# Calculation of Temperatures in Loading Guide C57.91

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# Proposal submitted in S 2019

- Form a TF to review thermal models in the Guide
- Out of available in the literature thermal models select the most appropriate for the Guide
- Introduce basic physics of heating and cooling of transformer’s various components along with corresponding mathematical equations in the differential form
- Suggest possible ways for solving those equations
- Consider merging C7 and Annex G to simplify the content for the reader
- Specify minimum input data set for the model proposed
- Give example(s) of how to apply the thermal model for selected real life transformer ( volunteer required from utility to provide data)

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# Why thermal models are important?

- **“Transformers are loaded by temperature” V . Montsinger, 1930**
- Verification of compliance with the temperature limits (tables C12.00.00; C57.91)
- Validation of temperature rise guarantee
- Prediction of loading/overloading capability
- Prediction of accelerated aging and life expectancy
- Prediction of gas bubble evolution temperature

# Why thermal models are important? (Cont')

- Estimation of thermal performance
- Design and execution of thermal protection
- Optimization of Cooling control
- Monitoring of Cooling efficiency
- Prediction of moisture of solid insulation
- Prediction of dielectric risk at cold load pick up
- Estimation of risk of failure related to combination of moisture and temperature effects on transformer operation
- Extensive use in online transformer monitoring systems



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# Nonlinear Dynamic System

$$d\Theta/dt=f(\Theta, t, K, \Theta_{a,} p) \qquad (1)$$

**IEEE**
- Clause 7: Analytical Exponential
- Annex G: Finite difference method

**Exact**
- Analytical Exponential
- Laplace transform

**Numerical**
- Finite difference
- Euler method
- Backward Euler method
- Runge–Kutta methods
- Bulirsch–Stoer
- Adams
- BDF
- etc

**Machine learning**
- Neural networks
- Kalman Filters
- System Identification

**IEC**
- Analytical Exponential
- Laplace transform
- Finite difference

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# Annex G: Conversion of mathematical equations to differential form (done)

- Why
- Implications

New edition follows the law of conservation of energy in the following form:

***The rate of increase of thermal energy stored in a transformer and its components must equal the rate at which thermal energy is supplied to the transformer from outside, minus the rate at which thermal energy leaves the transformer, plus the rate at which thermal energy is generated within the transformer.***

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# Annex A (normative) bubble generation model

T.V. Oommen called it “fundamental equation” – did not give any reference !

$$P_{int.} = P_{ext.} + ( 2\sigma / R_B ) \qquad \text{A .1}$$

This is known as Young–Laplace equation in spherical form

$$\theta_{bubble} = \left[\frac{6996.7}{22.454 + 1.4495 \ln WCP_a - \ln p_{tot}}\right] - \left[\left(e^{0.43WCP_a}\right)\left(\frac{v_g^{1.585}}{30}\right)\right] - 273 \qquad \text{A .2}$$

Gas free model — Impact of other gases — K -> °C

This is steady state model. Transient state model could be different!

# Factors affecting bubble formation

- Active water content of paper (water content of paper at the interface with the oil)
- Water content of oil at the interface with the paper affected by the bubble formation
- Capillary property of paper
- Gas voids in paper
- Surface tension of oil
- Temperature gradient of oil-paper interface
- Rate of temperature rise
- Static head pressure of the liquid above the area of bubble formation
- Dissolved gas content of oil
- Type of the oil preservation system.

# A bit of history: Gas Bubble Incipient Temperature

- 1984-1987: EPRI funded work resulted in two papers McNutt et.al 1985 and Fessler et.al 1989
- Fessler'89* used Freundlich sorption isotherms to derive the bubble model: $WCP = kp^{1/n}$ ; $k = A\exp(B/T)$
- *A*,*B* and *n* were found by regression analysis based on experimental data
- 

| A | B | 1/n |
|---|---|---|
| $2.173 \times 10^{-7}$ | 4725.6 | 0.6685 |

* Fessler, W. A., Rouse, T. O., McNutt, W. J. and Compton, O. R., *A Refined Mathematical Model for Prediction of Bubble Evolution in Transformers*, IEEE Transactions on Power Delivery, vol. 4, Nov. 1, pp. 391–404, Jan. 1989.

