Moisture in Transformer Oil Behavior

A deeper look into a complex phenomenon

Steven Jiroutek
Vaisala Inc.

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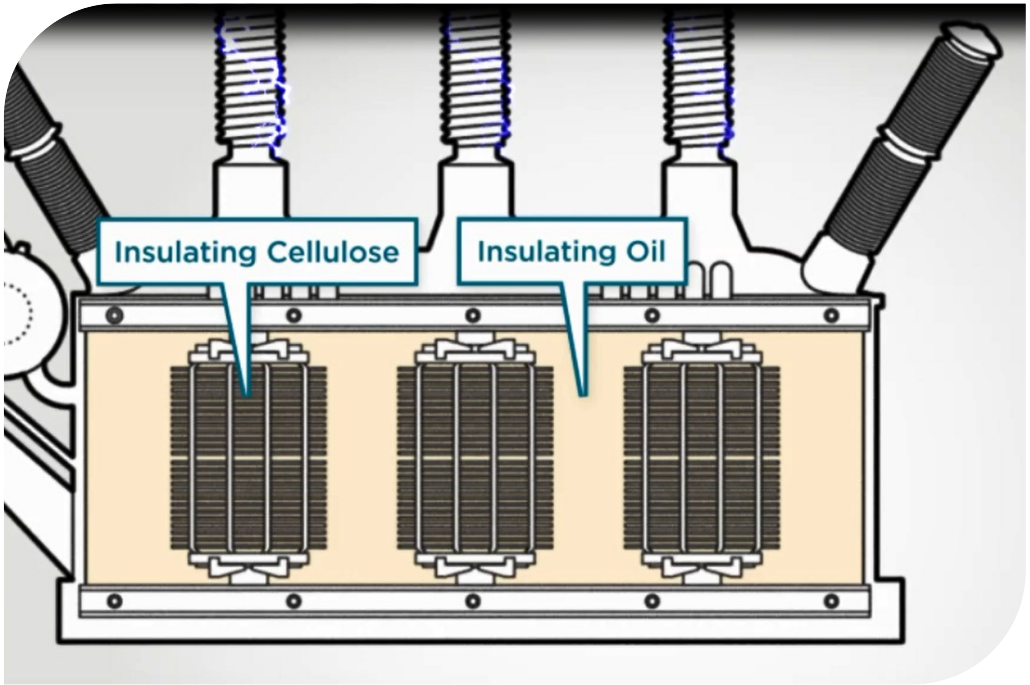
Transformers & Moisture

Transformers and moisture

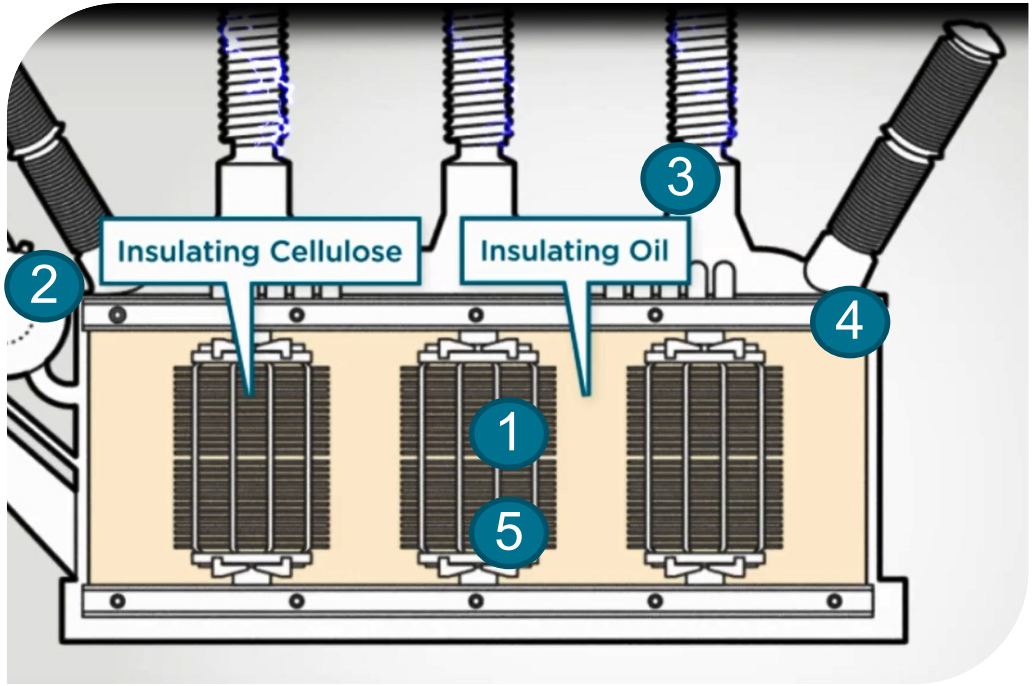
- Transformer windings are insulated with cellulose and surrounded by oil to ensure proper insulation and cooling.

- The insulation must be dry, because moisture
  1. Decreases the dielectric strength
  2. Accelerates cellulose decomposition (ageing)
  3. Increases risk of bubble formation at high temperatures
  4. Can condense during cool down.



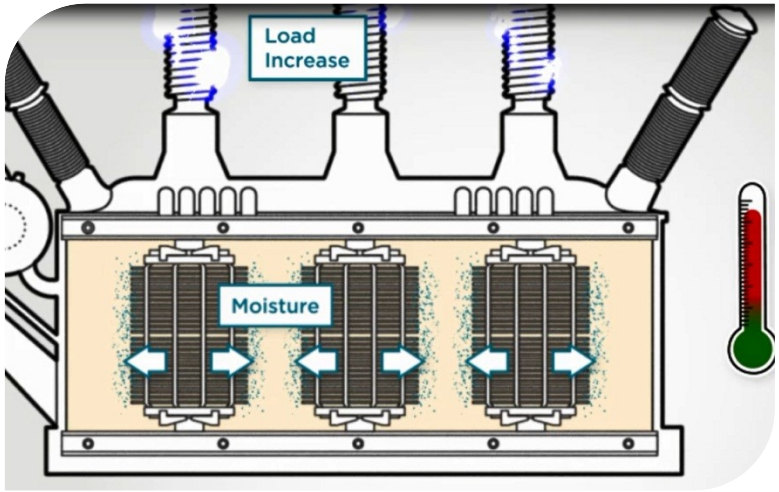
Moisture sources

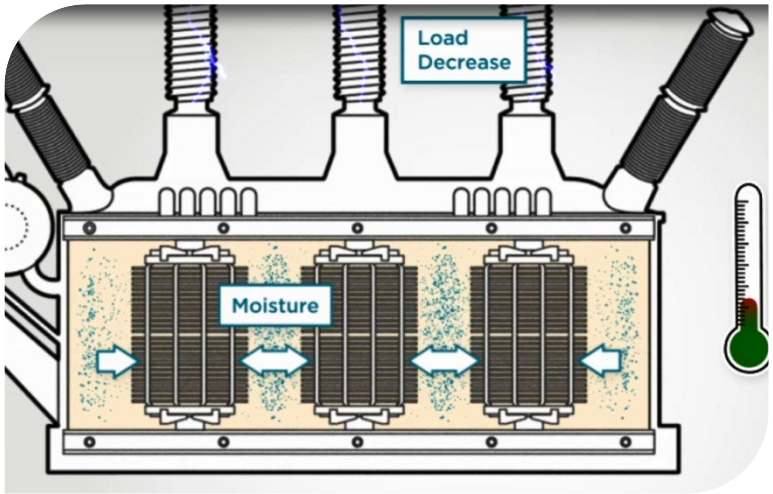
1. Residual moisture
2. From the atmosphere i.e. breathing during load cycles (e.g. saturated dehydrating breathers).
3. Through poor seals by the flow of moist air (created by a total pressure gradient).
4. During installation and / or repair
5. Water formed as the paper insulation ages



Moisture in solid insulation

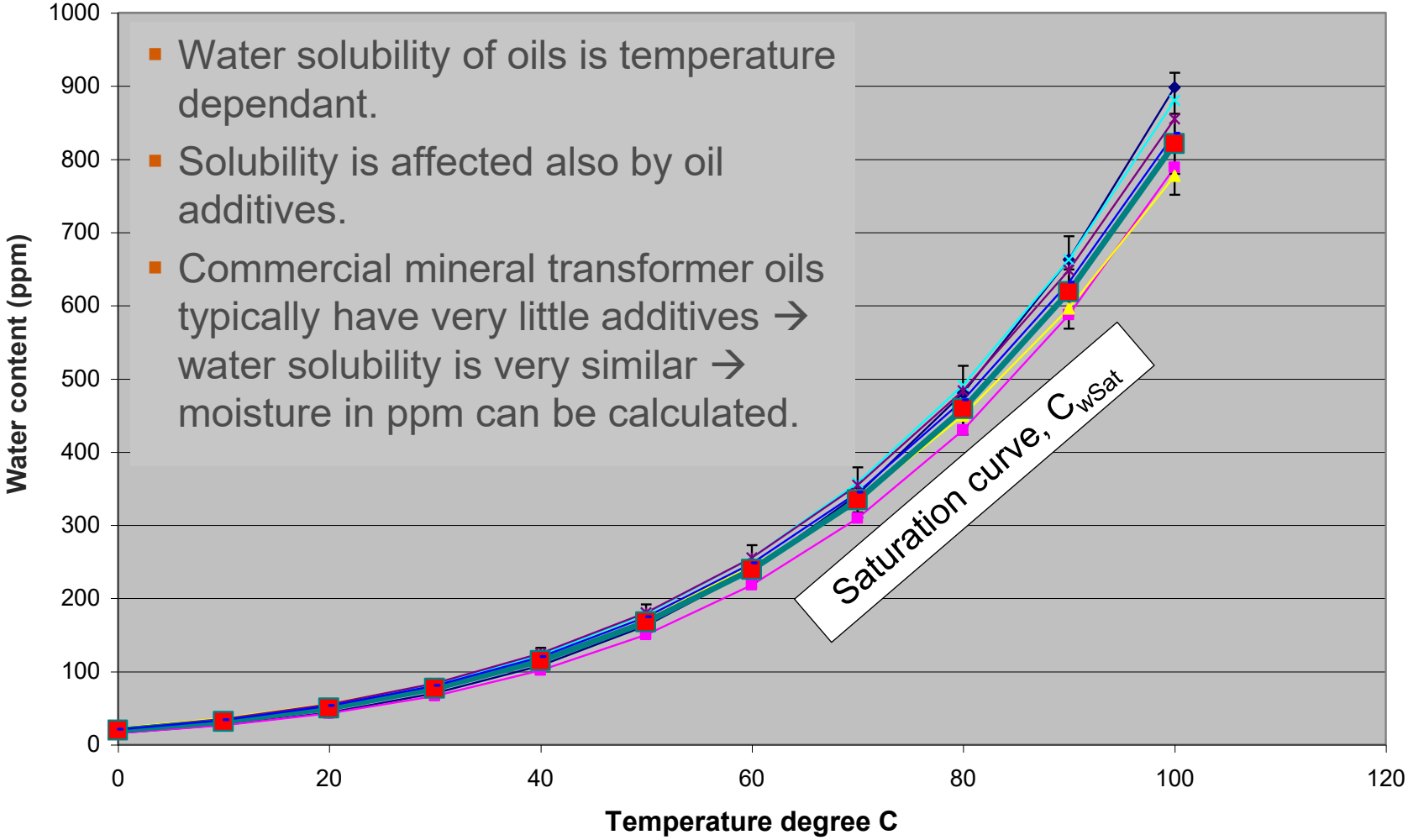
- ~99% of moisture is in solid insulation (=cellulose material)
- There is constant moisture exchange between oil and solid insulation during temperature transients.
  - As temperature increase water is released from cellulose and vice versa.
  - To reach moisture equilibrium in a wet transformer can take weeks!
  - Only moisture on the surface of solid insulations takes part in moisture exchange during daily load/temperature variation.
    - Moisture in deeper in paper remains rather stable.





