Thermal Design Considerations

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Yuriy holds a Master of Science Degree in Electrical Engineering from Ukrainian University of Engineering.

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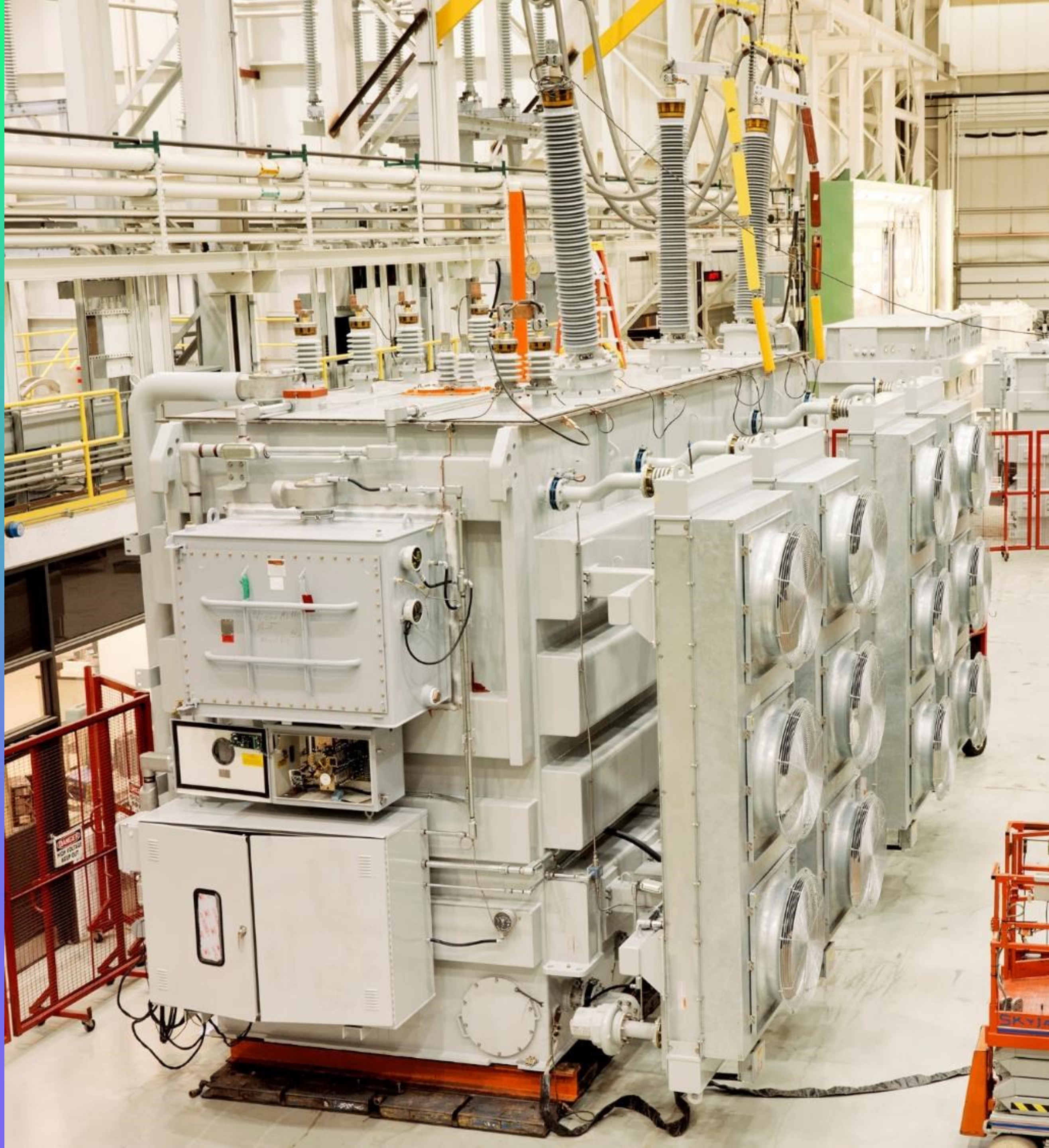

Agenda

1. Thermal Design
2. Insulation Life
3. Loading Beyond Nameplate Rating

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Thermal Design

Thermal Design

- Guaranteed Temperature Rise per IEEE Std C57.12.00
  - Average Winding Temperature Rise = 65ºC
  - Hot-spot Winding Temperature Rise = 80ºC
  - Top Oil Rise = 65ºC
- Ambient Temperature per IEEE Std. C57.12.00
  - Temperature of cooling air (ambient temperature) shall not exceed 40°C, and the average temperature of the cooling air for any 24 hour period shall not exceed 30°C

Thermal Design

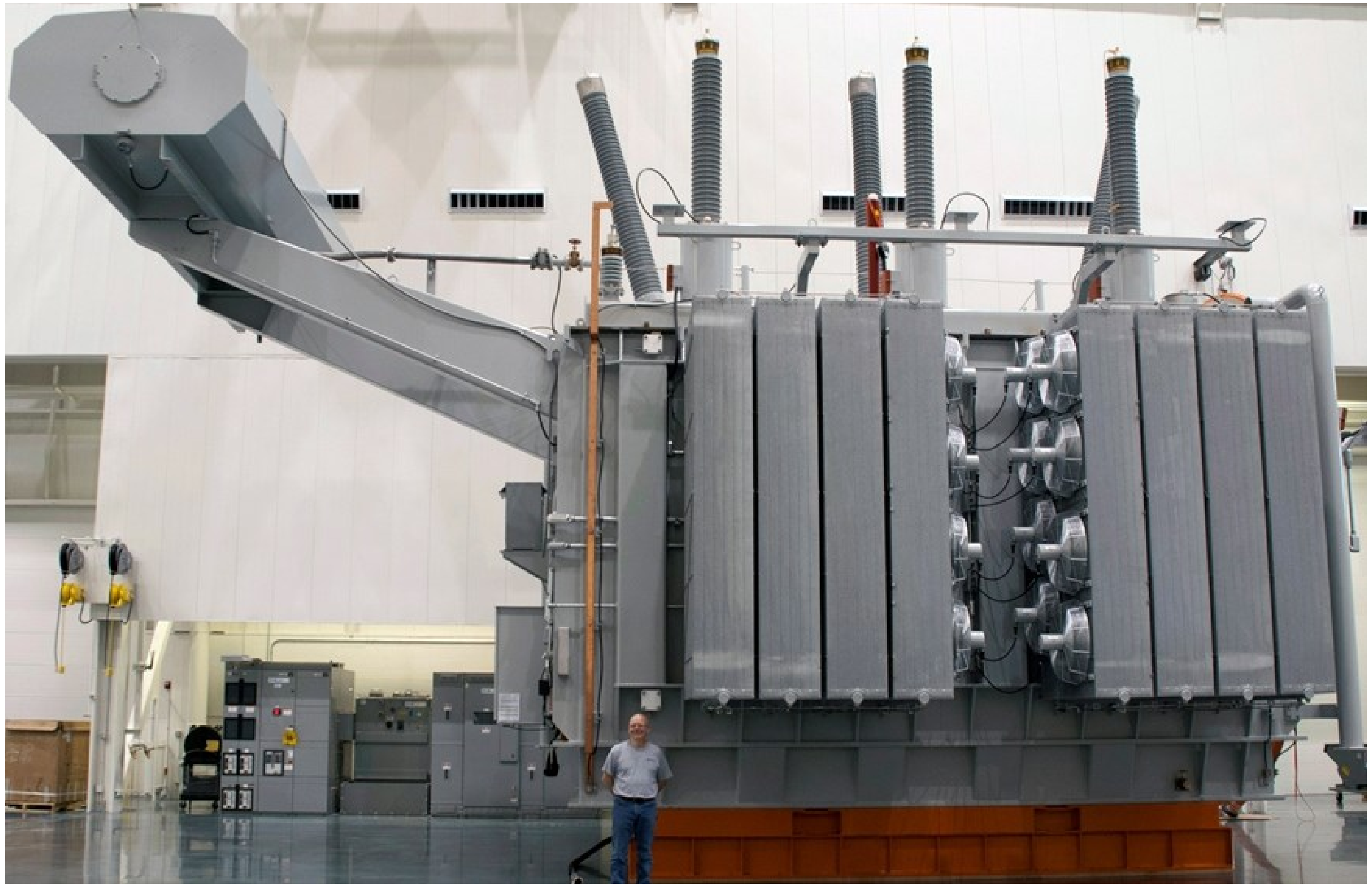
- Transformer cooling design must be capable of dissipating total loss at maximum MVA
  - Total Loss = No load loss + load loss at maximum MVA
- Standard cooling configuration is ONAN/ONAF/ONAF
- Select number of radiators, type of fans based on guaranteed sound level
- If an overload requirement is specified, perform overload calculations to meet specified temperature rise limits and loss of life limits during overload

