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Transformer Basics - Why Temperature is Important

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Application Engineer

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Transformer Basics

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Transformer Basics

- Paper Insulation Deteriorates at Elevated Temperatures
- Temperature Limits the Ability to Load a Transformer
- Higher Temperatures Lead to Gas Evolution and Insulation Damage

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Transformer Basics

- **Maximum Ambient per the IEEE Standard is 40º C (104ºF)**
- **Allowable Temperature Rise of Top Oil above Ambient is Either 55 or 65º (131ºF)**
- **Maximum Top Oil Temperature Is Either 95 or 105º C (221ºF)**
- **Allowable Winding Rise Above Ambient per the IEEE Standard is 80º C (176ºF)**
- **Maximum Winding Temp Rise 120º C (248ºF)**

Your Cooling System Is Designed for these Temperatures!

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How Does Temperature Affect Insulation?

- The Degree of Polymerization (DP) Indicates Paper Insulation Health
- DP Decreases with Exposure to High Temperature
- Initially Paper Has a DP of 1000 to 1200[1]
- At End of Life DP Will Be About 125
- Once DP Is Zero, any Through Fault Could Cause Movement which may result in Dielectric Failure

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1. “Recent CIGRE Developments on Transformer Aging” by Jacques Aubin et al

Bubble Formation

- All Transformers Have Some Moisture
- Bubble Formation Is the Generation of Water Vapor
- Bubble formation Occurs at Temperatures of 140º C
- Bubble Formation Leads to Transformer Failure

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Key Gases

- **Several gasses are known to indicate various internal problems**

H_2	Hydrogen	***All Heating Events***
CH_4	Methane	***Hot Metal***
C_2H_6	Ethane	
C_2H_4	Ethylene	***Arcing & Partial Discharge***
C_2H_2	Acetylene	
CO	Carbon Monoxide	***Insulation decomposition***
CO_2	Carbon Dioxide	
O_2	Oxygen	
♫	Heavy Metal	***Rock Band Remnants***

- **Excessive Key Gases Indicates a Problem**

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Heat Sources

- Overcurrent

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Heat Sources

- Overcurrent
- Harmonics or DC Offset

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Harmonics and DC Offset

- Variable Speed Drives, Furnaces, Computer.
- Geomagnetically Induced Current
  - Solar Mass Ejections
  - Disturbance of Earth's Magnetosphere
  - Induced in Long Transmission Lines
  - NERC TPL-007-1 Over 200KV

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Heat Sources

- Overcurrent
- Harmonics or DC Offset
- Overvoltage

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Overvoltage

- **System Voltage Problems**
- **Wrong Tap Selection**
- **Core Saturation Results in Overcurrent and Overheating**

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Heat Sources

- Overcurrent
- Harmonics or DC Offset
- **Overvoltage**
- **Internal Problems**

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Internal Problems

- Not Detected by Gauge
  - Shorted Core Laminations
  - Inadvertent Core Ground
  - Case or Other Metal in Magnetic Field
  - Arcing

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Heat Sources

- Overcurrent
- Harmonics or DC Offset
- Overvoltage
- Internal Problems
- LTC Problems

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LTC Problems

- Contact Problems
  - Mainly Older LTC's
  - Coking of Contacts
  - Eventually Leads to Failure in LTC
  - Can Fail Transformer
  - Can be Detected if LTC is Monitored

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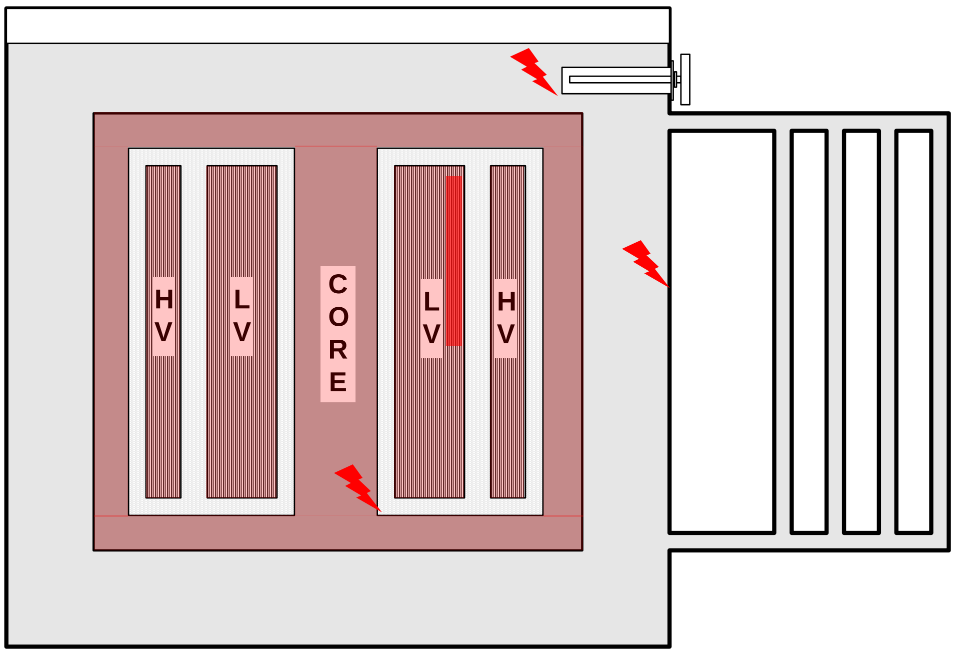
Heating Sources



- I^2R Heating from Windings
- Eddy Current Heating from Core
- Inadvertent Hot Spots
- Plugged oil path

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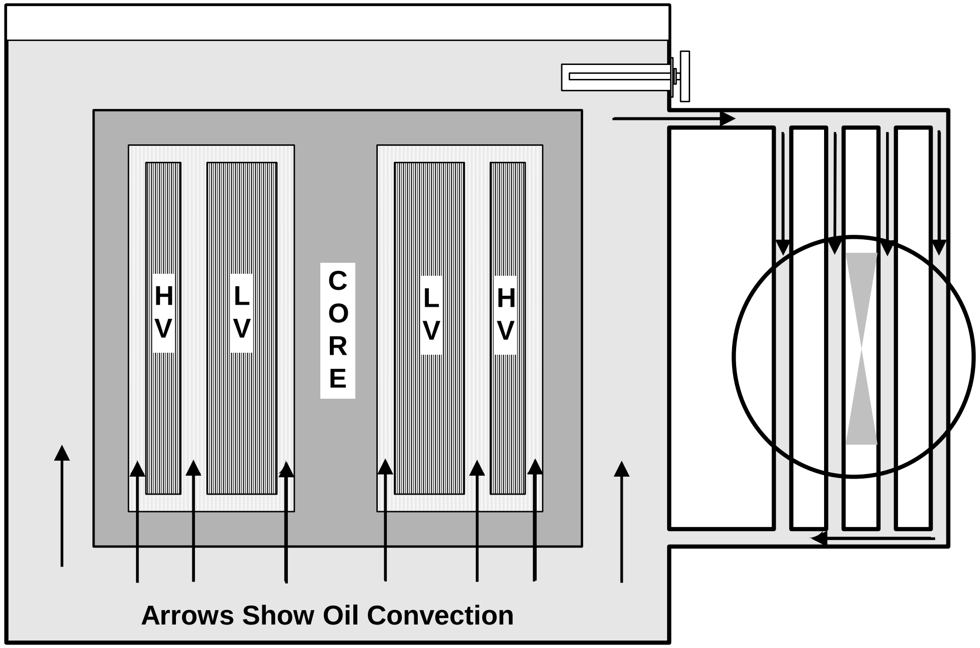
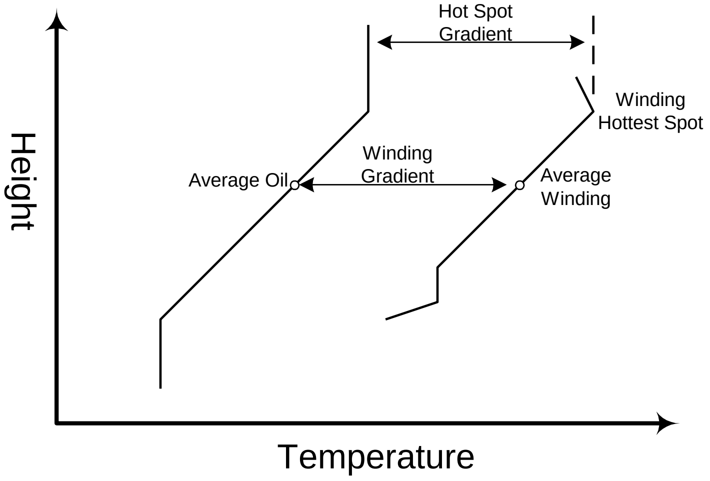
Cooling Basics