Moisture in Oil

Water solubility of oils



- Water solubility of oils is temperature dependant.
- Solubility is affected also by oil additives.
- Commercial mineral transformer oils typically have very little additives → water solubility is very similar → moisture in ppm can be calculated.

Relative saturation of oil (%RS)

- $ppm_{(v)}$ = parts per $million_{(by\ volume)}$ =
  1 gallon water / 1,000,000 gallons oil

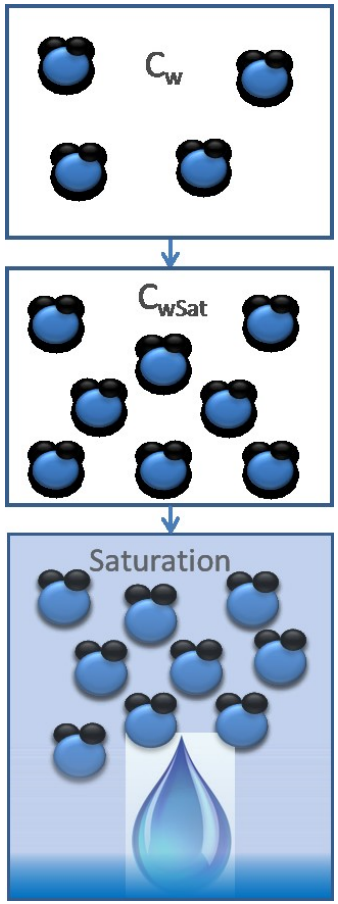
- Relative saturation is the ratio of actual water content to the maximum oil can hold at that temperature.

$$\%RS = 100 * \frac{C_w}{C_{wSat}(T)}$$

where

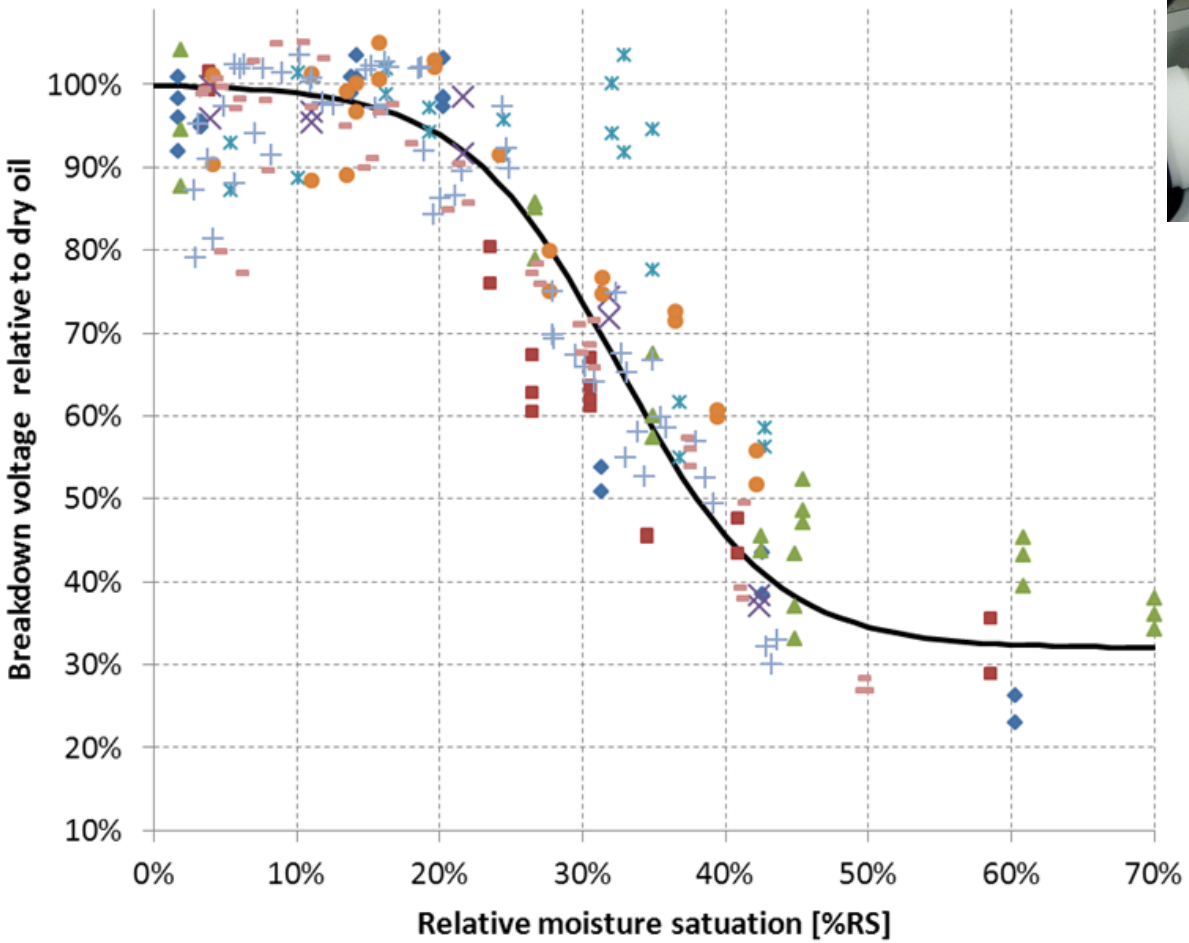
C_w = water content

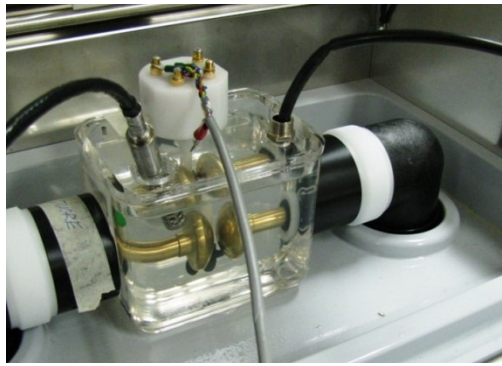
C_{wSat} = maximum water content at same T



if $C_w \geq C_{wSat}$ → saturation (liquid water formation)