Types of Oil Circulation

Natural Circulation

- Most commonly used for Power Transformers
- Due to losses in windings under load, thermosiphon action results in oil movement in the windings
- With natural circulation, oil velocity is low, resulting in 20–30 degrees C temperature difference between the bottom and the top radiator oil
- Most economical and lower maintenance; loss of one fan typically results in minor loss of cooling capacity

Radiator and Fan Considerations



Radiator and Fan Considerations

- Radiators are the most common means used to increase the amount of exposed oil surface area to the surrounding air
- Hot dip galvanized radiators offer several advantages over standard painted radiators
- Location of radiators is based on customer preference, footprint and cooling configuration
- Fans are a relatively inexpensive means to increase the rate of heat dissipation from the radiators

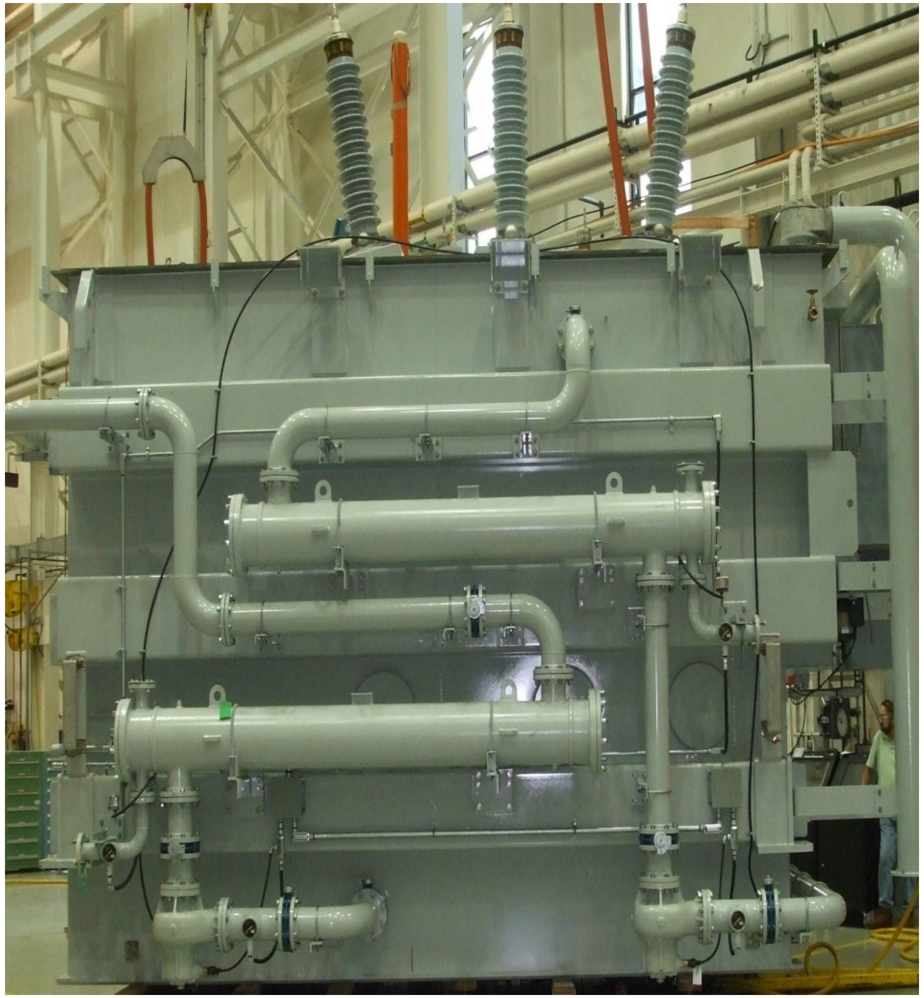
Types of Oil Circulation

Forced Oil

- Pumps are used to circulate oil, resulting in higher oil velocity and 4–8°C temperature difference between the bottom and top oil
- Used mostly for mobile transformers and large rating GSU transformers
- If forced oil is not directed, the oil flow in the winding is natural due to gravitational buoyancy, addition of the pump impacts cooler performance
- Higher maintenance, loss of one pump results in major loss of cooling capacity