- **Fans will aid cooling – ONAF**

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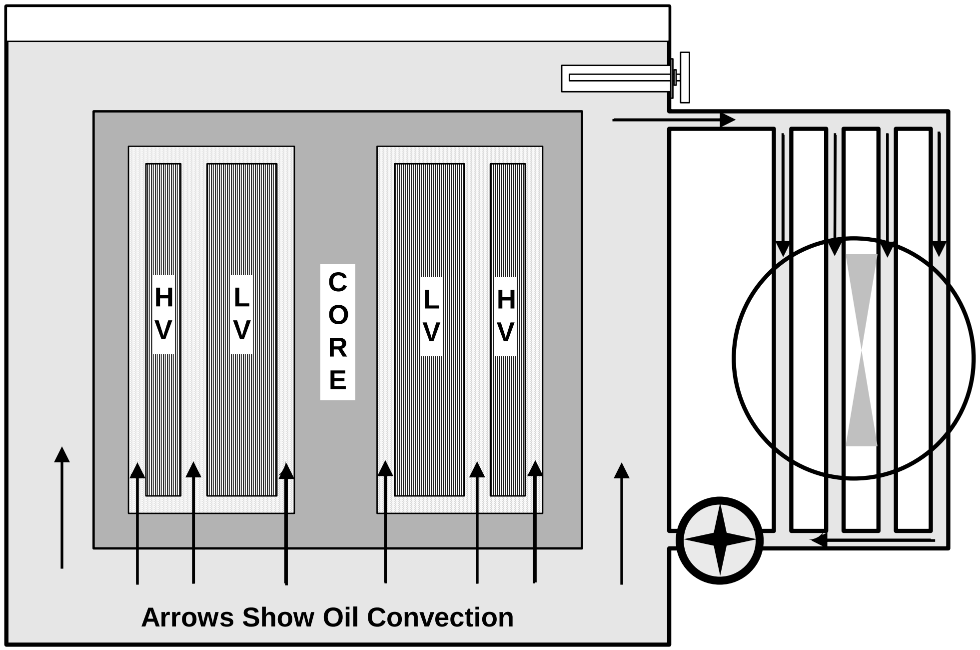
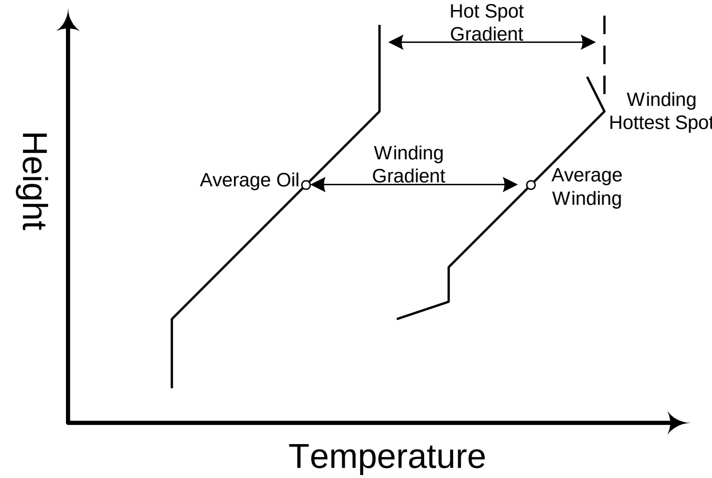
Cooling Basics





- **Fans will aid cooling – ONAF**
- **Adding an oil pump will further enhance cooling – OFAF**
- **Cooling Provides More Load Capability**

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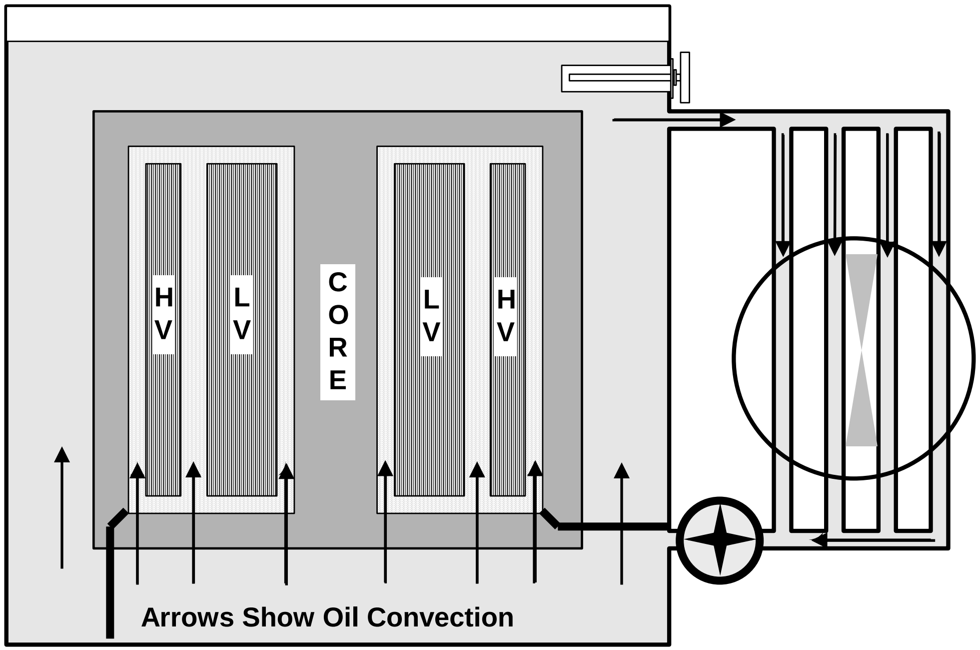
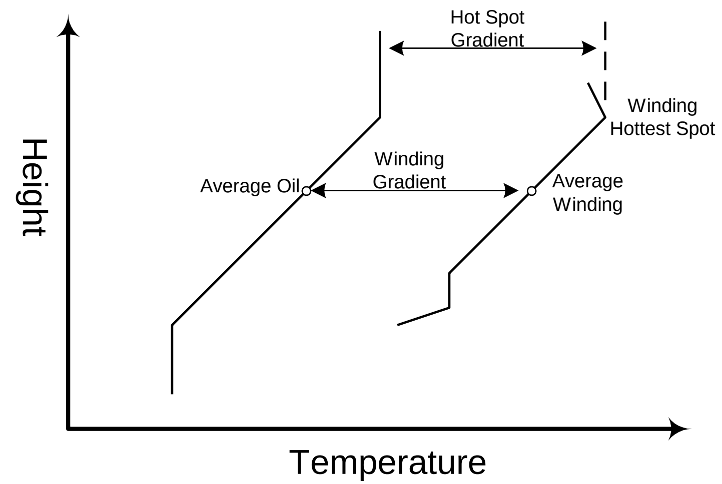
Cooling Basics





- **Adding directed oil flow further enhances cooling – DFOA or ODAF**
- **Baffles direct oil into the coils for greater cooling**
- **Design Has a small Gradient**

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Final Thoughts

- Keep your transformers hot and dry
- Don’t touch your transformers unless absolutely necessary
- Use Predictive Maintenance
  - ✓ Monitor your temperatures
  - ✓ Let automatic controls operate cooling
  - ✓ Be proactive in exercising the cooling system
  - ✓ Use antisipatatory cooling
  - ✓ Monitor your load tap changers
  - ✓ Monitor gases
  - ✓ Monitor your bushings

