Assessing Water Content in solid transformer insulation from dynamic measurement of moisture in oil

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Moisture in insulation

In transformer, there is several sources of moisture:

Residual moisture from manufacturing process: Good drying process should result in less than 0.5% moisture in paper

Leaks: Gasket and/or joints could leak

Insufficient maintenance: To be effective, Silica gel system needs constant maintenance, any lapse could result in large amount of moisture into the transformer

Moisture in insulation

In transformer, there is several sources of moisture:

Paper degradation: The thermal degradation of paper does generate water

This water will generate yet more paper degradation

Moisture is strongly absorbed by paper, once inside the transformer, it is difficult to remove.

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Moisture in insulation

Moisture in oil
- Can lead to water condensation

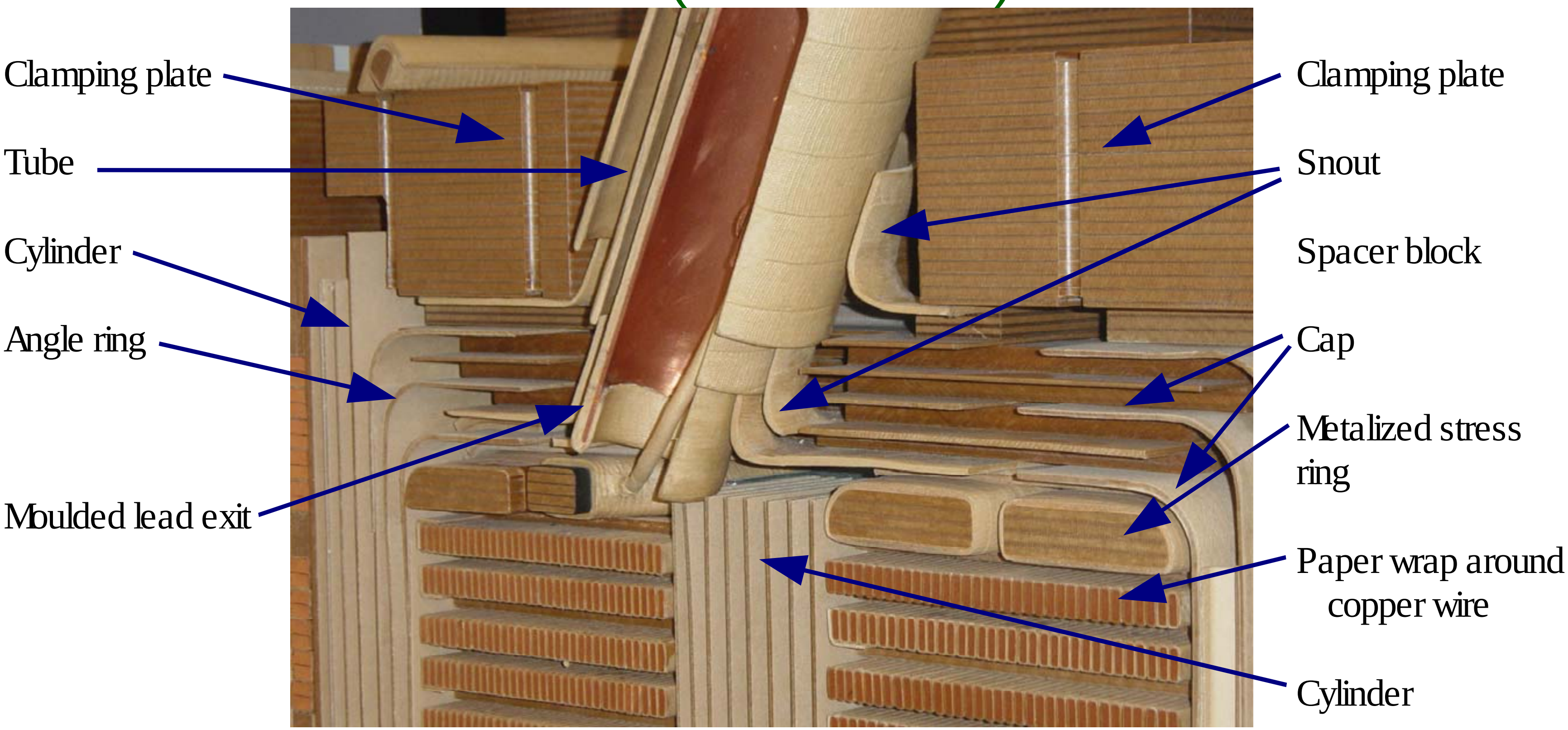
Moisture in winding paper is critical
- Reduces dielectric strength
- Increased risk of bubbling at high load
- Accelerates the rate of insulation aging

Moisture in pressboard barrier is critical
- Reduces dielectric strength

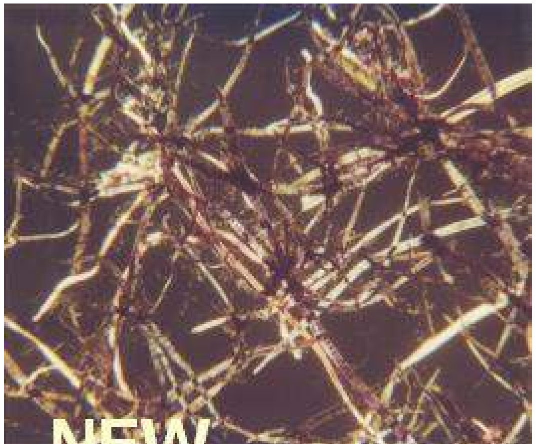
Only moisture in oil can be measured

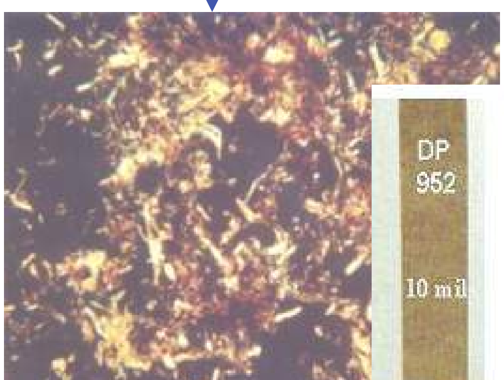
Paper is found in many forms in winding insulation

Cross-sectional view of a 400 kV transformer end insulation (220 kV-side)



Deterioration of oil and cellulose





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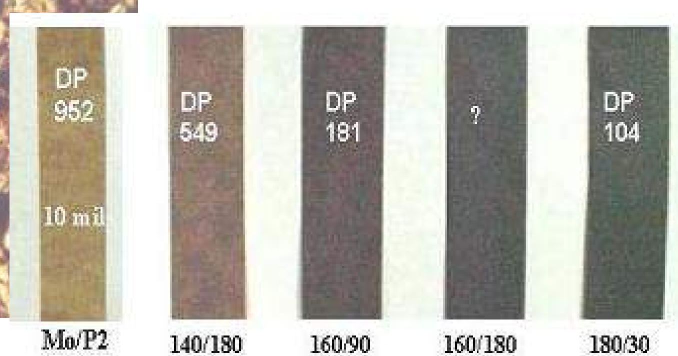

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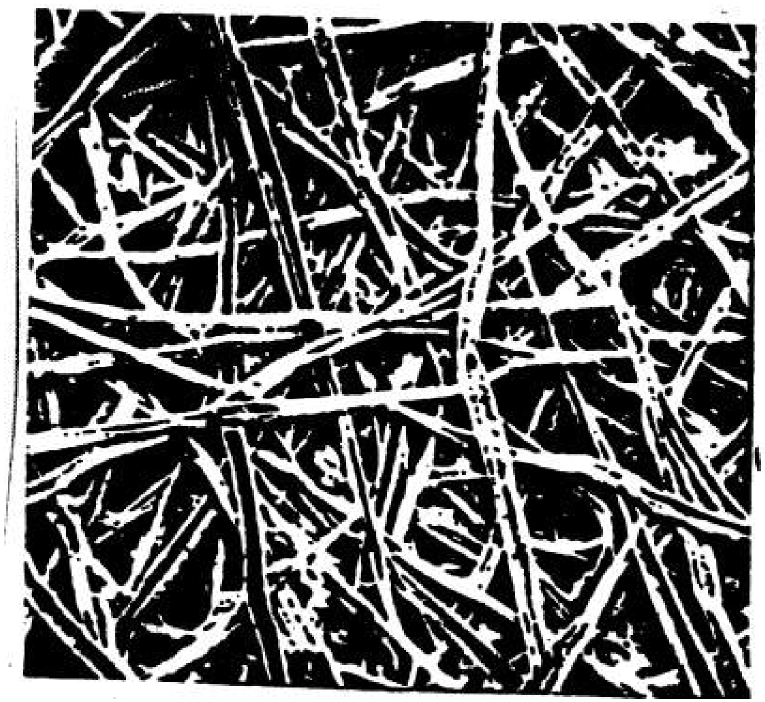
Paper consist of fibers

Paper structure



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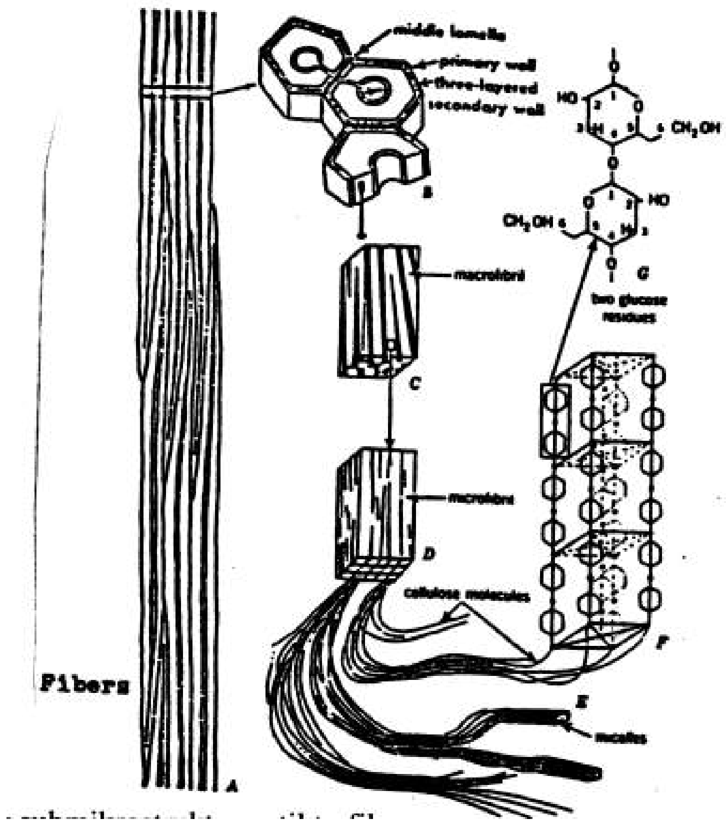
Paper fibre

Fibers are built from micro fibers - which consist of cellulose molecules

Micro and submicrofibers



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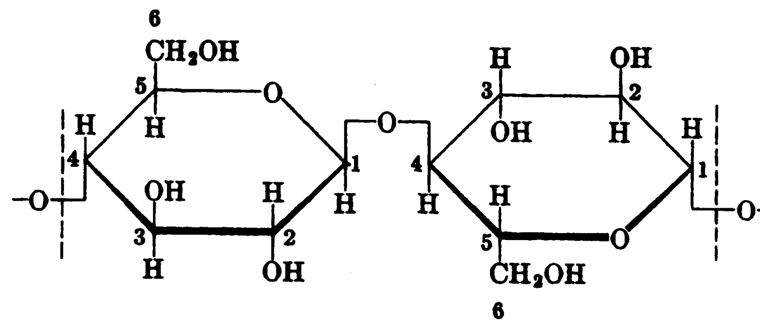
Cellulose molecule



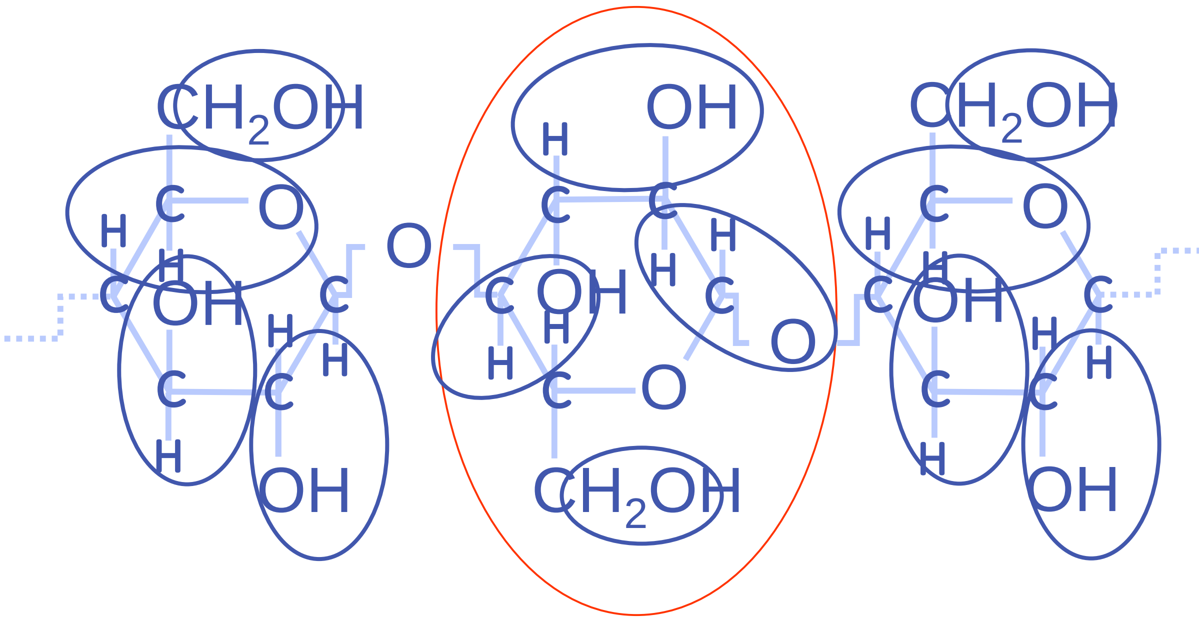
DP – Value

Average number of rings in the cellulose molecule chain

Where does water come from?

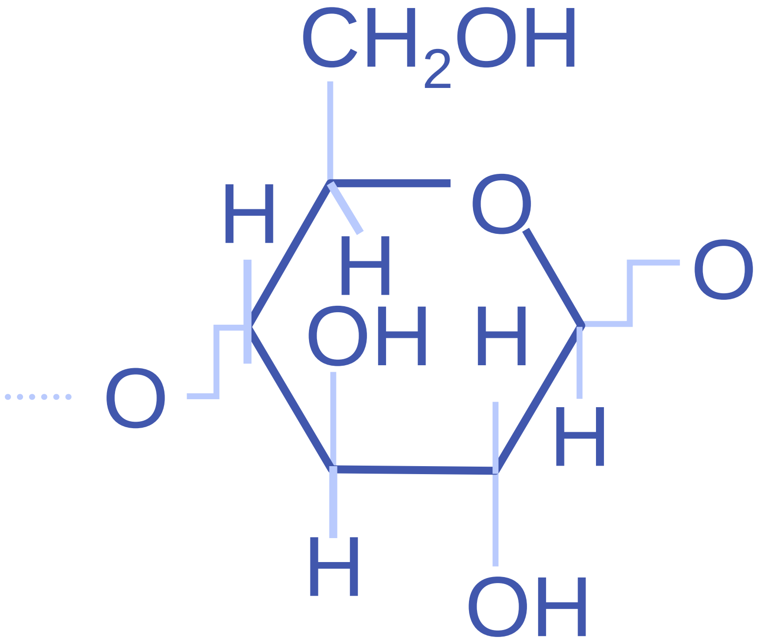
COMPOSITION OF PAPER

- - - - - - - - Cellulose - - - - - - - -



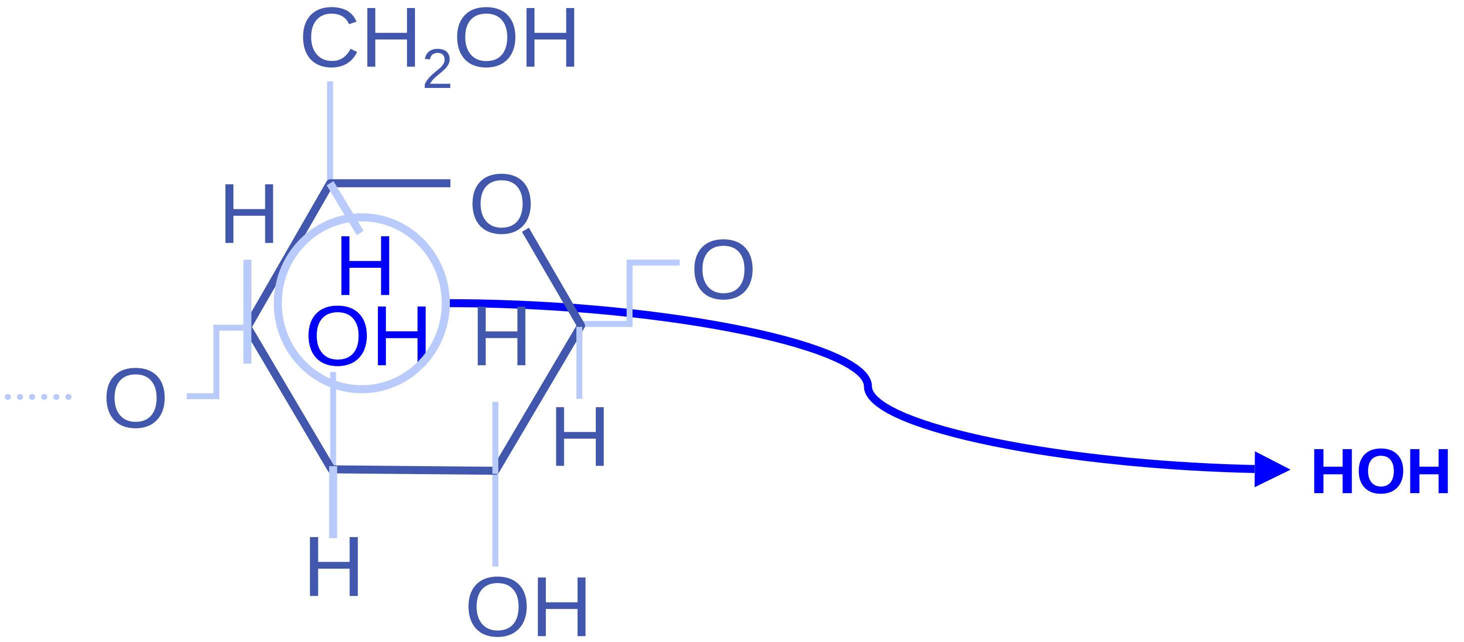
Glucose

Where does water come from?