Effect of %RS on breakdown voltage



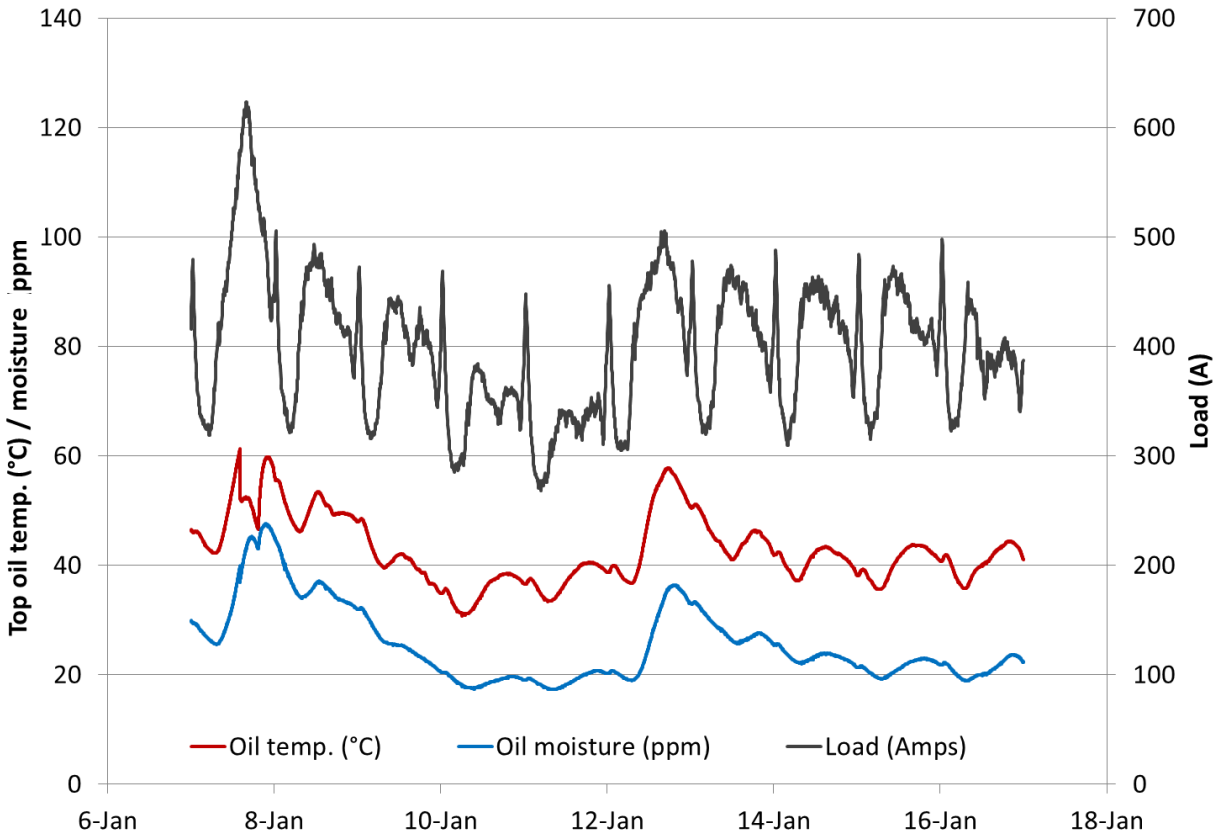


Sample 1
Sample 2
Sample 3
Sample 4
Sample 5
Sample 6
Sample 7
Sample 8
Model

Moisture Dynamics in a Loaded Transformer

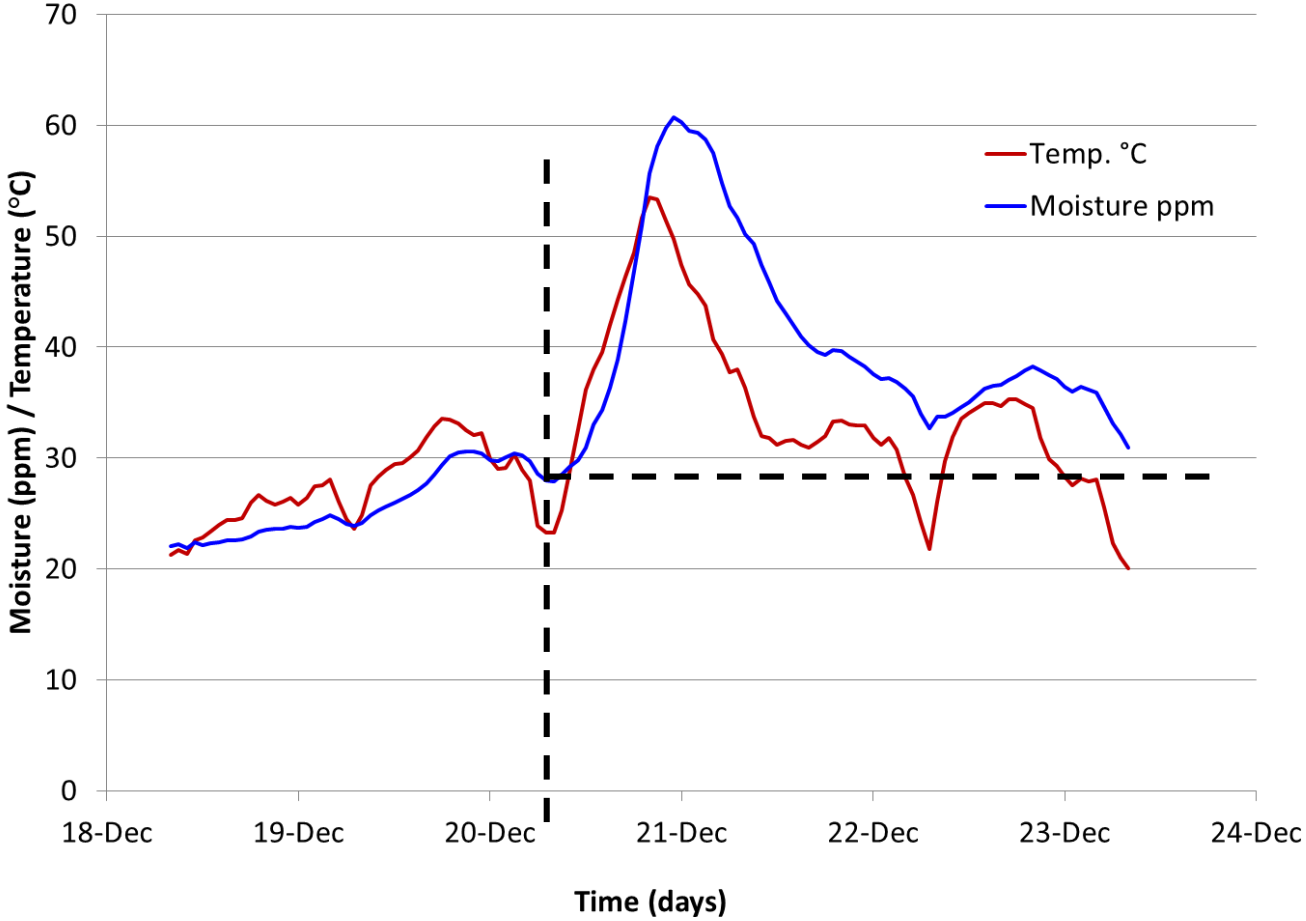
Moisture dynamics: load

- Water is released from surface of solid insulation and absorbed to oil as temperature increases due to loading.
- There is continuous moisture exchange between oil and paper during temperature fluctuation.



10 MVA, ONAN transformer

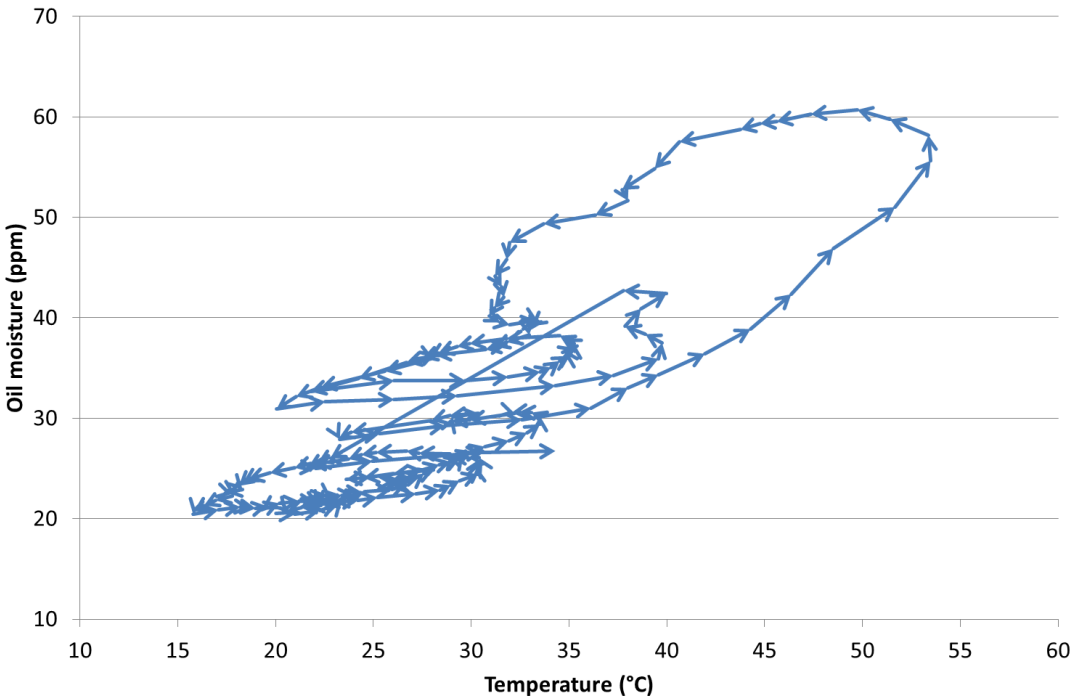
Moisture dynamics: desorption vs absorption rate