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Further Reading

- Electric Power Transformer Engineering, 3rd edition, CRC Press, Chapter 24, On-Line Monitoring of Liquid-Immersed Power Transformers
- IEEE Std C57.143-2012, IEEE Guide for Application for Monitoring Equipment to Liquid-Immersed Transformers and Components
- IEEE Std C57.91-2010, IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators

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Advances in Transformer Cooling Control and Monitoring

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Discussion Topics

- Oil Temperature Measurement
- Hot Spot Temperature Measurement Techniques
- New Strategies for Cooling Control
- Improving Reliability
- Load Tap Changer Condition Monitoring
- Strategies for Remote Communications and Local Monitoring

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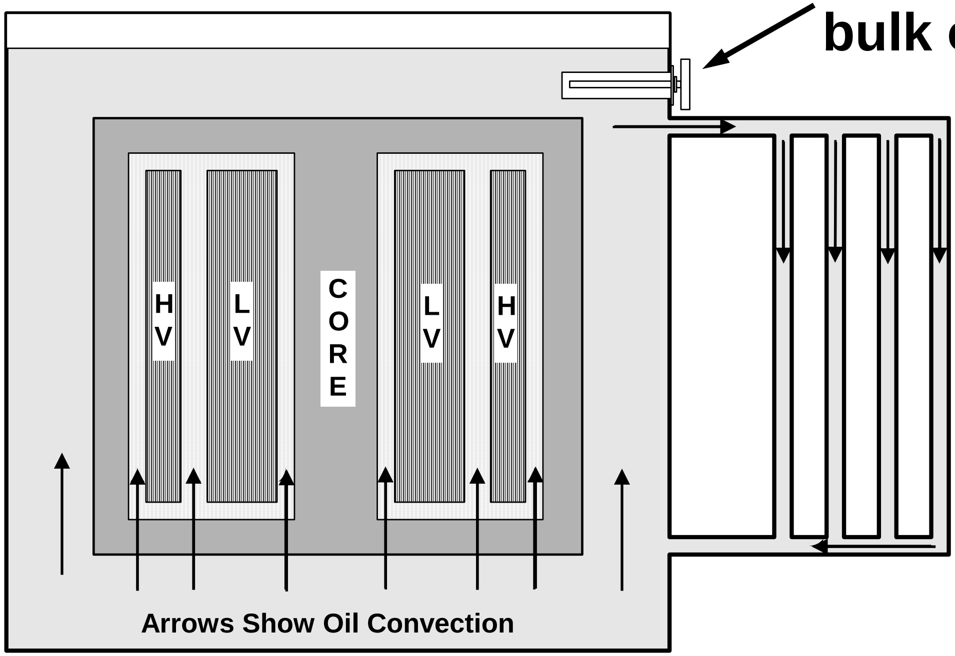
Oil Temperature

Direct measurement of the bulk oil in the top of the tank.



- Time constant (thermal lag) 2 to 3 hours. Responds very slowly.

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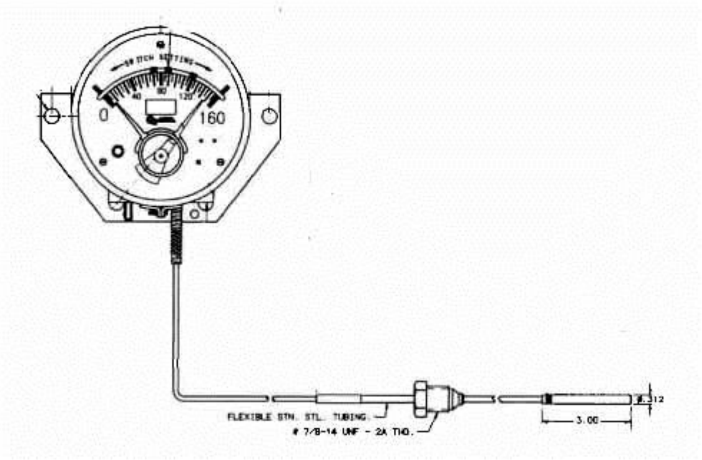
Capillary Tube Technology:



Advantages:

- Inexpensive, Depending on Options
- Simpler to Retrofit

Disadvantages:

- Not Rugged
- Limited Accuracy
- Limited Telemetry Options
- Limited Flexibility for Control
- No Failure Alarm

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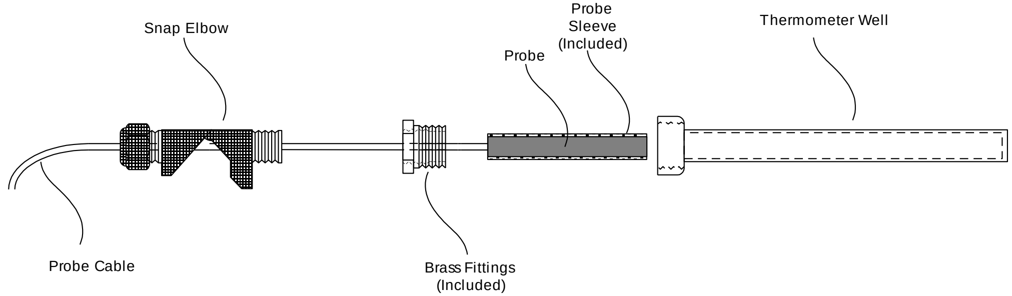
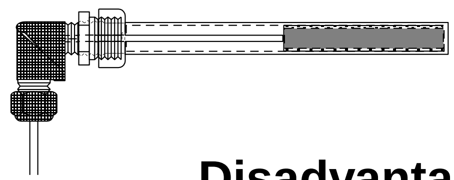
Electronic Technology:





Advantages:

- Rugged
- Superior Accuracy
- Variety of Telemetry Options
- Built-in or Programmable Control Logic
- Built-in Device Alarms
- Easy to set

Disadvantages:

- Can be More Expensive
- Retrofit May be More Difficult

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Methods:

- **Hot Spot Measurement by the Heated Well AKA - Simulated Method**
- **Direct or Fiber Optic Method**
- **Calculated Method**

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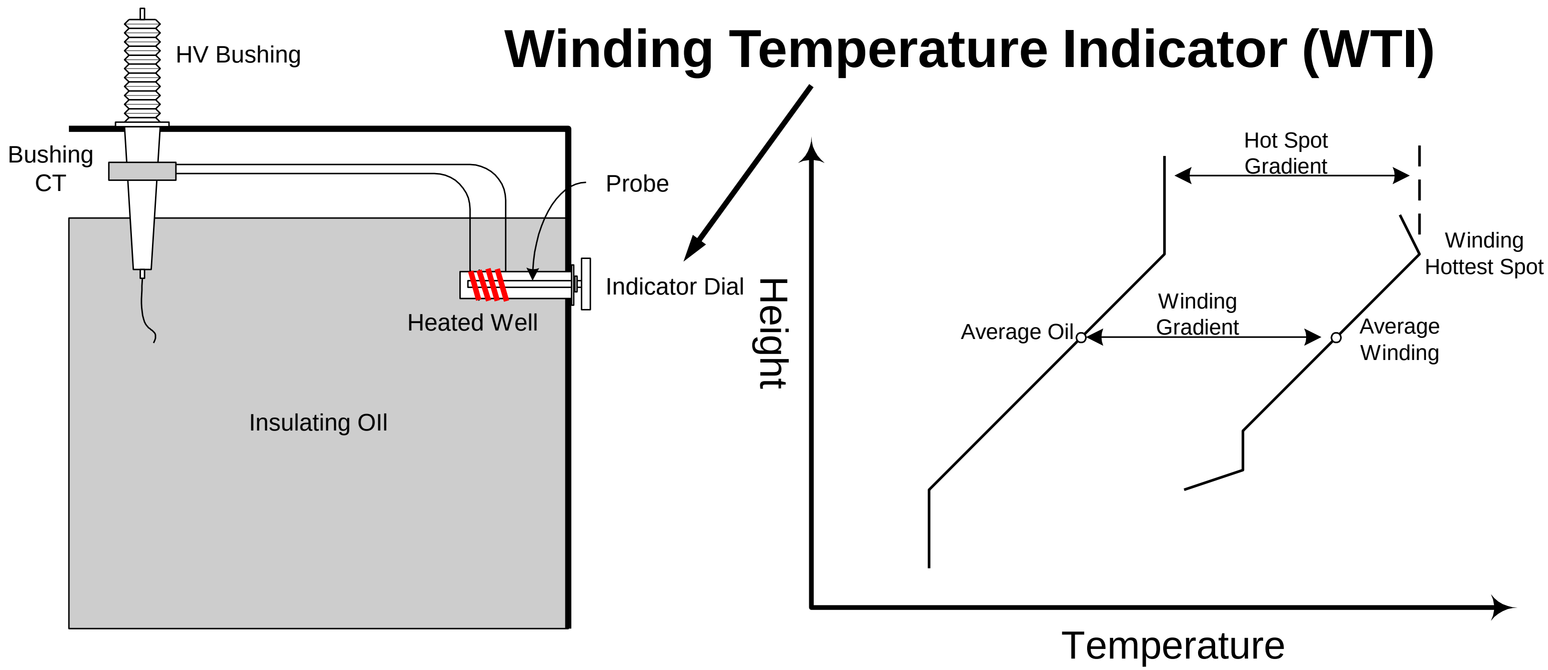
Winding Temperature