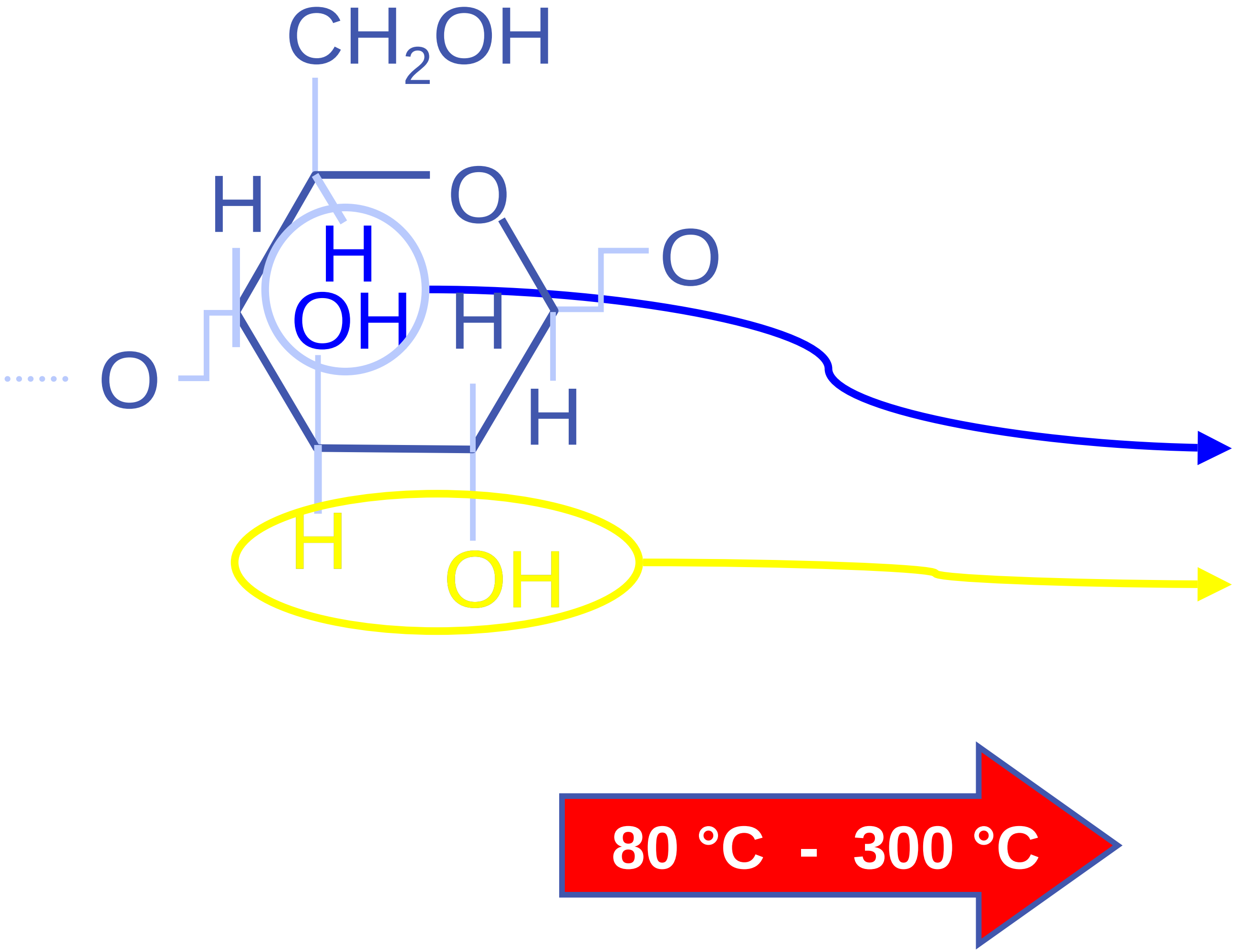
Glucose

Where does water come from?

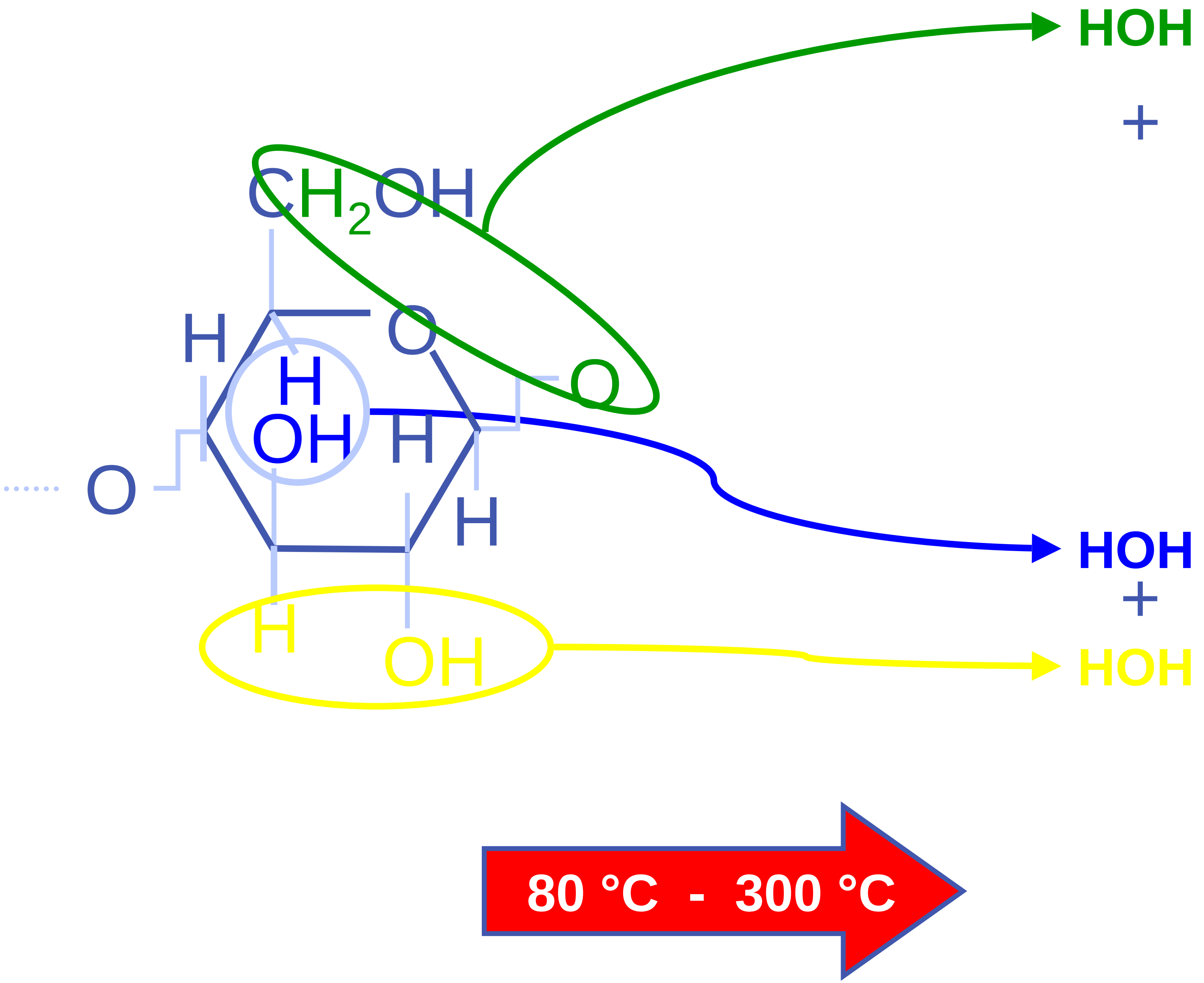


80 °C - 300 °C

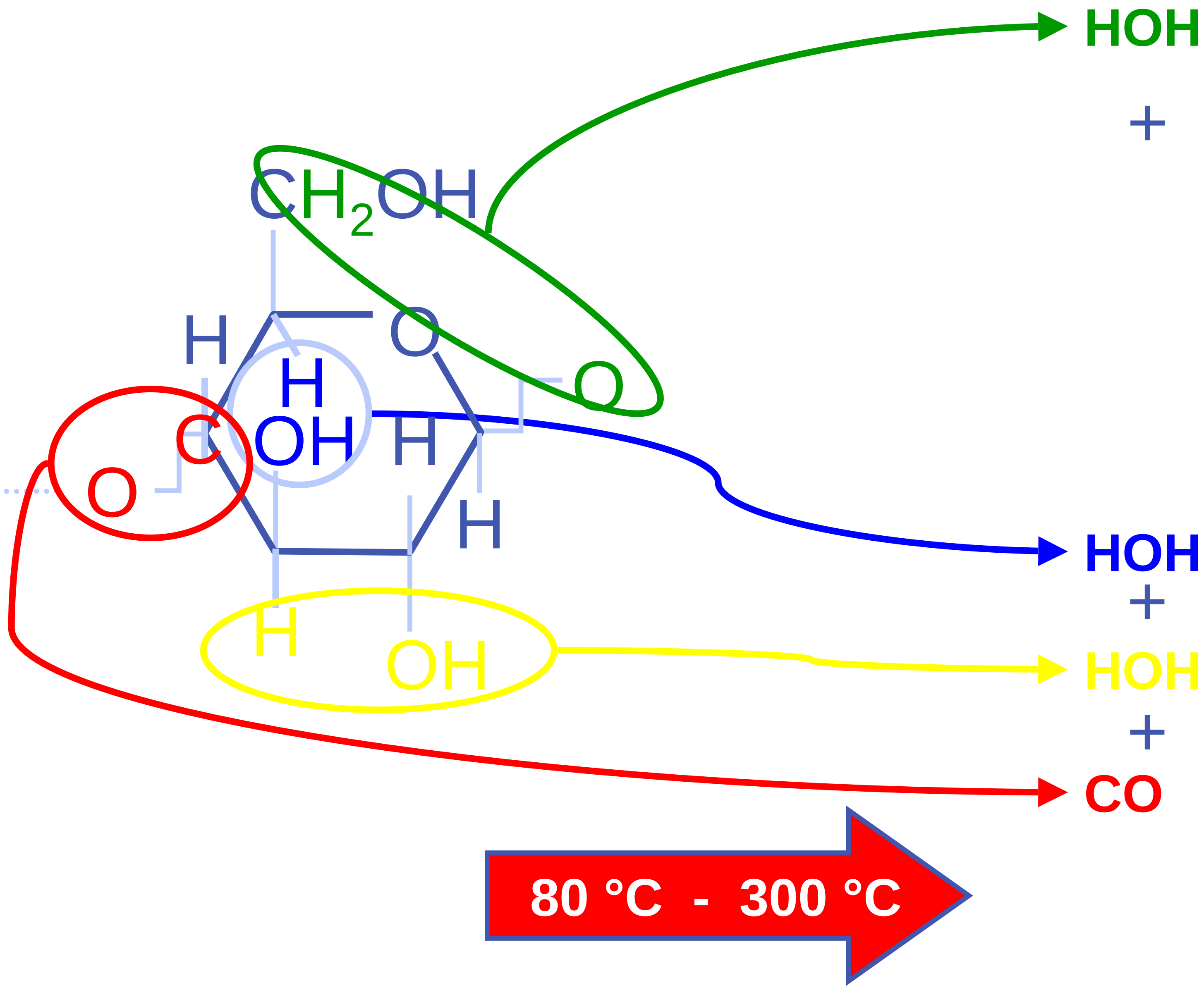
Where does water come from?



Where does water come from?



Where does water come from?



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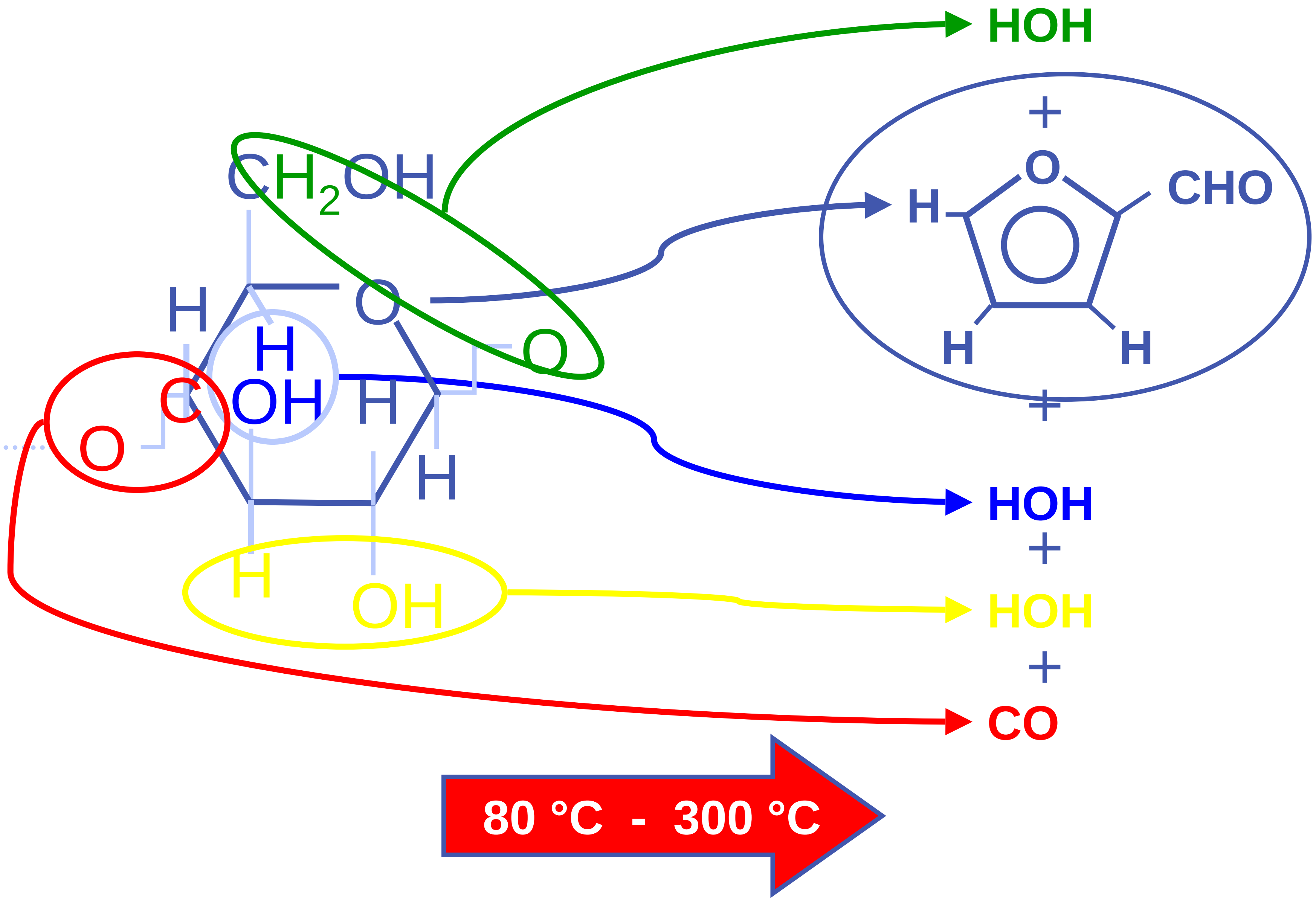
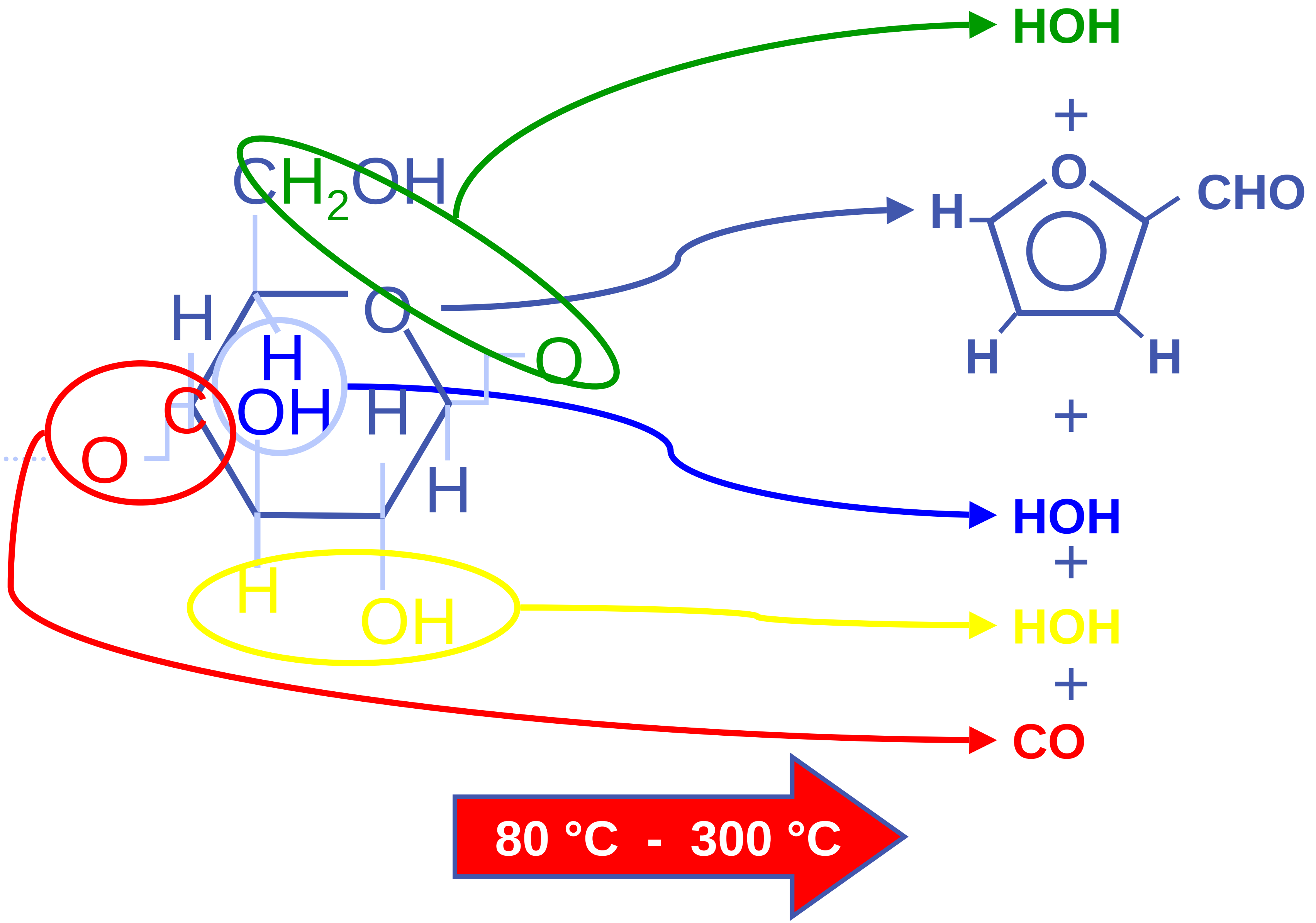
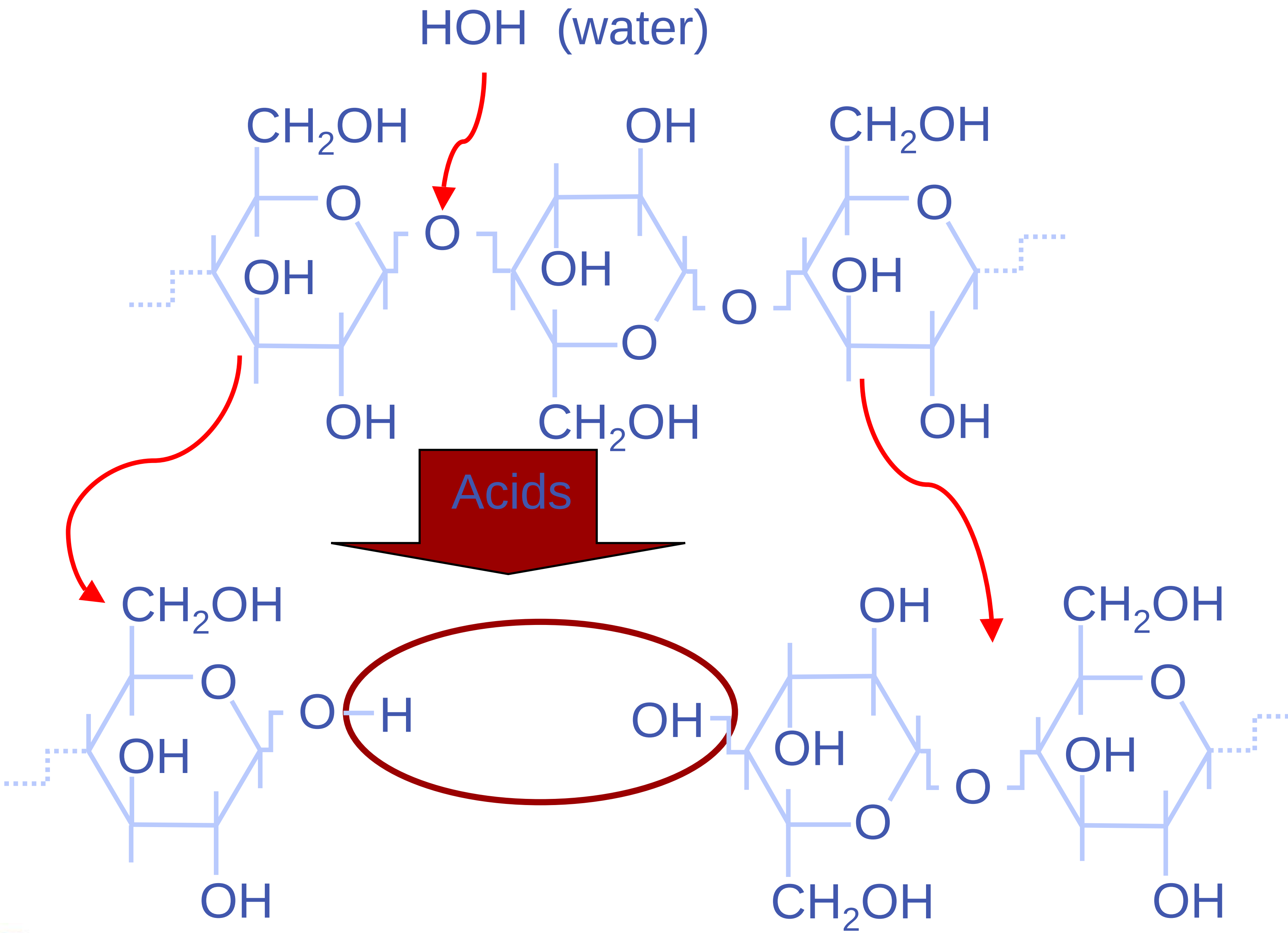


Where does water go?