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# Fessler water vapor pressure model 1989

$$C = 2.173 \times 10^{-7} \times P_v^{0.6685} \times \exp(4725.6/T) \qquad (7)$$

or

$$P_v = 5.8869 \times 10^{9} \times C^{1.4495} \times \exp(-6996.7/T) \qquad (8)$$

Fessler et.al. made a mathematical error! Du et.al corrected mistake in 1999!

$$P_v = 9.2683 \times 10^9 \times C^{1.4959} \times e^{(-7069/T)},$$

Based on EPRI funded work 1990-1992

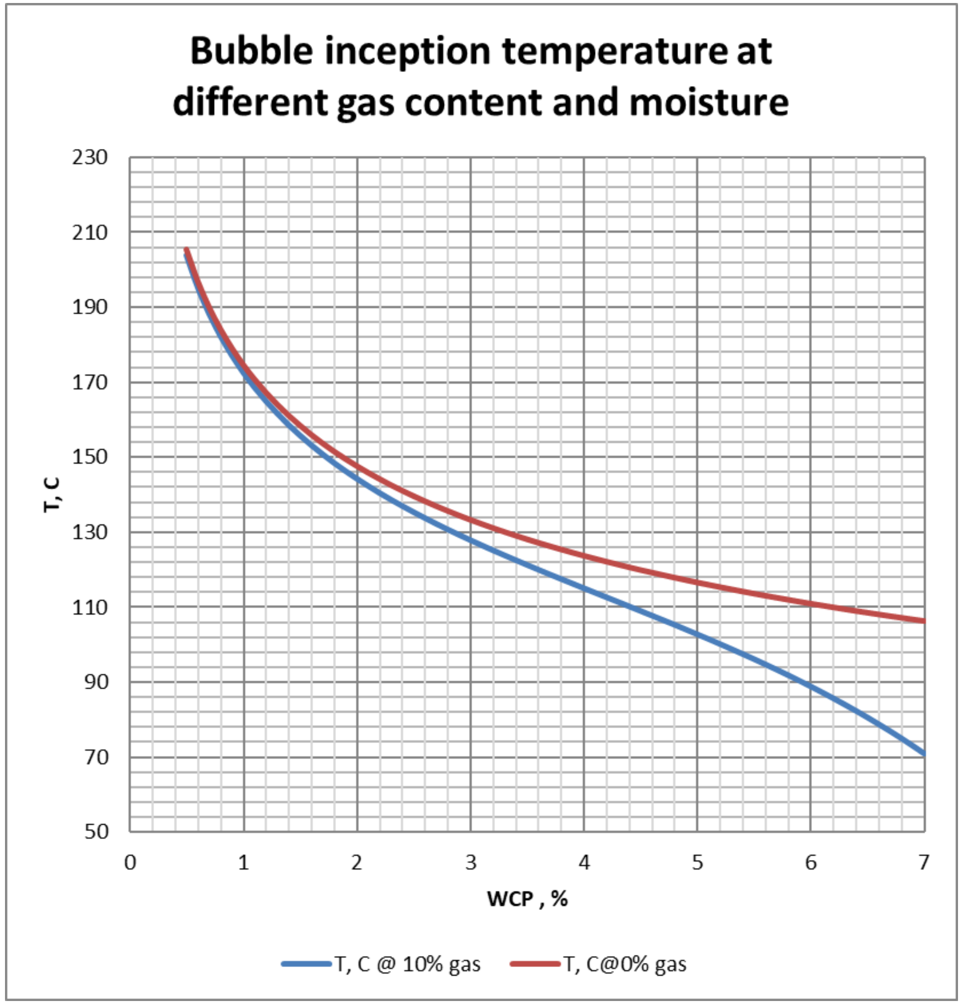
T.V. Oommen 2001 “**Bubble Evolution from Transformer Overload**”

$$\text{Ln } P = 22.454 + 1.4495 \ln W - 6996.7/T \qquad \text{(Eq. 1)}$$

$$T = [6996.7/22.454 + 1.4495 \ln W - \ln P] \qquad \text{(Eq. 4)}$$

# Error in Annex A: Bubble model

$$\theta_{bubble} = \left[\frac{6996.7}{22.454 + 1.4495 \ln WCP_a - \ln p_{tot}}\right] - \left[\left(e^{0.43WCP_a}\right)\left(\frac{v_g^{1.585}}{30}\right)\right] - 273$$