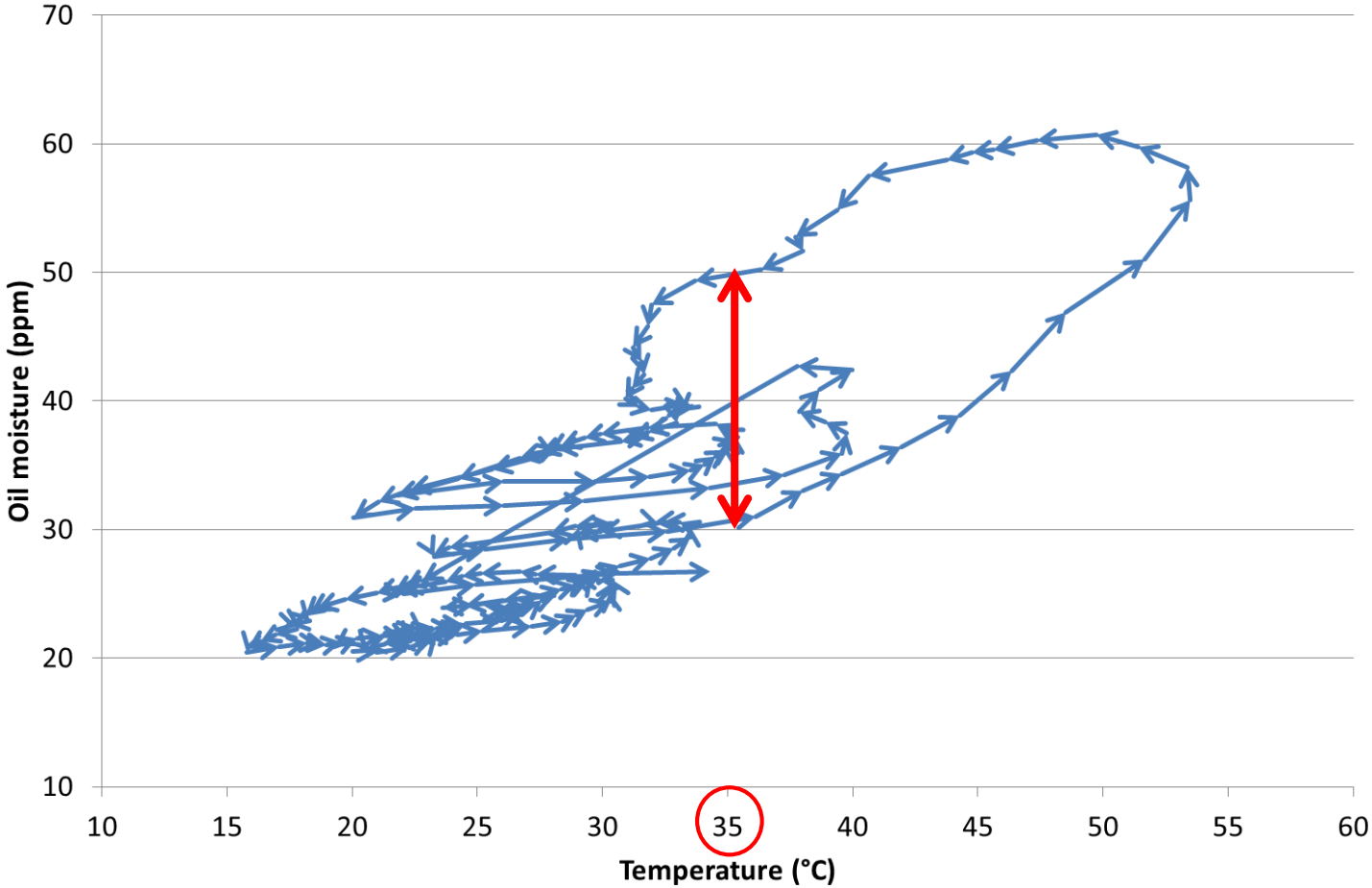
10 MVA, ONAN cooled transformer

Moisture dynamics: hysteresis

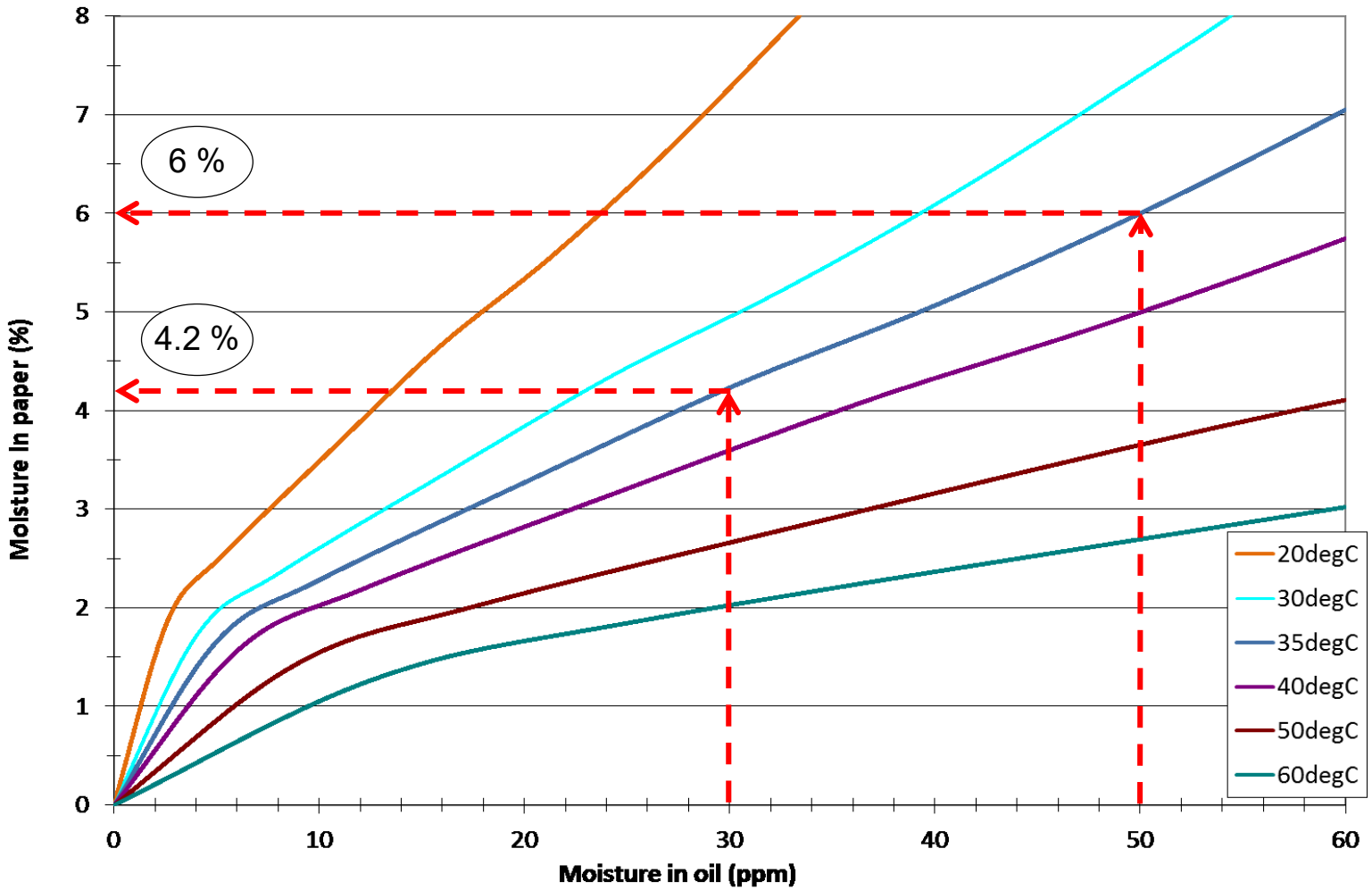
- Hysteresis in moisture exchange between oil and cellulose during temperature transients.
  - At cooling phase higher ppm value at same temperature.
  - Also previous temperature cycles affect ppm level.
- Makes interpretation of instantaneous ppm values challenging.



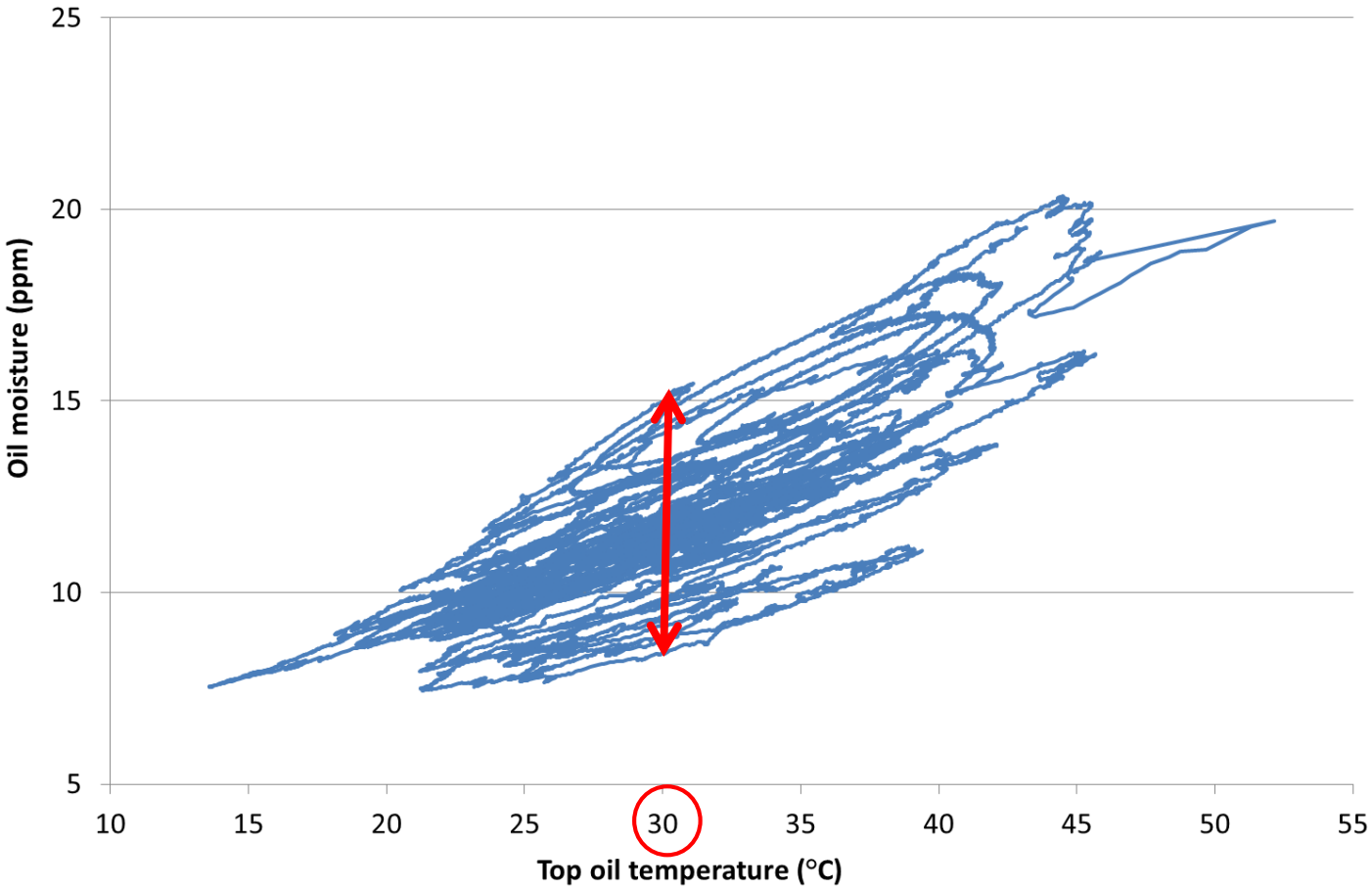
Oil sample from a loaded transformer, Case 1