The water will also degrade the paper



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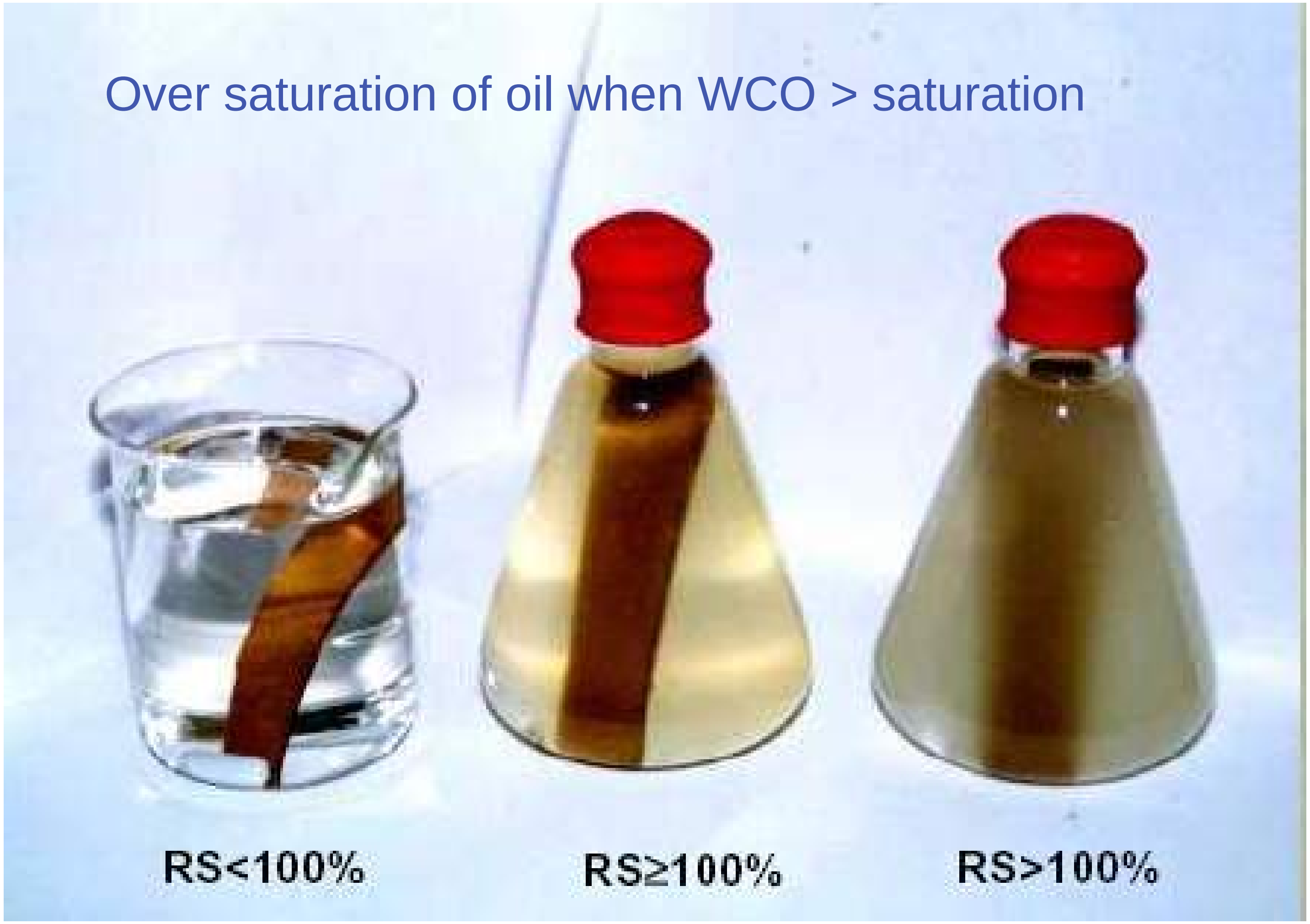
Impact of moisture in oil



V. Davydov, EPRI Moisture Management in Transformer Workshop, Nov.2002, Edison, New Jersey

Impact of moisture in oil

Sensors

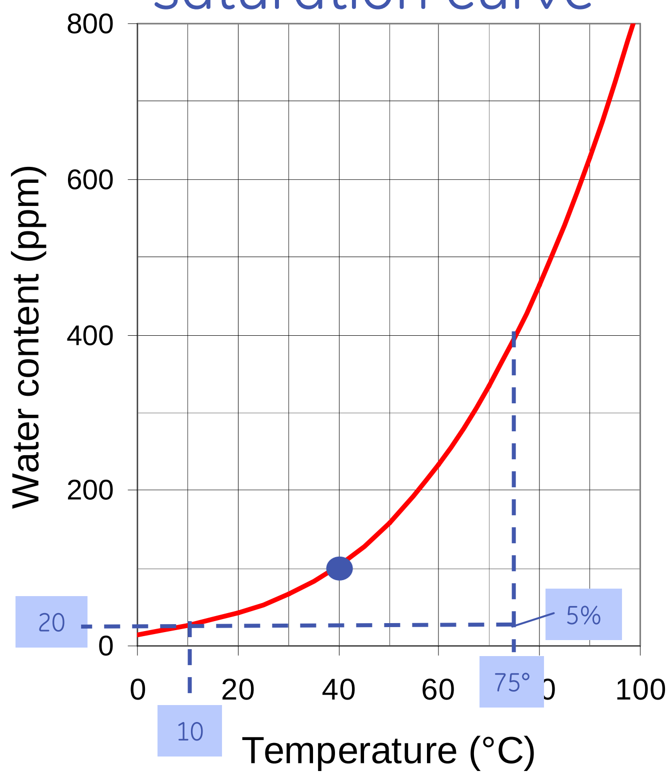
Sensor Relative Humidity (RH%)

5%

Sensor Temperature(°C)

75°C

Water-in-oil saturation curve



Output

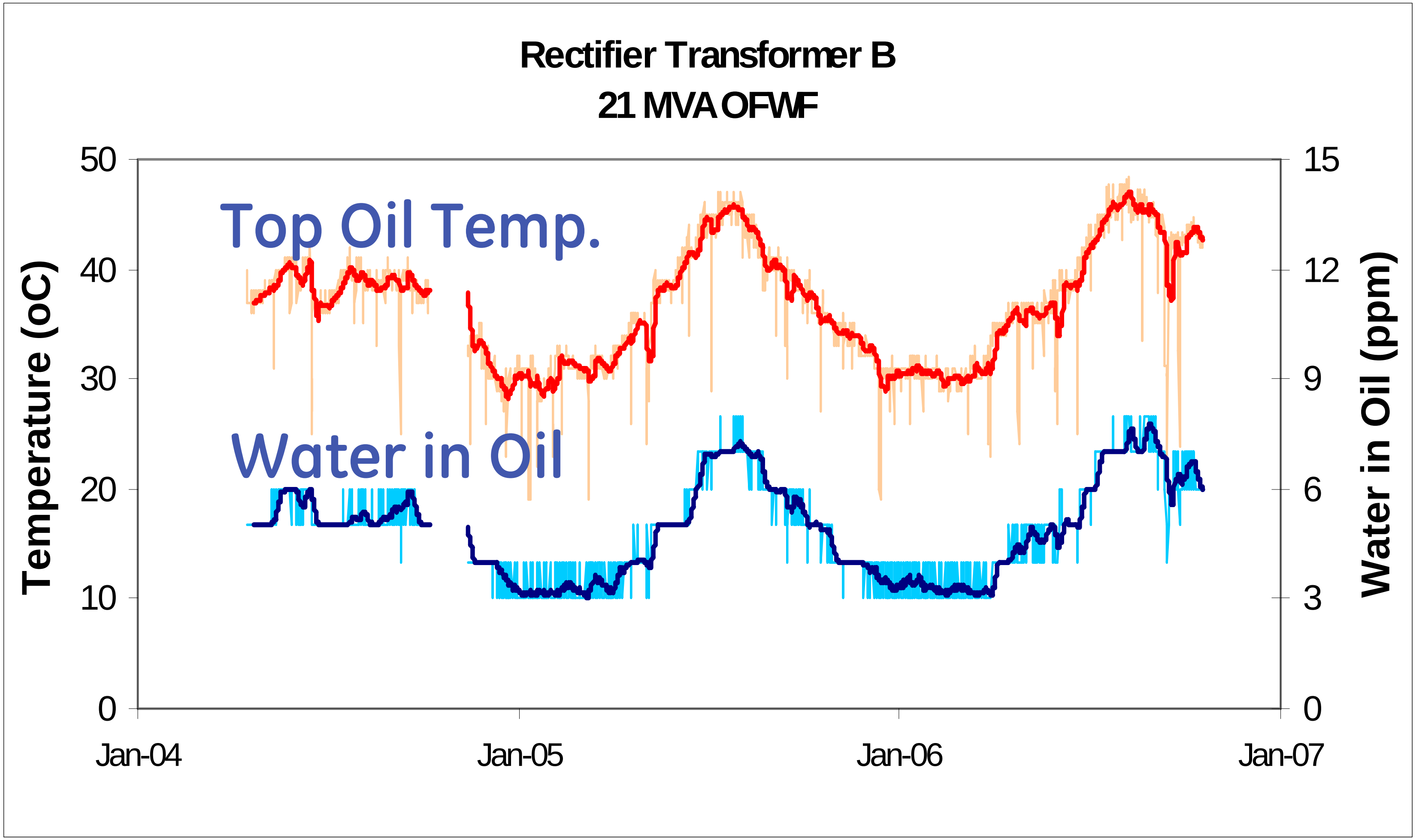
Absolute water content in oil (ppm)

20ppm

Condensation temperature (°C)

10°C

Change in water-in-oil concentration



Water content in oil varies with Temperature

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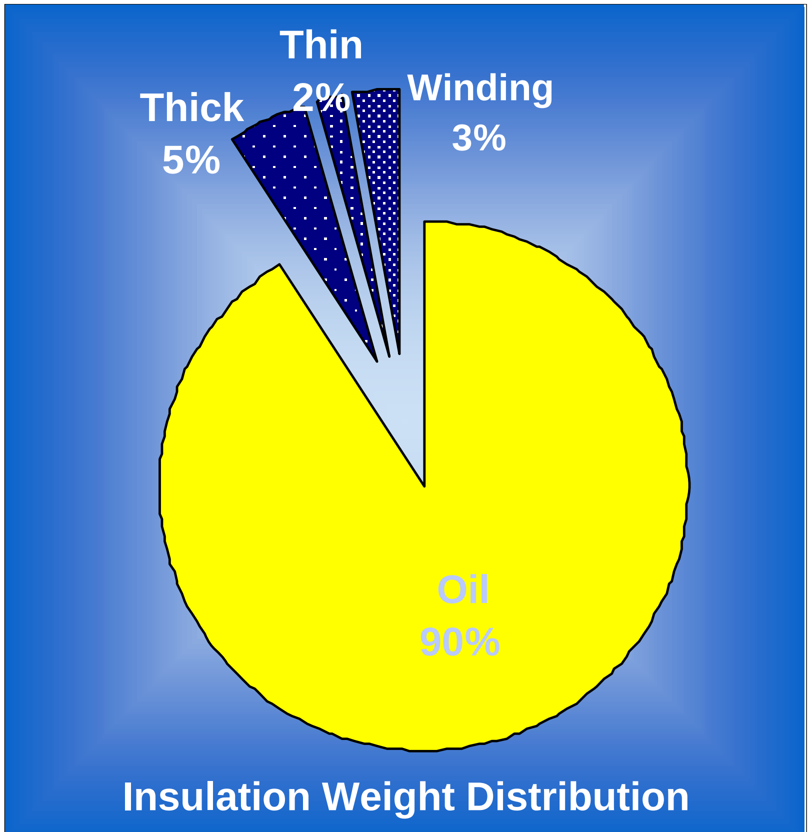
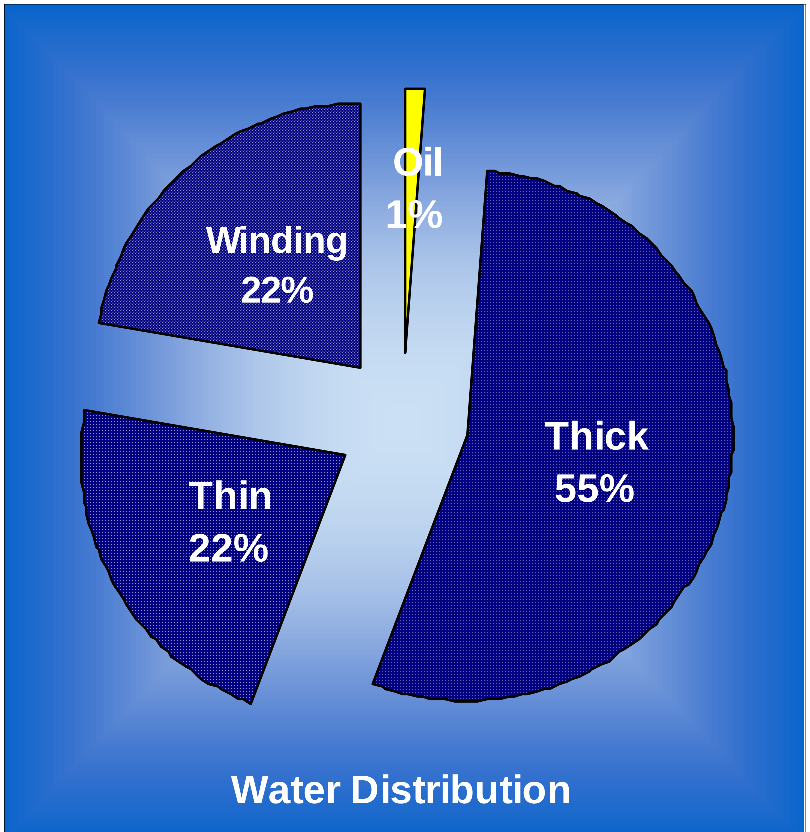
Most of the water is stored in the solid insulation





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Example of water distribution in a 25 MVA transformer with 3% moisture in paper

	40°C		80°C	
Oil (25 000litre)	**10 ppm**	**0.25 kg**	**80 ppm**	**2.0kg**
Paper (2500 kg)	**3 %**	**75 kg**	**2.93%**	**73.25 kg**
Total		**75.25 kg**		**75.25 kg**

- Most of the water is in the solid insulation
- Change in water content of oil does not entail a similar change in the water content of paper

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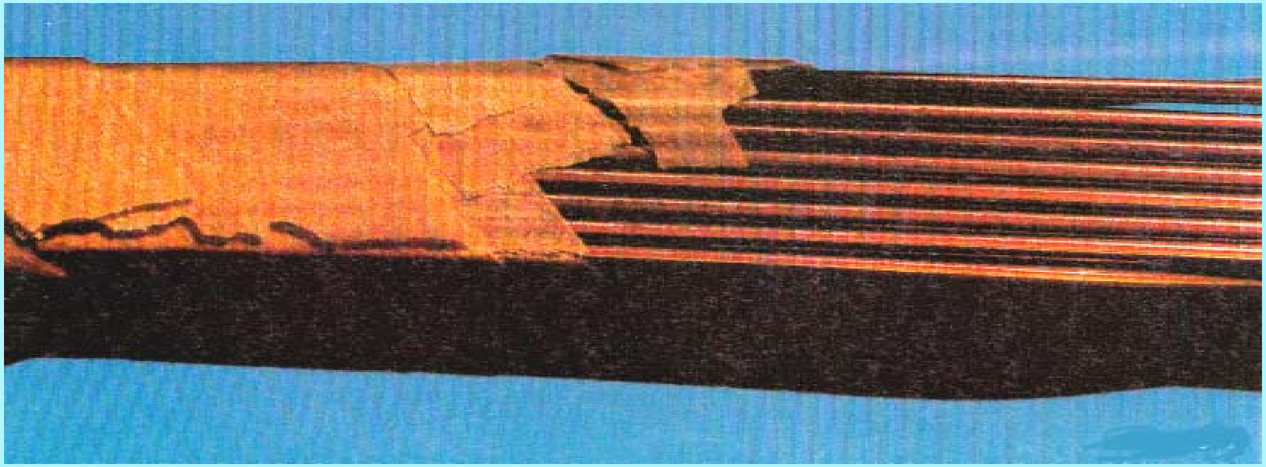
Paper Aging

- *Definition, End of life criteria*
- *Contributing factors*



Insulation aging is irreversible

Moisture content in transformer insulation is a persistent concern

Aging transformers tend to build-up moisture

IEEE Std 62 – 1995:

–Dry	0-2%
–Wet	2-4%
–Very Wet	4.5% +

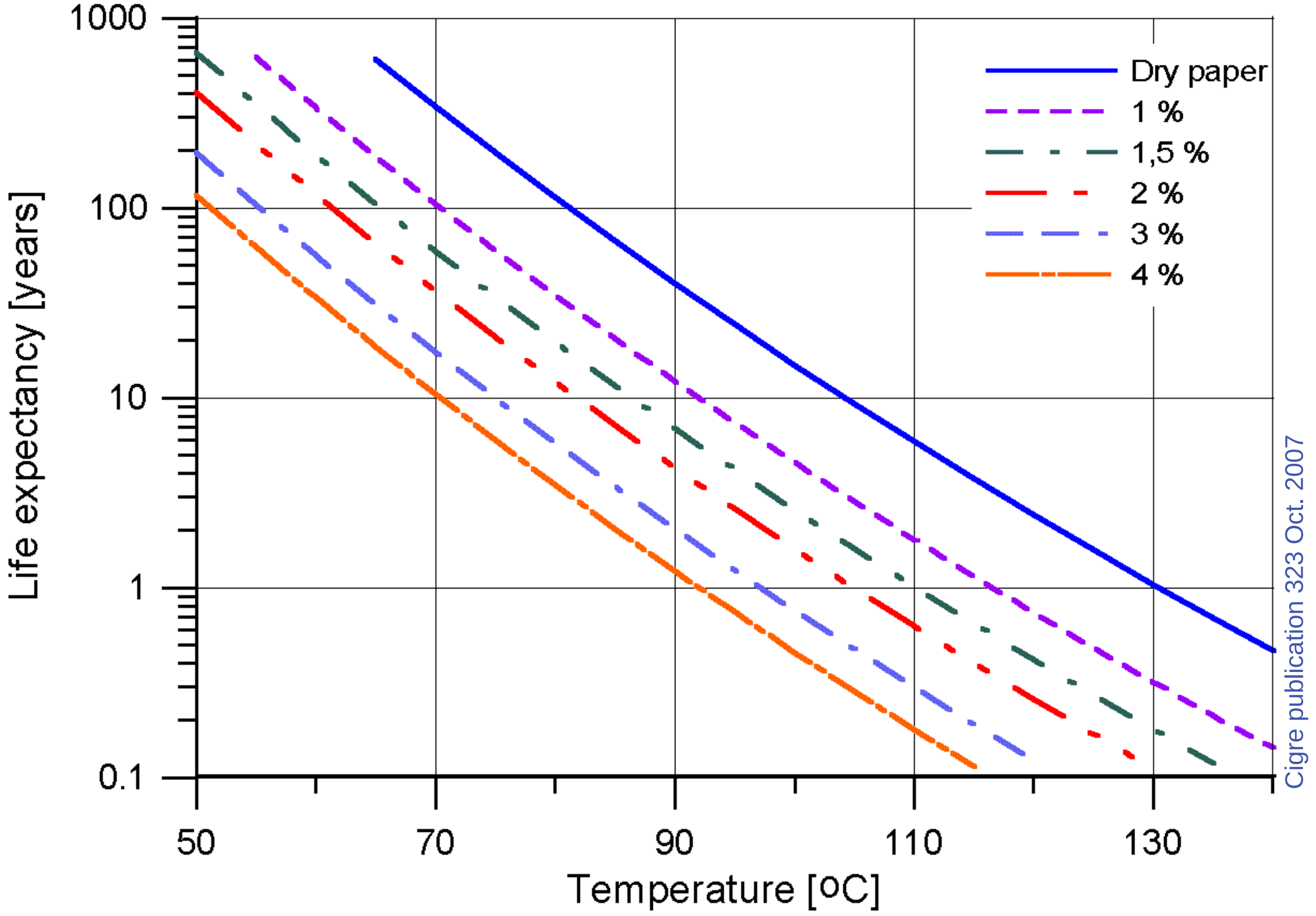
Only moisture in oil can actually be measured

Impact of moisture in paper

The amount of moisture in paper is a very important parameter to know, as it directly affects the following:

- Aging rate of the winding insulation
- Bubbling temperature (limits the amount of overloading of a transformer)
- Dielectric strength of the barriers at the bottom of the winding

Water accelerates ageing of Kraft paper



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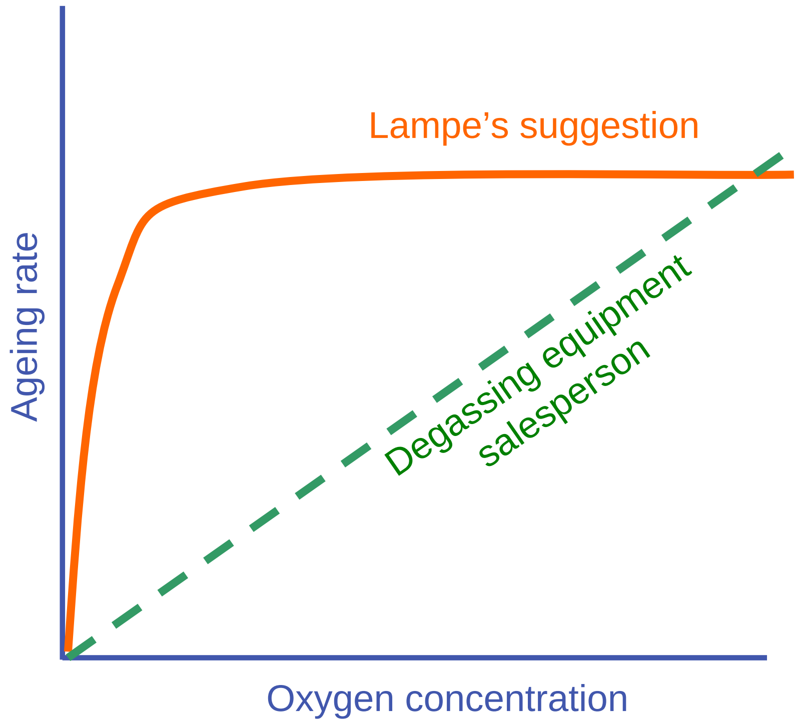
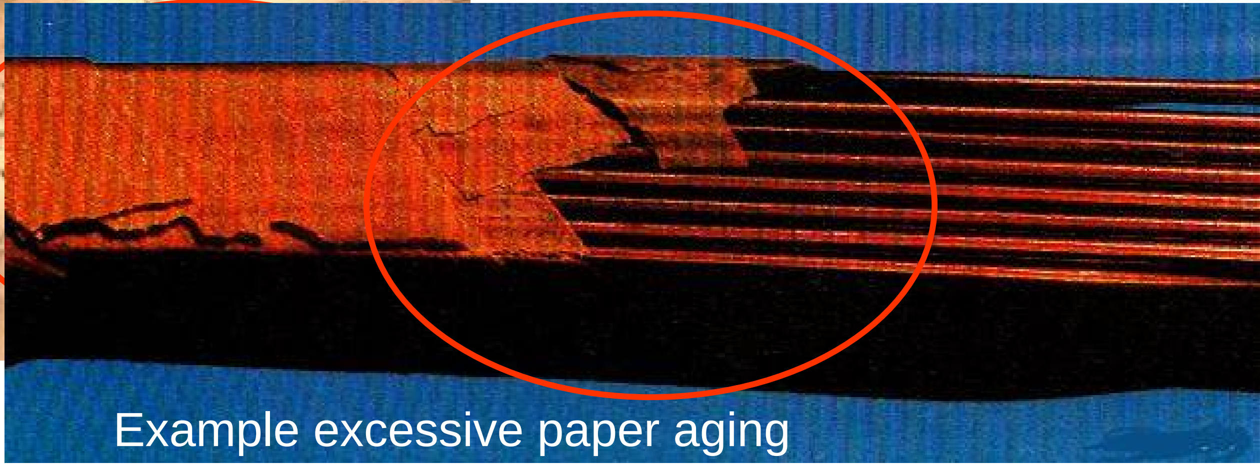
Oxygen accelerates ageing of paper



- Presence of oxygen has, in laboratory experiments shown an ageing acceleration by a factor 2-3
- Above 2000 ppm O_2 showed concentration independent ageing rates
- Oxygen saturated 30 000 ppm O_2
- Oxygen free 300 ppm O_2

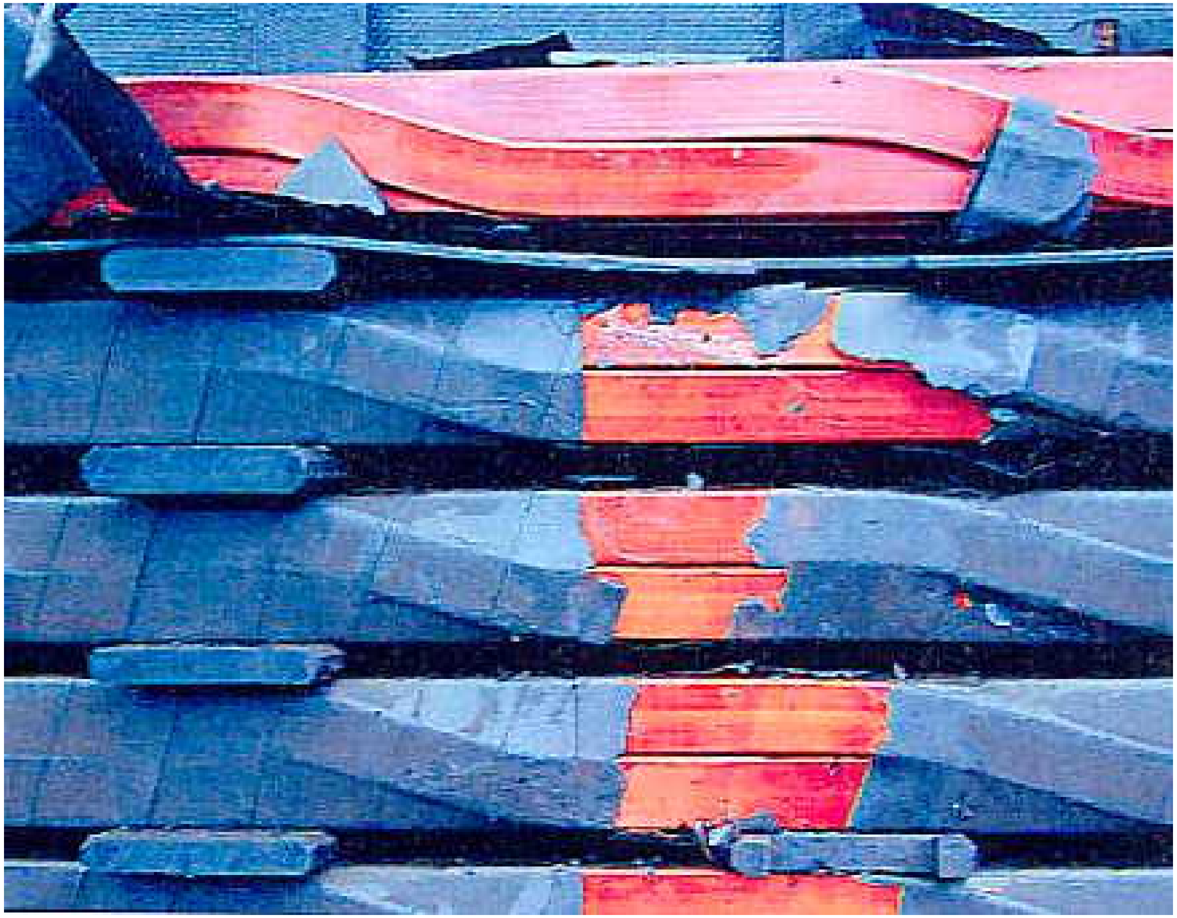
Cigre Brochure 323, October 2007

Example of Winding Paper Degradation



Evolution of fault at weak points

The weak points are candidates for a possible failure



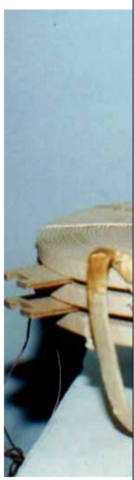
V. Sokolov Cigre Colloquium 1997

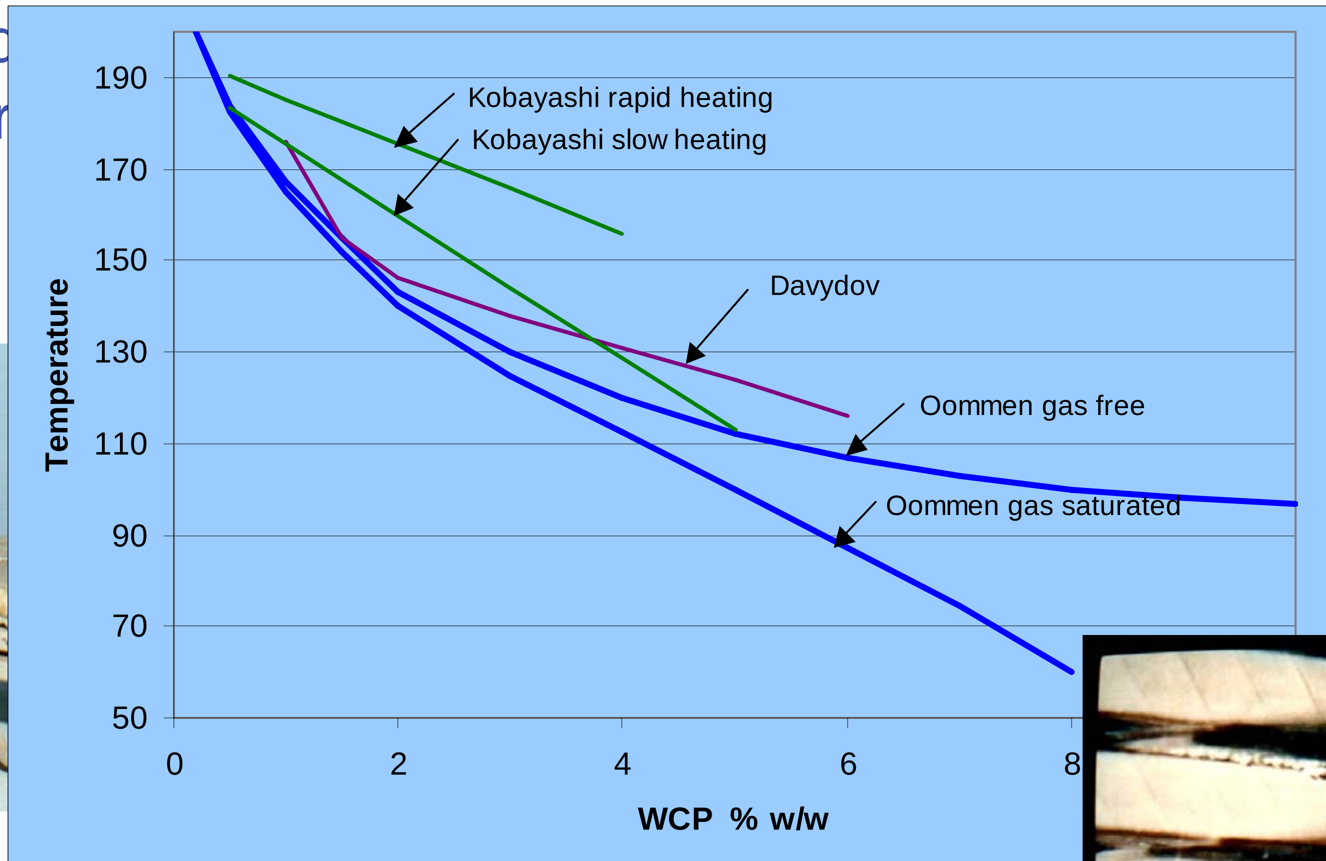
Impact of moisture in winding insulation

• Increased risk of releasing bubbles at high load

Resid

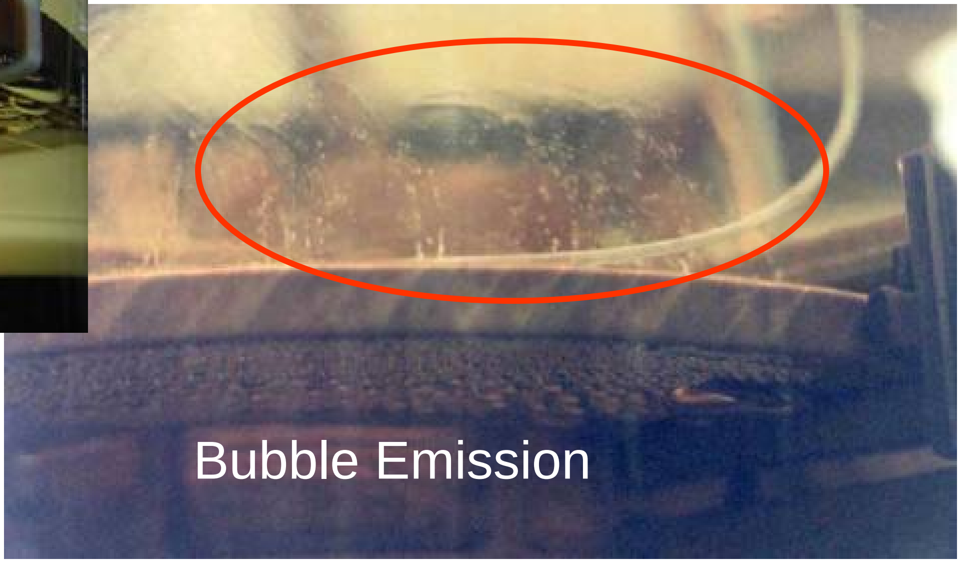
water





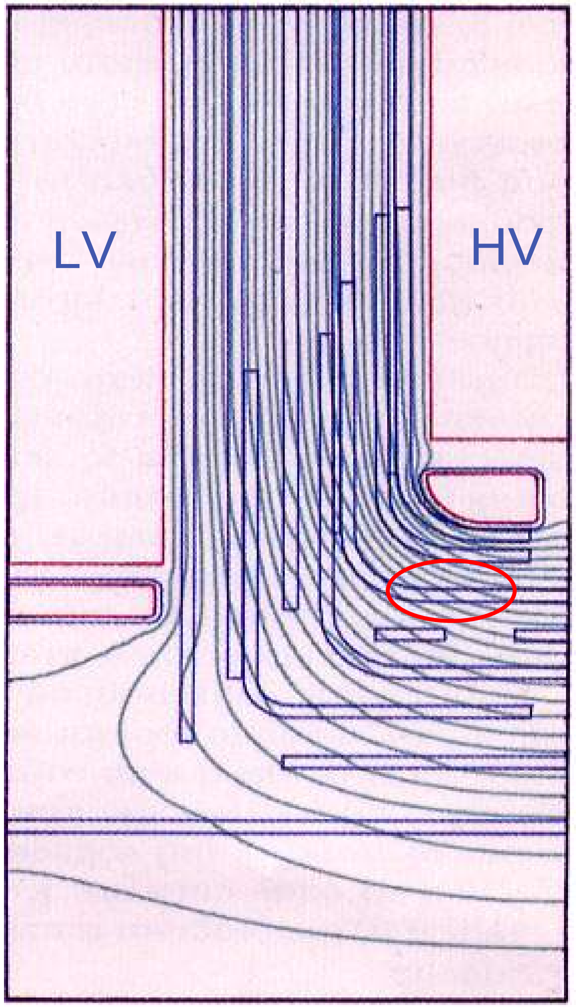
T.V.