Oil Forced Cooling

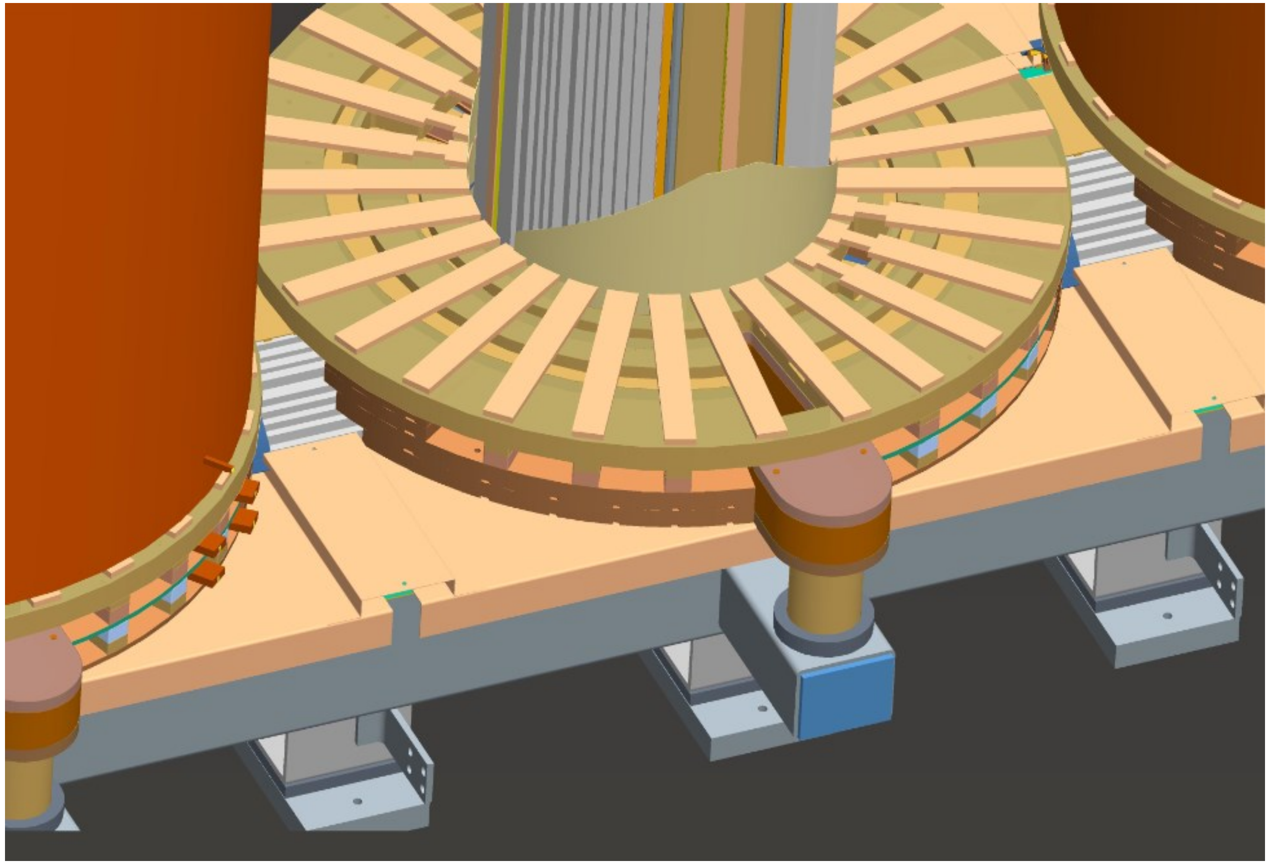
OFWF Cooling



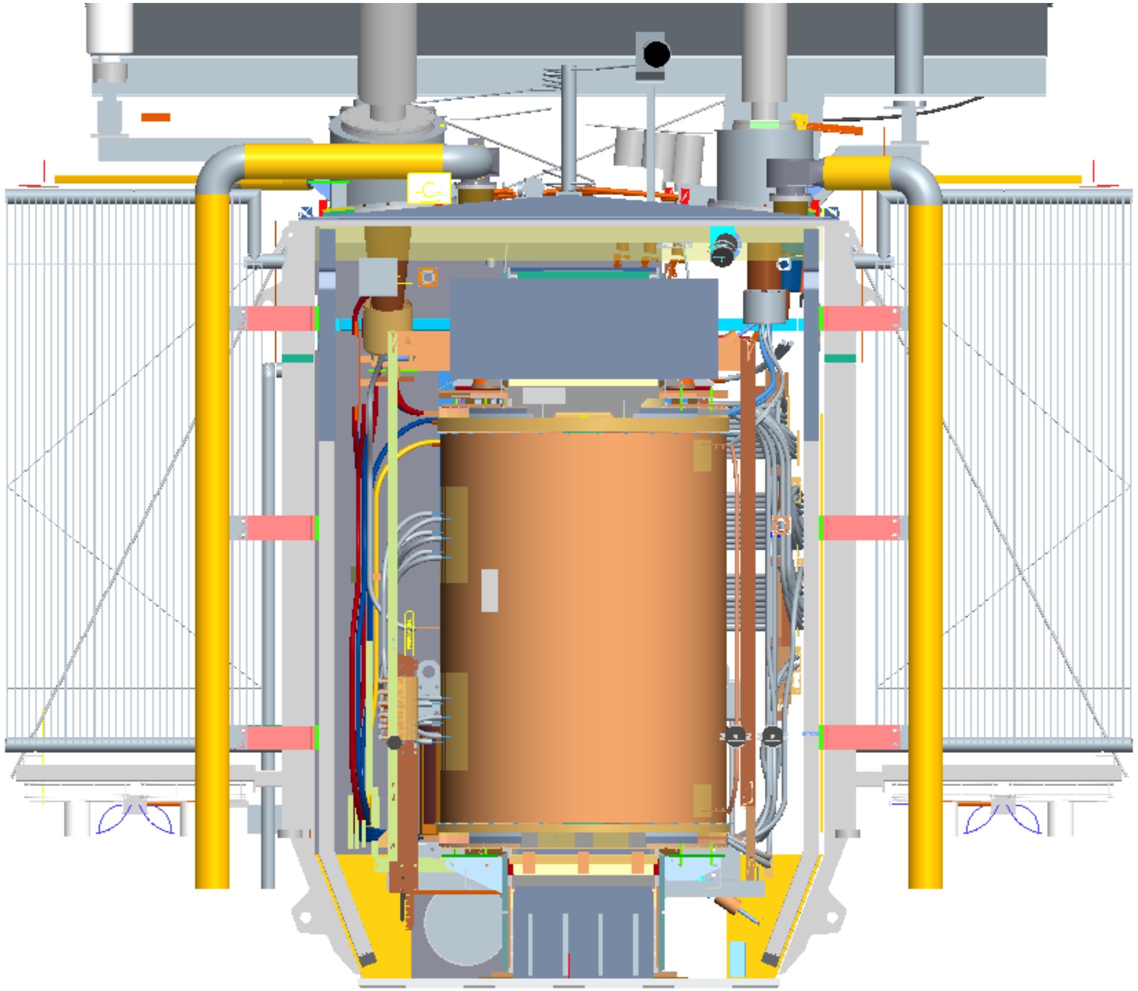
OFAF Cooling

Forced Oil Directed Cooling

In the forced oil directed arrangement, the cold oil is pumped
into the windings in a predetermined manner to ensure better heat transfer.

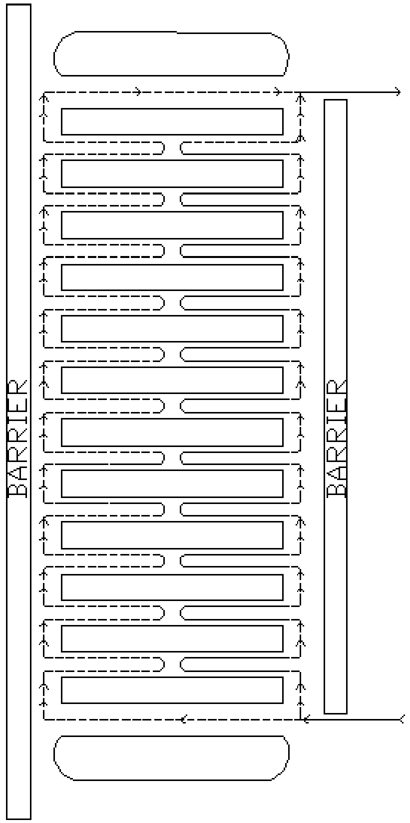


Oil Circulation Inside Transformer



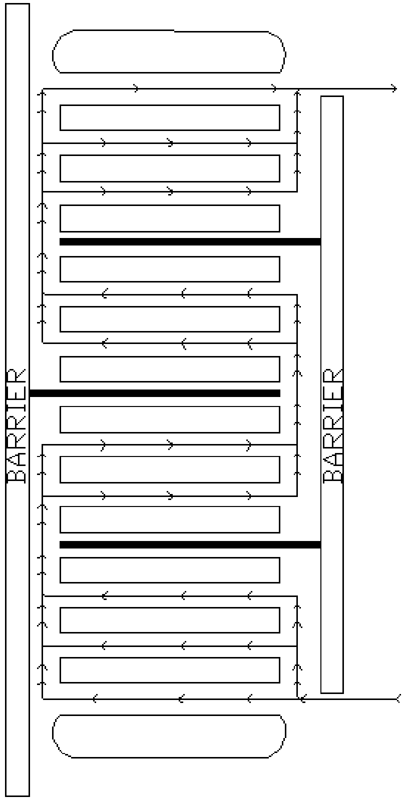
Oil Circulation Inside Transformer

Non-Guided Oil Flow



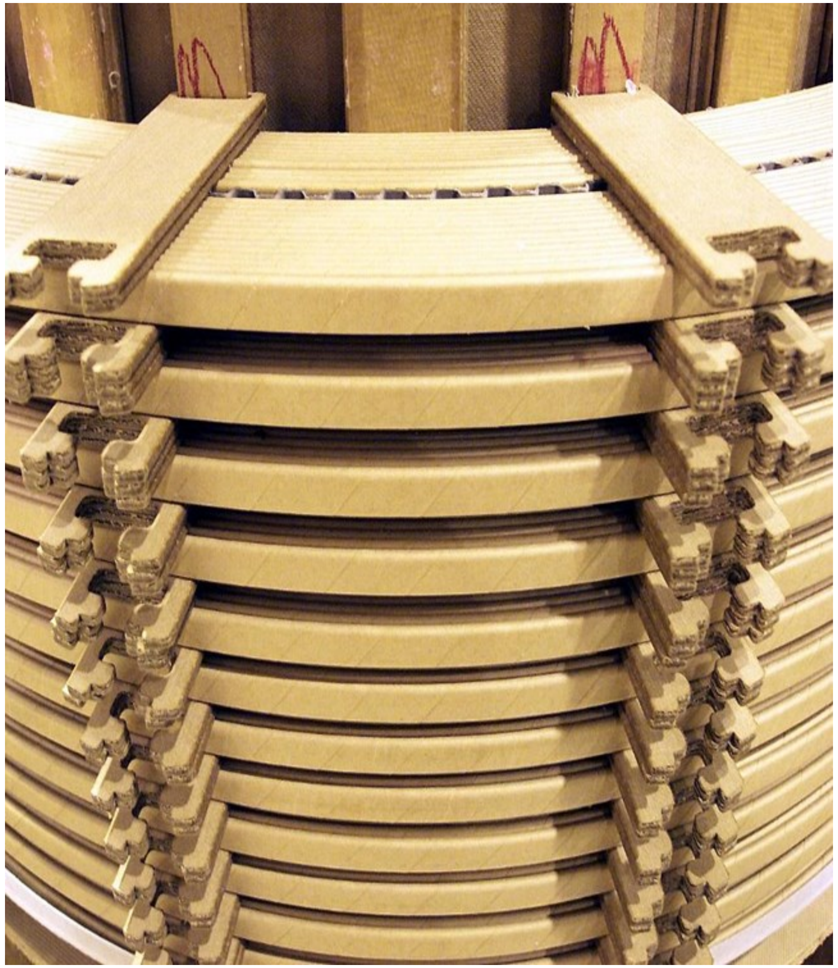
Oil is free to find its own path from the bottom of the winding to the top of the winding