From Fessler* , et al

$$\theta_{bubble} = \left[\frac{6996.7}{22.95 + 1.4959\ln(WCP) - \ln(p_{tot})}\right]$$

Corrected from Du et.al. 1999

$$\theta_{bubble\ new} = \left[\frac{7064.8}{22.95 + 1.4959\ln(WCP) - \ln(p_{tot})}\right]$$

* Fessler, W. A., Rouse, T. O., McNutt, W. J. and Compton, O. R., *A Refined Mathematical Model for Prediction of Bubble Evolution in Transformers*, IEEE Transactions on Power Delivery, vol. 4, Nov. 1, pp. 391–404, Jan. 1989.



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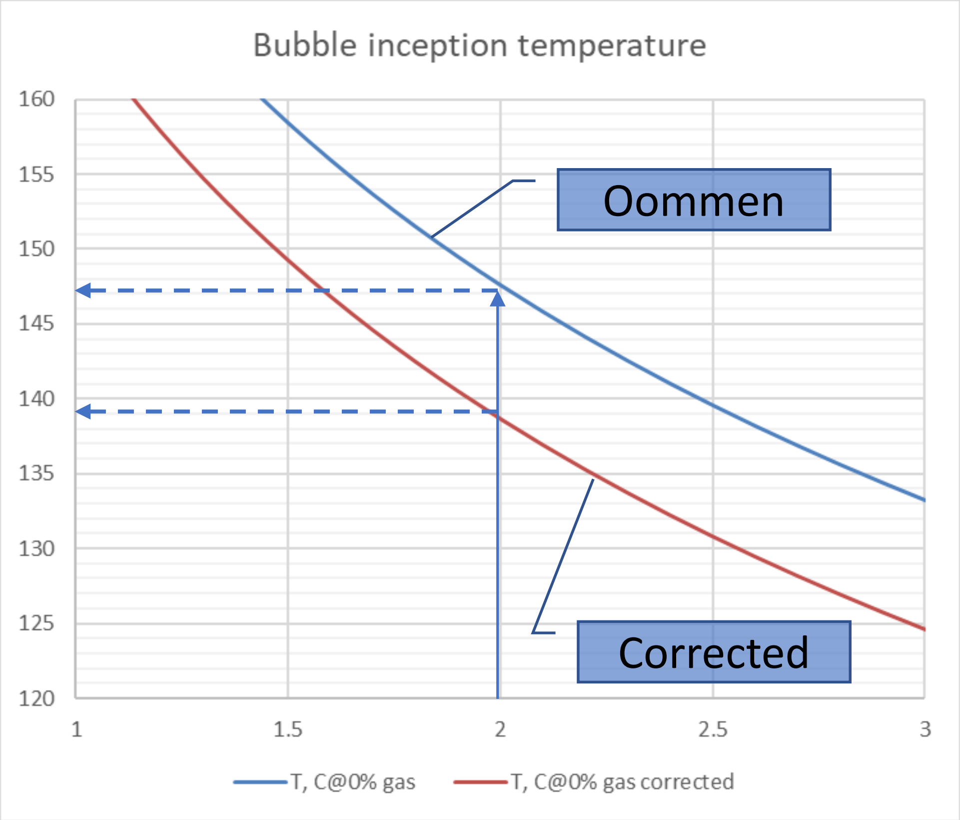
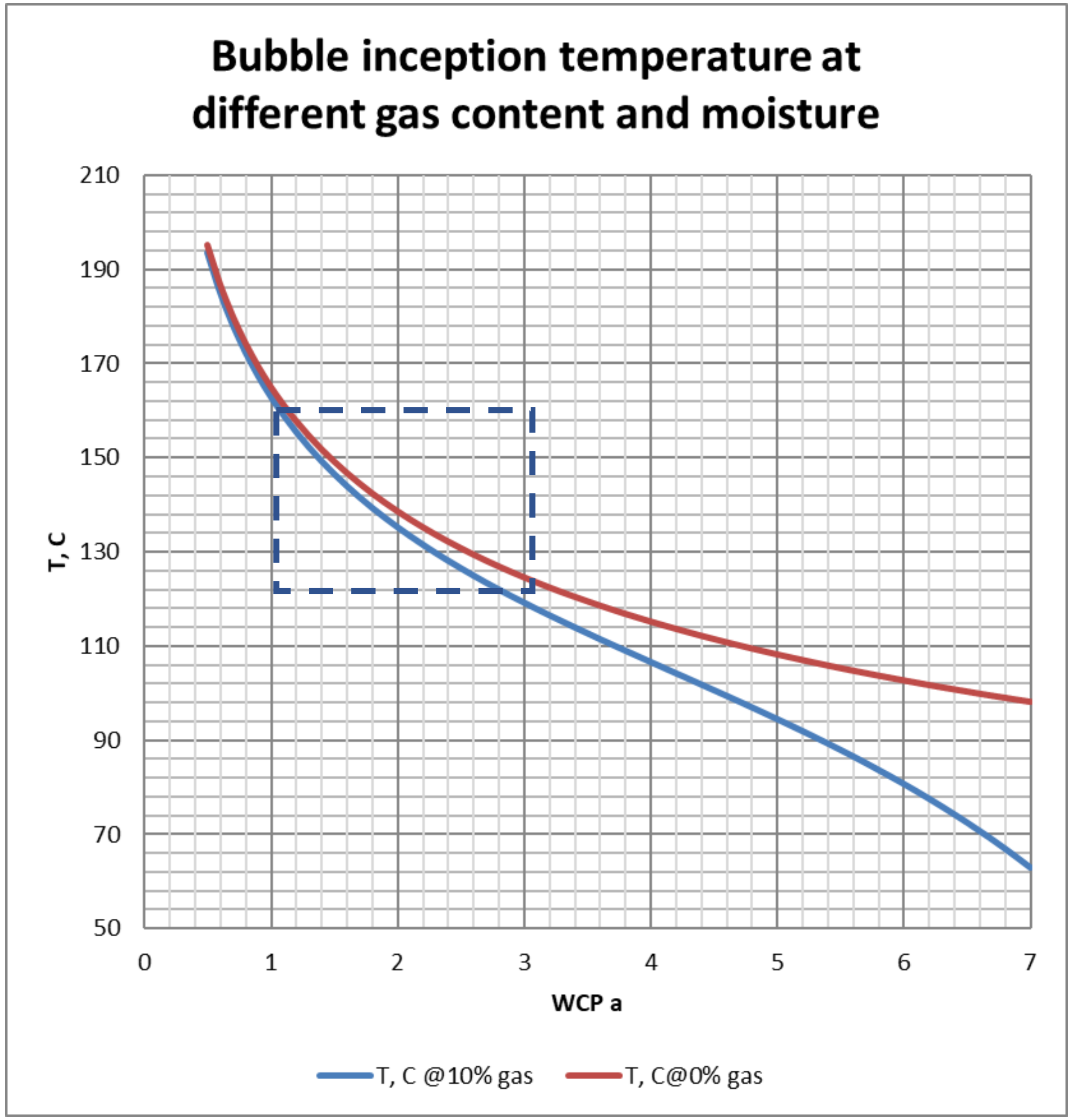
# Corrected model