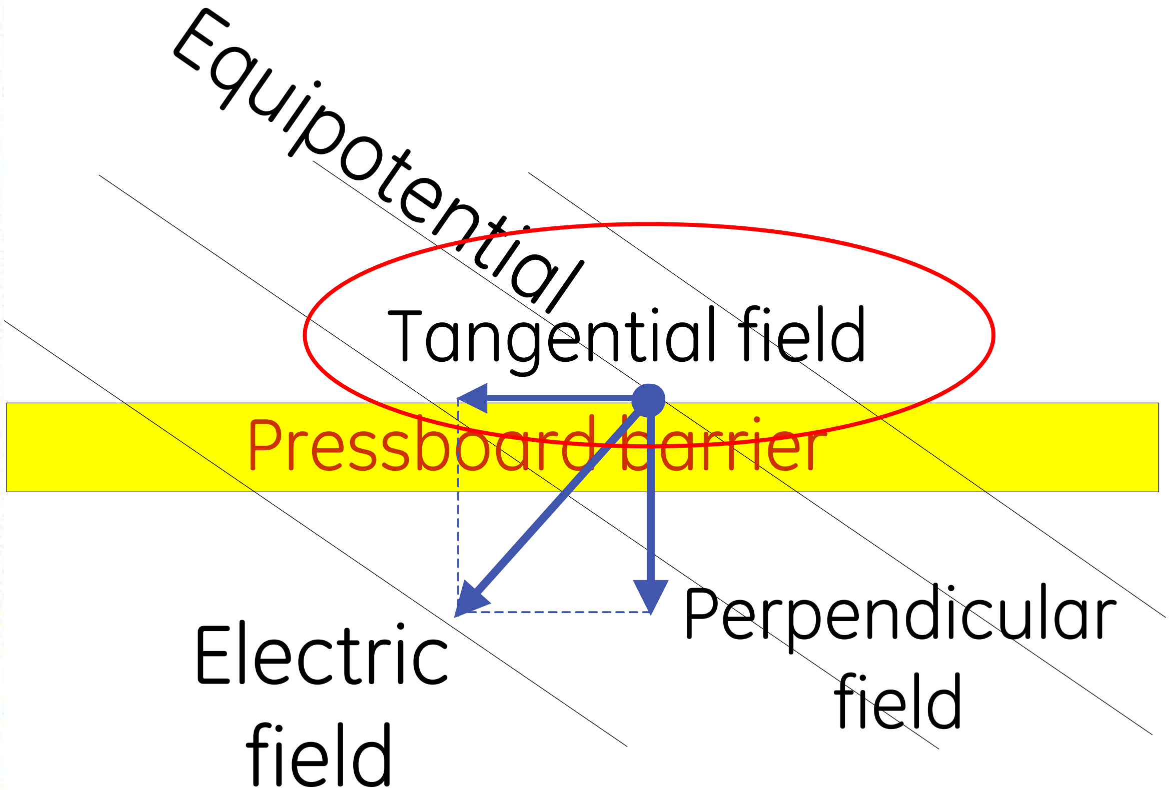
Example of Overheating



V. Davydov EPRI Moisture Seminar 2002

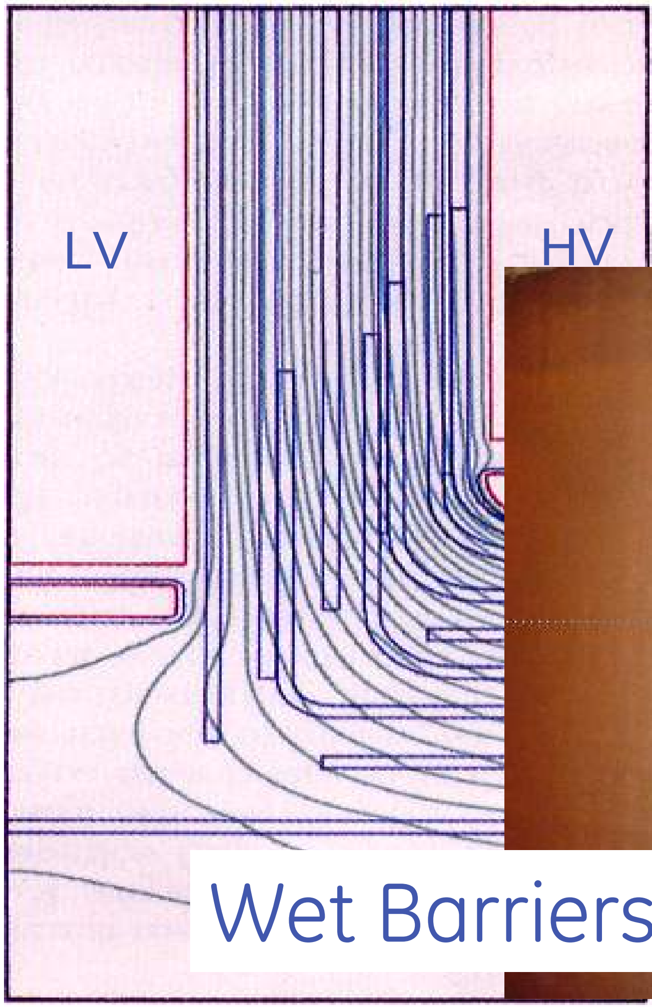
Moisture reduces dielectric strength of pressboard barriers

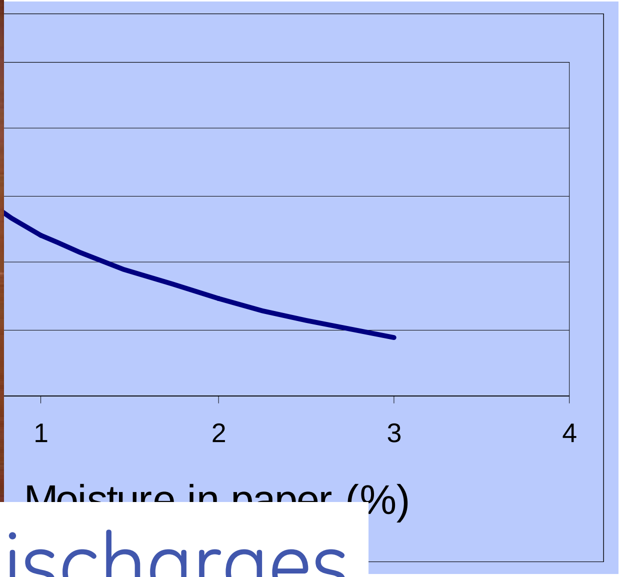




Moisture can promote tracking discharges on pressboard barriers

Surface discharges are more likely on angle rings

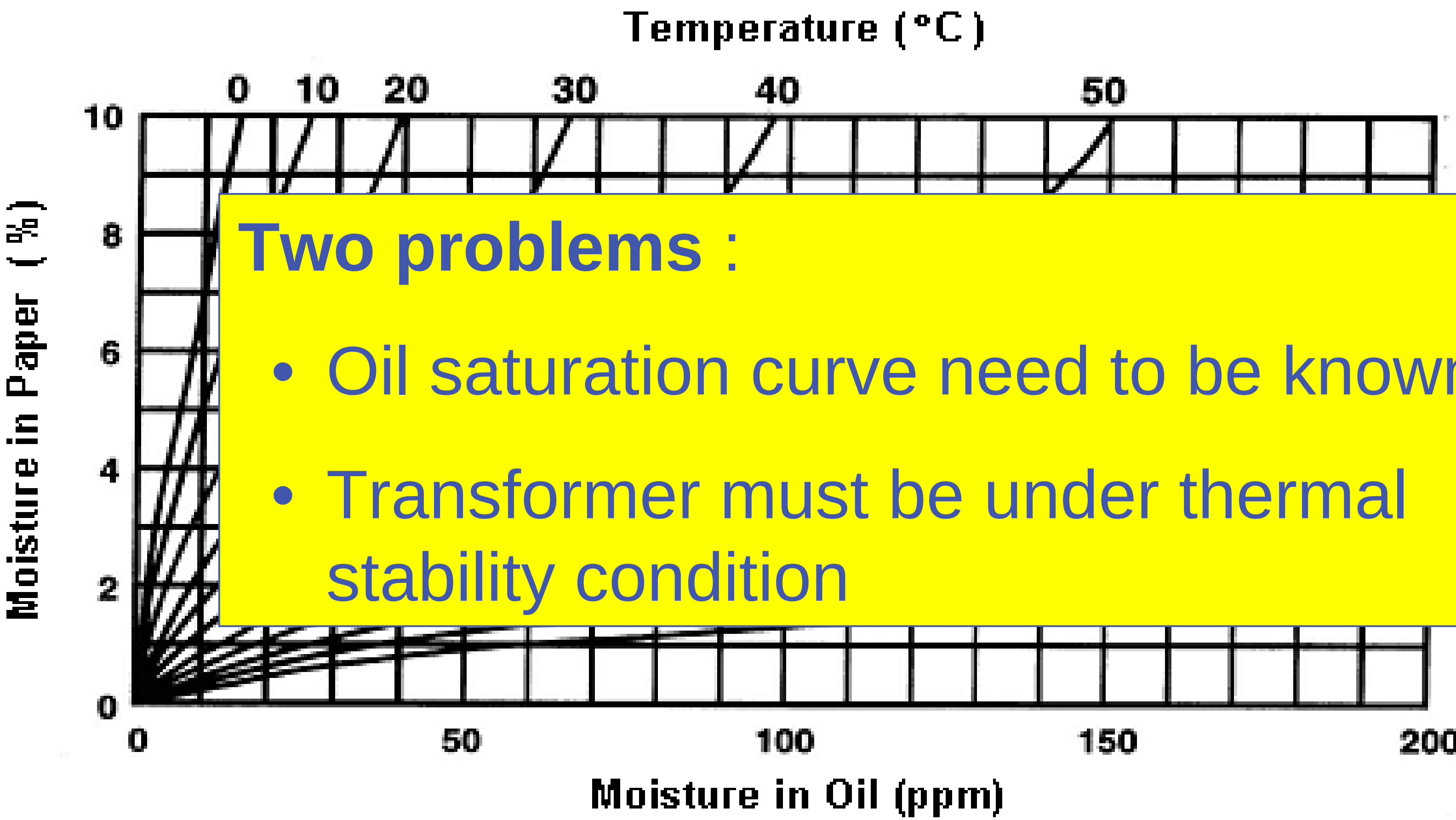




Wet Barriers = Strong Discharges

Alstom T&D, Merida, 2003

Assessing Water Content in Transformer Solid insulation



Two problems :

- Oil saturation curve need to be known
- Transformer must be under thermal stability condition

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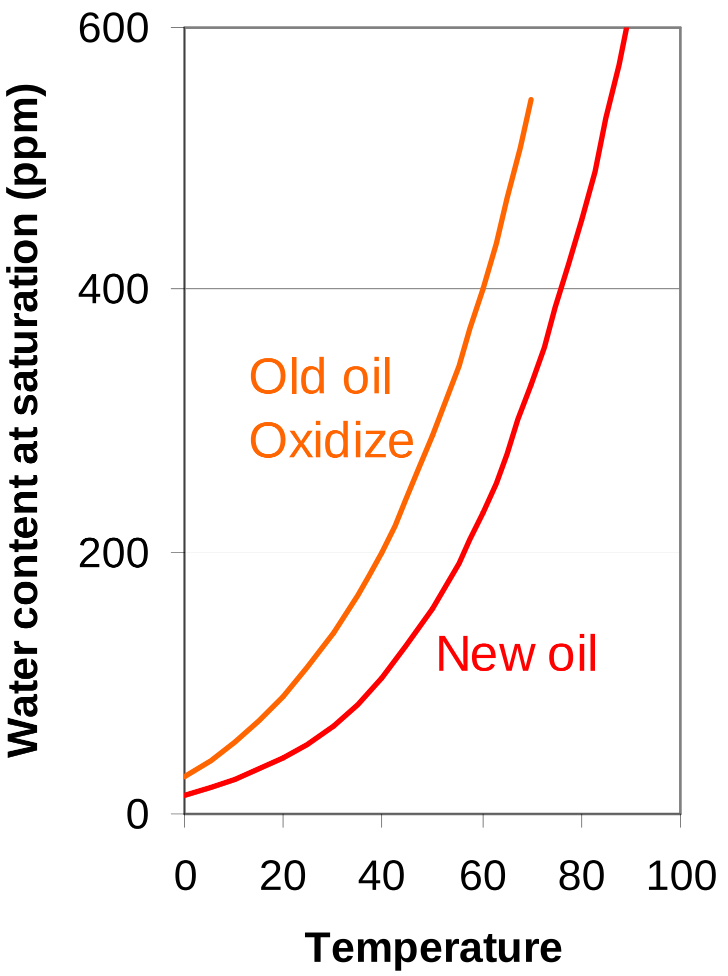
Determination of water in solid insulation from water in oil

The problem:

- Should we use absolute water content in oil (ppm) or Relative Saturation (RS)?
- Is water content uniform through the transformer solid insulation?
- How do we handle the diffusion time between paper and oil?

Oil saturation characteristics

- Water content in oil can be expressed in ppm
- This value must be related to oil saturation characteristics
- But saturation characteristic vary with type of oil and oil condition
- Therefore it is more convenient to consider Relative Saturation (RS)



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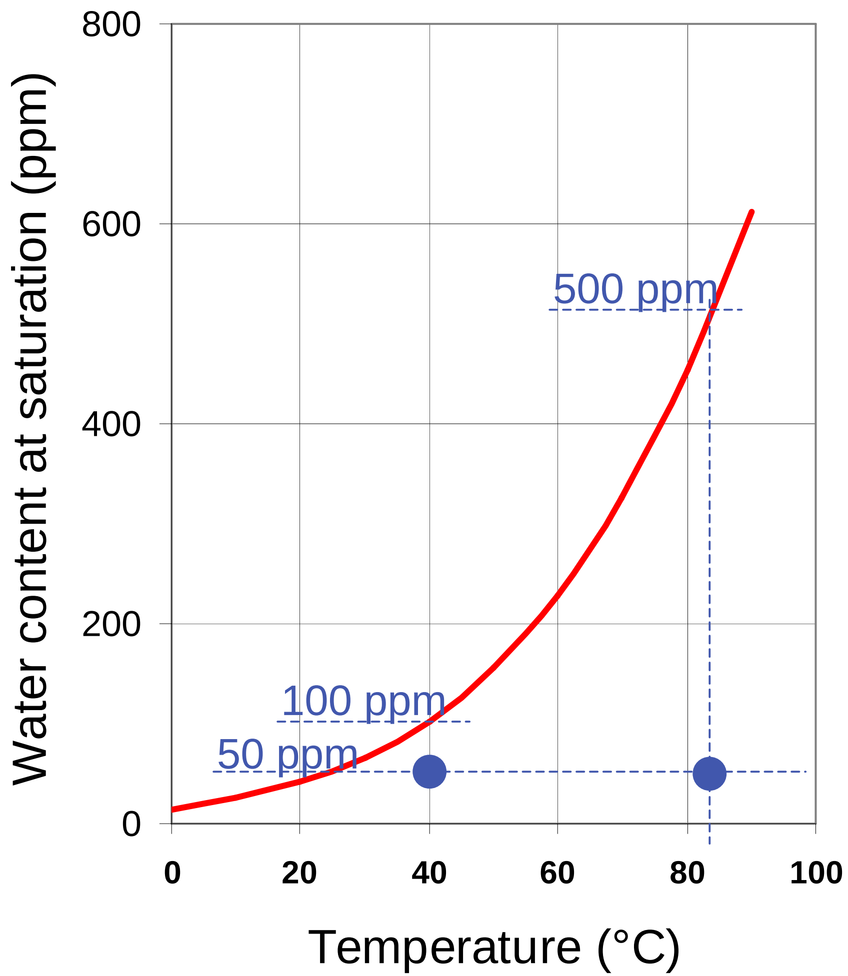
Relative Saturation (RS)

- Relative saturation is the moisture content relative to the saturation value at a given temperature
- At equilibrium,
  RS in oil = RS in paper
- It varies within the transformer
- Example:
  Sensor: 40°C, RS =50%
  Hot spot: 85°C, RS =10%



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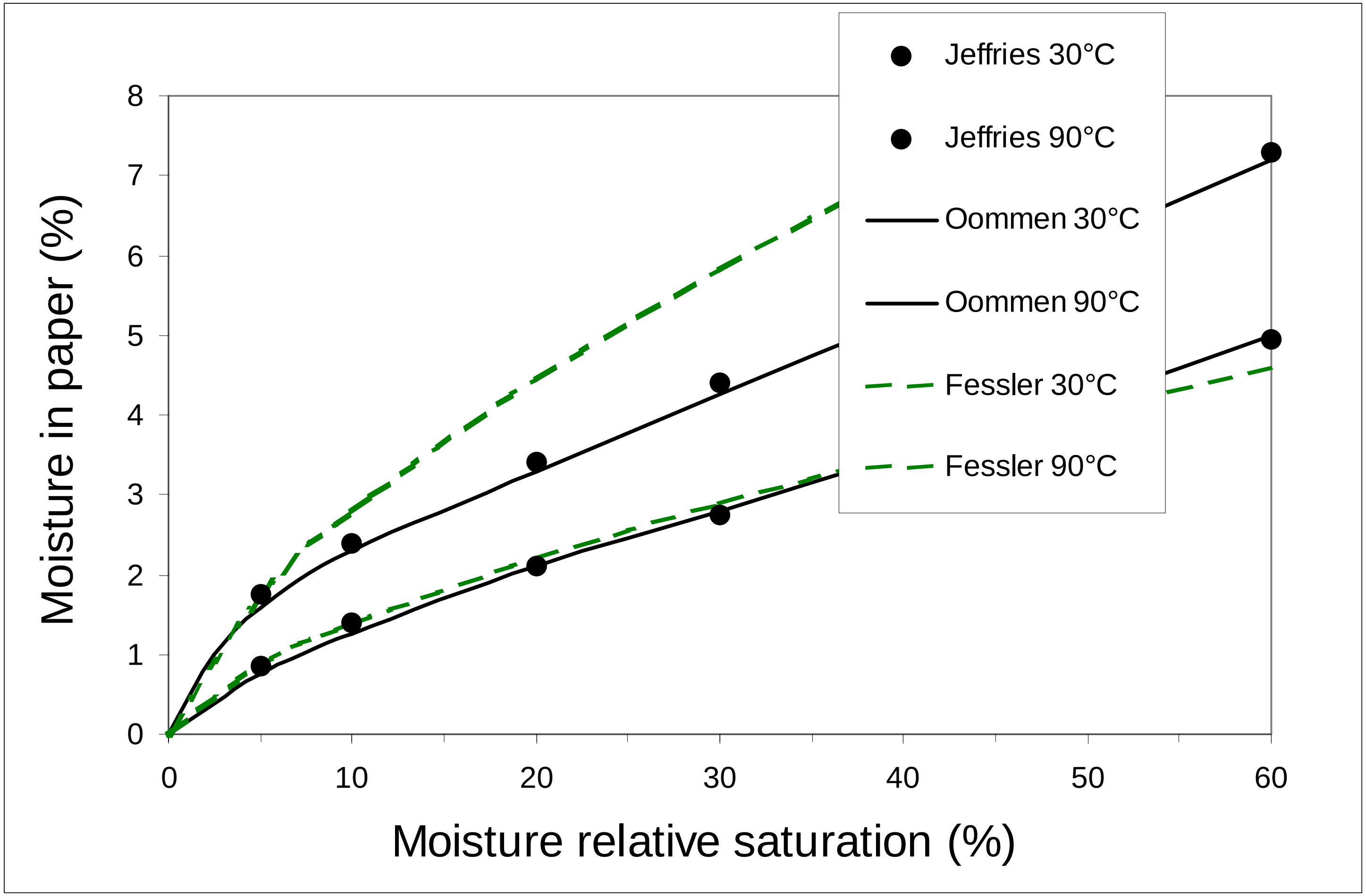
Moisture Migration Summary

- Equilibrium curve exist to relate moisture in paper to relative saturation in oil.
- These curves assume Equilibrium exists (the moisture has stopped moving between the oil and paper)
- But this is never the case.
- Many people make errors in using these charts, ‘blindly’ without considering equilibrium conditions which must exist, and their mistakes can be costly

Assessing Water Content in Transformer Solid insulation



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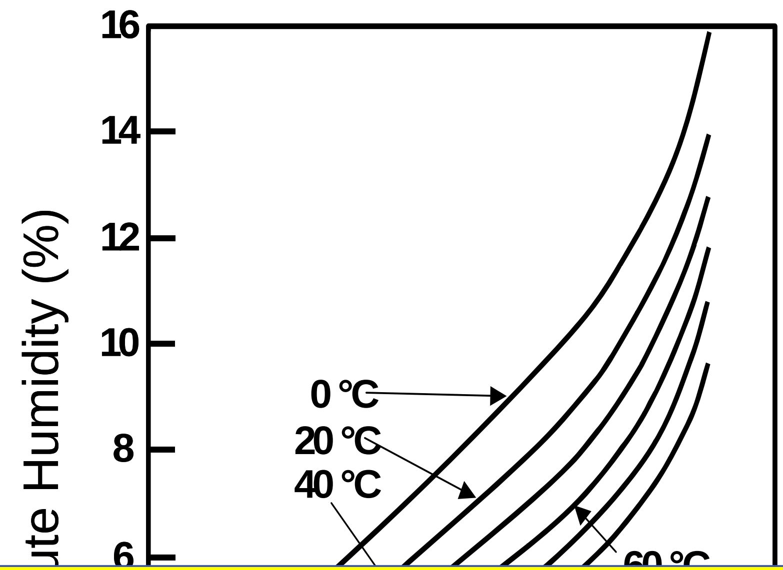
Moisture in paper