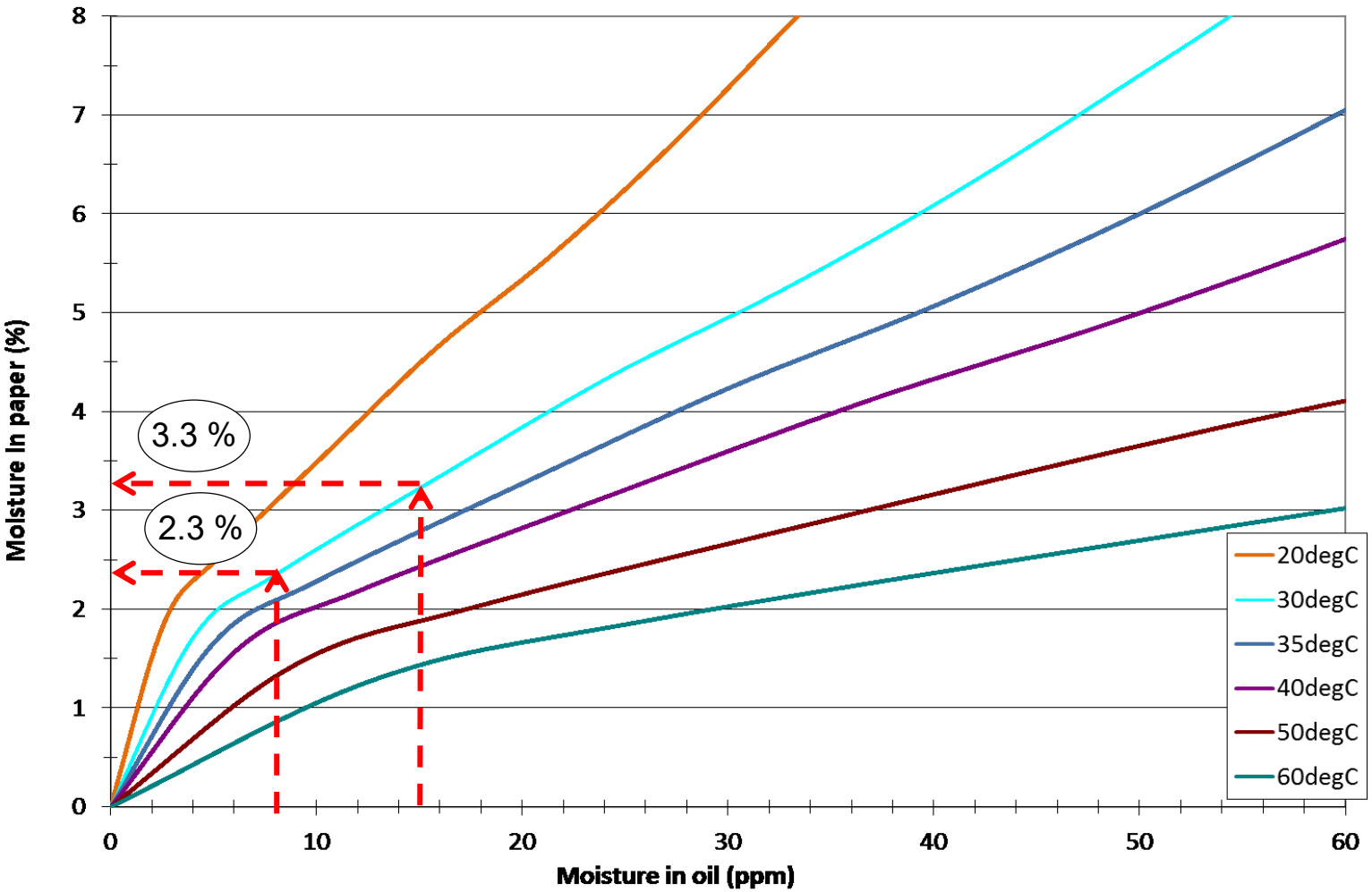
Paper moisture interpretation, Case 1



Oil sample from loaded transformer, Case 2



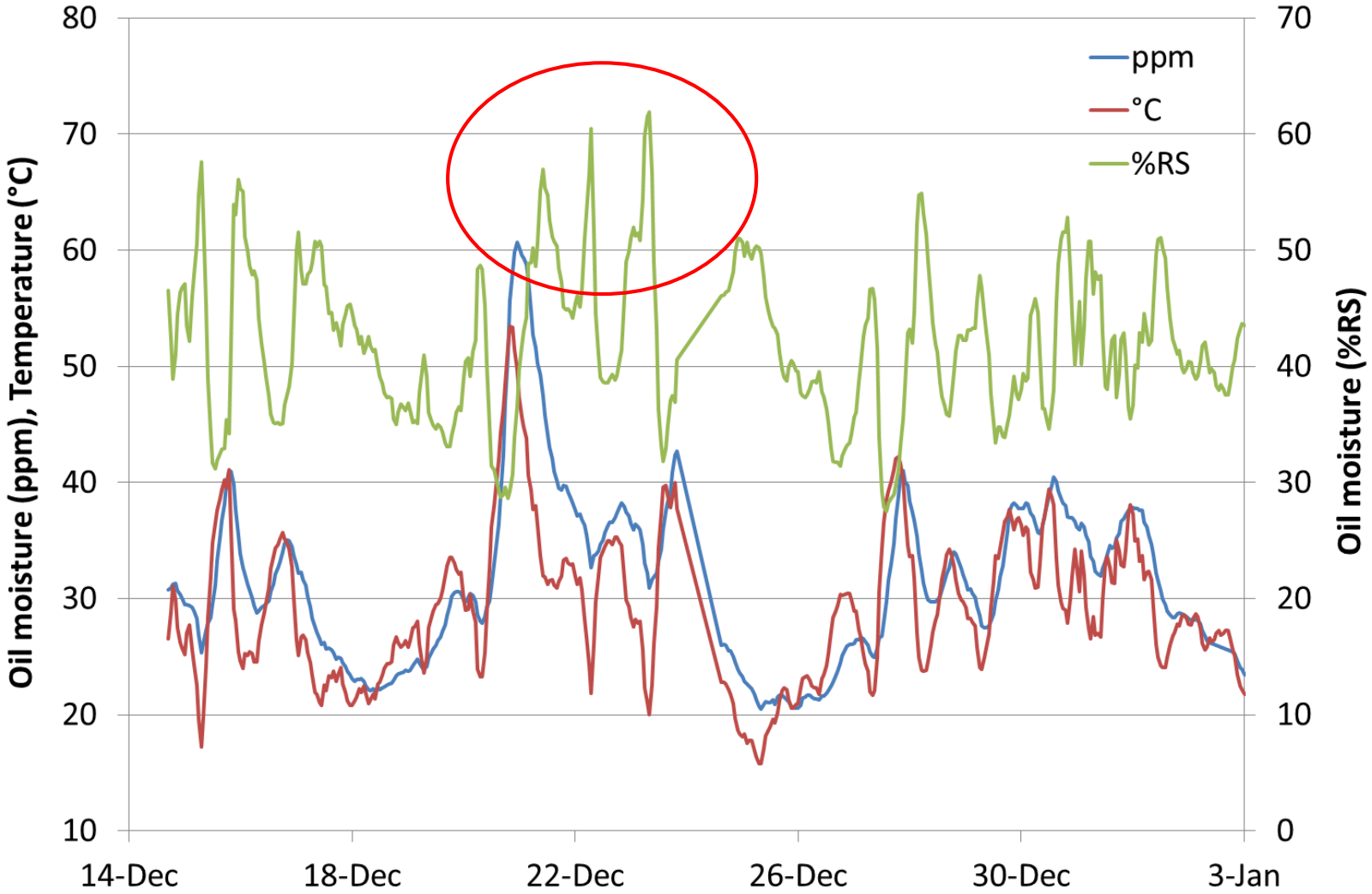
Oil sample from loaded transformer, Case 2