8 – 9 K difference at hot spot ~140C and WCP = 2%

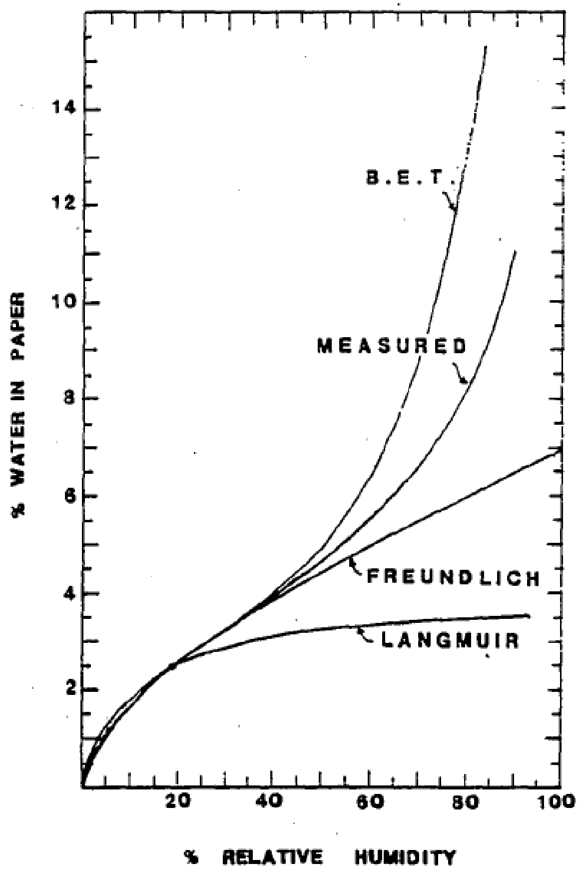



Hill et.al. "Improvements to the construction of bubble inception formulae", IEEE Access 2019

# Paper sorption isotherms used in bubble model: wrong type

- Oommen'83 tried to fit Freundlich's isotherm into measured data
- Concluded that no known isotherm exists that can be fitted to experimental curves
- Roizman'2005 fitted GAB model into measured data

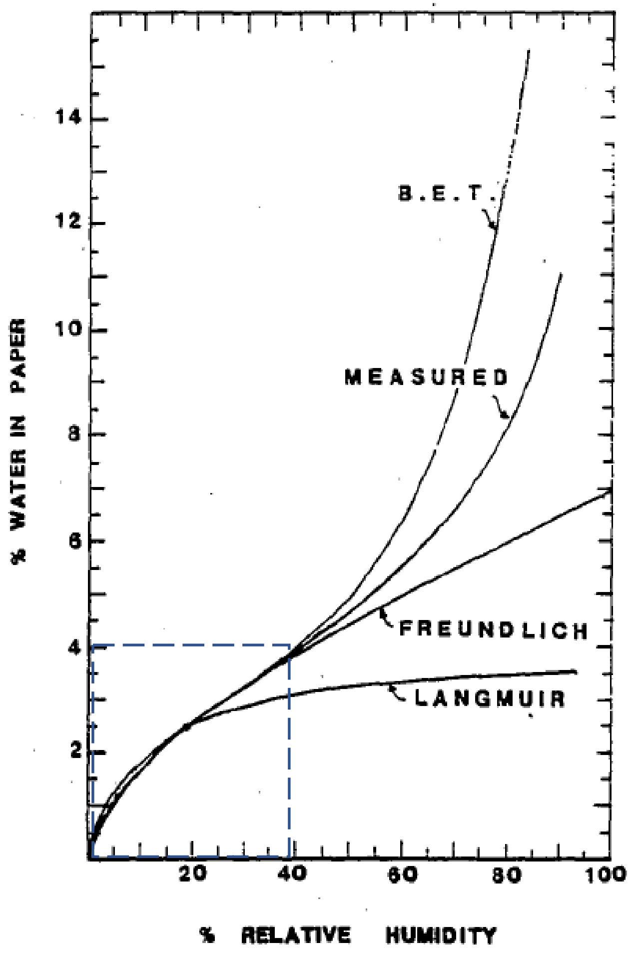
$$WCPa = \frac{WCP_0 \cdot C \cdot K \cdot Awp}{(1 - K \cdot Awp)(1 - K \cdot Awp + C \cdot K \cdot Awp)}$$




Comparison of various sorption isotherms with experimental curve for 70 °C

# Conclusion on bubble model structure

- Fessler model used by Oommen in Annex A is of wrong type
- Nevertheless, up to 4% WCP Fessler's approximation works well
- No need to use Roizman's more accurate but more 'data demanding' formulae for bubble inception temperature model



# Proposed changes

- Correct mathematical errors in bubble inception temperature model
- Update text and examples
- Add assumptions and model limitations
- Update historical facts and provide corresponding references



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