Equilibrium curves are now available to convert moisture in oil into moisture in paper without considering oil saturation characteristics



But we still need:

- Temperature of oil-paper interface
- Diffusion time constant
- Facility for integrating results over long period of time

Moisture Migration Summary

- Paper at different temperatures inside the transformer will will have different moisture levels
- Different areas of the insulation system have different thickness (winding insulation versus barrier insulation)
- The Equilibrium condition therefore will take much longer for barrier insulation versus winding insulation

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Typical diffusion time constant (in days)

	Insulation Thickness		
Temperature	1mm	2mm	4mm
80 °C	0.9	3.6	14
60 °C	4.2	17	67
40 °C	20	79	317
20 °C	93	373	1493

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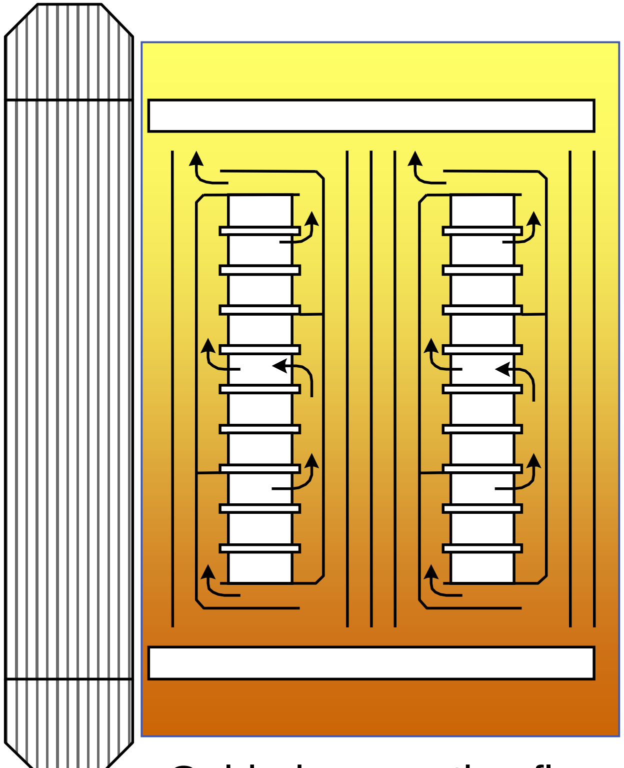
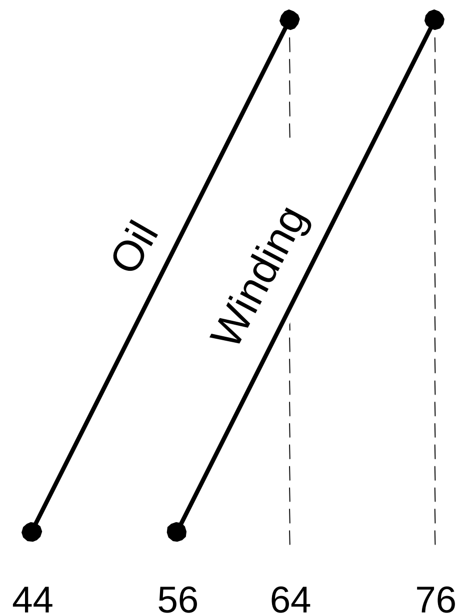
Moisture in paper varies within the transformer

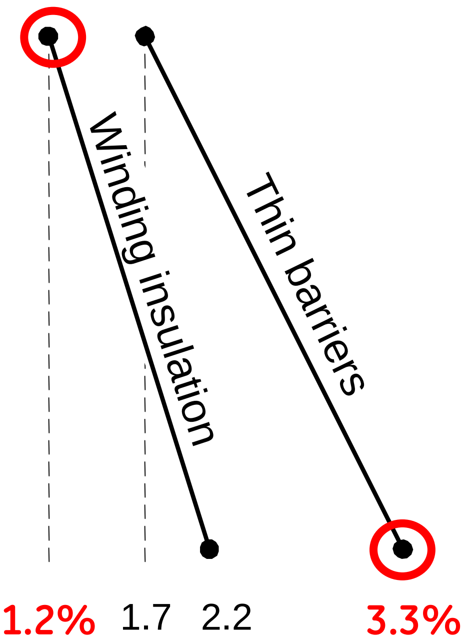
Area of Interest for moisture in paper



Guided convection flow through disk windings



Temperature (^{o}C)



Moisture content (%) at equilibrium condition

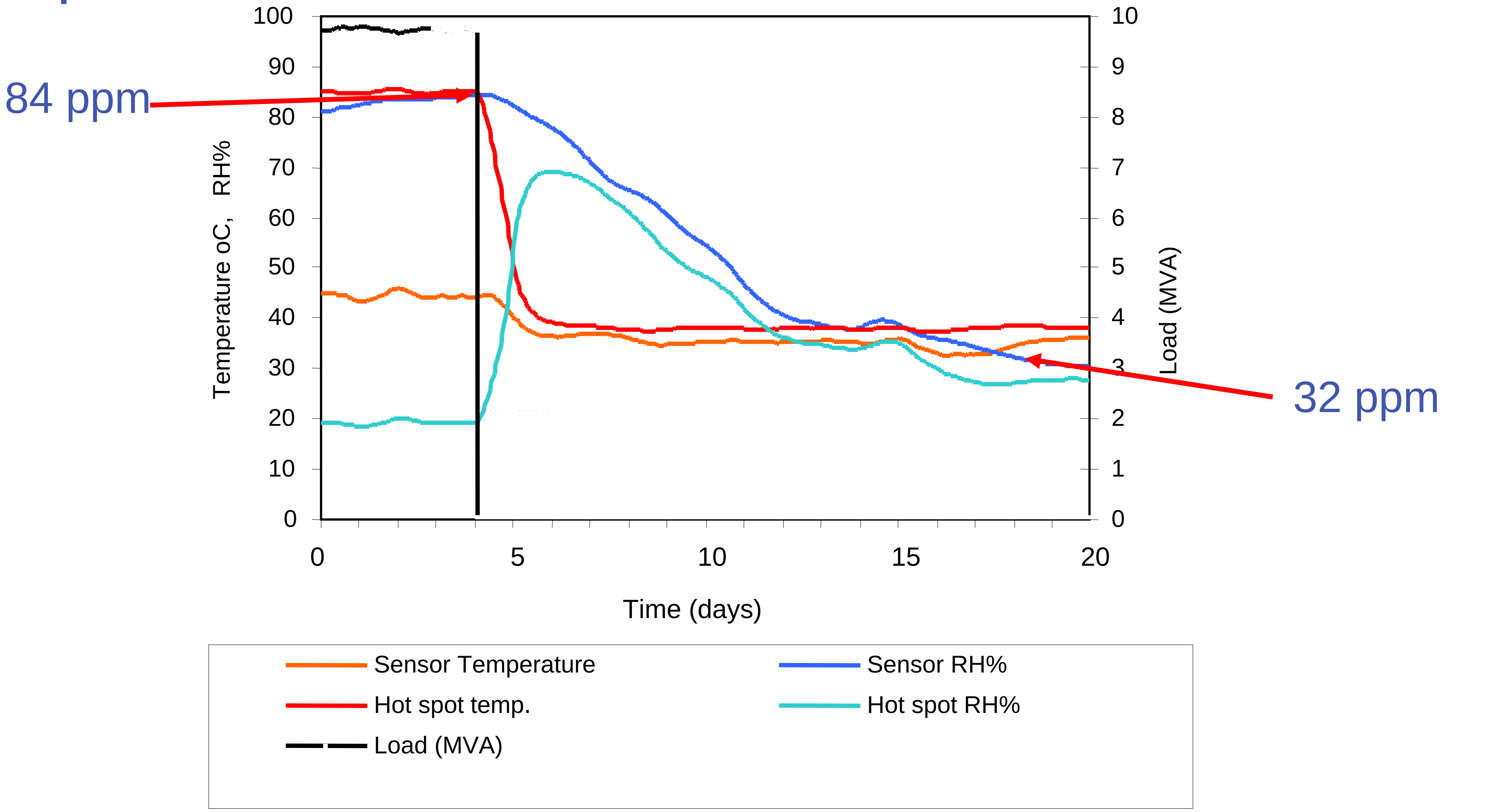
Migration of moisture in transformers

- Moisture content in solid insulation, is not a single value
- It appears impractical to assess the moisture content of the thick insulation
- Lowest part of pressboard barriers is the most critical location and should determine needs for dying
- Sensitivity analysis indicates that the value assigned to diffusion time constant is not critical

Migration of moisture in transformers

- There is a correlation between the amount of water in the oil and in the paper
- However, this correlation is dynamic and is changing as a function of transformer loading
- The dynamics of the distribution of water in the transformer is quite complex and changing

Moisture inside the transformer moves back and forth between the oil and paper by diffusion as a function of temperature



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What to do?

Hydran M2

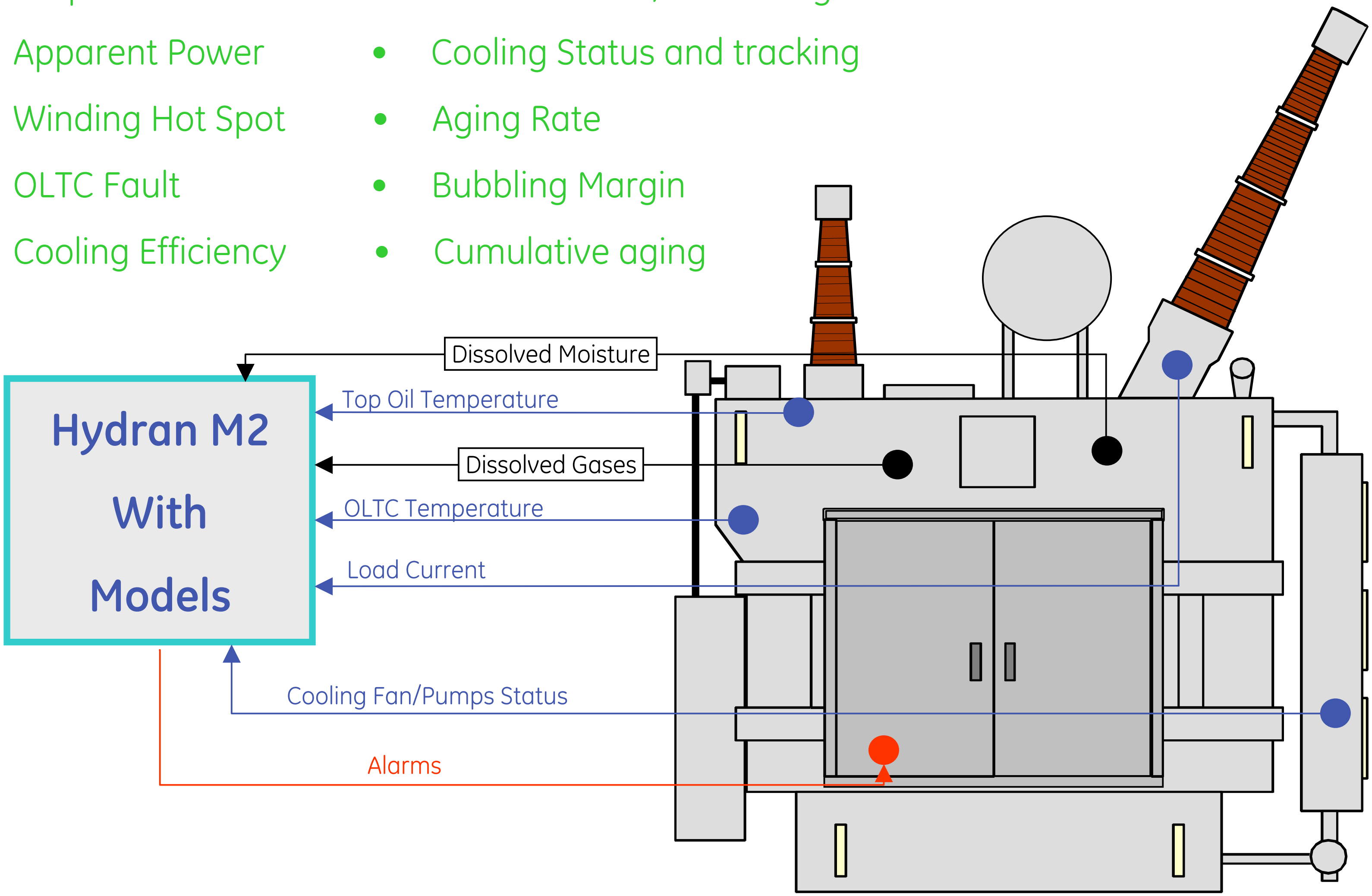
Advanced Gas and Moisture monitor

- H2 and CO
- Moisture in oil
- Trending
- 4 analog inputs
- Data Logging
- Networking
- Integrated Modem/TCP-IP

Typical HYDRAN M2 Installation

The Hydran M2 as Advanced Transformer Monitor

- Incipient Fault
- Apparent Power
- Winding Hot Spot
- OLTC Fault
- Cooling Efficiency
- Moisture in Oil, in Windings and in Barriers
- Cooling Status and tracking
- Aging Rate
- Bubbling Margin
- Cumulative aging



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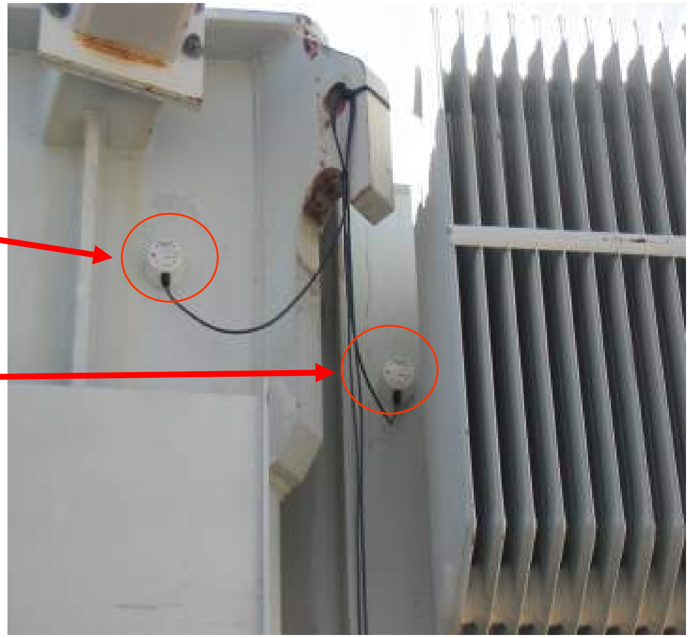
Temperature and Load

Top oil

OLTC



Ambient Temperature Sensor

Magnetically Mounted Temperature sensor

Clip-On load sensor

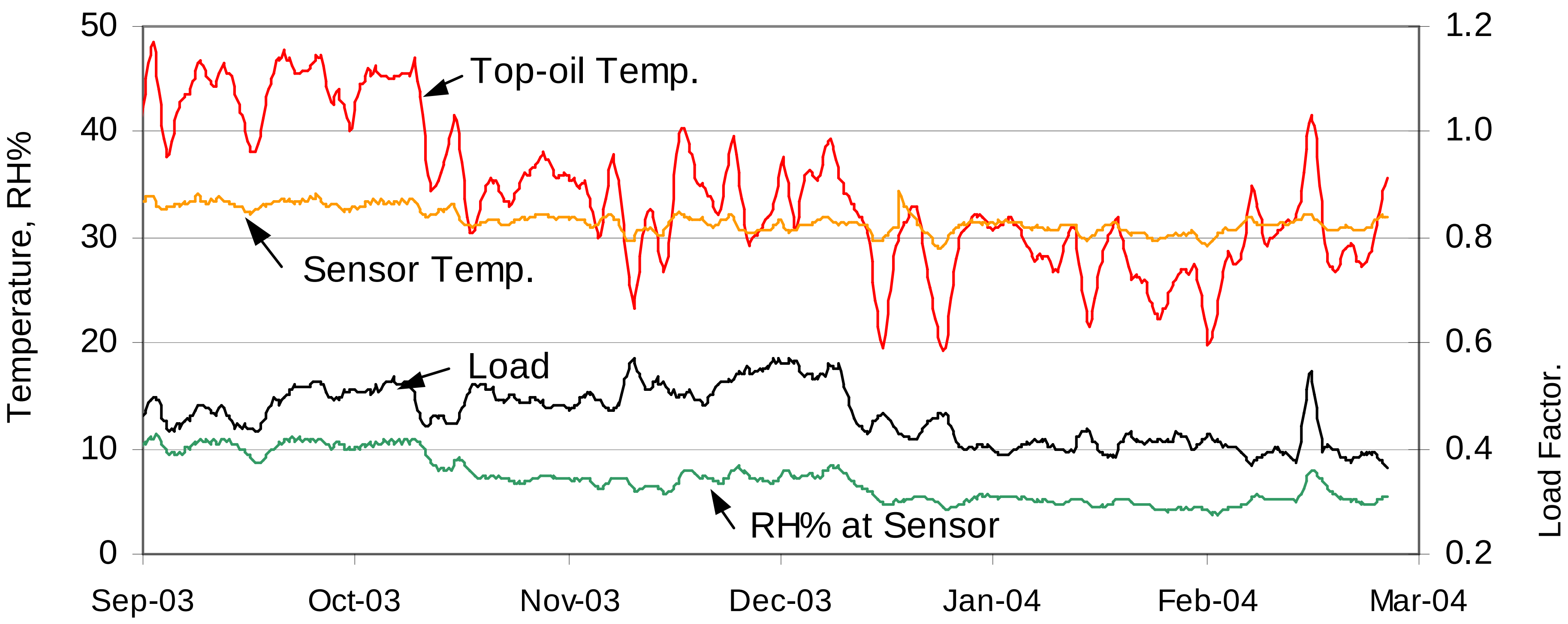
Field experience with on-line moisture monitoring