Winding Temperature Indicator (WTI)



Used to Start Cooling

- Uses CT circuit to react to loading
- Resistive well with either mechanical gauge or RTD
- Does Not React Quickly to Sudden Load Increase

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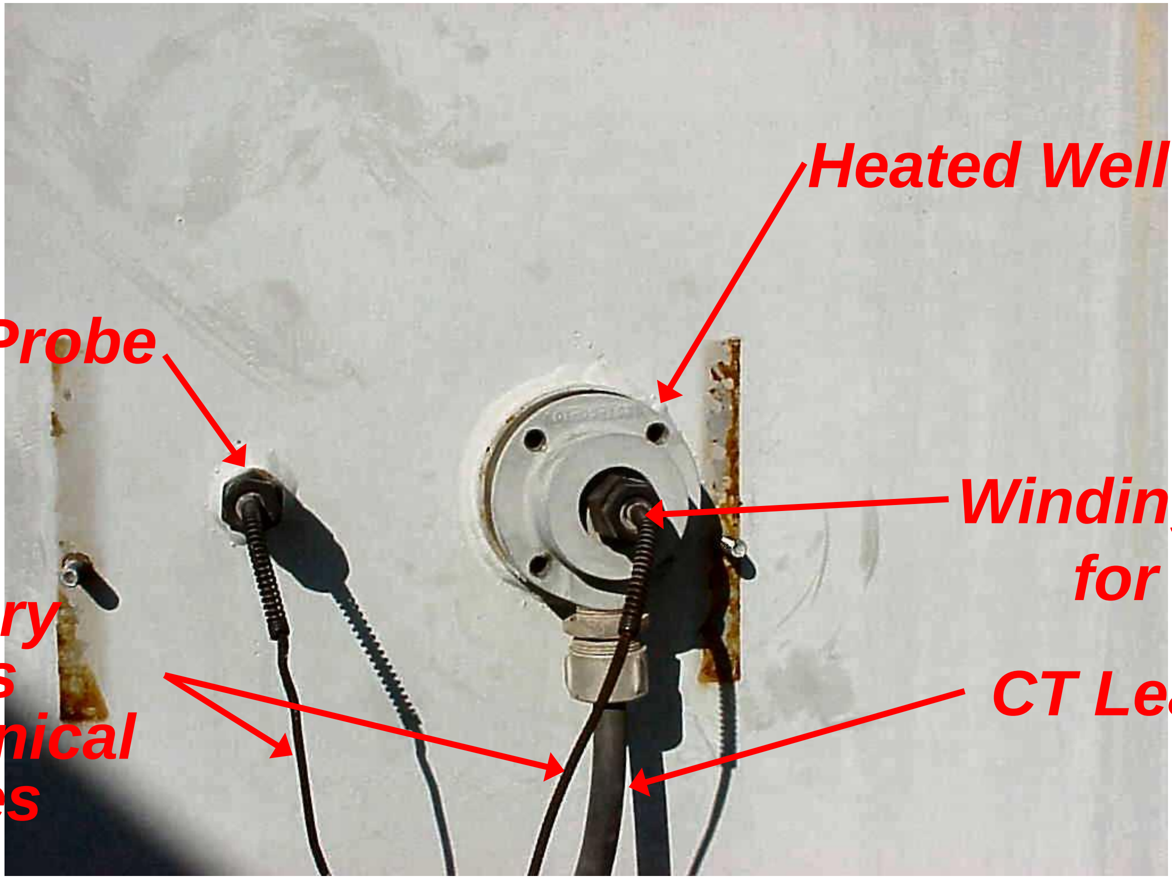
Mechanical Gauges

Temperature Probes in Wells



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Mechanical Gauges

Heated Well

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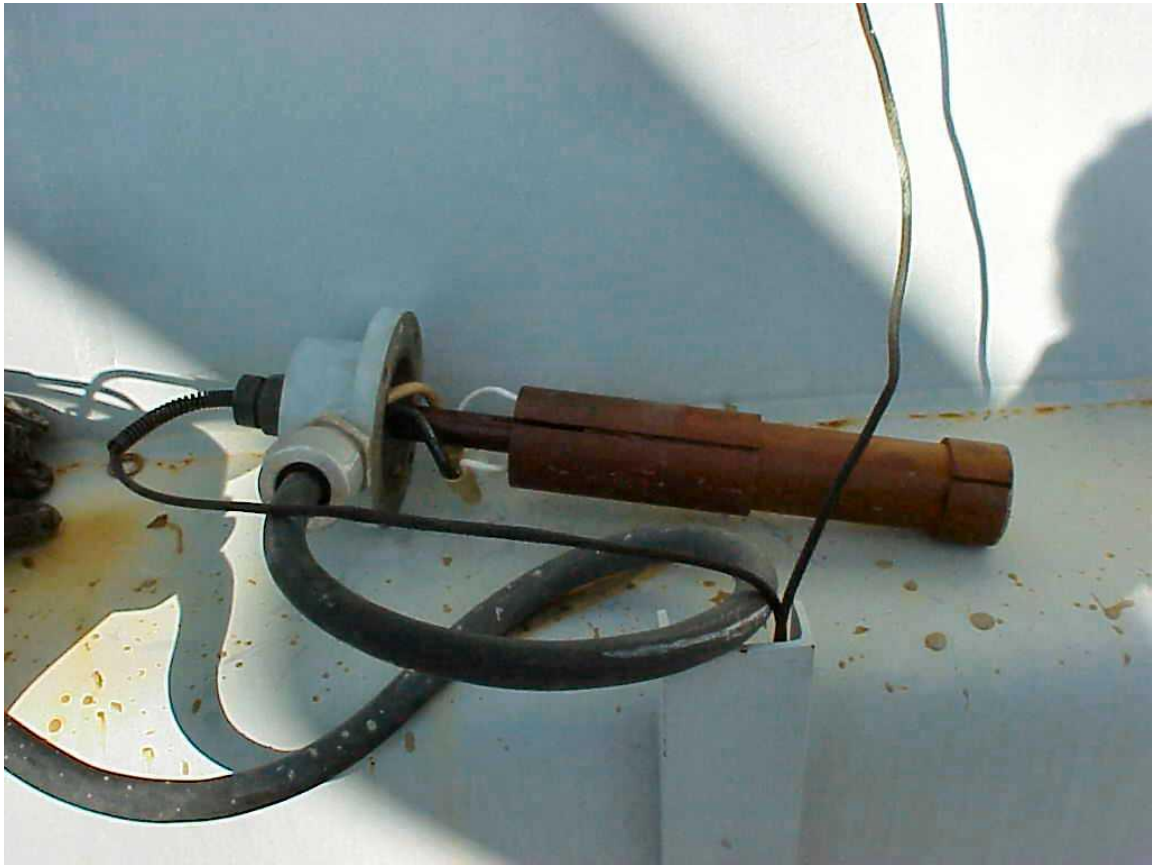
Sending unit with Heater