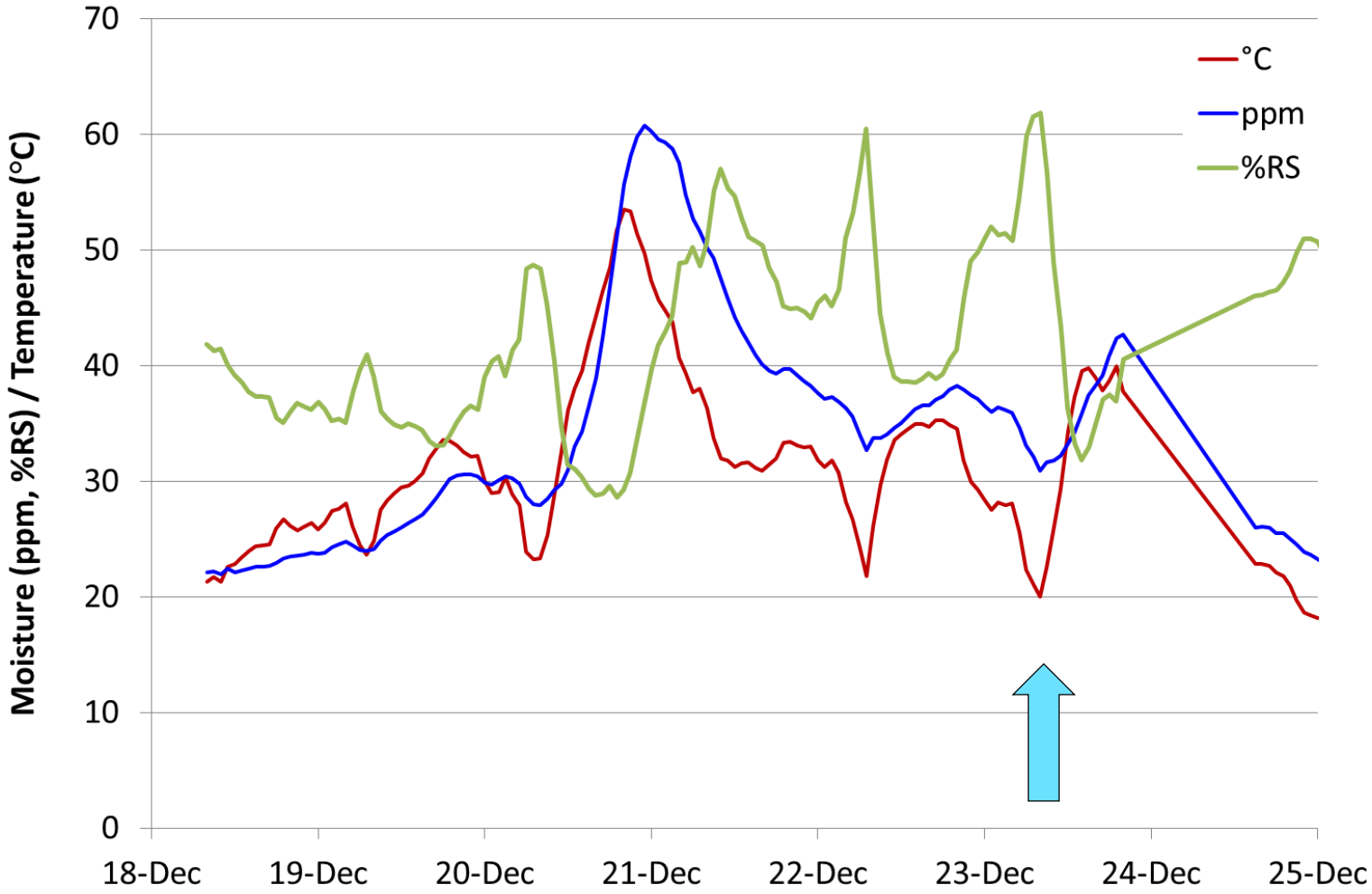
Moisture dynamics: %RS

- In case of quick temperature decrease %RS of oil increases
  - Temperature decreases due to load and/or ambient temperature decrease during night.
  - There is risk of saturation in oil of wet transformers
    - →formation of liquid water i.e. "raining in oil"
    - →dramatic decrease of dielectric strength
    - →corrosion and rust in pipelines
- Rarely does an equilibrium exist between the cellulose and oil
  - due to load and temperature variations → constant moisture exchange
  - difficult to define correct moment to take an oil sample.

Moisture dynamics: %RS of oil



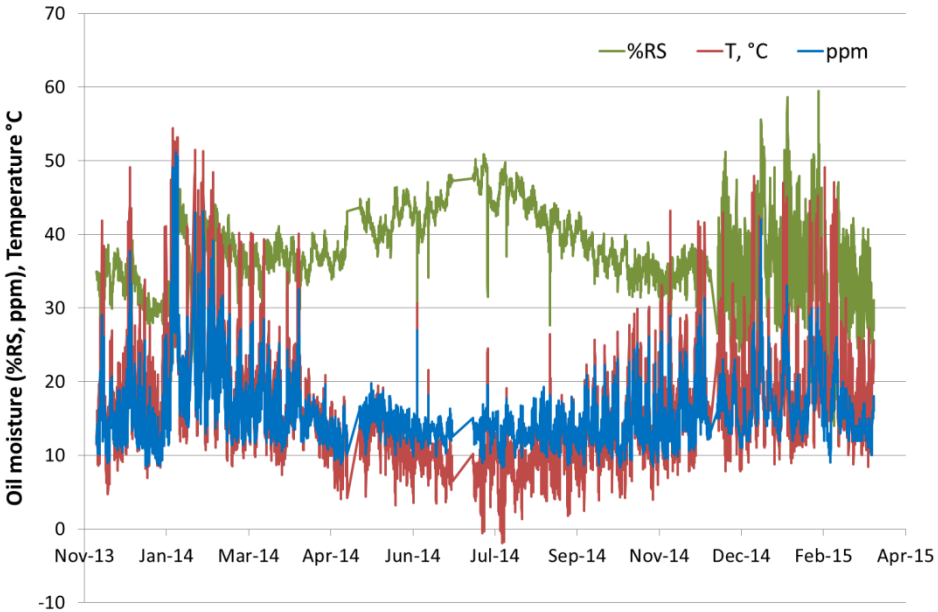
Moisture dynamics:%RS of oil (zoomed data)



Online Monitoring

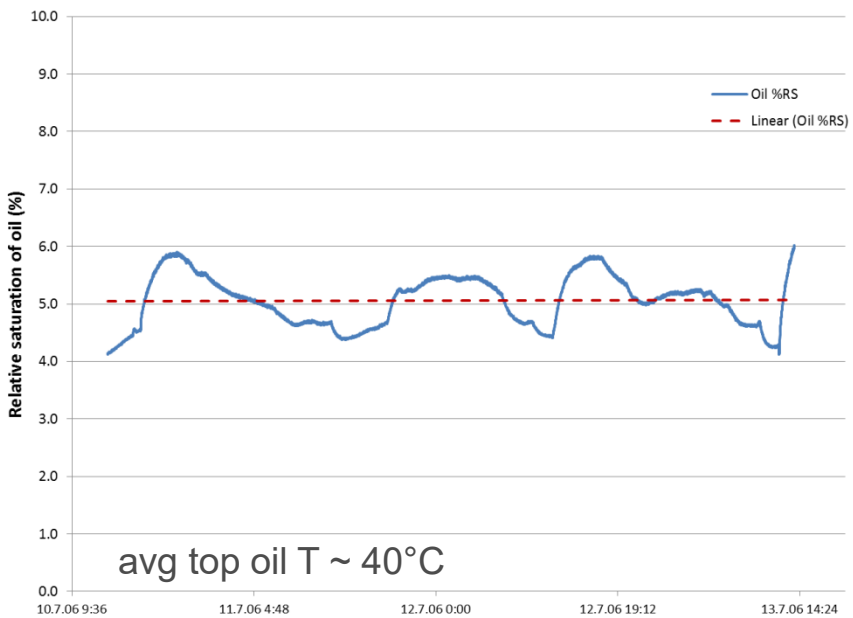
Benefits of %RS online monitoring

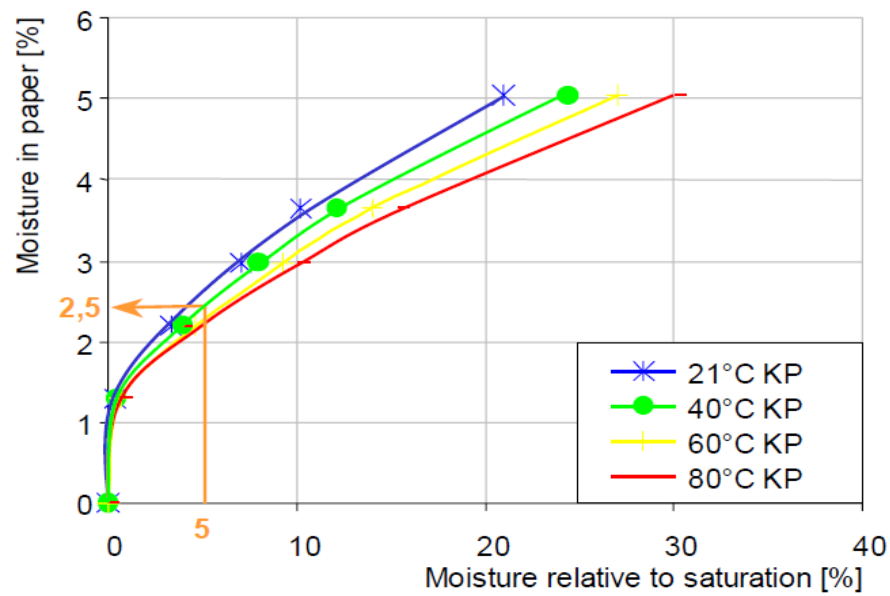
- Can be measured online.
  - Only real time moisture monitoring gives true picture of moisture 24/7/365
- Indicates whether dielectric strength of oil is decreased due to moisture.
- Indicates whether there is risk of free water formation e.g. when monitoring in the return pipe after radiator.



