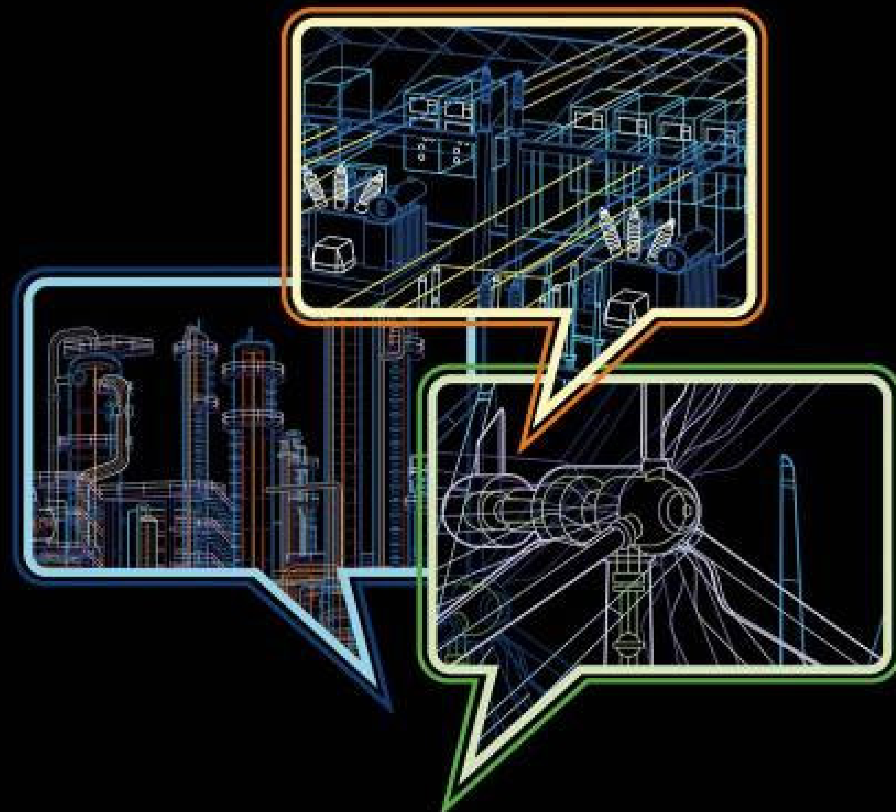

ABB Automation & Power World: April 18-21, 2011

WPO-112-1
Factors to Consider in Risk Assessment & Life Extension of Power Transformers

Ed teNyenhuis – ABB TRES Canada

WPO-112-1
Factors to Consider in Risk Assessment & Life Extension of Power Transformers

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- Abstract - Much attention is rightly focused on reliability risks from the aging fleet of power transformers and on the enormous cost in both dollars and time to replace them. But many factors beyond age place a transformer at risk of failure. This workshop considers the main contributing factors, their likelihood of impact on a particular unit and steps that can be taken to extend their life within a limited budget

Your safety is important to us
Please be aware of these emergency procedures

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- **In the event of an alarm, please proceed carefully to the nearest exit. Emergency exits are clearly marked throughout the hotel and convention center.**
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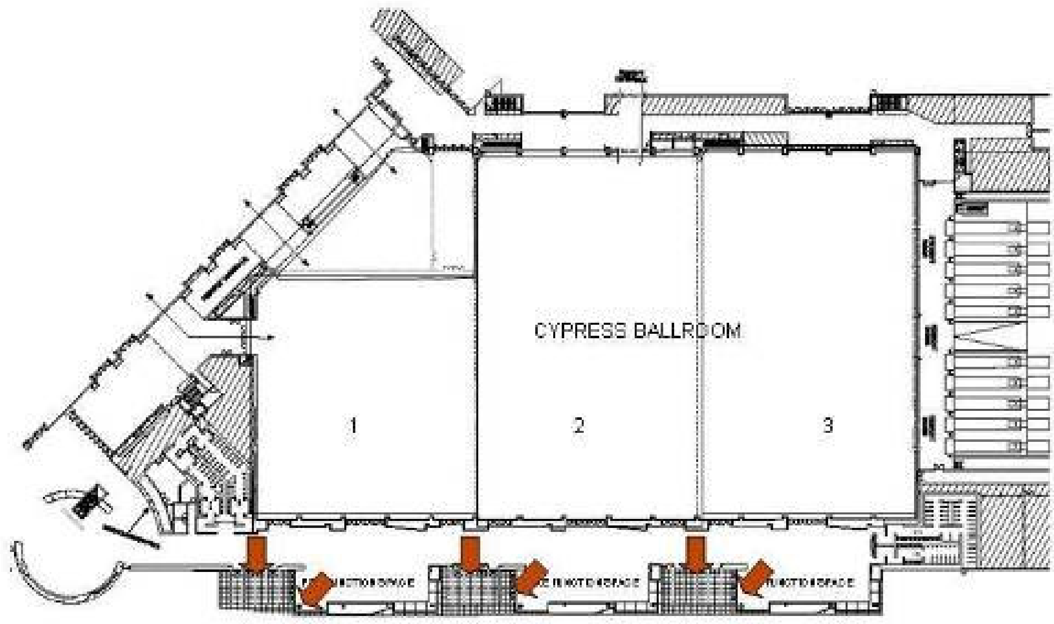
Your safety is important to us
Convention Center exits in case of an emergency



Know your surroundings:

- **Identify the meeting room your workshop is being held in**
- **Locate the nearest exit**