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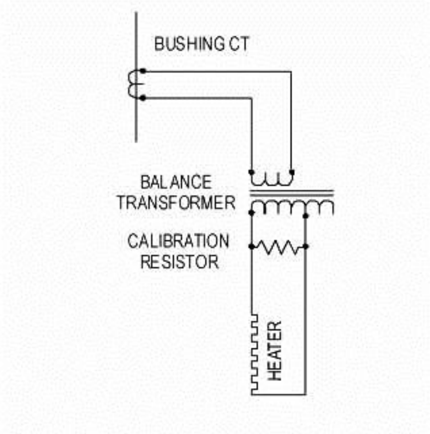
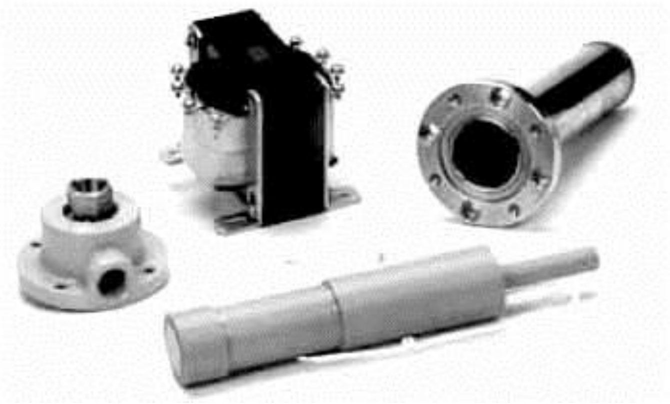
Simulated Method:





Advantages:

- Low Initial Cost

Disadvantages:

- No Failure Alarms
- Inherently Inaccurate
- High Replacement Cost
- Limited Telemetry Options
- Limited Control Options
- Slowest Response Time

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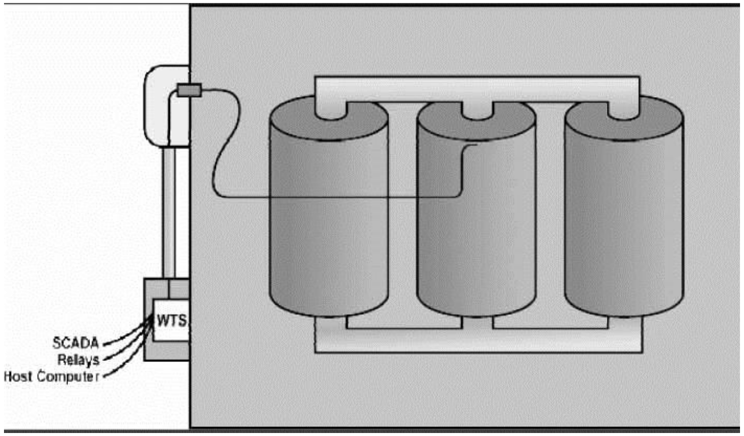
Direct or Fiber Optic Method:



Advantages:

- Direct Hot Spot Measurement
- Telemetry Options
- Can be Most Accurate
- Fast Response Time

Disadvantages:

- Very High Cost
- Very Difficult to Retrofit
- Fragile, Difficult to Install

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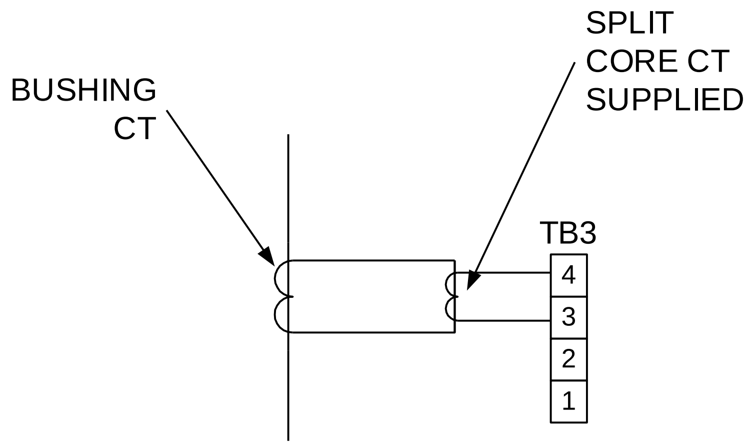
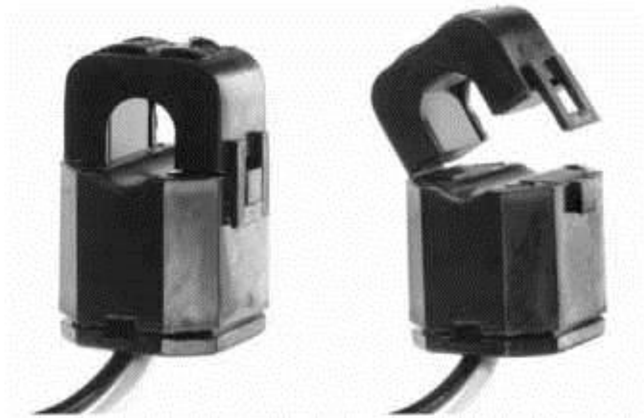
Calculated Method :





Advantages:

- Easy Retrofit
- Telemetry Options
- Lowest Maintenance
- Built-in Control Options
- Built-in Failure Alarms

Disadvantages:

- Not as Accurate as Direct Method
- Requires Access to WTI CT or Bushing CT's
- Slower Response Time

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Calculated Method Continued:

$$T_{Winding_U} = T_{RTO} * \left(Load * CTRatio / RatedLoad\right)^{2*m} + T_{TopOil} \quad [1]$$

Where:

$T_{WindingU}$ = Ultimate calculated winding temperature

T_{RTO} = Hot Spot Rise over Top Oil temperature at rated load

Load = Measured load current

CTRatio = Primary CT ratio

Rated Load = Rated load current

m = 1.0 for directed FOA or FOW, 0.8 for all other cooling

T_{TopOil} = Measured Top Oil temperature

[1] ANSI C57.91-1995

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Electronic Temperature Monitor Control Options:

- **Set Points for Cooling Controls, Alarms, and Tripping Settable Through the Front Panel or PC**