Benefits of %RS monitoring

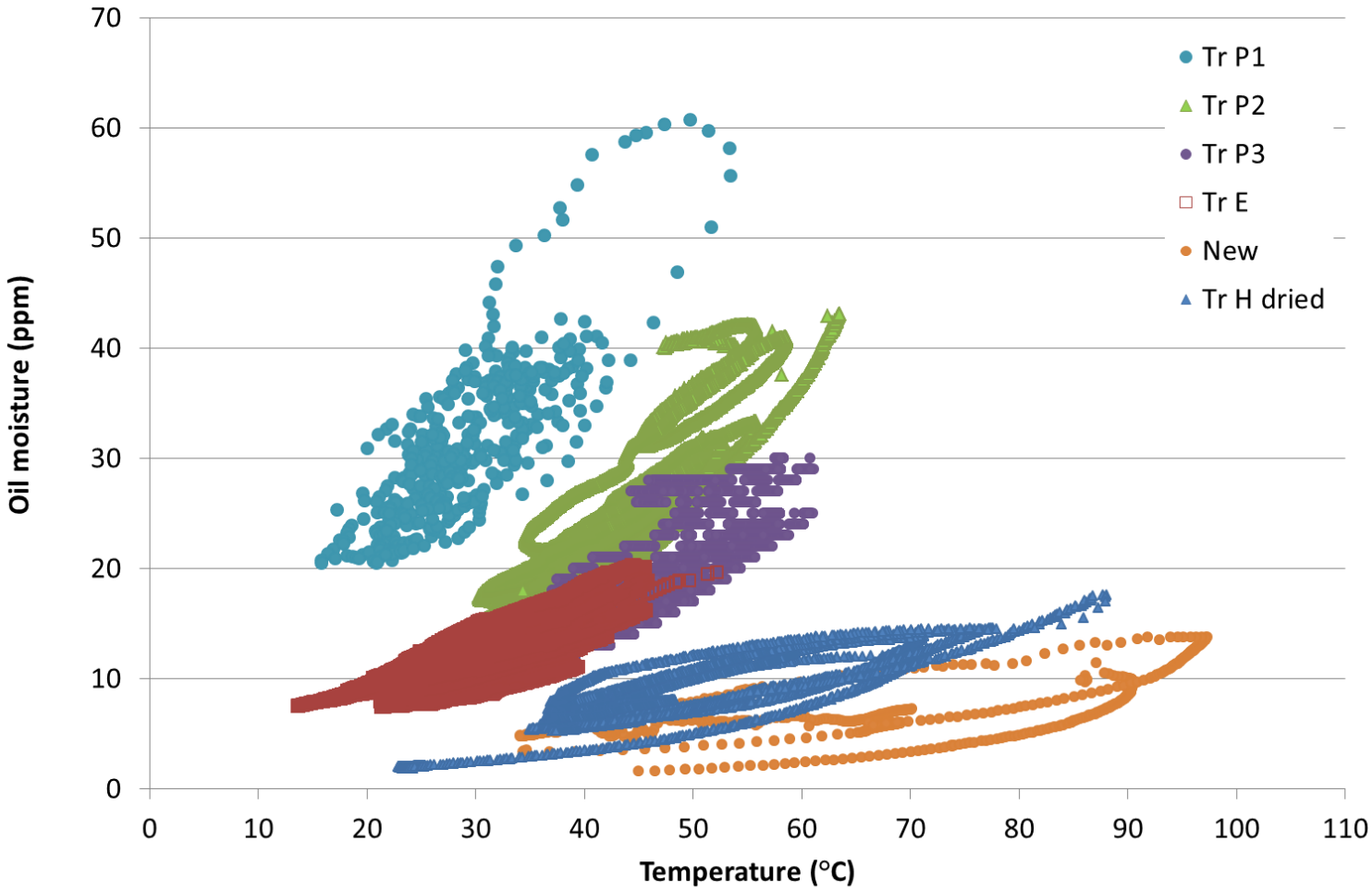
- Gives better indication of moisture in solid insulation regardless of the oil type or age.
- Averaging %RS allows





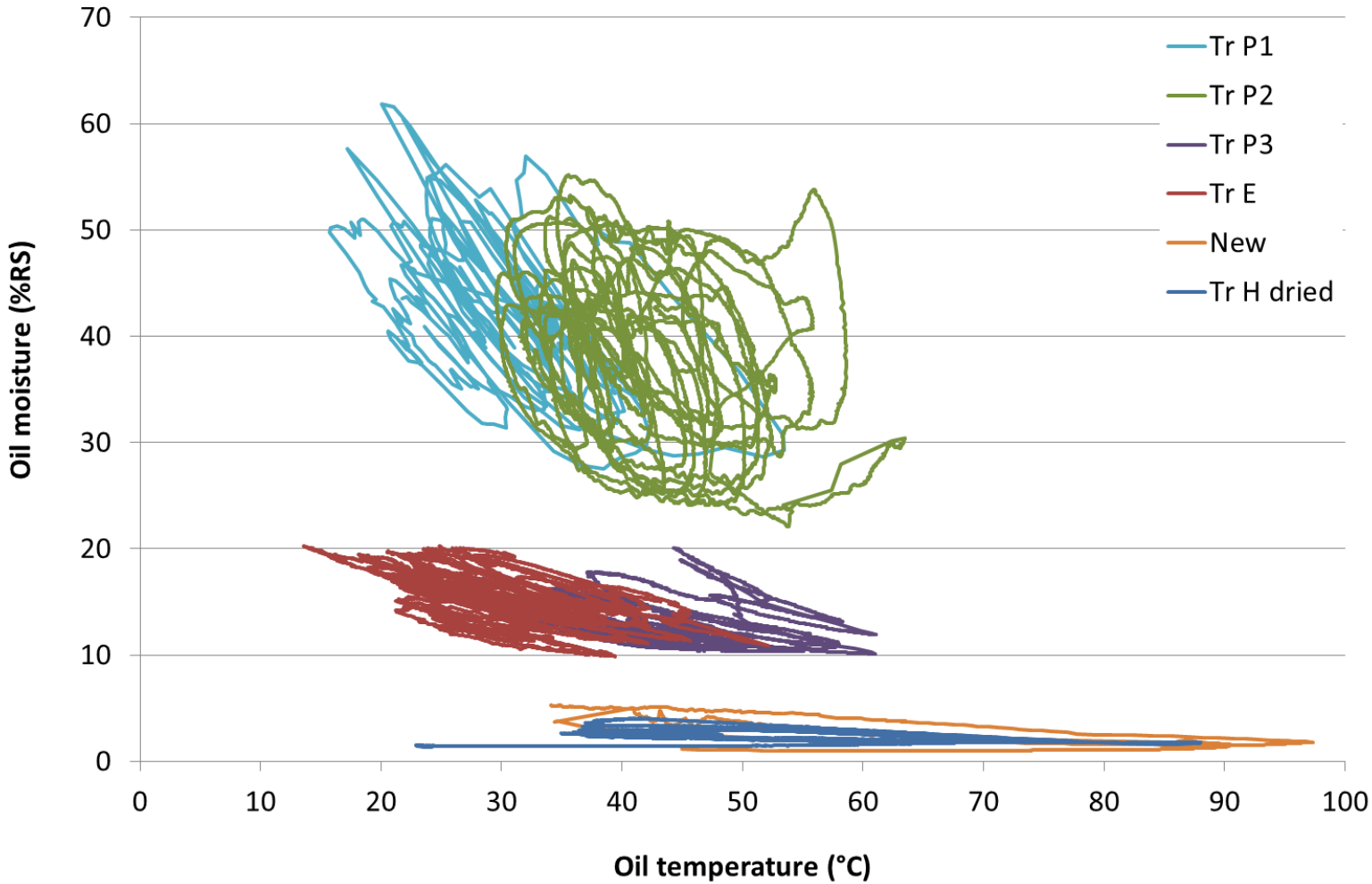
ref. Cigre Brochure 349, WG A2.30

Ranking transformer fleet (ppm)



10...60 MVA primary distribution transformers

Ranking transformer fleet (%RS)