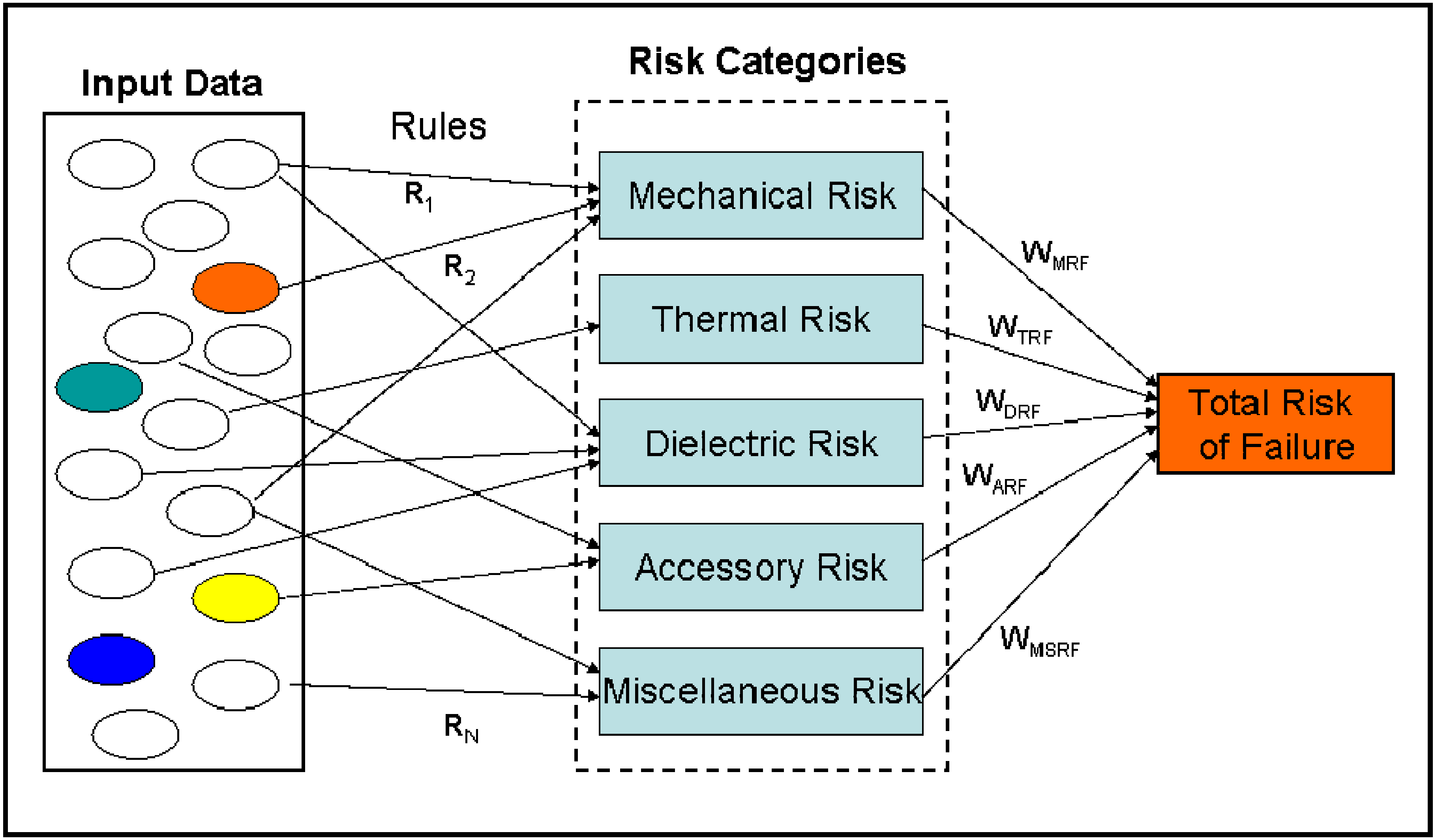
Agenda

- Failure Statistics
- Risk of failure
- Life Extension
- Case Study / Examples
- Q & A

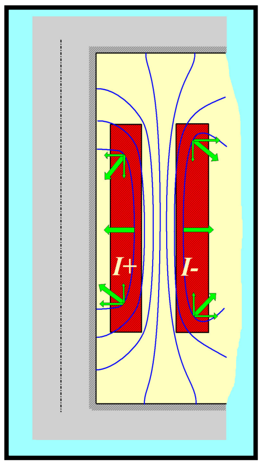
Transformer Failure Rate
Some statistics

- Industry failure rate has been around 2 to 2.5%
  - Higher for units with LTC's
  - Higher for increasing kV
- Source of the failures
  - 43% winding insulation
  - 16% load tap changers
  - 19% bushings
  - 22% other
  - (Reference = Doble)
- Average age in the industry is close to 40 years

Overall Risk Assessment



High Level Transformer Risk of Failure
Stresses Acting on Power Transformers



Mechanical Stresses

- **Forces between conductors, leads and windings due to overcurrents or fault currents caused by short circuits and inrush currents**

Thermal Stresses

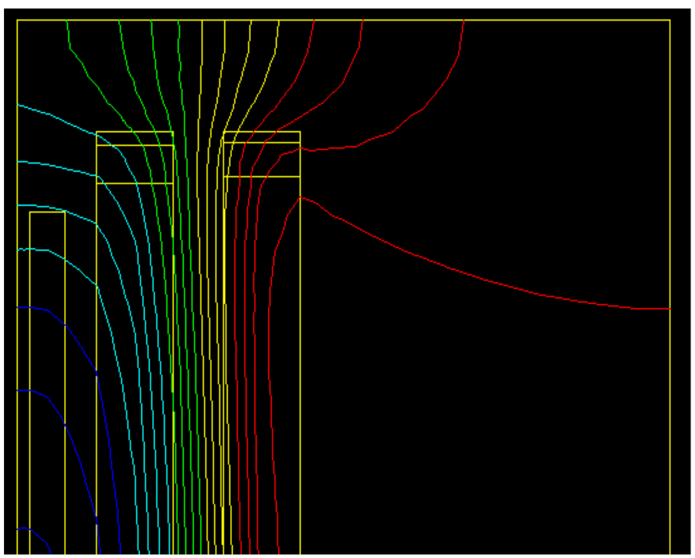
- **Due to local overheating, overload currents and leakage fluxes when loading above nameplate ratings; malfunction of cooling equipment**

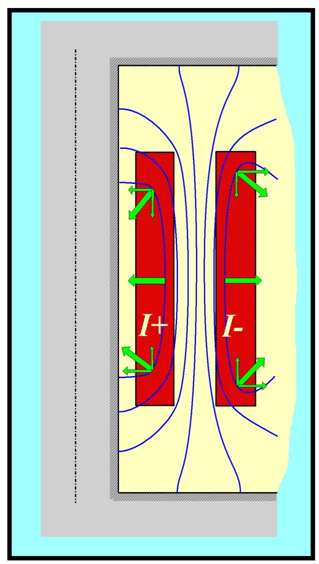
Dielectric Stresses

- **Due to system overvoltages, transient impulse conditions or switching transients**

Mechanical Risk Aspect

- Winding failure due to through fault is common type of failures
  - Can be the result of a single throughfault or the cumulative effect of many throughfault or inrush events
- Risks for short circuit failure:
  - Transformer design (strength of the windings)
  - Type of blocking
  - Dielectric and thermal condition of the windings
  - Reclosing practice
  - Average number of through-faults experienced by the transformer in a given year