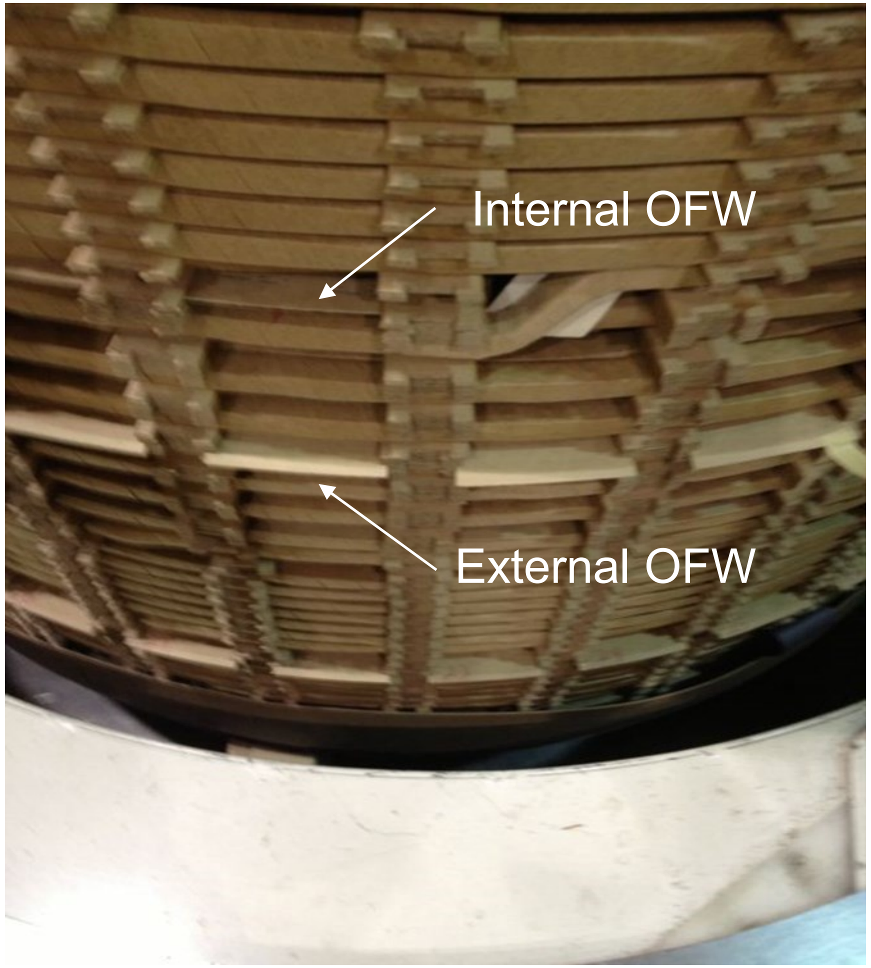
Guided Oil Flow



Strategic washers are placed in the winding to direct the oil flow along specific pathways

Non-Guided & Guided Flow Washers in Winding

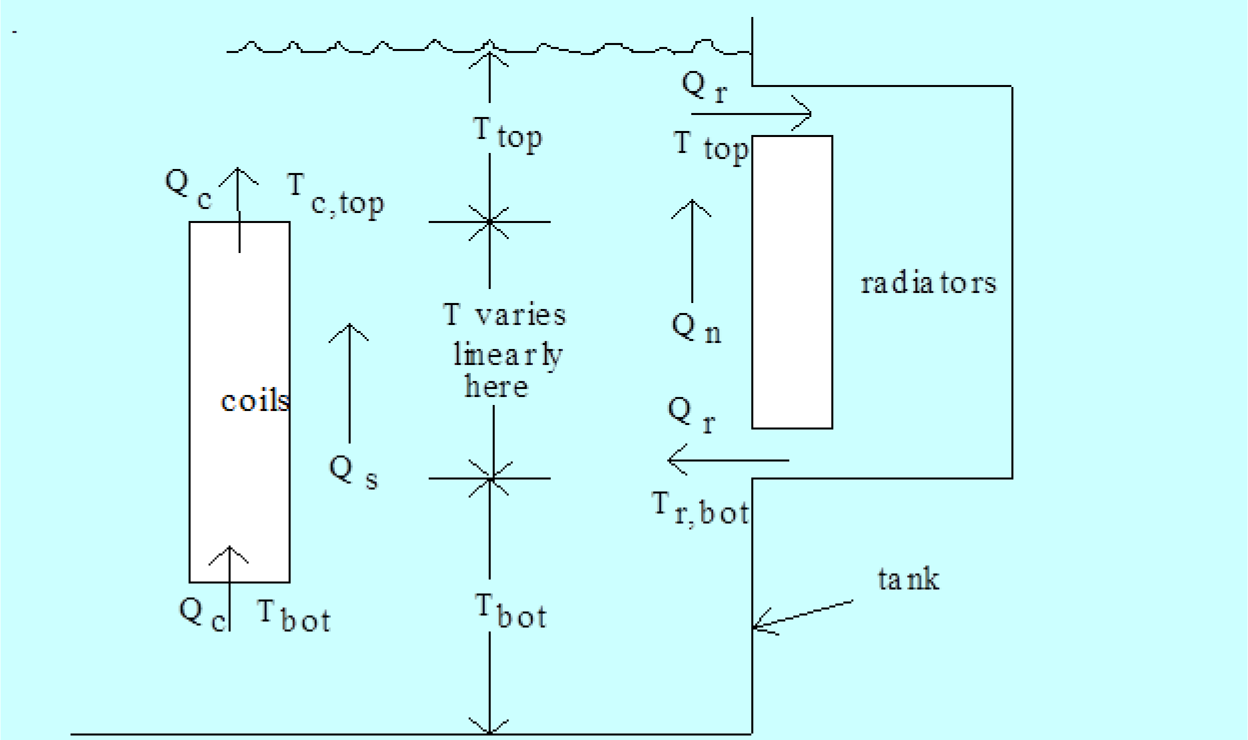




Thermal Software

- Models the entire transformer, including the windings, tank, and radiators; allows for convection and radiation heat transfer from the tank and radiators with or without fans
- Calculates the top, mean and bottom tank oil temperature rises
- Calculates each winding gradient
- Calculates steady state and transient overload temperatures
- Determines m and n components, the thermal time constant and loss of life
- Capable of modeling pumped flow capabilities for both steady state and transient conditions

Thermal Performance



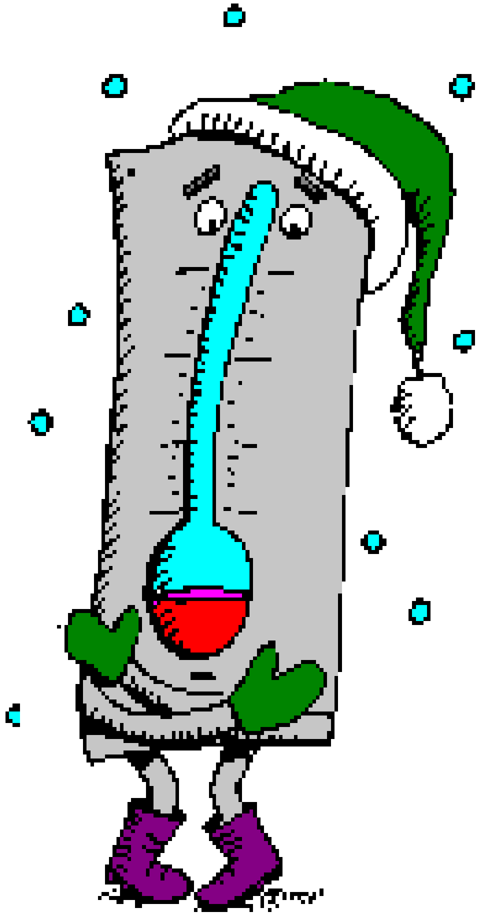
Assumed oil temperature distribution inside tank. The oil flows, Q , as well as the flow weighted temperatures are also indicated.