US Western Utility

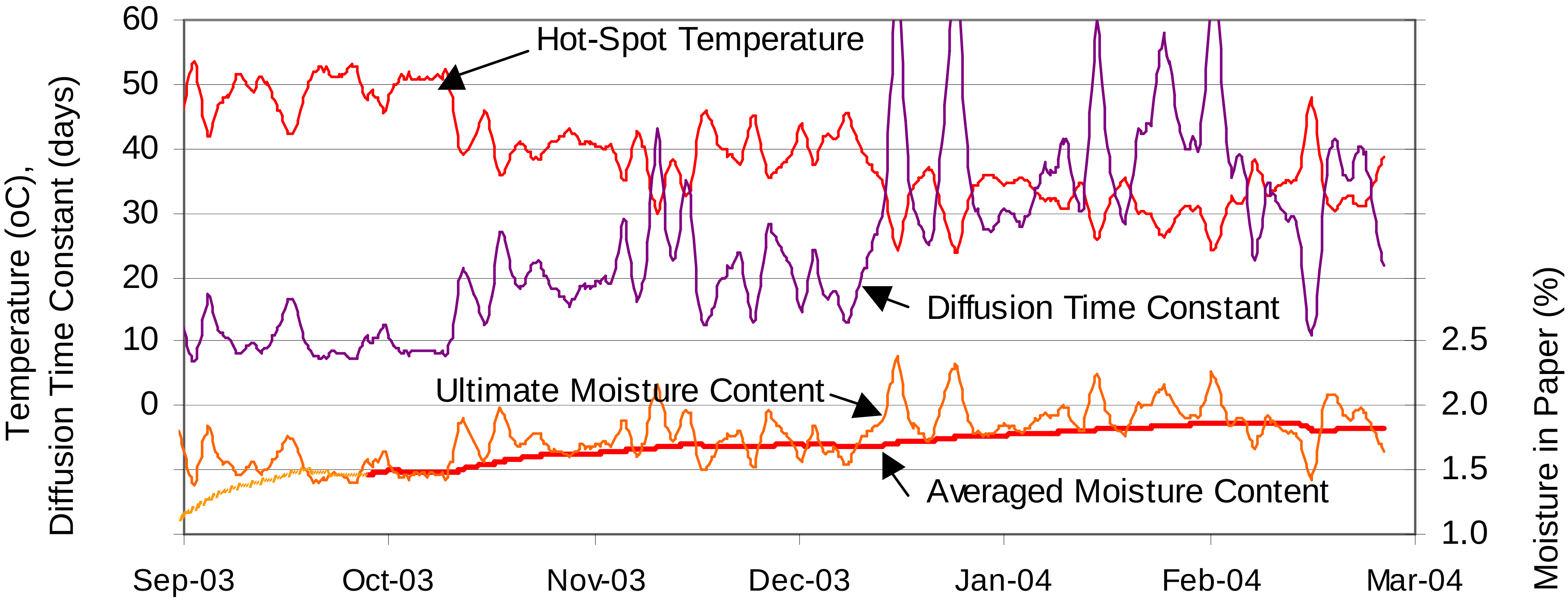
50MVA, Core type,
230 / 13.8 kV
55°C rise

Hydran M2 mounted on spare cooler outlet

Field data recording for moisture assessment - 50 MVA transformer



Moisture content in winding insulation - 50 MVA transformer



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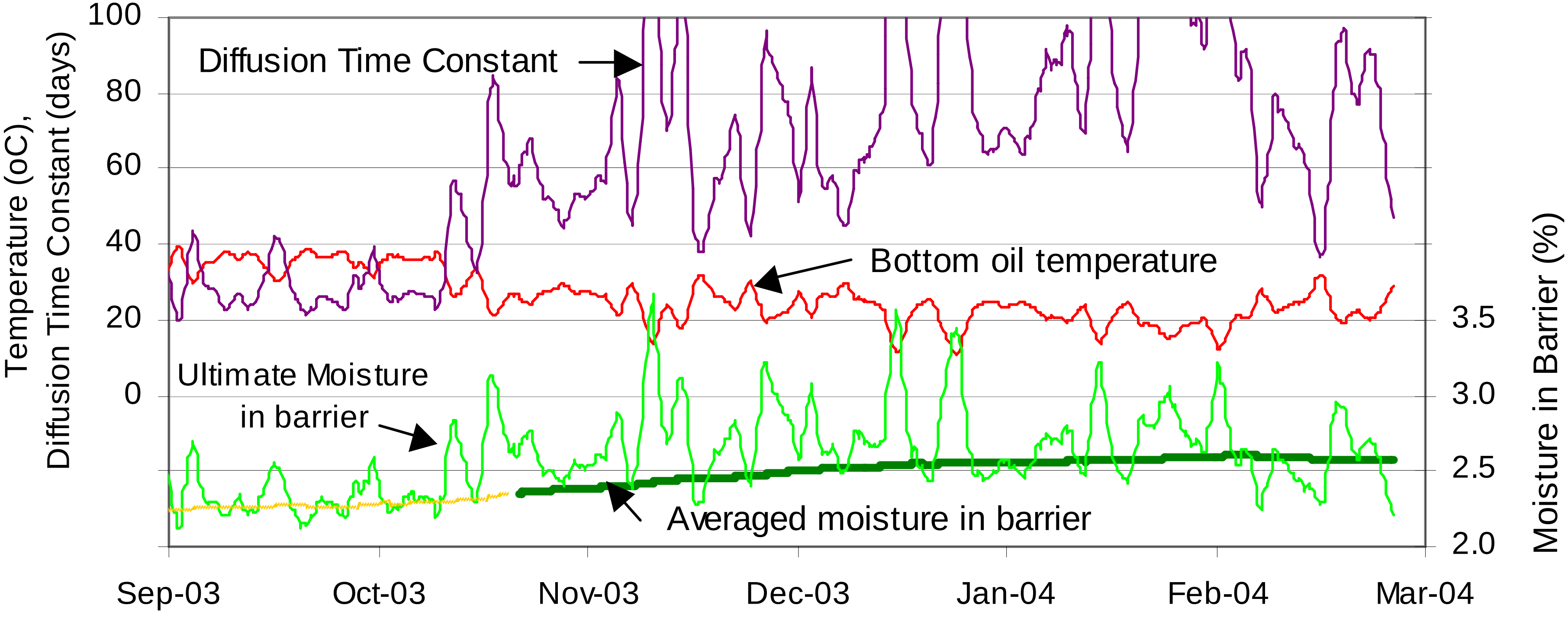
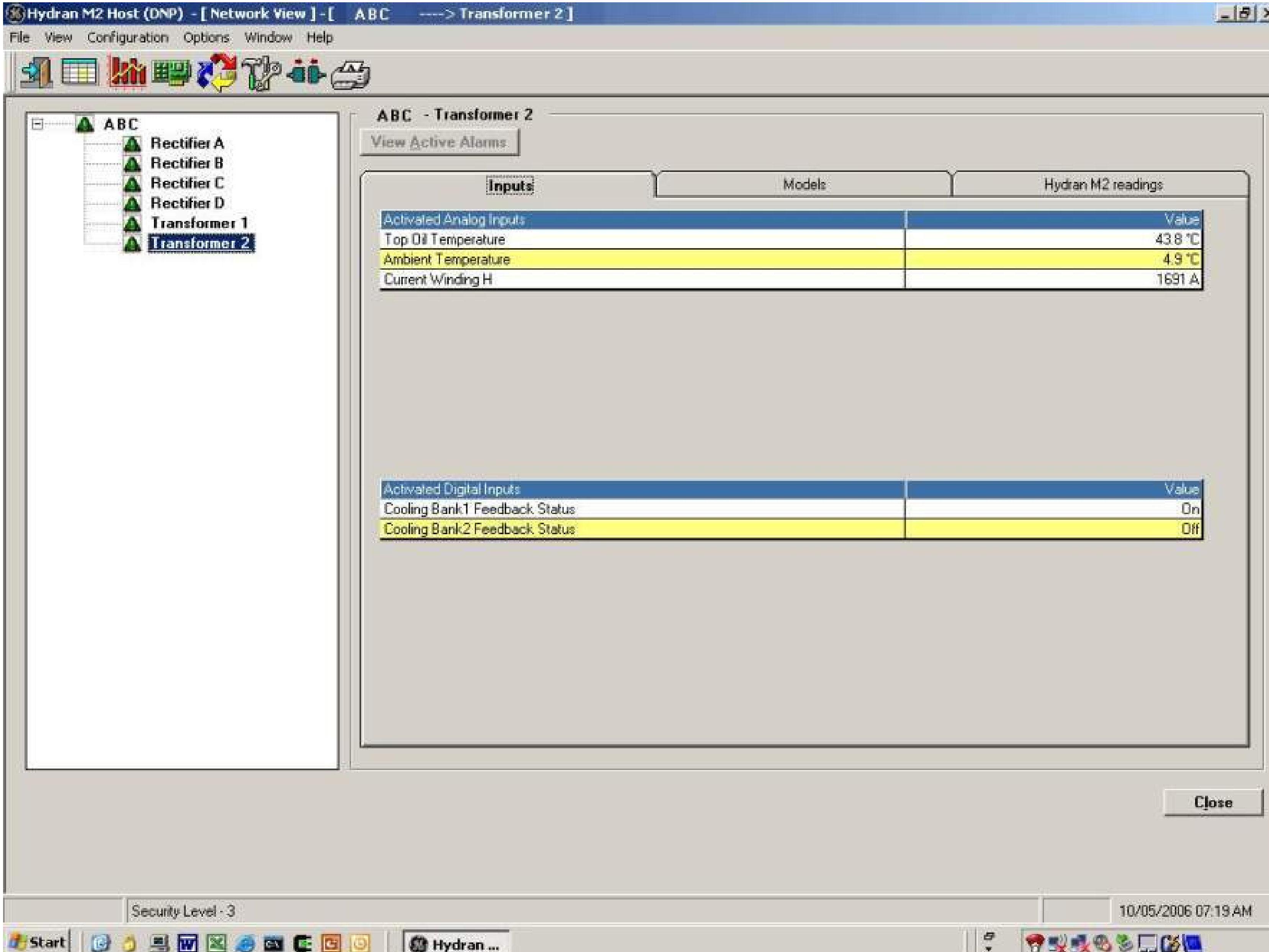
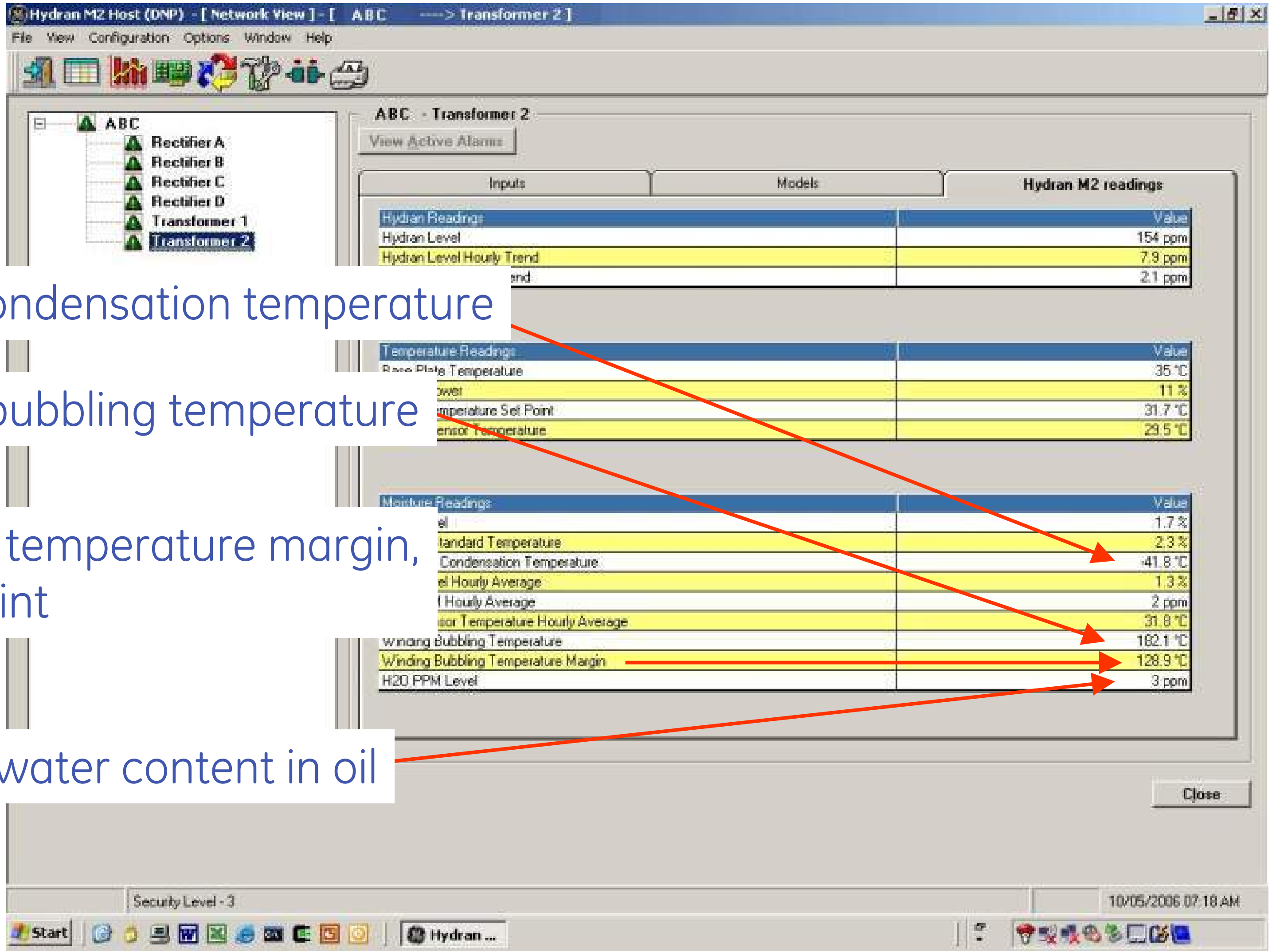
Moisture content in pressboard barrier - 50 MVA transformer




Hydran M2 Host (DNP) - [Network View] - [ABC ----> Transformer 2]
File View Configuration Options Window Help
ABC
Rectifier A
Rectifier B
Rectifier C
Rectifier D
Transformer 1
Transformer 2
ABC - Transformer 2
View Active Alarms
Inputs
Models
Hydran M2 readings
Activated Analog Inputs | Value
Top Oil Temperature | 43.8 °C
Ambient Temperature | 4.9 °C
Current Winding H | 1691 A
Activated Digital Inputs | Value
Cooling Bank1 Feedback Status | On
Cooling Bank2 Feedback Status | Off
Close
Security Level - 3
10/05/2006 07:19 AM
Start
Hydran ...

Moisture and Bubbling Model



Water condensation temperature

Winding bubbling temperature

Bubbling temperature margin, alarm point

Absolute water content in oil

Moisture and Bubbling Model

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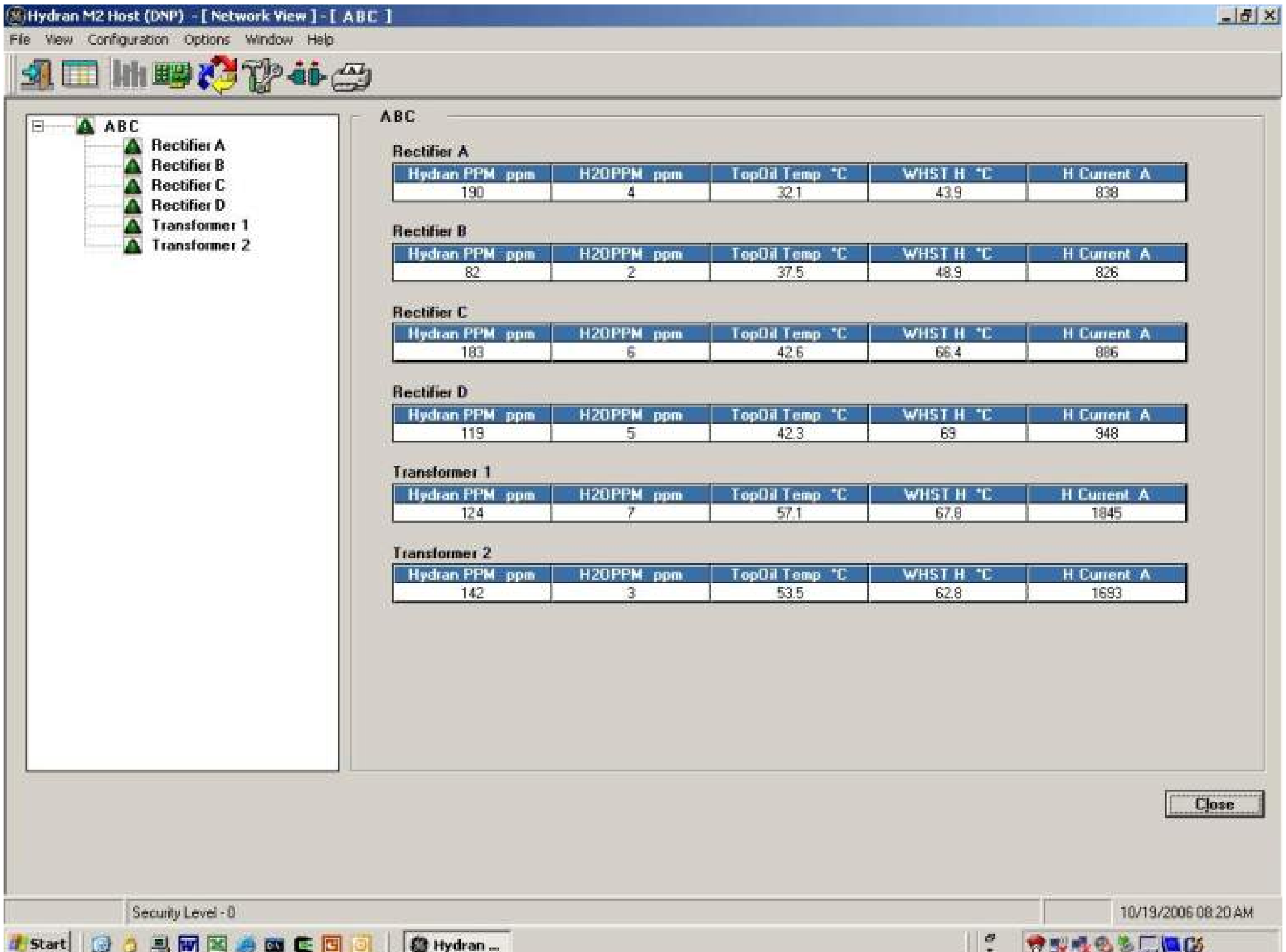
HYDRAN M2– Communications, real time survey



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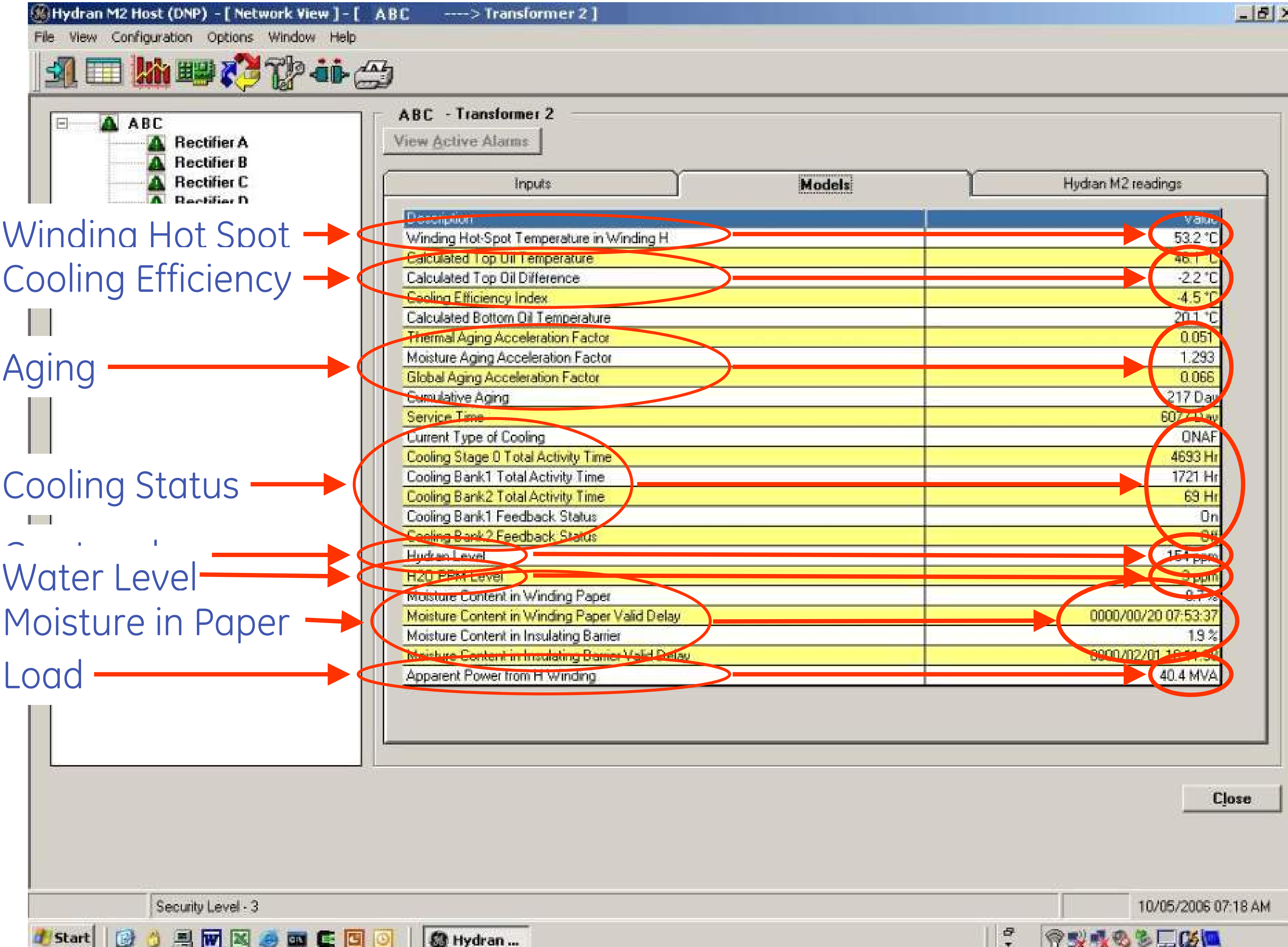

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How degraded is my insulation?