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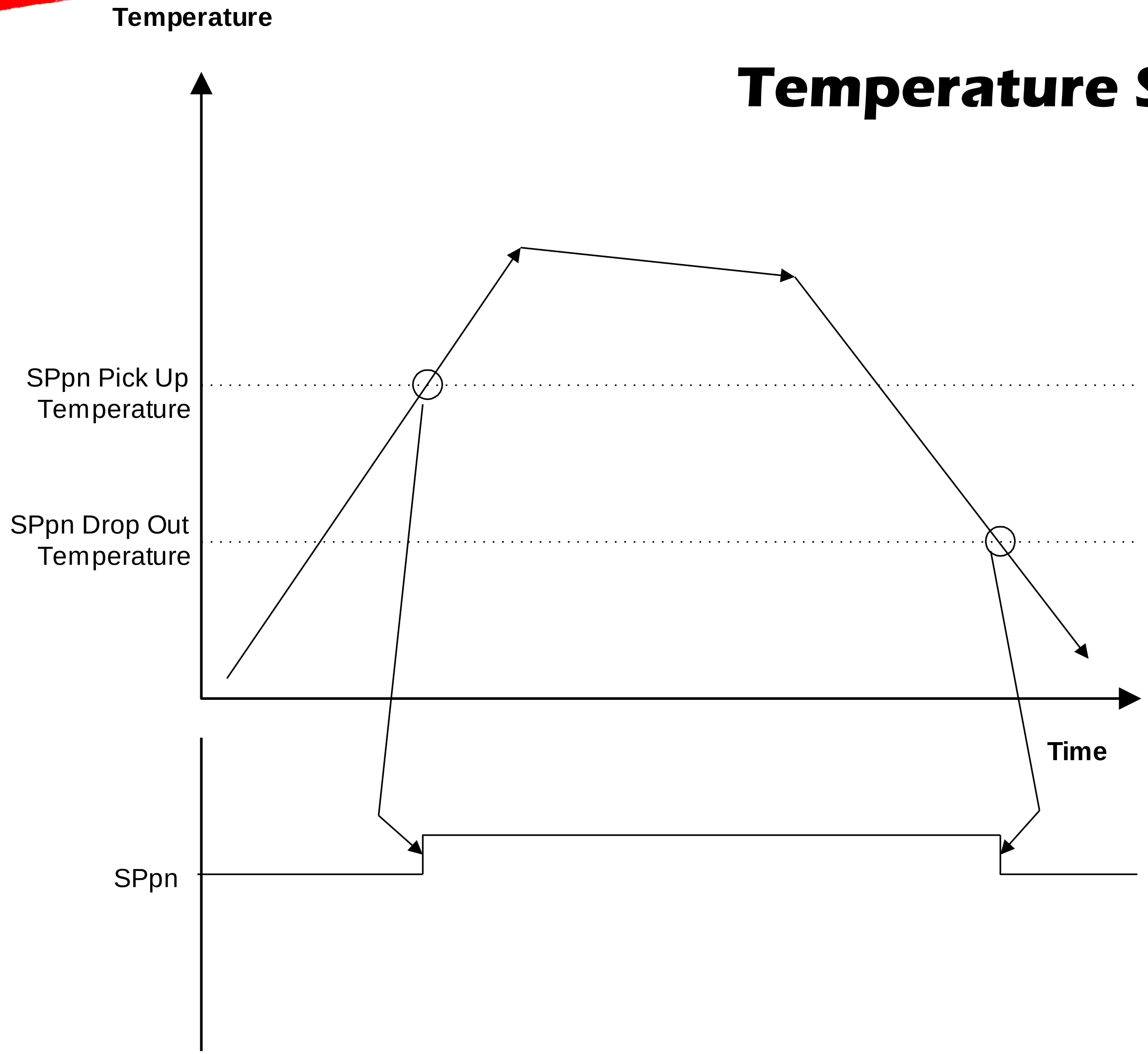
Temperature Set Points



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Electronic Temperature Monitor Control Options:

- Set Points for Cooling Controls, Alarms, and Tripping Settable Through the Front Panel or PC
- Full Programmable Scheme Logic Reduces External Wiring

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Examples of Scheme Logic:

The outputs are completely programmable:

- Consolidate high temp alarms to control a single output:

  OUT1 = SP11 + WSP1

  Where SP11 is the top oil temp alarm and WSP1 is the winding temp alarm

- Control an output for fail-safe operation:

  OUT2 = !SP22

- Block operation of pumps in cold climates:

  OUT2 = !SP14 * (SP12 + WSP1+ LSP1)

  Where SP14 is set to operate in Under Temp.

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Electronic Temperature Monitor Control Options:

- Set Points for Cooling Controls, Alarms, and Tripping Settable Through the Front Panel or PC
- **Full Programmable Scheme Logic Reduces External Wiring**
- **Built-in Fan Bank Alternate Feature**

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Electronic Temperature Monitor Control Options:

- **Universal Power Supplies**
- **Monthly, Weekly, Daily Fan Exercising Available**
- **Command Cooling on Sudden Increase of Load for Pre-Cooling**

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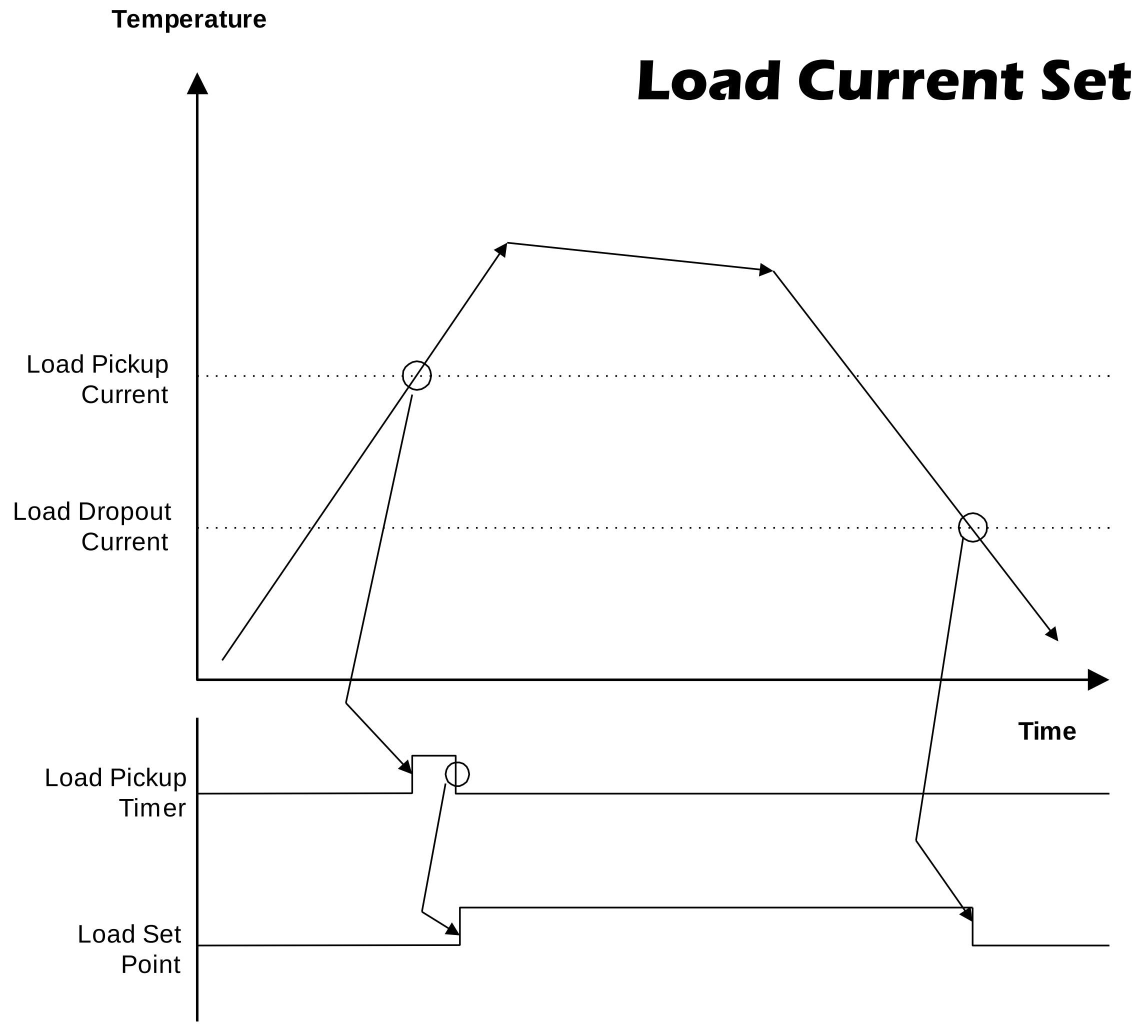
Load Current Set Point



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Electronic Temperature Monitor Control Options:

- Universal Power Supplies
- Monthly, Weekly, Daily Fan Exercising Available
- **Command Cooling on Sudden Increase of Load for Pre-Cooling**
- **Universal Temperature Probes Ease Retrofit**