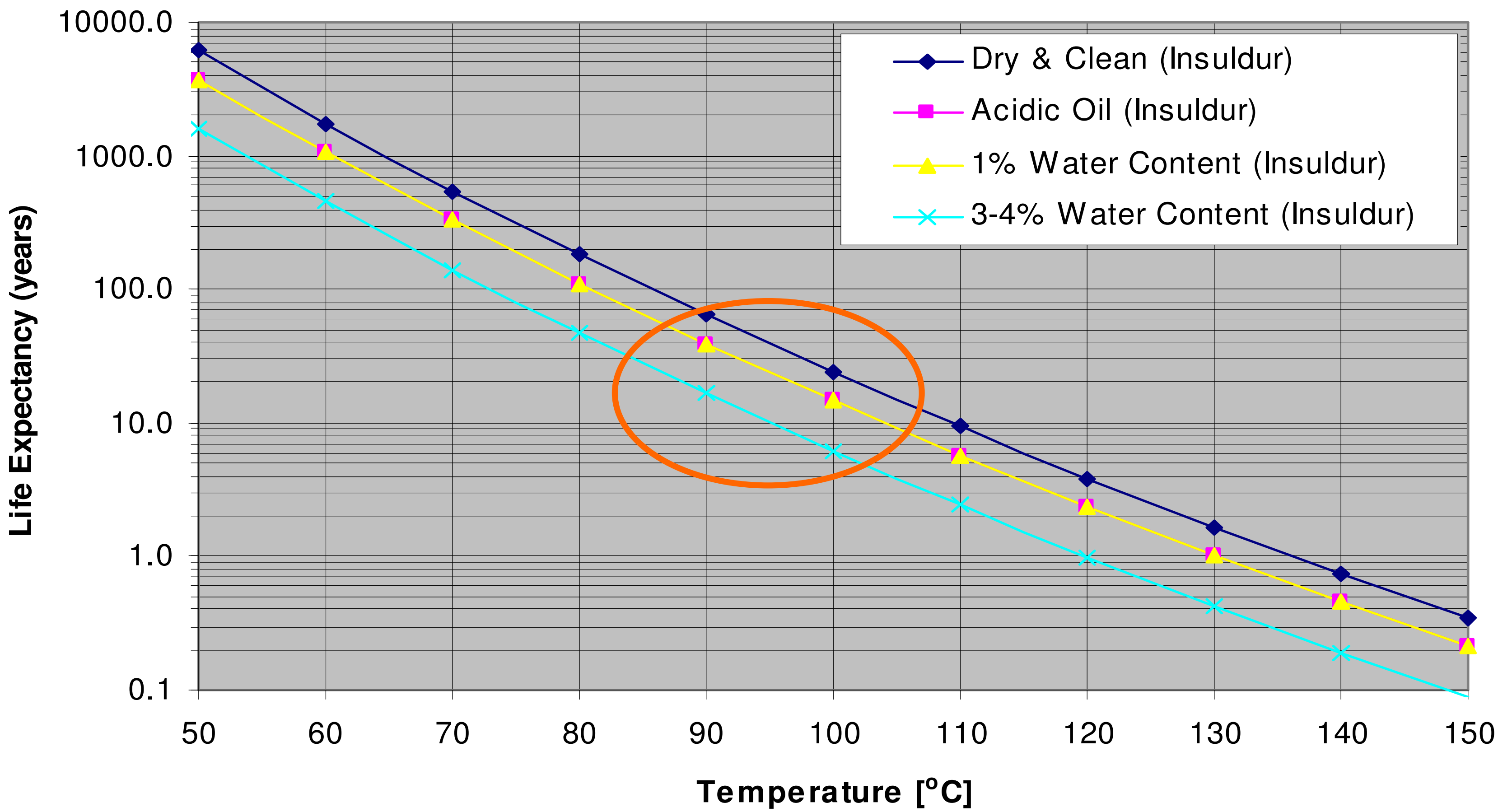


Thermal Risk Aspect

- An important factor in the risk of a mechanical failure is the condition of the paper insulation
- Thermal risk conditions
  - Hot cellulose
  - Hot metal
  - Hot cellulose + metal
- Typical influential factors are:
  - Temperature
  - Age of the transformer insulation
  - Relative compositions of produced carbon oxides
  - Oxygen & moisture in the oil
  - Hydrocarbon gases
  - Load profile
  - Cooling equipment – present condition
  - Hot spots in metallic materials such as core or current carrying contacts (determined from DGA)
- End of life cellulose does not necessarily mean high risk of failure

Degree of Polymerization – DP
Life Expectancy Based on DP and Other Factors

For long insulation life expectancy, it is important to keep the insulation dry, keep acidity and oxygen concentration of oil low and provide good cooling



It is assumed that the DP of transformer insulation is approx. 1,000 at the start of life and approx. 200 at the end of life. This graph shows the expected life of thermally upgraded insulation (Insuldur) under various conditions.

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Dissolved Gas Analysis
Evaluation - Characteristic Gases

Fault Pattern	Key Gas	Secondary Gases	Possible Findings
Conductor Overheating	CO_2/CO (Carbon Oxides)	CH_4 and C_2H_4 if the fault involves an oil-impregnated structure	Discoloration of paper insulation. Overloading and/or cooling problem. Bad connection in leads or tap changer. Stray current path and/or stray magnetic flux.
Oil Overheating	C_2H_4 (Ethylene)	CH_4 and smaller quantities of H_2 and C_2H_6. Traces of C_2H_2 if fault is severe or involves electrical contacts.	Metal discoloration. Paper insulation destroyed. Oil heavily carbonized.
Partial Discharge	H_2 (Hydrogen)	CH_4 and minor quantities of C_2H_6 and C_2H_4	Weakened insulation from ageing and electrical stress. Pinhole punctures in paper insulation with carbon and carbon tracking. Possible carbon particles in oil. Possible loose shield, poor grounding of metal objects.
Arcing	C_2H_2 (Acetylene)	H_2, and minor quantities of CH_4, C_2H_4	Metal fusion, (poor contacts in tap changer or lead connections). Weakened insulation from ageing and electrical stress. Carbonized oil. Paper destruction if it is in the arc path or is overheated.

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Dissolved Gas Analysis
Typical Problems Diagnosed

- Overloaded transformers
- Overheating caused by problems with cooling systems
- Local overheating caused by blocked oil duct inside the transformer
- Overheating due to oil circulating pump problems (bearing wear, impeller loose or worn)
- Overheating due to circulating stray currents in the core, structure, and/or tank
- An unintentional core ground may cause heating by providing a path for stray currents.
- Bad connections in the leads or by a poor contact in the tap changer can cause a hotspot
- Discharges of static electrical charges that build up on shields or core and structures that are not properly grounded may cause hotspots that produce gassing
- Hotspots that may be caused by electrical arcing between windings and ground, between windings of different potential, or in areas of different potential on the same winding, due to deteriorated or damaged insulation
- Windings and insulation that may be damaged by faults downstream (through faults), causing large current surges through the windings
- Voltage surges caused by nearby lightning strike or switching surge or closing out of step may result in immediate arcing or arcing that develops later
- Aged insulation that may be damaged by a voltage surge. When this happens, clearances and dielectric strength are reduced. Partial discharges and arcing may develop. during a through fault and cause total mechanical and electrical failure
- High noise level (hum due to loose windings) can generate gas due to heat from friction

Advanced Diagnostics for Power Transformers
Decisive factors/Side information

Production of gases

- **Load**
- **Temperature**
- **Oxygen concentration**
- **Single/multiple analyses**
- Mass and volume
- *Oil type*

{ Application, load profile; Age; Design; Normal/abnormal events }

Spurious signals

- **Tapchanger-leakage**
- Not relevant gases (rusting, chemical reactions, previous gassing, etc..)

Loss of gases

- **Loss through conservator**
- Cellulose

{ **Open or Closed conservator**; **Load profile** }

Other aspects

- Accuracy of analysis (do not mix data from different labs)
- "Burn-in"
- "Brothers and sisters"
- Reason for analysis and previous history
- Normal behaviour

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Electrical Risk Aspect

- Involves both design and condition issues
- Elements involved:
  - Inherent design dielectric strength
  - Testing done on the unit (impulse level, switching surge done?)
  - Location (near lightning prone areas)
  - Design of the over voltage protection (arrestor type)
  - Dissipation factor (tanδ, power factor) of the insulation
  - Oil quality results
  - The amount and distribution of dissolved gases in oil
  - Wind farms (tend to have higher rate)