Typical Thermal Performance Calculation Variables

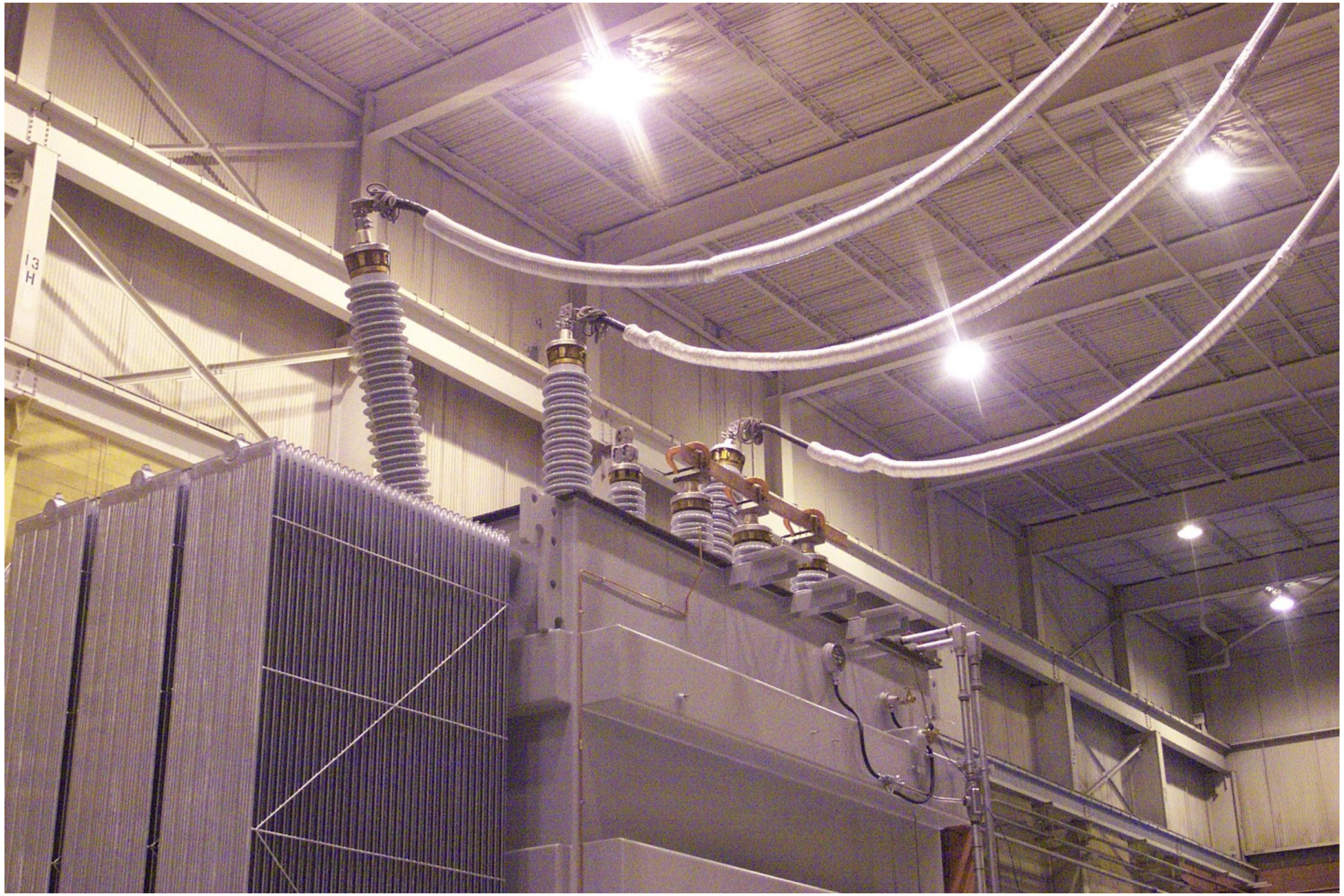
$$\boxed{\text{Loss per unit area } \Rightarrow \text{ Gradient}}$$

Temperature Rise Tests

- Performed at both self-cooled (ONAN) rating and maximum forced air (ONAF) rating for all new designs or as required by customer spec
- Overload temperature rise tests performed if required by customer specification
- Temperature results from a thermal duplicate can be supplied as an alternative to performing temperature rise tests



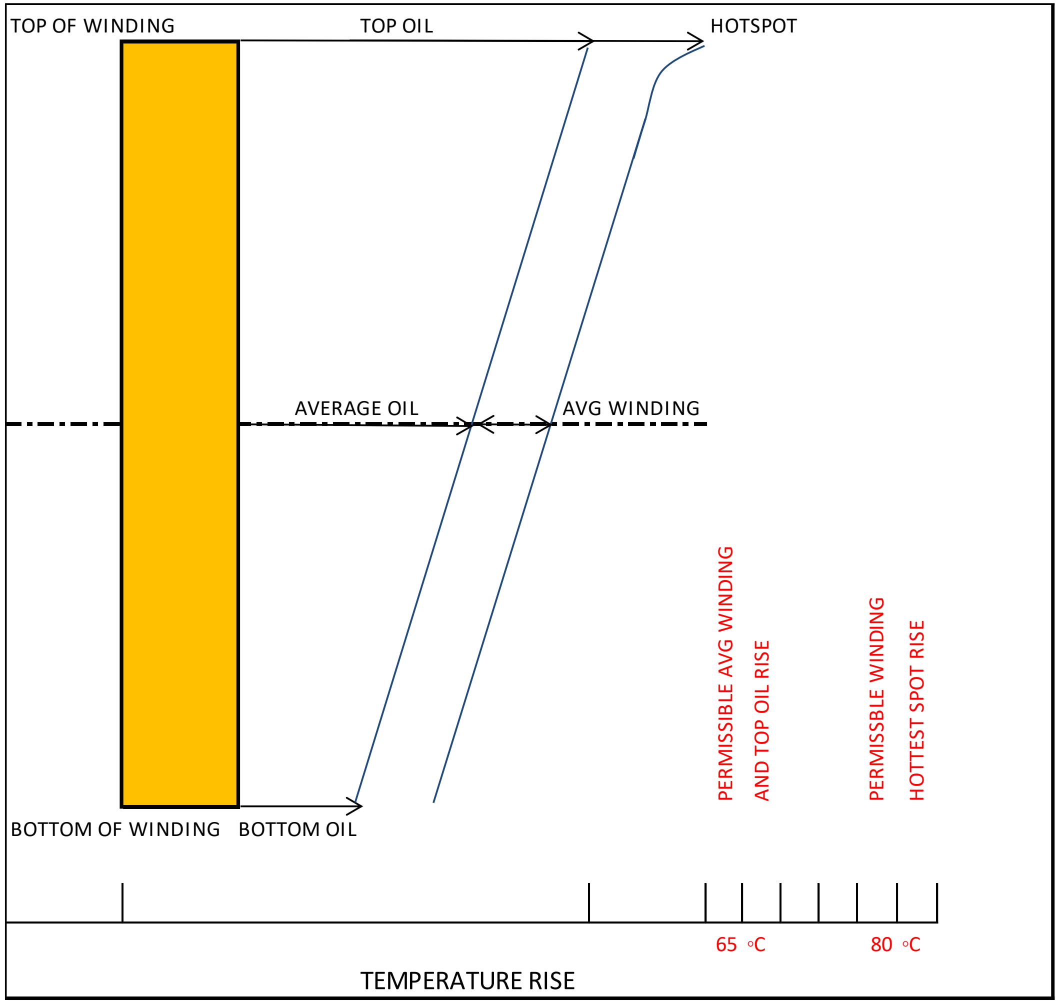
Temperature Rise Test Connection



Temperature Rise Calculations

- Measurements during Temperature Rise Test:
  - Top oil temperature, Top and bottom radiator oil temperatures, 3 ambient temperatures and Hot winding resistance at shut down
- Top oil Rise = Top oil temperature – average ambient
- Mean oil rise = average of top & bottom radiator oil temperatures – average ambient
- Average winding temp = (Hot Resistance/Cold Resistance) * (234.5 + cold resistance ambient) – 234.5
- Winding Gradient = Average winding rise – mean oil rise
- Hot spot Rise = Top oil rise + Hot spot gradient
  - Hot spot gradient = Average gradient (1 + k)
  - k = hot-spot factor based on maximum eddies due to actual radial and axial leakage field

