2% unaged sample is comparatively lower than the 3% and 5% moisture oil. Similarly 3% 42 days aged sample oil has higher oil conductivity than the 2% 42 days ageing sample. Table 7 shows the calculated values of paper and oil conductivity from the polarisation/depolarisation current measurements [9].

Table 7: Paper and oil conductivity for some selected samples.

Dry S/m	2% H_2O S/m	3% H_2O S/m	5% H_2O S/m	2% H_2O 43days Ageing S/m	3% H_2O 43days Ageing S/m	Oil/ Paper
2.2×10^{-13}	3.4×10^{-13}	2.62×10^{-12}	7.74×10^{-12}	8.79×10^{-12}	1.33×10^{-11}	Oil
5.8×10^{-15}	4.4×10^{-13}	1.046×10^{-12}	3.1×10^{-12}	3.9×10^{-12}	5.6×10^{-12}	Paper

5. MOLECULAR WEIGHT MEASUREMENTS BY (GPC) ANALYSIS

Prior to molecular weight measurement, the cellulose in the paper samples (which is the major component, and that responsible for providing the mechanical strength of the paper) was converted to the cellulose tricarbanilate derivative using the method described previously by Hill et. al. [5]. After purification of the cellulose tricarbanilate, it was subjected to molecular weight analysis by Gel permeation Chromatography at room temperature using tetrahydrofuran as the eluent.

A typical GPC chromatogram with molecular weight distributions for a new paper and a 25 years old transformer paper is shown in Figure 10. Figure 10 shows that the higher the elution volume the lower is the molecular weight. As the paper is 25 years old, the peak molecular weight has been significantly reduced and the shape also changes significantly. Two average molecular weights are commonly used.

Number average molecular weight: $M_N = \Sigma(n_i M_i)/\Sigma n_i$

Weight average molecular weight: $M_W = \Sigma(n_i M_i^2)/\Sigma n_i M_i$

Where, n_i is the number of chains of mass M_i.

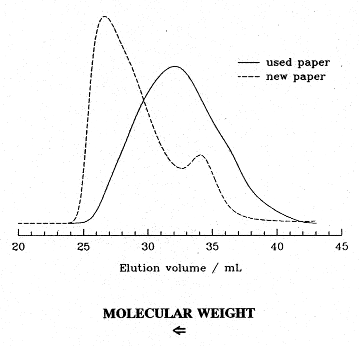

Figure 10: GPC Chromatograms of a new and old paper.

Table 8: Molecular weights of 2 and 3% ageing samples

Samples	M_w	M_n	Dispersion $[M_w/M_n]$
NEW	582365	179632	3.2
2% 42 days	566767	220117	2.5
2%83 days	504893	148530	3.4
2%125days	499330	136675	3.6
3% 42 days	468925	120547	3.8
3%83 days	434485	114445	3.8
3%125days	422752	107110	3.9

The molecular weight results are presented in Table 8. The molecular weight of the aged samples decreased slightly as they aged with 2% moisture content. However, the molecular weight dropped significantly as they are aged when the amount of moisture present increased to 3%. This result is more consistent than those obtained from the RV measurement.

6 CONCLUSIONS

An attempt has been made to separate the ageing and moisture effects on the polarisation measurements. The major hurdle in analysing this was some uneven temperature distribution inside the oven. Otherwise, the trend of producing higher moisture from ageing at higher temperature for longer periods is generally reflected in both the polarisation current and RV results. The polarisation current has been found to be very sensitive to moisture. The oil and paper conductivity have both been found to be sensitive to moisture and ageing. Similarly the central time constant has been found to be sensitive to moisture and ageing as well. When the higher moisture is produced from ageing, it is understood that the moisture and ageing become inseparable. However, the comparison of unaged and aged samples produced some interesting results. From the molecular weight measurements both weight-average and number-average molecular weights show small reductions for 2% moisture aged samples, while there is a significant reduction in molecular weight for the 3% moisture aged samples. Further research is in progress and the current problems will be resolved with better-designed controlled experiments. Modelling of polarisation processes are in progress and this will also help to investigate this separation of ageing and moisture impacts. Finally, our current investigation will be extended to correlate polarisation measurement results with a number of chemical test results. This will be particularly useful for predicting remaining life of transformers insulation.

7 ACKNOWLEDGEMENTS

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