Risk Calculation – Accessory Risk Aspects

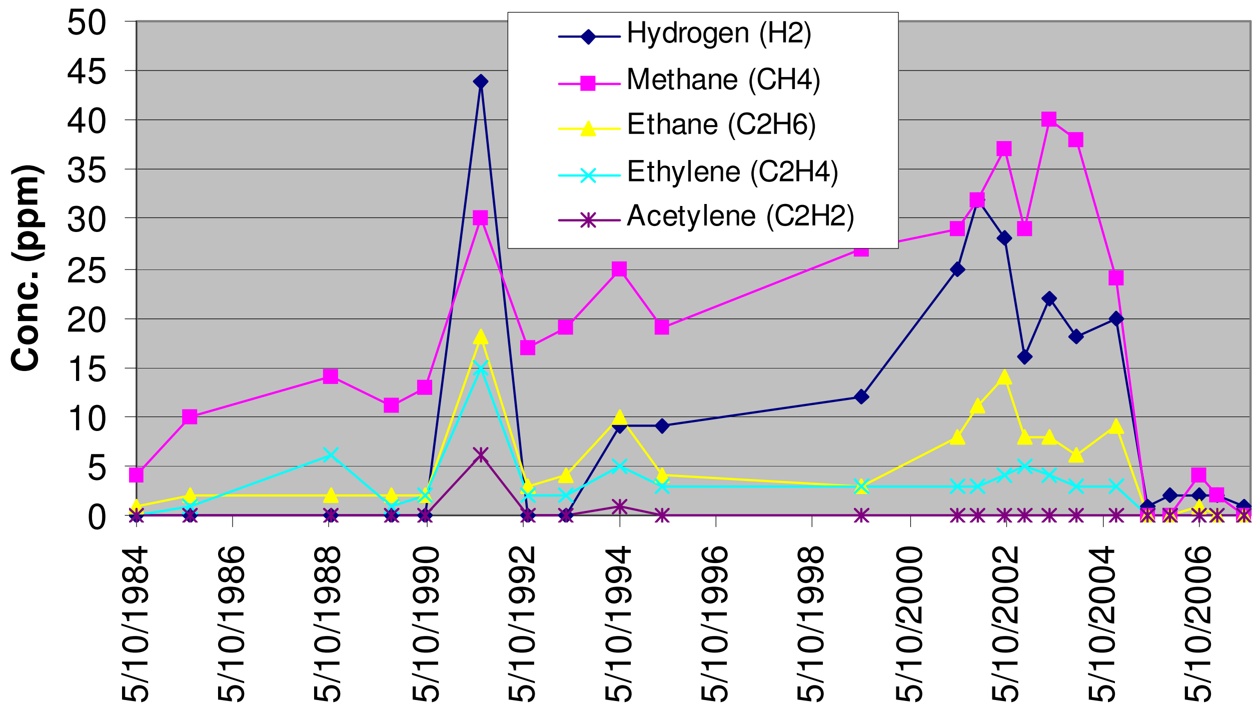
- Accessory failure refers to the loss of service of the transformer due to either the failure or operational breakdown of an accessory:
  - oil coolant pumps
  - tap changers
  - bushings
- The risk of accessory failure is based on:
  - Type of accessory, and
  - Diagnostic evidence from DGA, dissipation factor (tan δ) results, or other analyses.

Risk Calculation - Random Risk Aspects

- External causes not associated with the design or condition of the transformer itself
- Takes into account other types of failure risks not accounted for in the other factors
- Examples
  - Location (i.e. near seismic zone)
  - Static electrification risk (due to the design type, potential high oil velocity, and/or cooling operation philosophy)
  - Type of transformer

Condition Data Assessment

- **The history of the following condition data is reviewed:**
  - **Dissolved Gas in oil Analysis (DGA)**
  - **Oil Quality (including moisture in cellulose)**
  - **Furans**
  - **Power Factor**
- **Increasing trends and abnormalities are explored**



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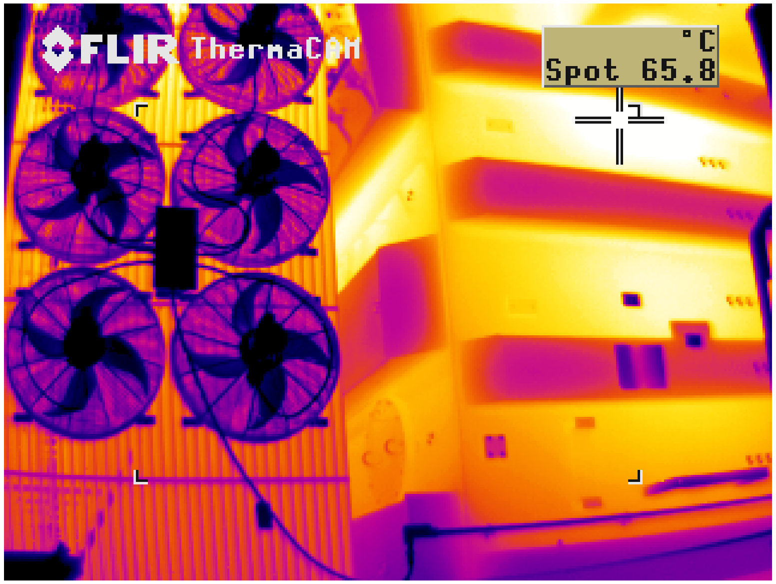
Routine Electrical Testing

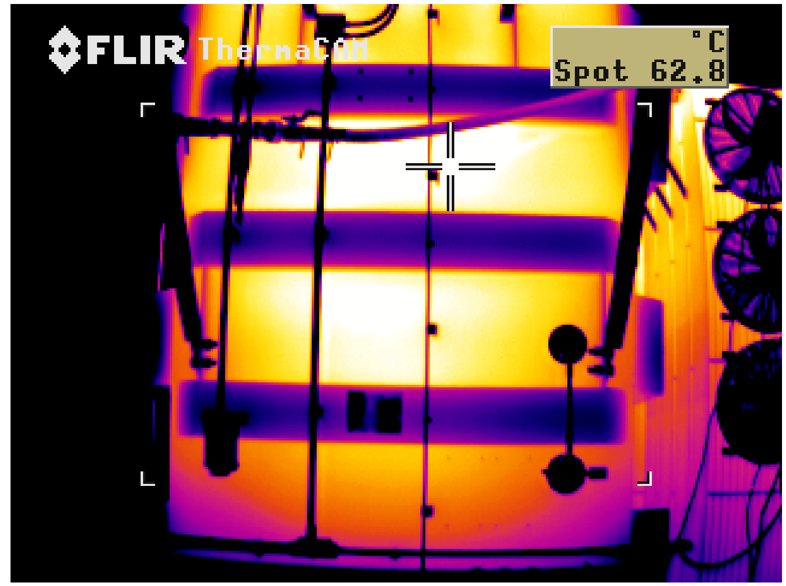
- Ratio
- Winding Resistance
- Winding Power factor
- Insulation resistance (meggar)
- Bushing power factor
- Excitation test

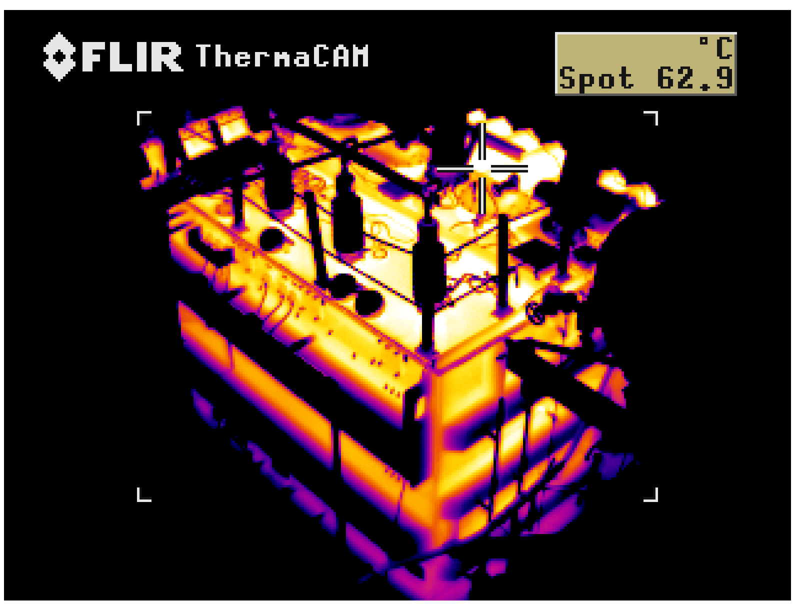
Thermal Stresses in Power Transformers
Thermography