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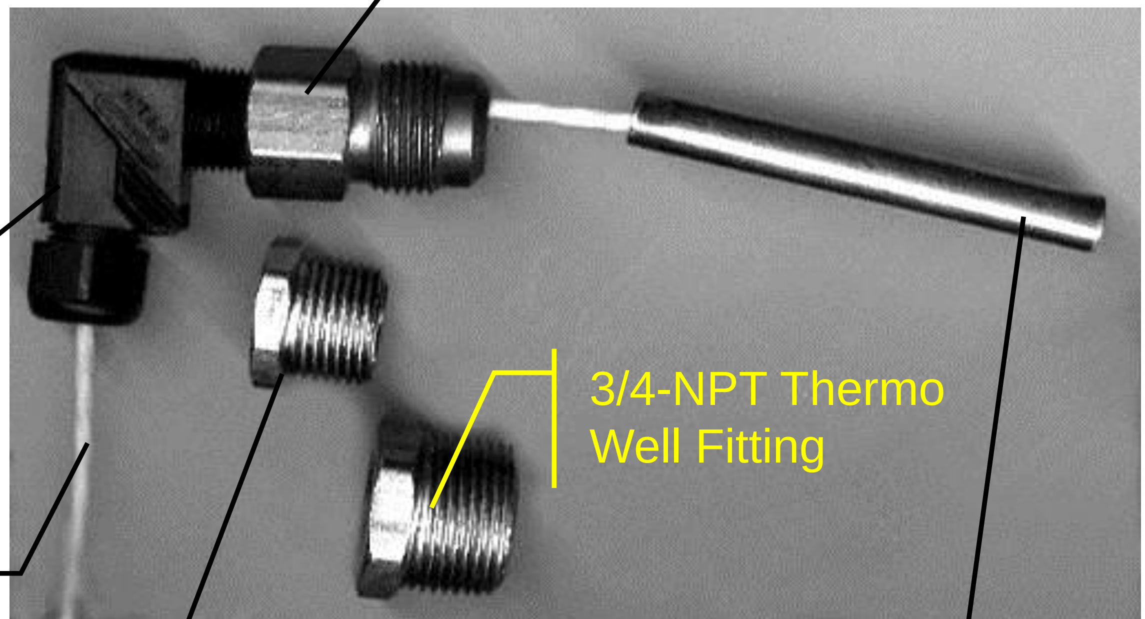
Universal Probe:

7/8-UNF2 Thermo Well Fitting



150 PSIG 90°
Liquid Tight
Strain Relief

FEP Teflon Jacket &
Conductors

1/2-NPT Thermo
Well Fitting

Probe: 3/8” DIA x 3” LONG

Probe Sleeves Included

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Electronic Temperature Monitor Control Options:

- Universal Power Supplies
- Monthly, Weekly, Daily Fan Exercising Available
- Command Cooling on Sudden Increase of Load for Pre-Cooling
- **Universal Temperature Probes Ease Retrofit**
- ***Alarms When Things Go Wrong.***

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Conventional Wisdom:

We Don’t Need Electronic Temperature Monitors.

We Turn On Fans in May and Turn Them Off in October.

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Conventional Wisdom Debunked:

- Increases Wear & Tear on Fans
- Running Fans Through the Summer Wastes Energy.
- How Will You Know When There is a High Temperature Alarm?

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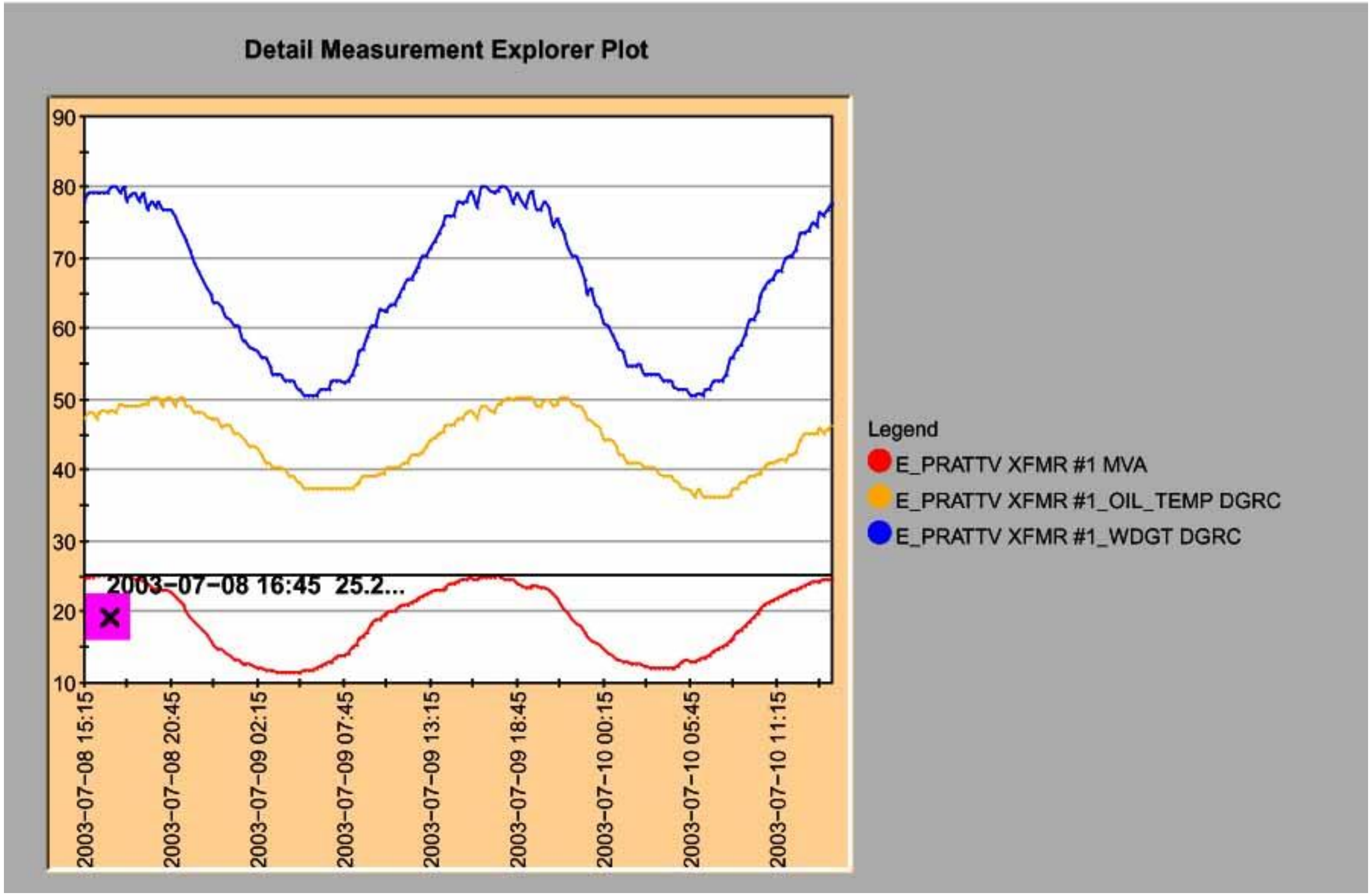
Load Profile:



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The Analysis:

- 24 MVA Unit
- Unit Has Two Stages of Cooling With a Total of 12 fans.
- Each Fan Motor is 1/3 HP Running at 230VAC.
- Used NOAA Data to Extrapolate
- Compared Running Fans Continuously From May Through October vs. Automatic Control.