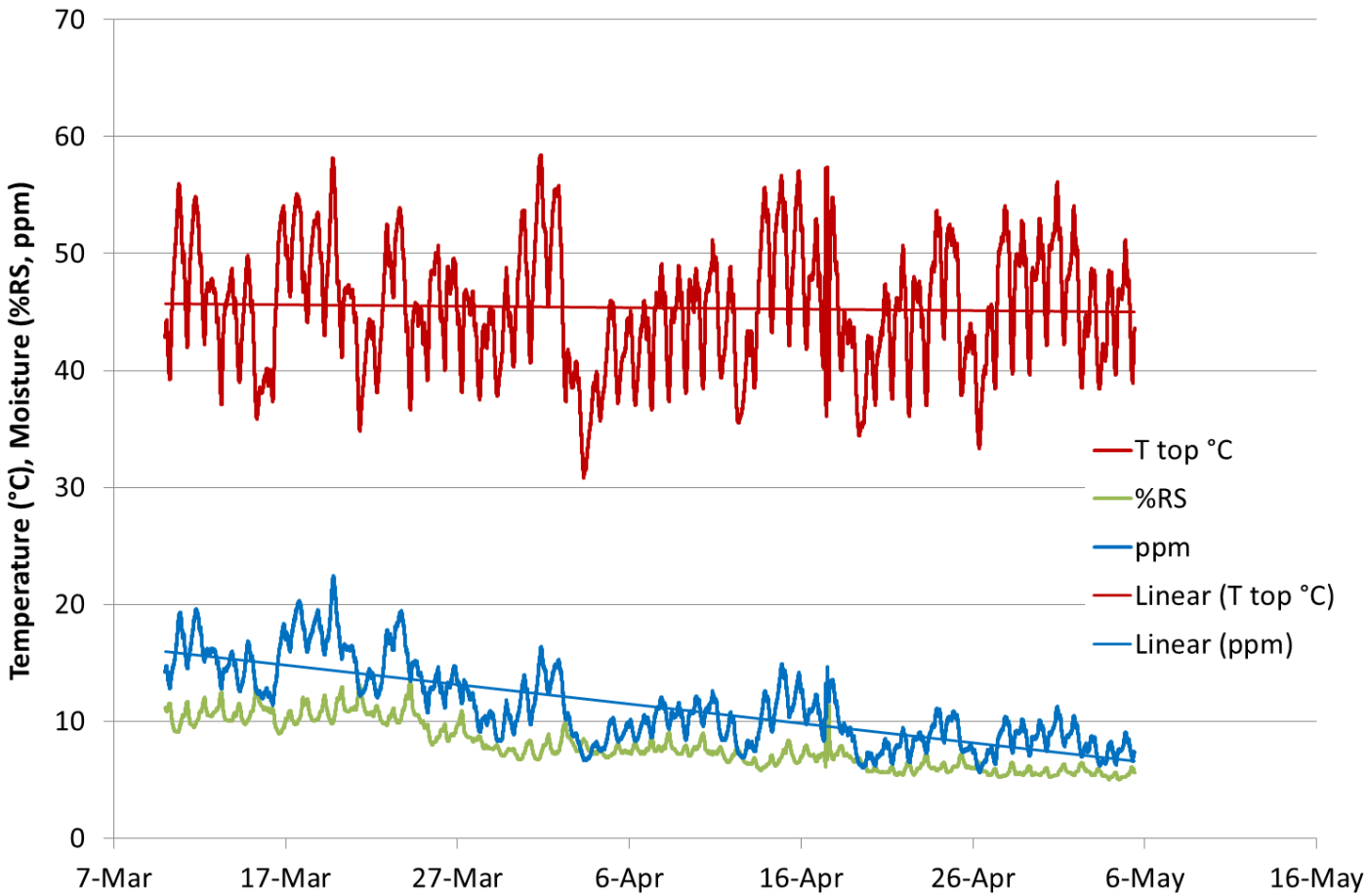


Online Drying

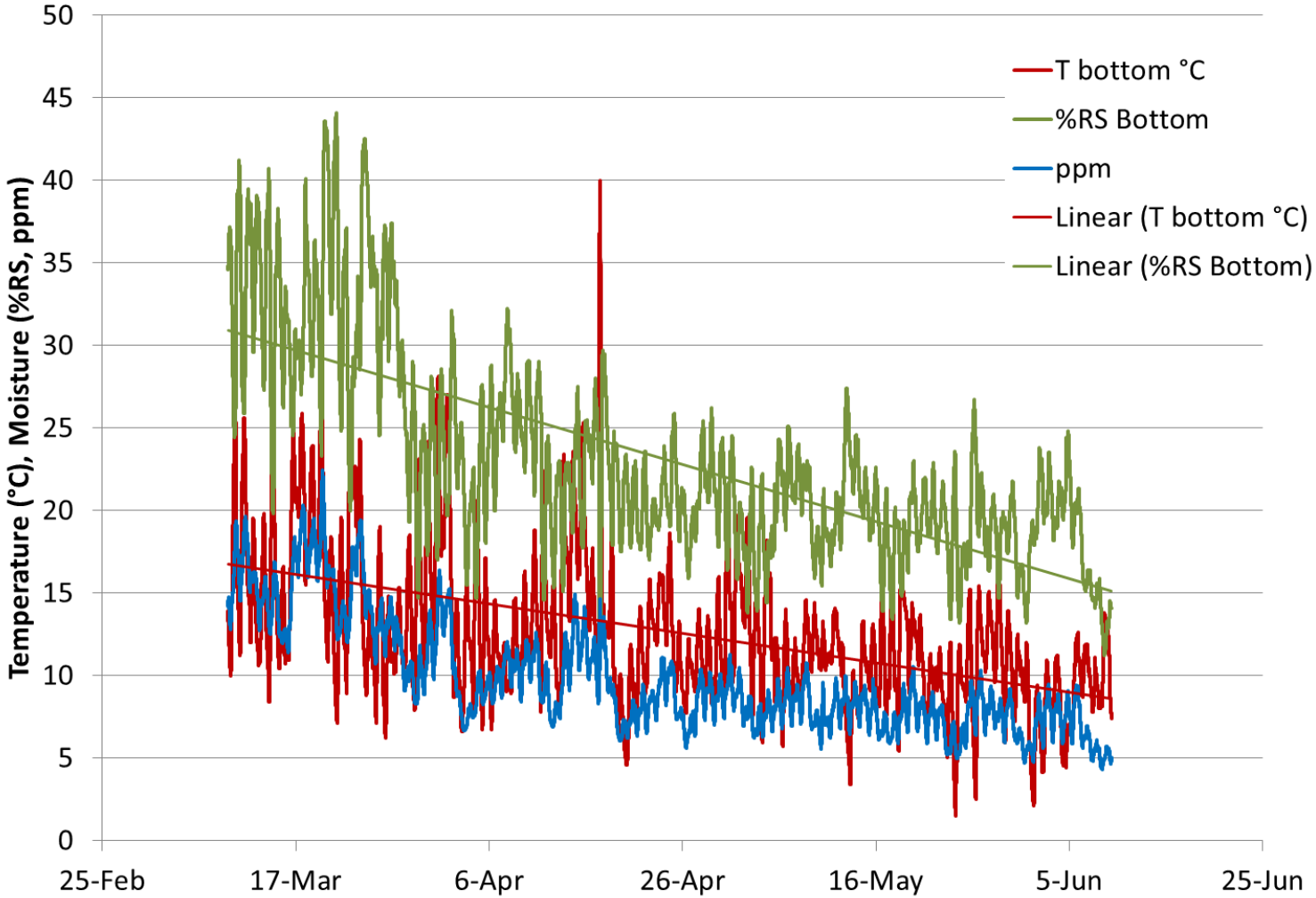
Online drying

- Dryers can be also used in connection to a loaded transformer. Oil is circulated through the drying unit removing water and then returned back to the transformer.
- As only water on the surface of solid insulation is involved in moisture exchange only that is available for drying at time.
- One main benefit with online drying is that with wet transformers the oil can be kept dry and thus dielectric strength of oil maintained.

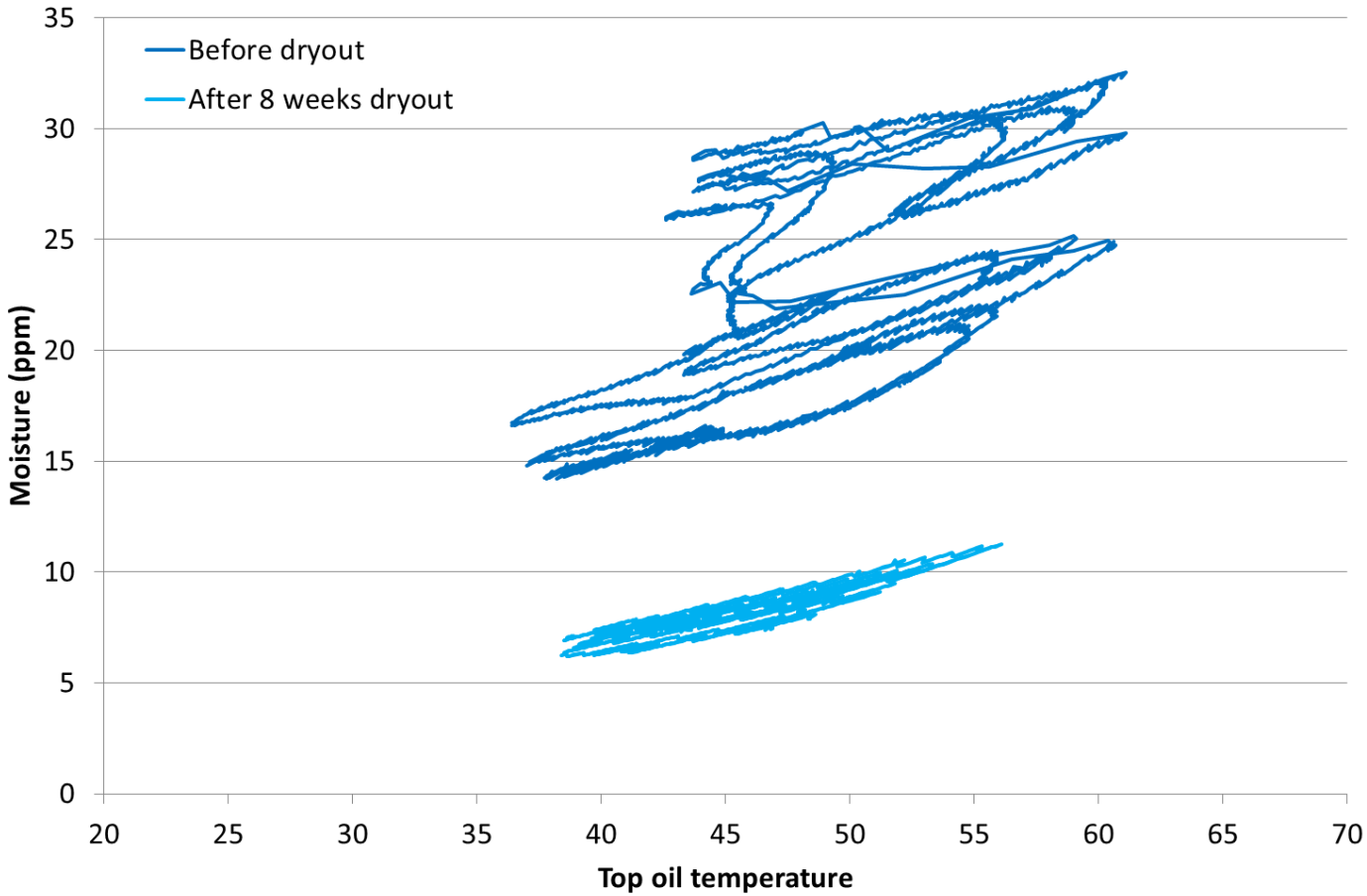
During dryout (top oil)



During dryout (bottom oil)



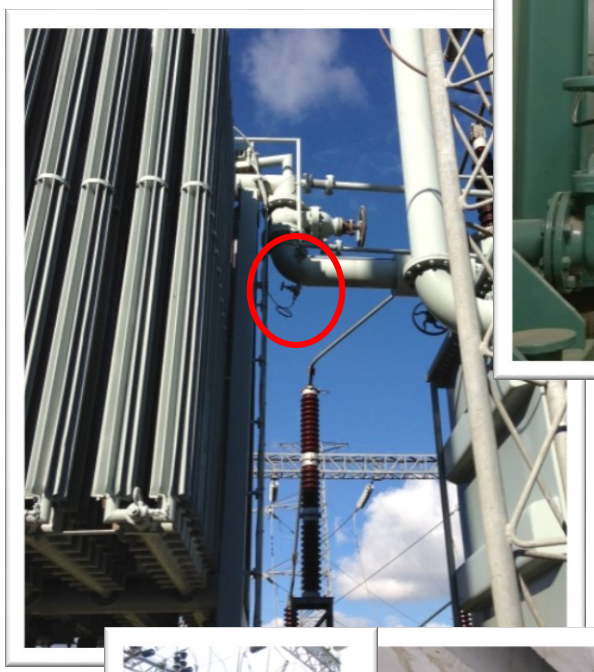
Oil moisture before and after dryout



Sensor Installation

Installation examples

- The sensor should be installed in a location where oil flows freely around it.
- Most beneficial locations are along oil cooling circulation → representative oil.
- Avoid "dead-ends" and bottom of pipe bending.
- If the sensor is not in oil the full variation in temperature and moisture may not be seen, but the most extreme peaks may be ”filtered” off.



Thank you!

- For more information:
- www.vaisala.com/power
- Resource for white papers, case studies and application notes

steven.jiroutek@vaisala.com