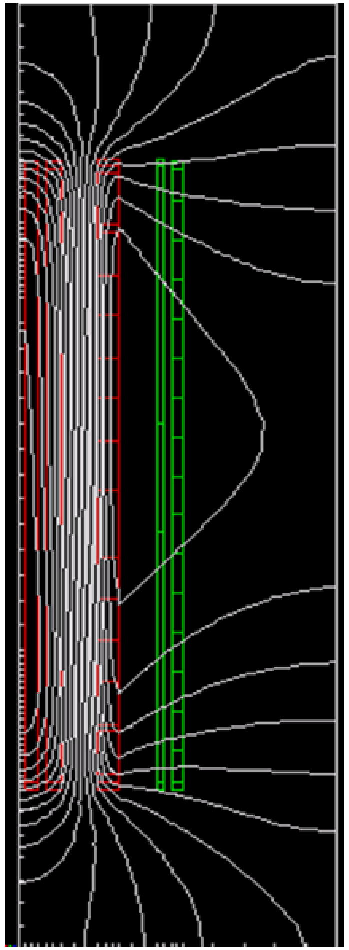
Temperature Distribution Model



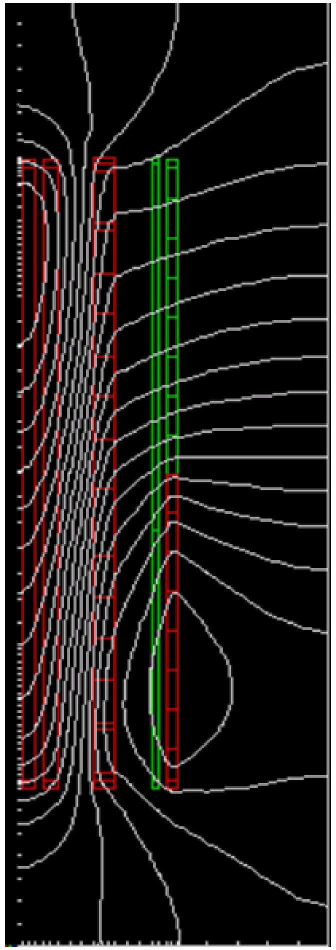
Winding Gradient

- Average gradient is the difference between the average conductor temperature and the average oil temperature in the tank
- Higher the gradient the greater the amount of cooling required
- Gradient ~ current density, watts/square inch of winding surface area, inverse of oil velocity
- Hot spot gradient is higher than average gradient and depends on maximum eddy loss

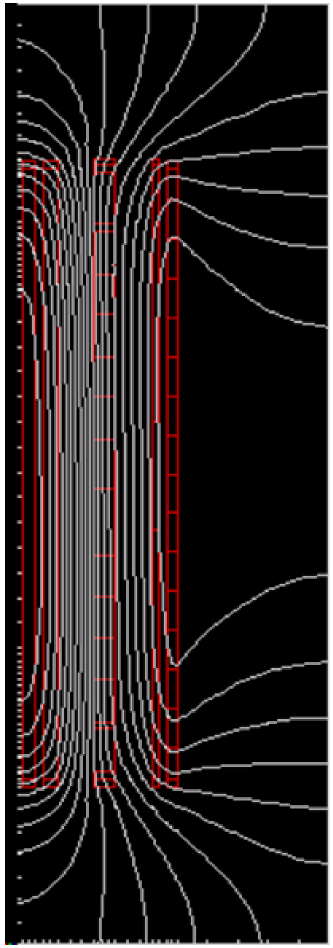
Hot Spot Temperature Calculation - Example



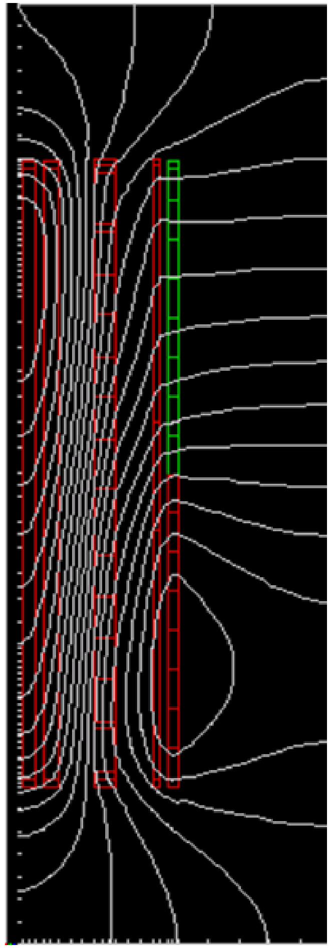
28 kV, 175.5 kV



28 kV, 195.5 kV

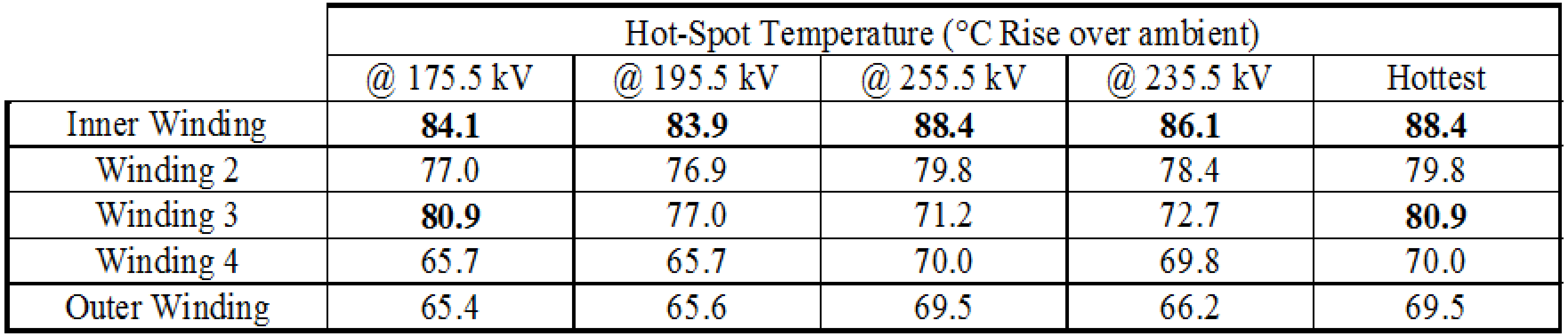


28 kV, 255.5 kV



28 kV, 235.5 kV

Hot Spot Temperature Calculation - Results



	Hot-Spot Temperature (°C Rise over ambient)				
	@ 175.5 kV	@ 195.5 kV	@ 255.5 kV	@ 235.5 kV	Hottest
Inner Winding	**84.1**	**83.9**	**88.4**	**86.1**	**88.4**
Winding 2	77.0	76.9	79.8	78.4	79.8
Winding 3	**80.9**	77.0	71.2	72.7	**80.9**
Winding 4	65.7	65.7	70.0	69.8	70.0
Outer Winding	65.4	65.6	69.5	66.2	69.5

The inner winding and Winding 3 had to be redesigned to lower the hot-spot temperature rise below 80°C

Insulation Life

Insulation System

- Combination of highly refined hydrocarbon-based oil and cellulose paper insulation of high purity makes up the insulation system of a typical oil-filled transformer
- Oil impregnation of the paper allows it to operate at a high voltage stress without dielectric breakdown
- Insulation deteriorates from the effects of temperature, moisture and oxygen
- Moisture and oxygen content in transformer can be minimized by oil preservation systems:
  - Sealed tank design with nitrogen preservation system
  - Conservator system with an air bladder
- This leaves insulation temperature as the controlling parameter of insulation deterioration

Failure of Insulation System

General category of events contributing towards failure of Insulation system:

- Deterioration/aging of insulation over a long period of time due to exposure to temperature, moisture and oxygen
- Operating incidents like overload, short-circuit, and dielectric transients stress aged insulation

Insulation System

TransformerFireVideo.mpg

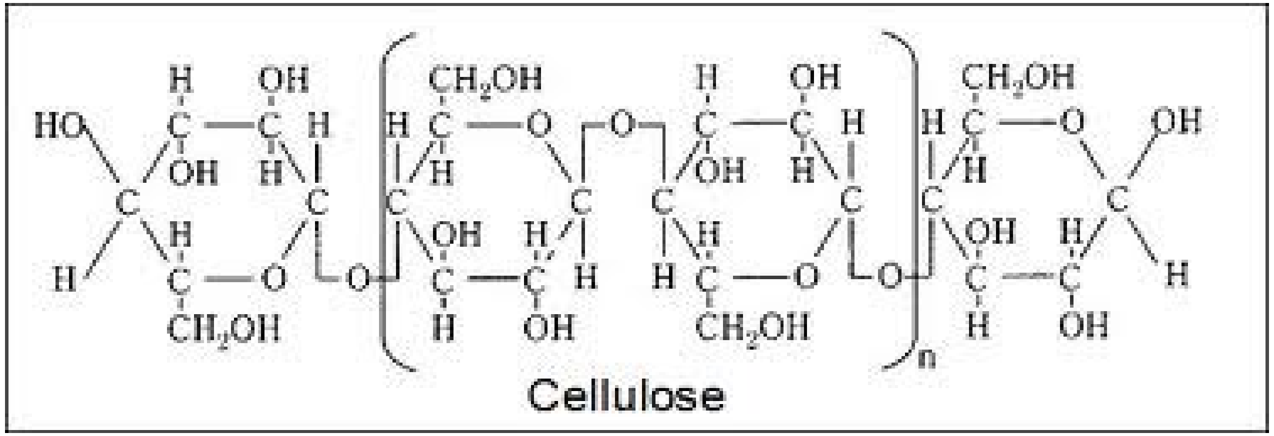
Insulation Requirements

- Maintain dielectric strength for impulse/switching voltages
- Maintain mechanical strength against short circuit stresses
- Mechanical strength deteriorates long before dielectric strength becomes an issue
- Direct and Indirect tests to assess insulation condition
- Direct Tests
  - Tensile Strength Test used as a measure of deterioration
    - First used in the 1920s, criteria for an end of insulation life estimated to be at 50% retained tensile strength
    - Later, levels as low as 20% retained tensile strength were considered to be end of insulation life
    - Requires a fairly large sample of insulation, which is difficult to get from a transformer