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The Conclussion:

- **Fans Run Continuously May-October:**

  18,243 Kwh

- **Fans Automatically Controlled:**

  6,558 Kwh

- **Total Savings:**

  11,685 Kwh

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Improving Reliability

- **Savings Minimal On Units Less Than 18 MVA.**
- **There Are Big Savings on More Lightly Loaded Units**

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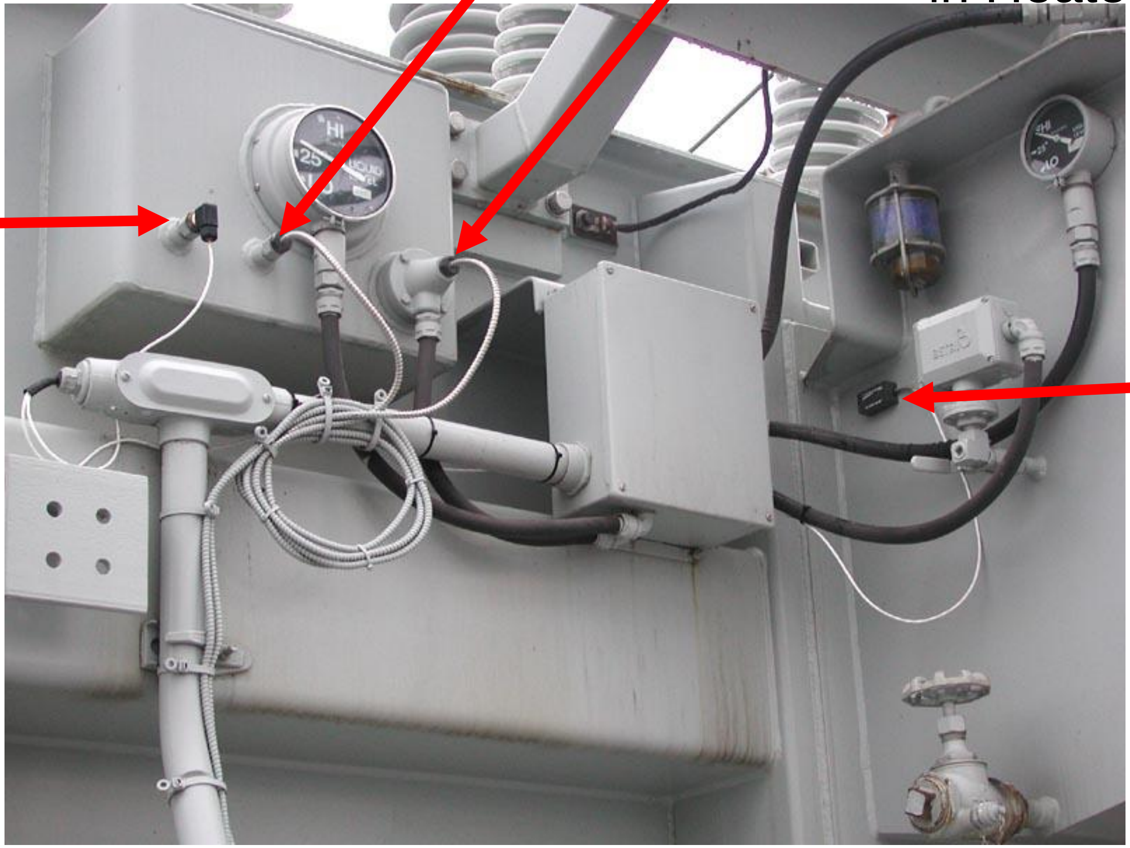
LTC Condition Monitoring

Old Mechanical Top Oil Capillary Tube

Old Mechanical Winding Capillary Tube in Heated Well

Top Oil RTD



LTC Tank RTD Magnetic Mount

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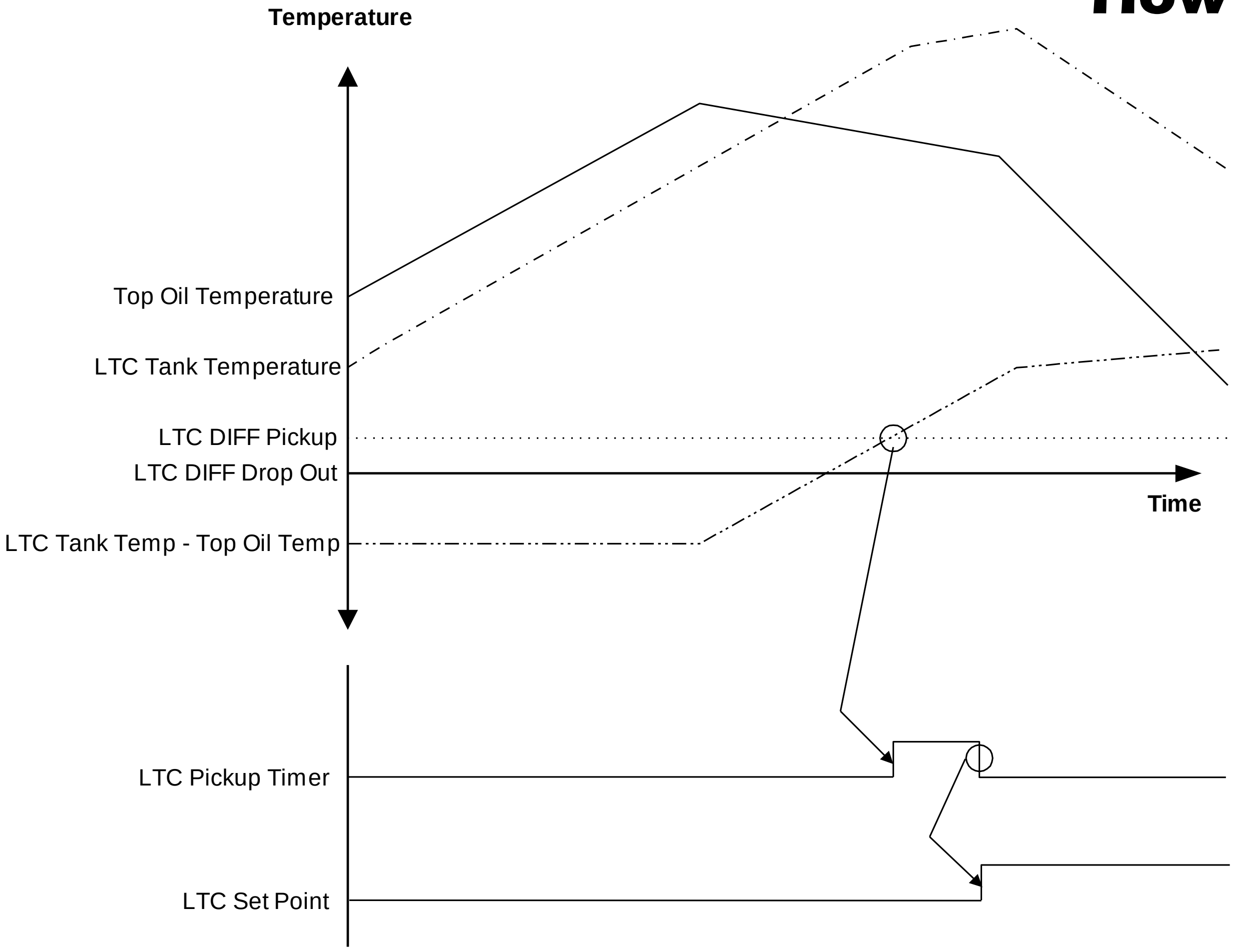
How It Works:



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Remote Communications Strategies

- Telemetry Through Analog Outputs
- ASCII Data Through RS-232 For Protective Relays & SCADA
- DNP3.0 or MODBUS For Telemetry, Status and Control

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Local Data Monitoring Options

- Report of Min and Max Temperatures
- Data Logging:
  - Rolling Data Log.
  - Data exports as a text file (CSV) to MS Excel.
  - Stores Months of Data Time Stamped Every 60 Min.
  - Selectable Time Base & Points for increased storage.
  - Power back up for clock to ride through outages

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Conclusions

- Retrofitting of Capillary Tube Gauges with Electronic Temperature Monitors (ETM's) is an Economical Option.
- The Benefits of ETM's Outweigh the Drawbacks for use on all New Units.
- ETM's Permit Strategies to Lower Maintenance Costs.
- ETM's Permit Strategies to Improve Transformer Life.
- ETM's Allow Multiple Methods of Temperature Data Acquisition to Facilitate Better Loading Decisions and Forensics.
- An ETM with Top Oil and Winding Temperature Measurement Will Likely Cost Less Than a Mechanical Top Oil Gauge (then you still have to buy the winding gauge, a second well, and the heated well apparatus).

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