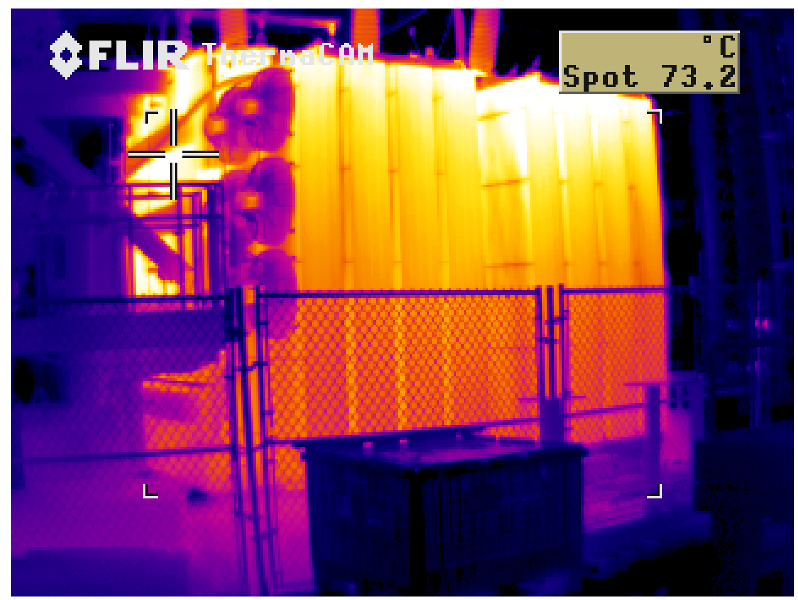
- Thermography is a method of inspecting electrical and mechanical equipment by obtaining heat distribution pictures
- Most components in a system show an increase in temperature when malfunctioning
- By observing the heat patterns in operational system components, infrared thermography can be used to detect:
  - loose connections
  - unbalanced load and overload conditions
  - component deterioration
  - Oil flow and oil level problems
- Criteria for Evaluating Infrared Measurements
  - Faults are often identified by comparing heat patterns in similar components operating under similar loads
  - The temperature rises of all objects above a reference point are recorded
  - Severity of hotspots are evaluated in regards to how high they are above the reference temperature

Thermal Stresses in Power Transformers
Thermal Scans are Valuable



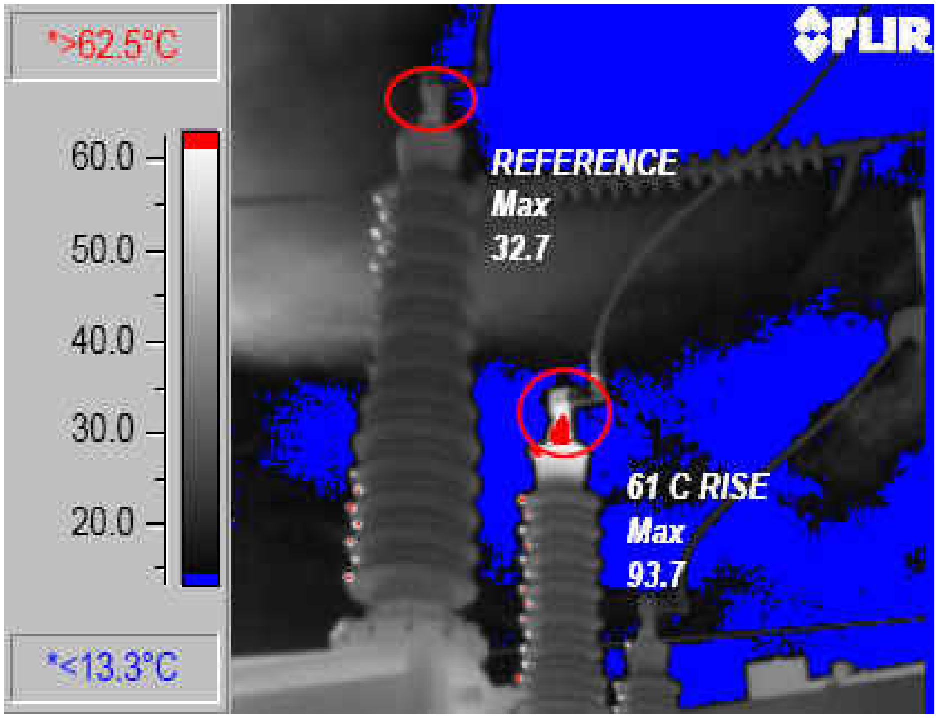






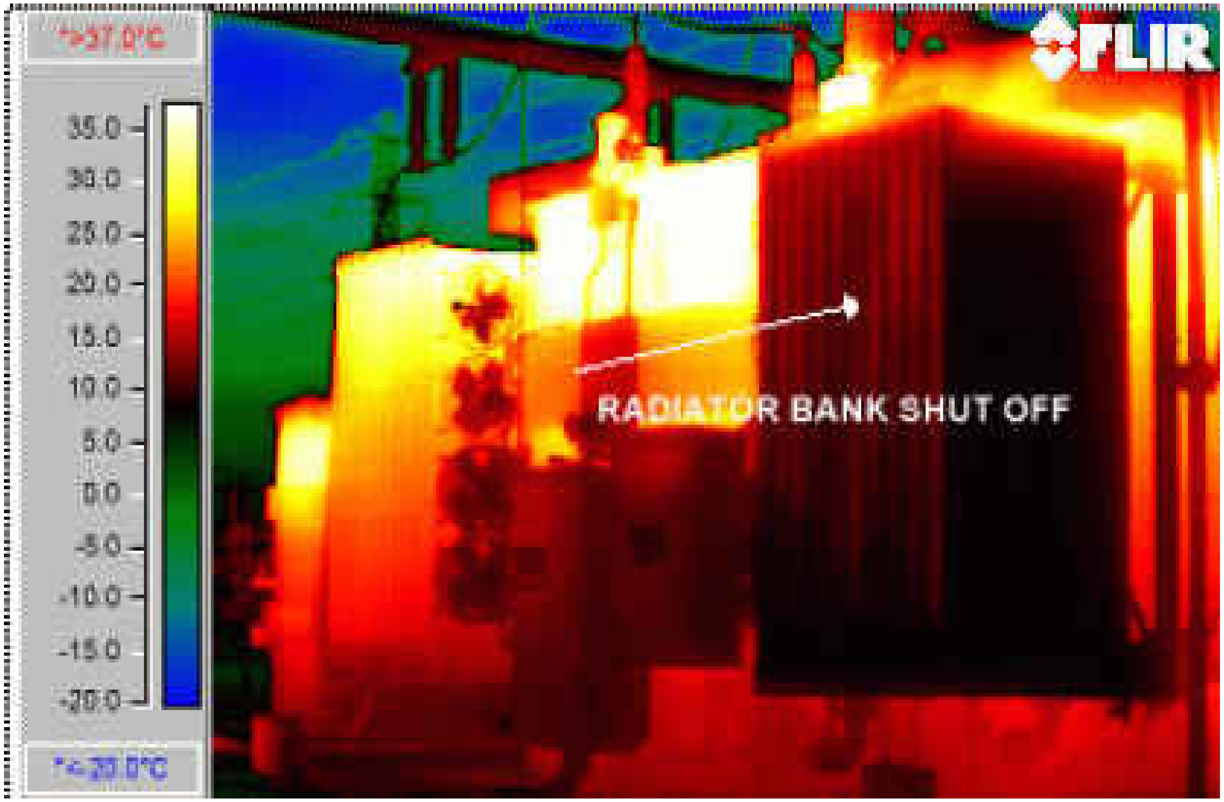
Thermal Scan Value
Example – Loose Bushing Terminal Connection