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Detection of paper degradation
CO2 / CO

- **CO_2/CO ratios < 3** indicate fault involving paper degradation
- **CO_2** can also come from atmosphere in open breathing transformers
- **CO** can come from oil oxidation, paint, varnishes and phenolic resins

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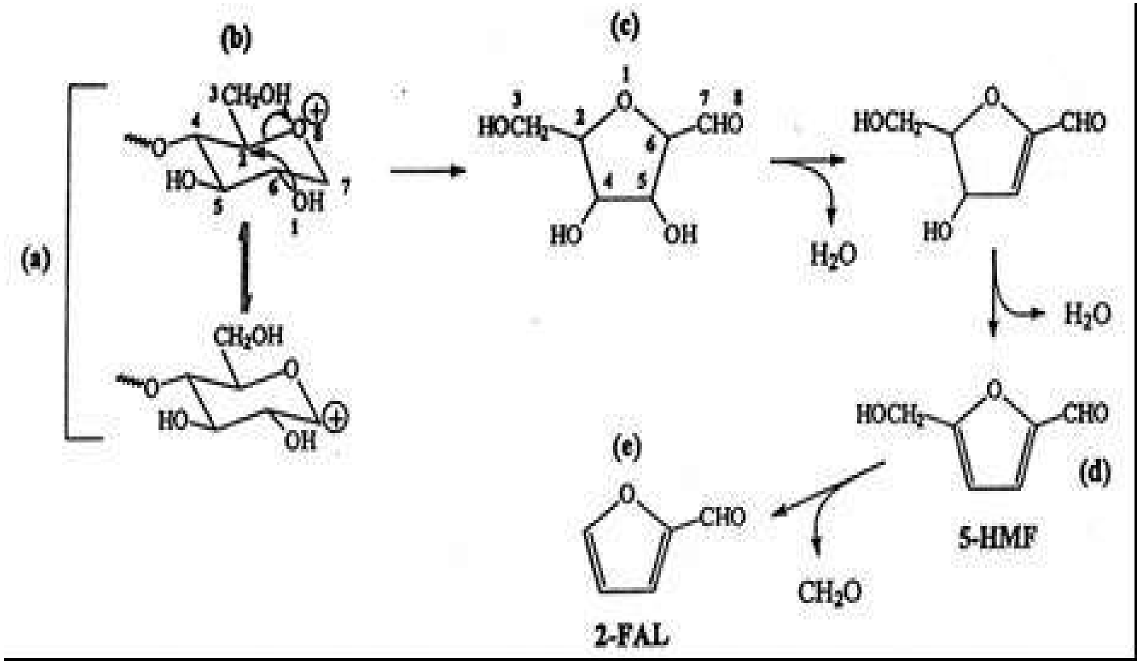
Detection of paper degradation
from furanic compounds



Several furanic compounds are generated during paper decomposition

2FAL is the most stable and most abundant compound

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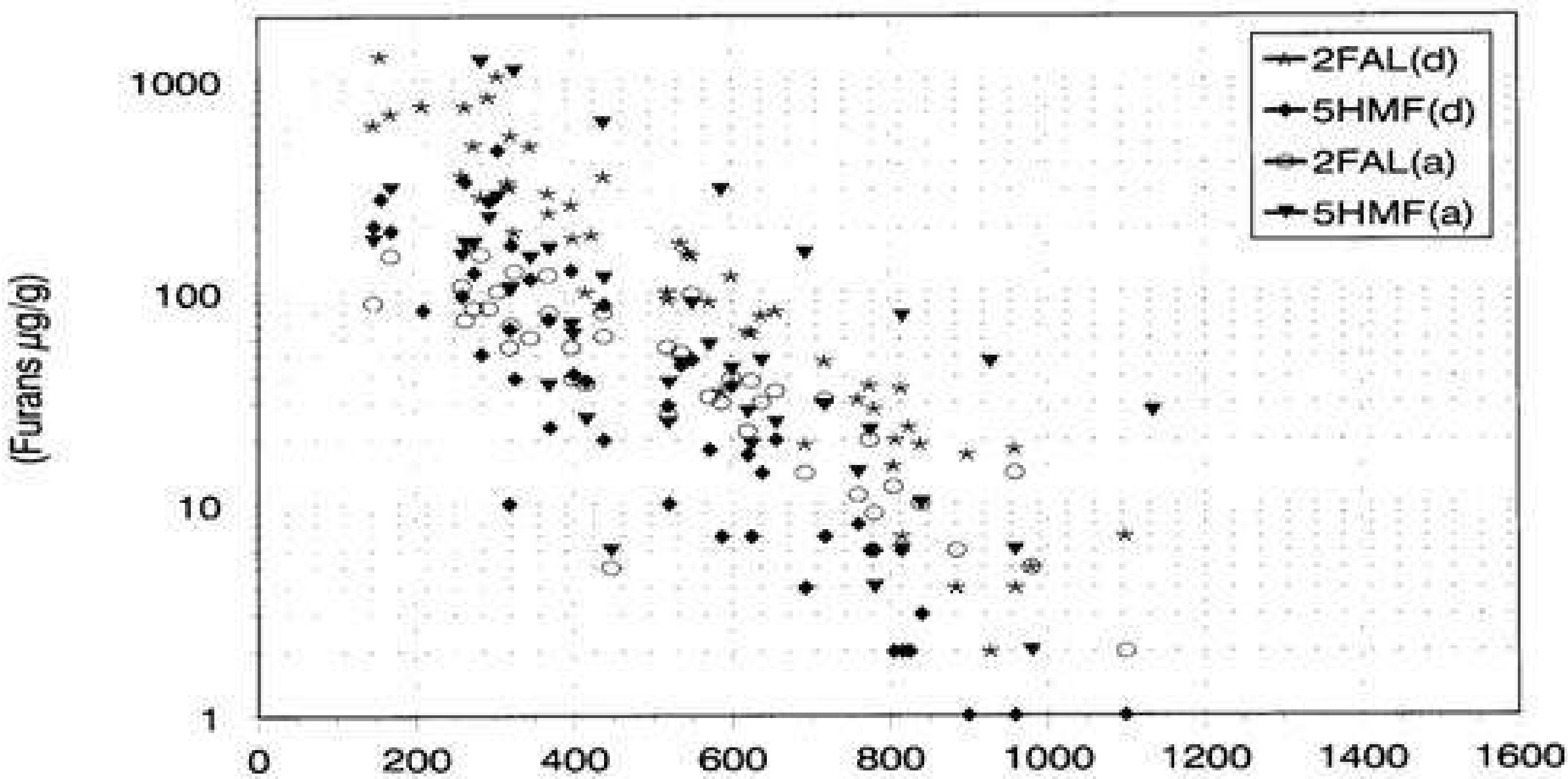
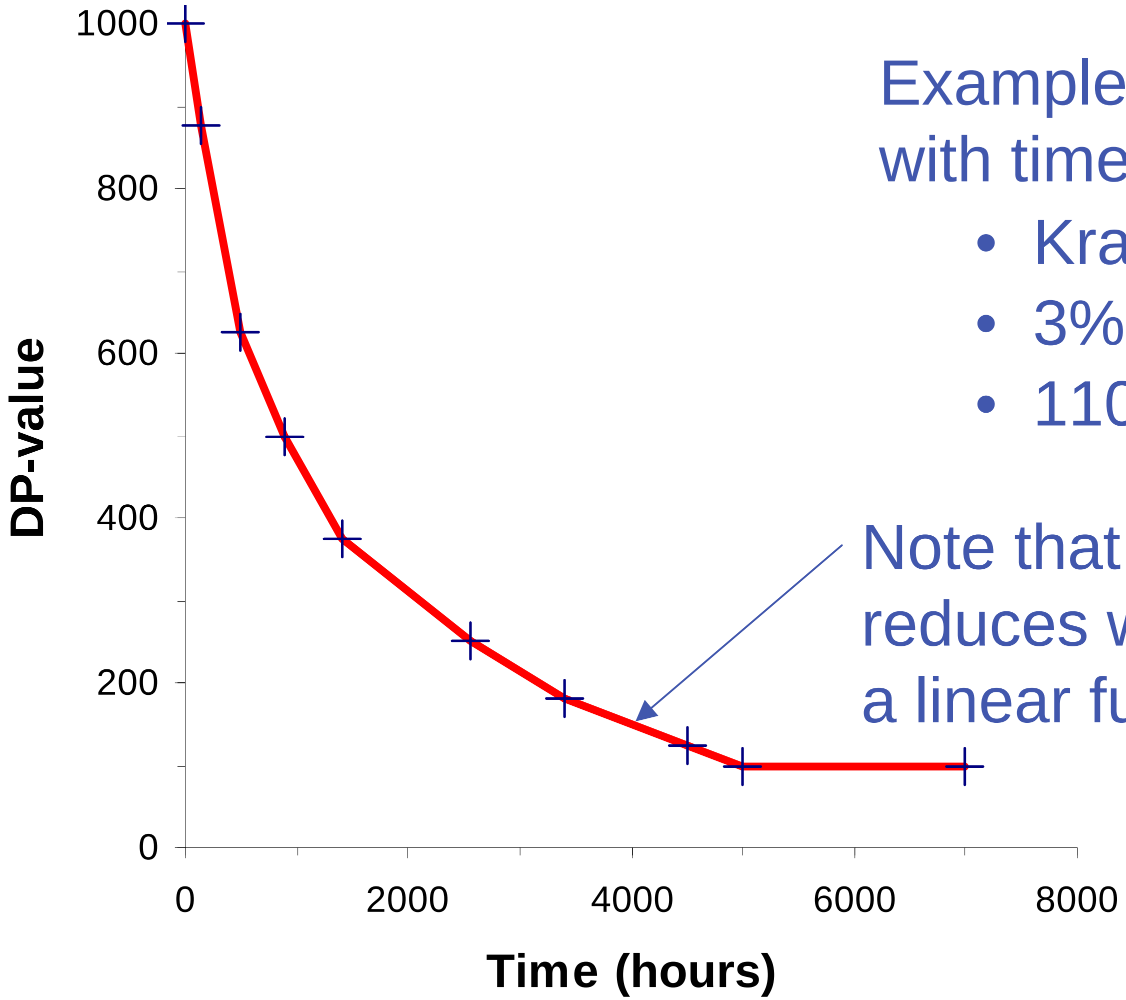


Increasing furanic compound content correlate with falling DP

Cigre Brochure 323, October 2007

Reduction of DP with time

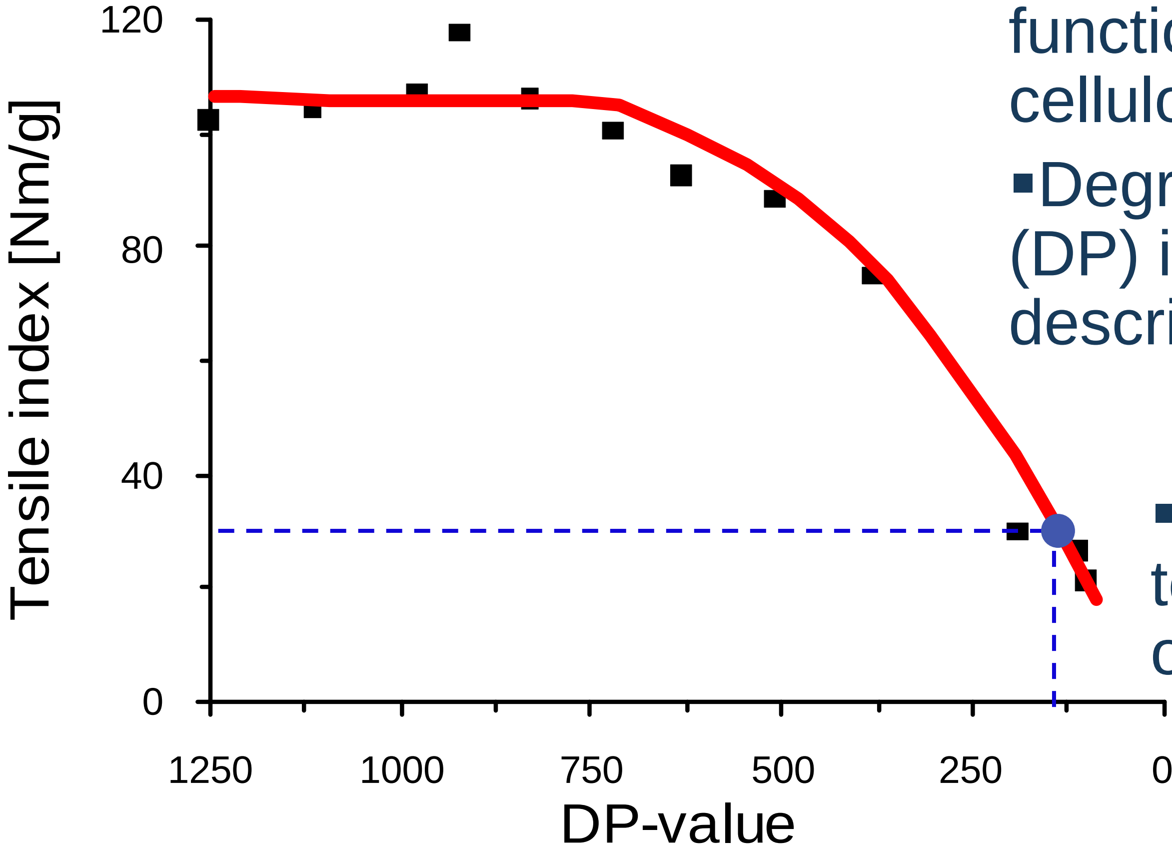


Example of DP reduction with time for

- Kraft paper
- 3% water content
- 110°C

Note that rate of DP reduction reduces with time; aging is not a linear function

Mechanical strength is reduces with DP



- Mechanical strength is a function of length of cellulose chains in fibres
- Degree of polymerisation (DP) in cellulose fibres describes ageing condition

- DP of 200 correspond to remaining strength of about 30%

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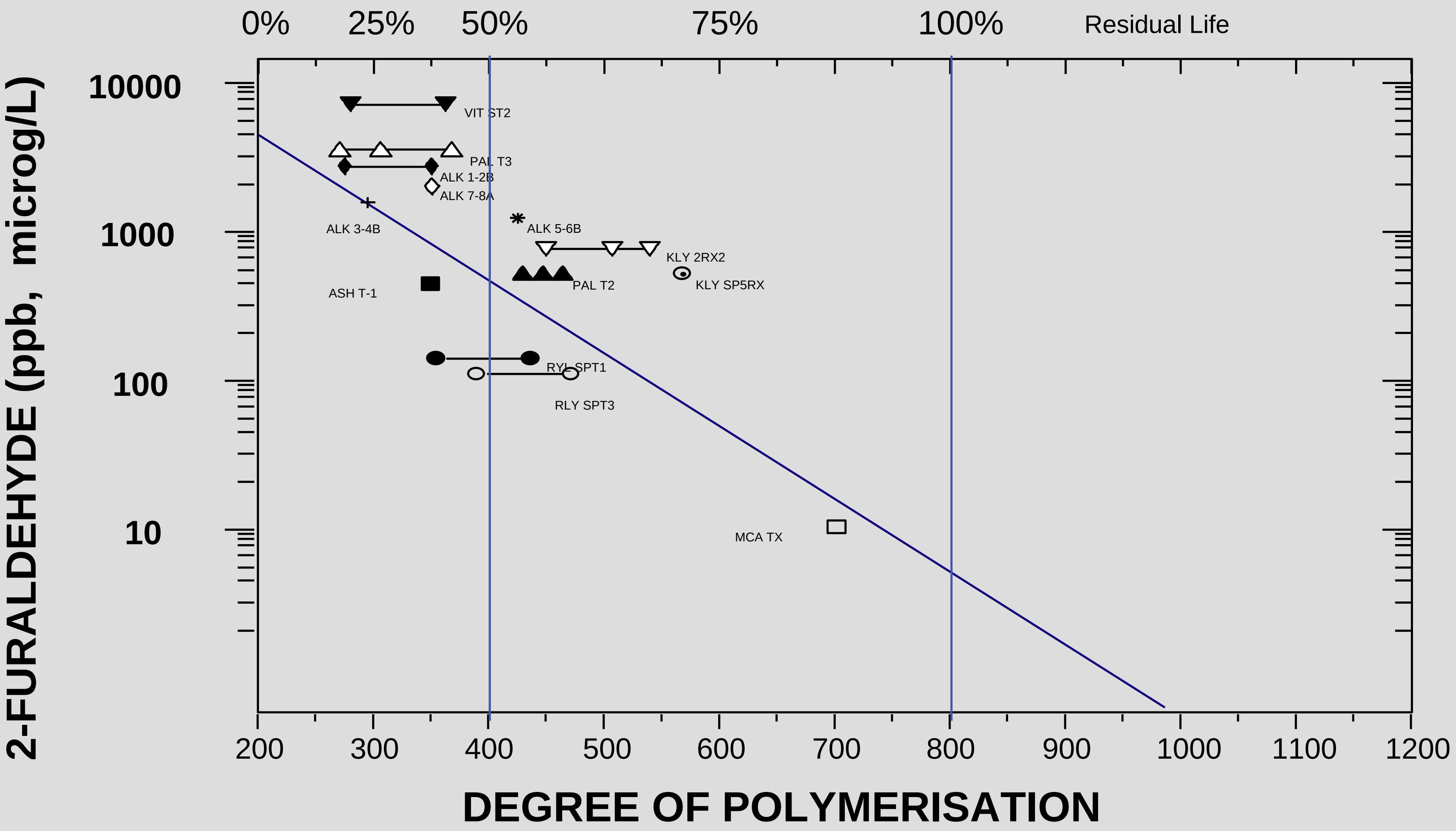
DEGRADATION OF PAPER

CORRELATION BETWEEN 2-FAL and DPV



In Conclusion

- As temperature and load change, so does the movement of water inside the transformer, between the paper and the oil
- In Practice, the perfect equilibrium needed to use the published curves almost never exist in a transformer
- Only a dynamic model, computed online in real time, can make a good evaluation of the amount of moisture in the paper, in the areas of interest

imagination at work

Trademarks

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Thank you