Direct tests to assess insulation condition

Degree of Polymerization Test used as a measure of deterioration

- DP test refers to the average number of glucose rings in the molecule (1000–1200 for new insulation, with an endpoint or minimum of 200 for aged insulation)
- Requires only a small sample of insulation
- DP value provides much better indication of cellulose insulation mechanical characteristics than loss of tensile strength



Cellulose

Indirect tests to assess insulation condition

- Indirect Tests are performed on the byproducts of paper in the oil
  - Most popular
  - Oil samples can be taken when the transformer is operating
- Indirect tests
  - Dissolved Gas Analysis
    - Carbon Monoxide and Carbon Dioxide generated due to degradation of paper
  - Furfuraldehyde Analysis by high performance liquid chromatography is a means of estimating degradation of insulating paper.
    - Furfural is one of degradation product of cellulose in oil
    - Estimation of DP from Furfural content
    - Type of oil preservation, oil degassing, mechanical filtration and electrical discharge affects the furfural content

Insulation Life

- “Normal” Insulation Life for well-dried and oxygen-free insulation systems with the Hottest-spot temperature maintained at 110°C (see table below)
- Many transformers last much longer than “normal” life since the hot-spot temperature does not stay this high constantly due to load and ambient temperature variations

Criteria	Normal Insulation Life	
	Hours	Years
50% retained tensile strength of insulation (from C57.92 criteria)	65,000	7.42
25% retained tensile strength of insulation	135,000	15.41
200 retained DP in insulation	150,000	17.12
Distribution Transformer Functional Life Test data (former C57.91 criteria)	180,000	20.55

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Loading Beyond Nameplate Rating

Effects of Loading Beyond Nameplate Rating

- Increased loss of insulation life due to higher temperatures
- Generation of free gas at temperatures of ~ 140º C and beyond could result in a dielectric failure
- Increased resistance in the contacts of tap changers due to build-up of oil decomposition
- Oil expansion may be greater than capacity of transformer, causing pressure build-up and pressure relief device operation
- Other risks are cited in IEEE C57.91

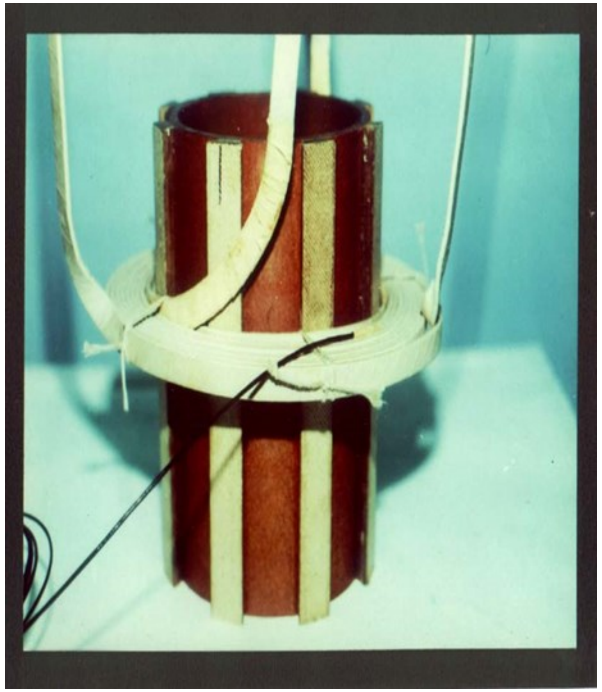
Free Gas Generation: Bubble Evolution

- Sources of Bubbles
  - Gasses dissolved in oil
  - Gasses generated from decomposition of insulation
  - Water vapor from paper insulation in windings
- Sudden release of gas/vapor as bubbles is possible under overloading
- BUBBLE GENERATION FROM OVERLOADING IS MOSTLY DUE TO WATER VAPOR RELEASED FROM PAPER INSULATION

Free Gas Generation: Bubble Evolution

The bubble evolution temperature may be estimated by the following equation:

$$\Theta_{bubble} = \left[\frac{6996.7}{22.454 + 1.4495\ \text{In} W_{WP} - \text{In}\ P_{pres}} \right] - \left[\left(\text{EXP}^{(0.473 W_{WP})} \right) \left(\frac{V_g^{1.585}}{30} \right) \right] - 273$$



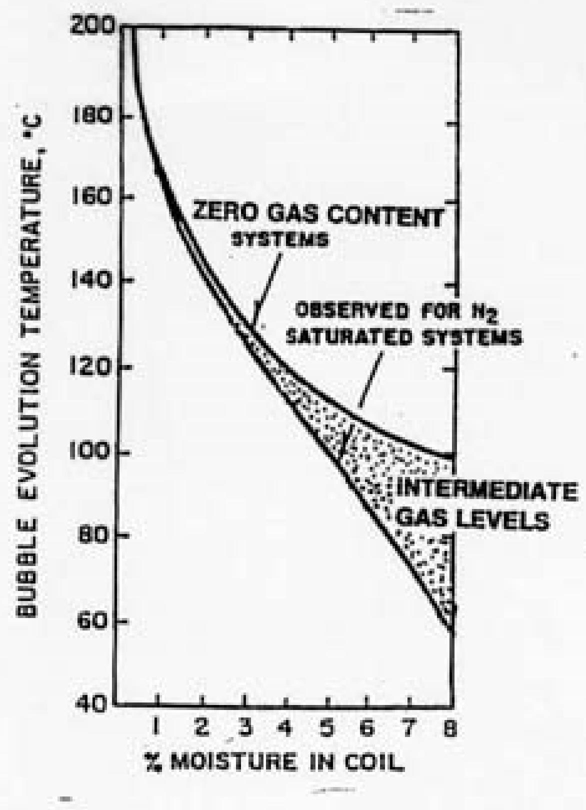
Where:

P_{pres}	Total pressure, mm mercury (torr.)
V_g	Gas content of oil, %(v/v)
W_{WP} (dry basis)	Per cent by weight of moisture in paper
Θ_{bubble}	Temperature for bubble evolution, °C

Free Gas Generation: Bubble Evolution

Bubble Generation

- Gas blanketed units and conservator units show little difference in bubble evolution at low moisture levels
- Increasing gas saturation in oil lowers bubble evolution temperature only at high moisture levels
- Bubble generation from overload is mostly due to water vapor released from paper insulation
- Accepting 140 °C as hot-spot temperature limit appears to be valid for moisture content above 1.5%

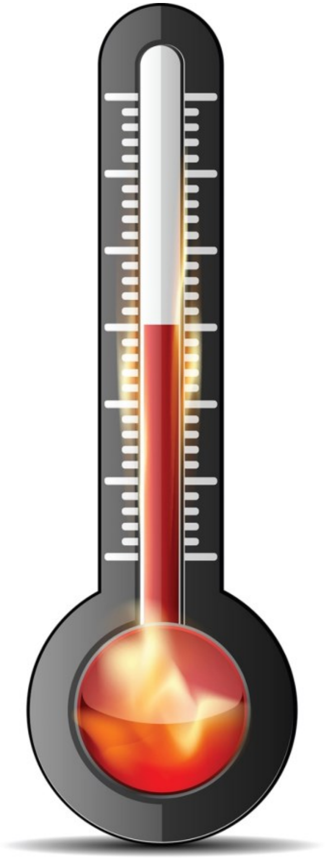


MODEL TEST RESULTS

Temperature Limits for Overload

- Hottest-spot conductor temperature = 140º C for Long Time and 180º C for short-time emergency loading
- Top oil temperature = 110º C
- Maximum loading = 200%
- IEEE standard temperature rise allows 24H average ambient of 30º C, with maximum of 40º C

Actual ambient temperatures should be used to compute the transformer's loading capability. Transformers surrounded by buildings/walls can result in re-circulation of heated air and higher ambient.