- **When there is a loose connection at the terminal from the bushing to the bus work, it will lead to overheating of the bushing top terminal when under load.**
- **The thermograph will show the bushing terminal as hot, while the body of the porcelain will show normal temperatures.**



Thermal Scan Value
Example – Blocked Oil Flow in Radiators

- In case of a malfunction that stops or restricts the flow of oil through a radiator, this will show up on an infrared scan.
- The image will reveal dim areas where the oil flow is restricted and brighter areas where normal oil flow is taking place



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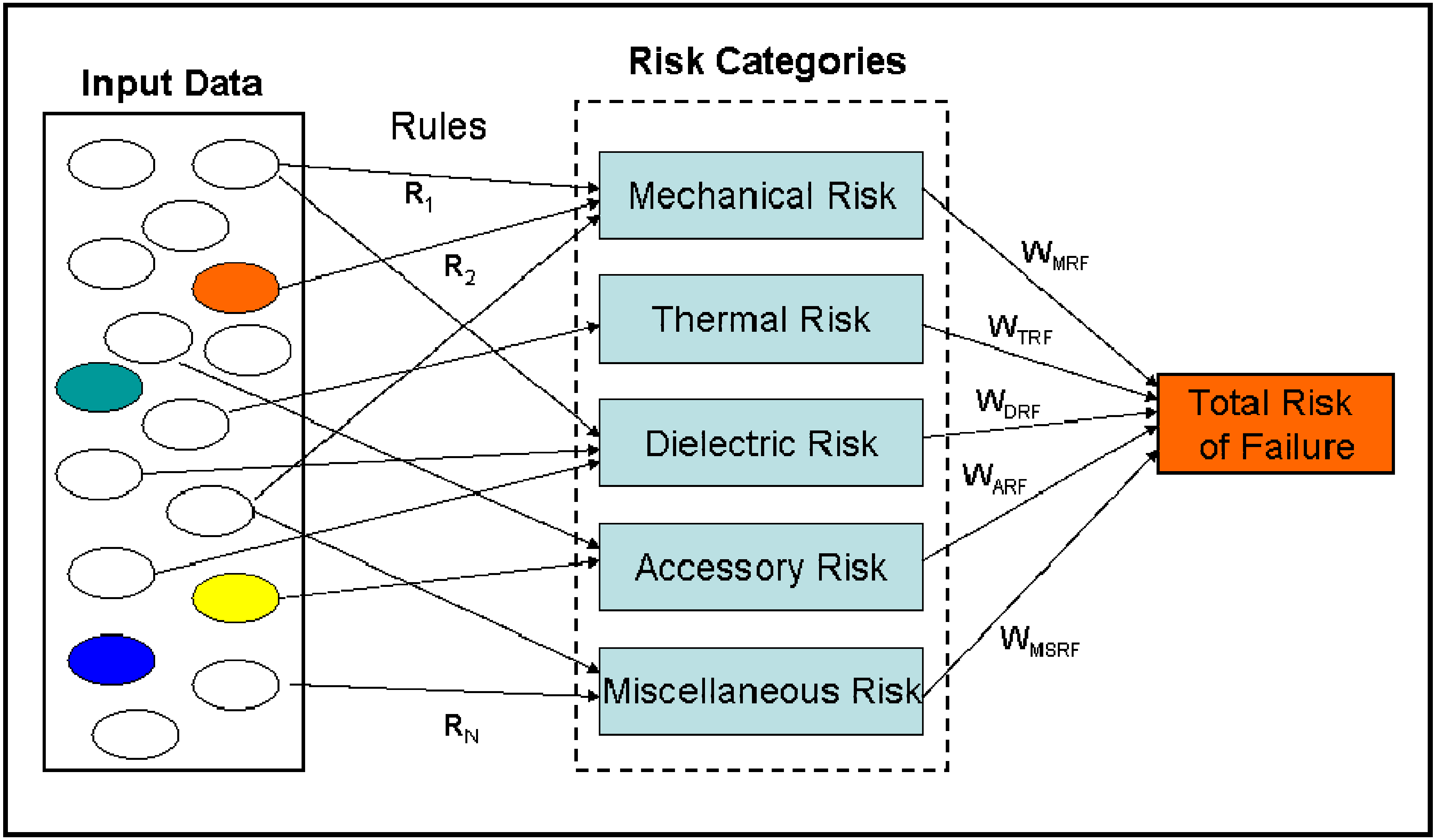
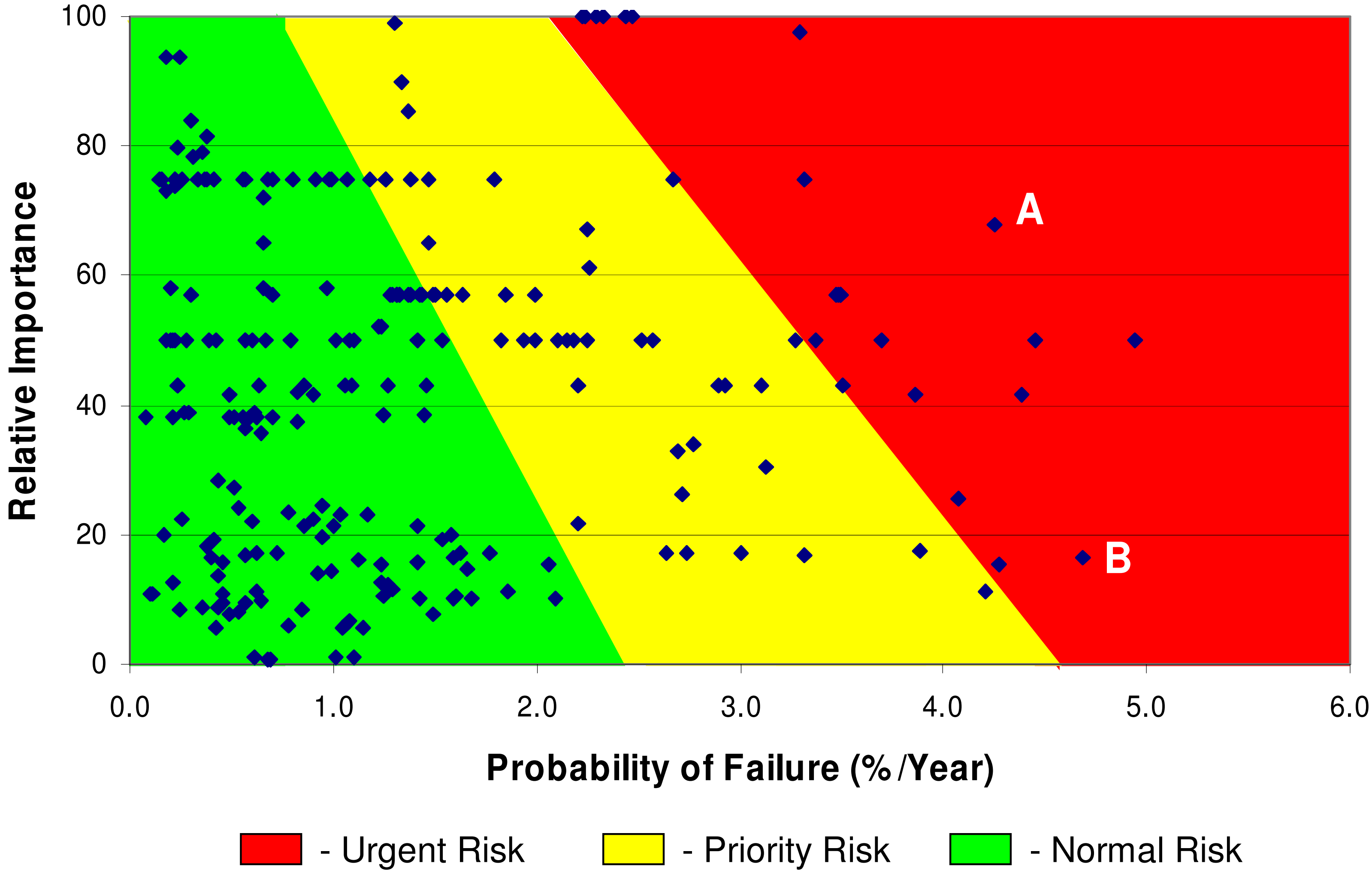
Overall Risk Assessment