Calculation of Overload Temperatures

- Overload temperature rise must be calculated accurately with a method / software which can predict m & n exponents and thermal time constant for different overload conditions
- To limit temperature rise values high speed fans can be used during overload, if higher sound level is acceptable
- IEEE C57.91 explains two methods for calculating oil and winding temperatures:
  - Section 7 is a simplified non-iterative calculation that can be put into a spreadsheet application
  - Annex G is a computer program written in basic. Utilizes a convergence process to determine the maximum loading capability. Allows for variation in ambient temperature. Also provides an estimation of the loss of insulation life for the loading cycle

Industry Practice Transformer Loading

Theoretical Life – Aging Acceleration Factor

$$F_{AA} = exp\left(\frac{15000}{110+273} - \frac{15000}{HST+273}\right)$$

HST = Hot Spot Temperature °C

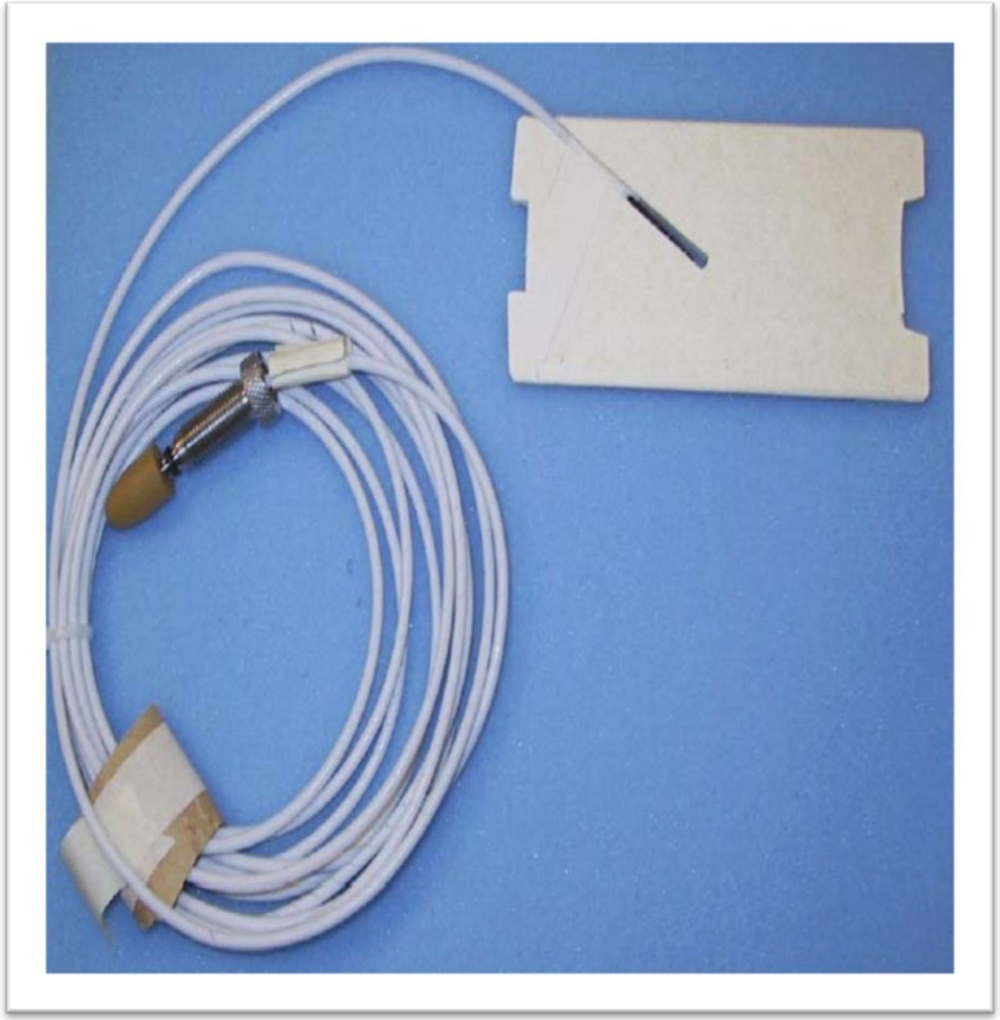
$$FEQA = \frac{\sum_{n=1}^{N} FAAn\Delta tn}{\sum_{n=1}^{N} \Delta tn}$$

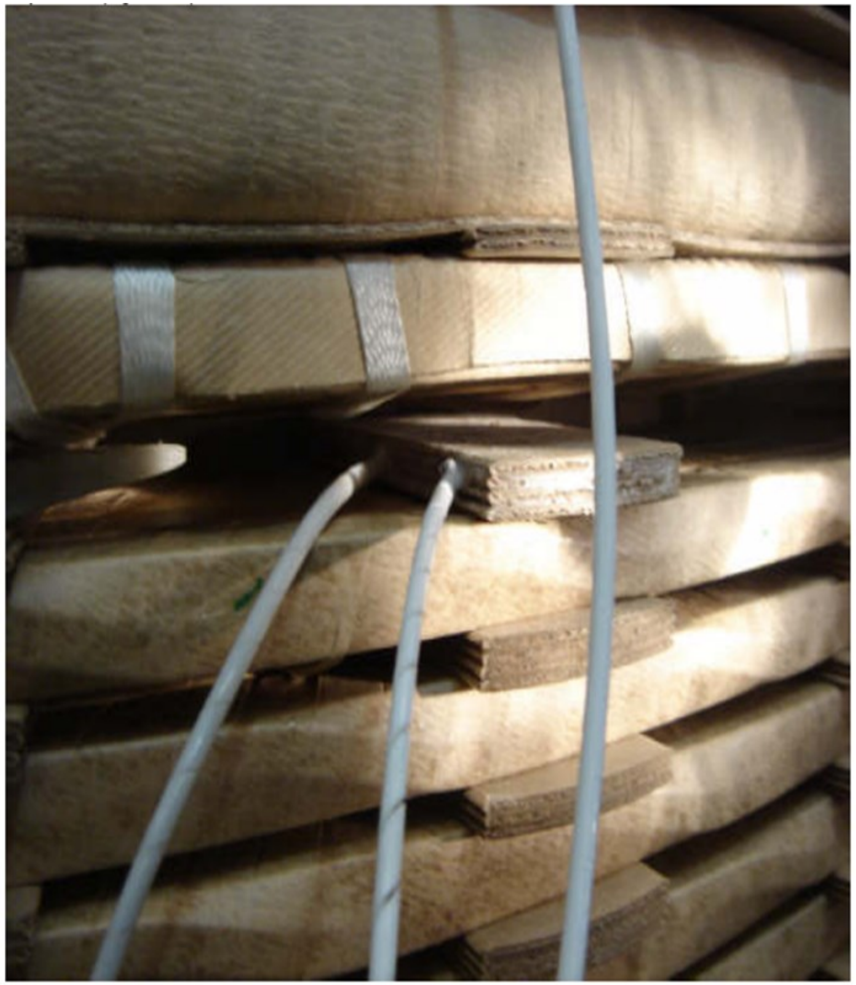
$$\%\ \text{Loss of life} = \frac{F_{EQA} \times t \times 100}{\text{Normal insulation life}}$$

Measurement of Overload Temperatures

- Conventional temperature monitors measure simulated winding hot spot temperature (top oil + incremental rise due to winding hot spot gradient based on CT current) which may not respond quickly under overload conditions
- If frequent variable overloading is required beyond 125% nameplate rating then it may be beneficial to measure winding temperature hot-spot with the help of Fiber optics device to limit overload to a safe temperature limit; the following need to be considered:
  - Probes are difficult to position / locate
  - Risk of damage during manufacturing of core and coil assembly
  - Expensive system ($30k+ with 4–8 probes)

Fiber Optic Installation





Conclusions

- Transformers need to be properly designed to meet guaranteed and overload temperature rises
- Transformers must be properly maintained to minimize moisture and oxygen content
- Hottest-spot temperature is the key to insulation life
- Ambient temperature plays a significant part in loading capability
- Follow the guidelines in IEEE C57.91 for overloading and monitor the hot-spot temperature, top oil and DGA during overload conditions

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Questions