Risk Profile
Importance vs. Probability of Failure



Typical On-Site Services to Improve Reliability

- Engineering Assessments (MTMP™)
- Diagnostic Testing
- Site internal repairs/upgrades
- Bushing Replacement
- Unit Uprates / Cooling Systems
- Oil processing
- Control system upgrade
- Internal Inspections
- Conservator tank modifications
- Tap Changer Maintenance/Replacement
- Biodegradable fluid retro fills
- Transformer Dryouts

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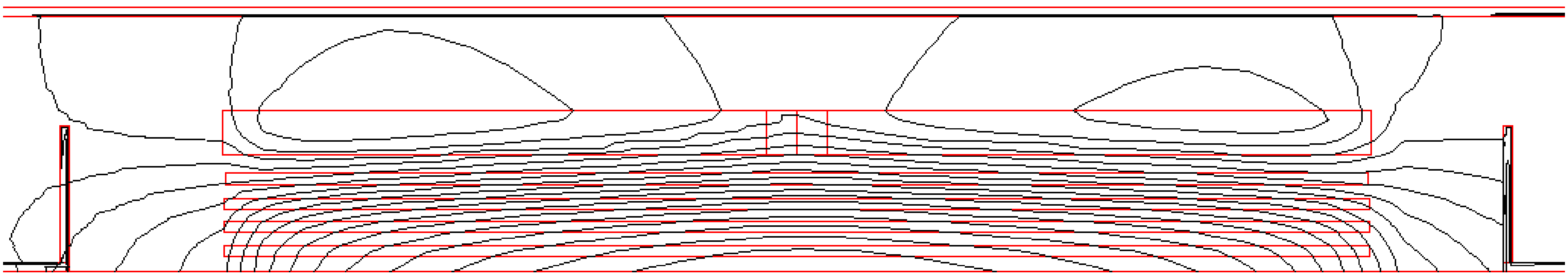
Engineering Transformer Design Study

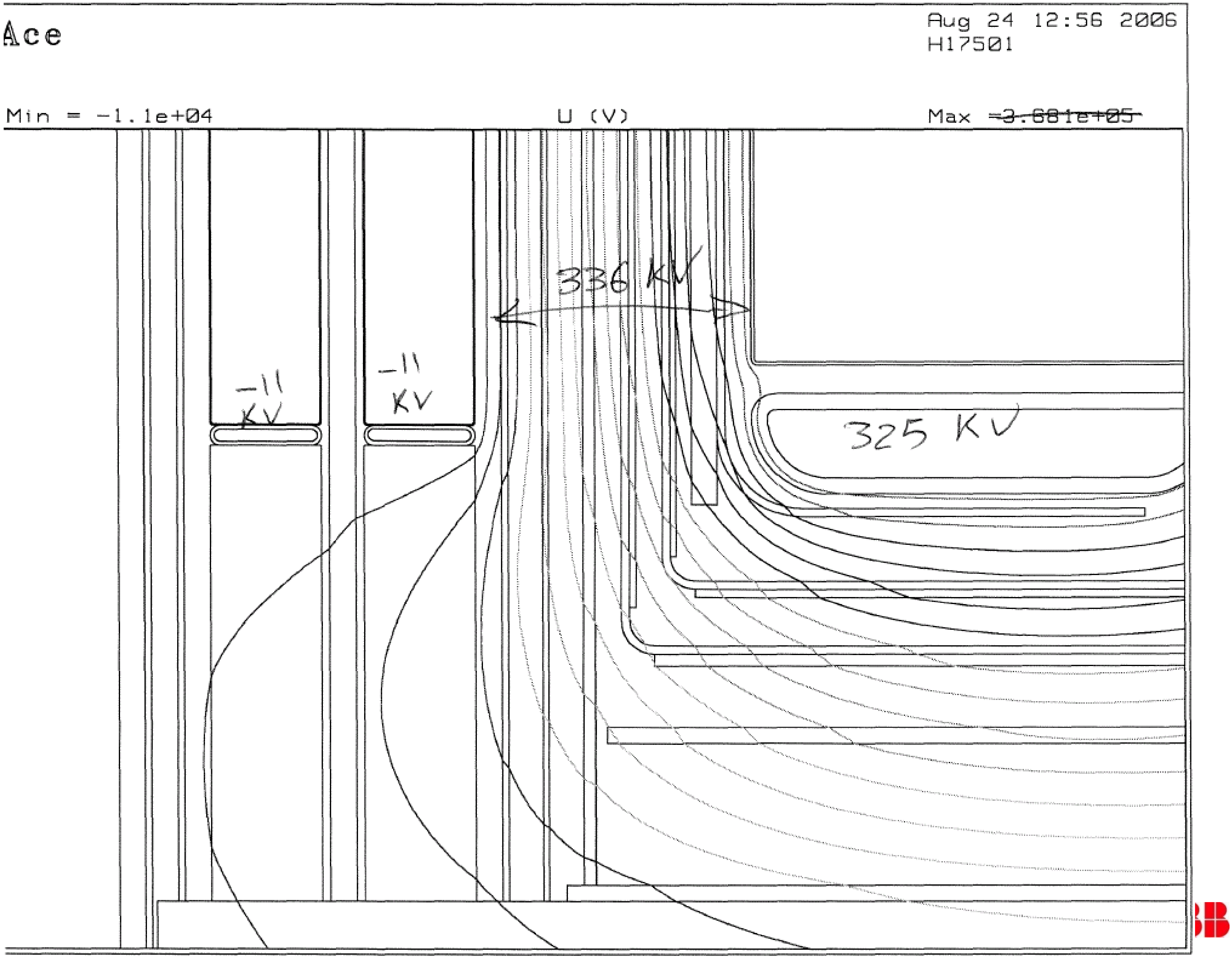
- Leakage flux calculation



- Temperature calculation of windings & metal parts
  - Determine aging rate and remaining life in cellulose
- Short Circuit Force Calculation
- Dielectric Plots
- Condition Assessment – Maintenance and field measurement aspects
- Life Assessment - Overall Ranking
- Recommendations

Temperature Calculation

			Calculated [°C]	Allowed [°C]
Average oil rise			42.2	65
Top oil rise			46.2	65
Regulator				
	Common Winding	Average Rise	62	65
		Hot Spot Rise	72	80
		Coil Lead Rise	68	80
		Cable Rise	58	80
	Series Winding	Average Rise	64	65
		Hot Spot Rise	68	80
		Coil Lead Rise	71	80
		Cable Rise	68	80
	Tap Winding	Average Rise	62	65
		Hot Spot Rise	74	80
		Coil Lead Rise	62	80
		Cable Rise	75	80
	Outer Core Steel Rise Due to Stray Flux		77	100
	Core Hot Spot Rise		90	100
	Tie Plate Rise		90	100
	Core Clamp Rise		75	100
	Tank Rise (at Regulator)		71	100



Ace
Aug 24 12:56 2006
H17501
Min = -1.1e+04
U (V)
Max =3.681e+05
336 KV
-11 KV
-11 KV
325 KV

Advanced Diagnostic Testing

- PD / Acoustics
- On site induce/PD testing
- SFRA Measurements
- Dielectric Spectroscopy

Frequency Response Analysis (FRA)

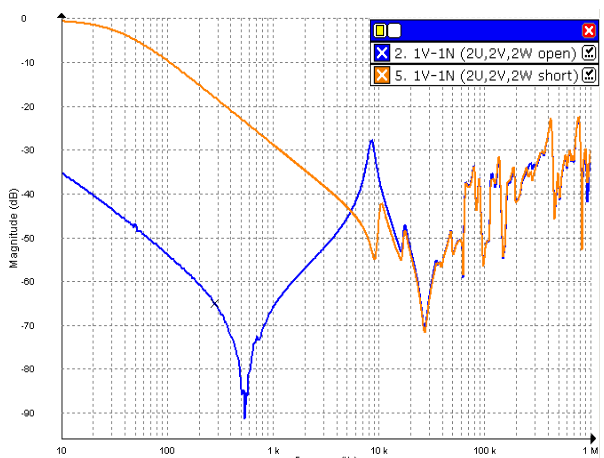
Frequency Response Analysis (FRA) is used to verify the geometry of the active part in a transformer (deformation and/or displacement of windings and core).

Example of problems diagnosed:

- **Axial Winding Collapse - excessive axial forces during a fault**
- **Hoop Buckling - excessive compressive forces during a fault**
- **Shorted Turns - produced by turn-to-turn faults**

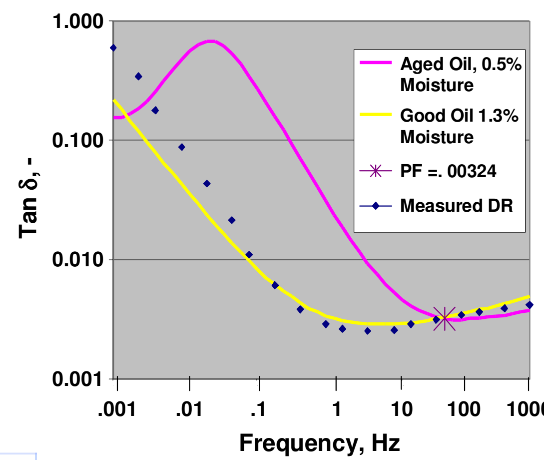
Interpretation tools:

- **Comparison with a reference data from the same unit or results from similar units**
- **Utilization of own library and experts knowledge**



Dielectric Frequency Response (DFR)

The Dielectric Frequency Response test (DFR) provides more information about the dielectric behavior of the insulation system (properties of cellulose and oil insulation separately distinguished). The test consists of a series of power factor or tan δ measurements at multiple frequencies.

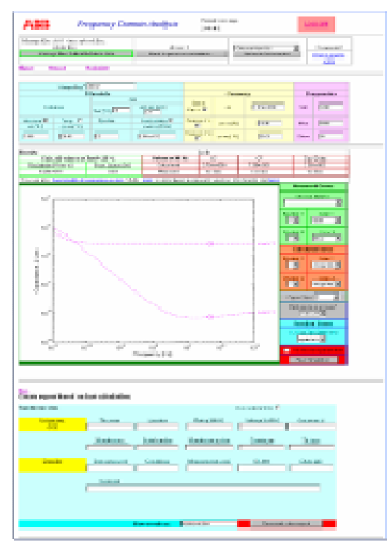


Example of problems diagnosed:

- **Moisture in the cellulose insulation**
- **High oil conductivity due to aging or overheating**
- **Contamination of windings**
- **Core grounding problems**

Interpretation tools:

- **ABB's DFR analysis tool (software)**
- **Comparison with a reference data from the same unit**
- **Utilization of own library and experts knowledge**



Oil Reprocessing

- Acids can be removed from oil to renew the oil
- Use oil rig with fullers earth type system (modern systems are regenerative)
- On line oil processing does a better job removing the acids
- Replacement of oil may need to be done if oil is too degraded

Transformer with FPE Tap changer

Old FPE Tapchanger Removed

New Tank Assembly Being Installed

Transformer with RMV II Tap changer – After retrofit

Load Tap Changer Condition Improvements
Sampling of Tap Changer Retrofit Projects

- Westinghouse URT → UVT
- Federal Pacific TC-25 → UVT
- W URT-HC → Reinhausen RMV-I
- GE LRT → Westinghouse UVT
- Ferranti Packard RT → UVT
- Westinghouse URT → RMV-II
- Moloney MC → Reinhausen RMV-I
- FP TC-25 → Reinhausen RMT-I
- FP LR-525 → Reinhausen RMT-I
- GE LRT-500 → Reinhausen M (in-tank)
- Westinghouse URH → Reinhausen M
- Westinghouse UNR → RMV-II
- GE LR-83 → Reinhausen RMV-II
- Installation of Westinghouse UVT to non-LTC transformer

Transformer Field Dryouts
Purpose for Drying

- Cause of moisture in transformers
  - Is a natural byproduct of aging (function of temperature, oxygen & moisture)
  - Leak (bad gasket) or defect
  - Free breathing of the transformer
  - (On site internal repairs requiring exposure of the unit)
- Deteriorates the electrical & mechanical strength of the windings
- Increases aging rate of the cellulose
- Limits the overload capability
  - Possible to get free water (if a wet unit is rapidly cooled down – winter shutdown)
  - Risk of bubble formation in the insulation at much lower hot spot temperatures (i.e. 140℃) compared to dry insulation

Low Frequency Heating (LFH)
Principles

- Apply a low frequency (1 - 50 mHz) current to the HV windings – approximately 20 – 50% of nominal current
- Benefits of the low frequency
  - Much lower impedance voltage so there is no risk of a flashover
  - Negligible eddy ($\sim f^2$) or stray losses ($\sim f^{1.5}$) – thus uniform heating of the windings
  - Reduced power requirement
- Temperature of the windings is carefully controlled
- Apply oil spray during LFH heating to heat non winding insulation
- LFH typical process:
  - Initial heating/circulation of core/coils using hot oil (assisted by LFH)
  - Vacuum
  - Begin cycles of LFH heating with hot oil spray followed by vacuum
  - Temperature progresses up to 110C (winding temp)
  - Final vacuum
- Shorter overall process time compared to hot oil treatment

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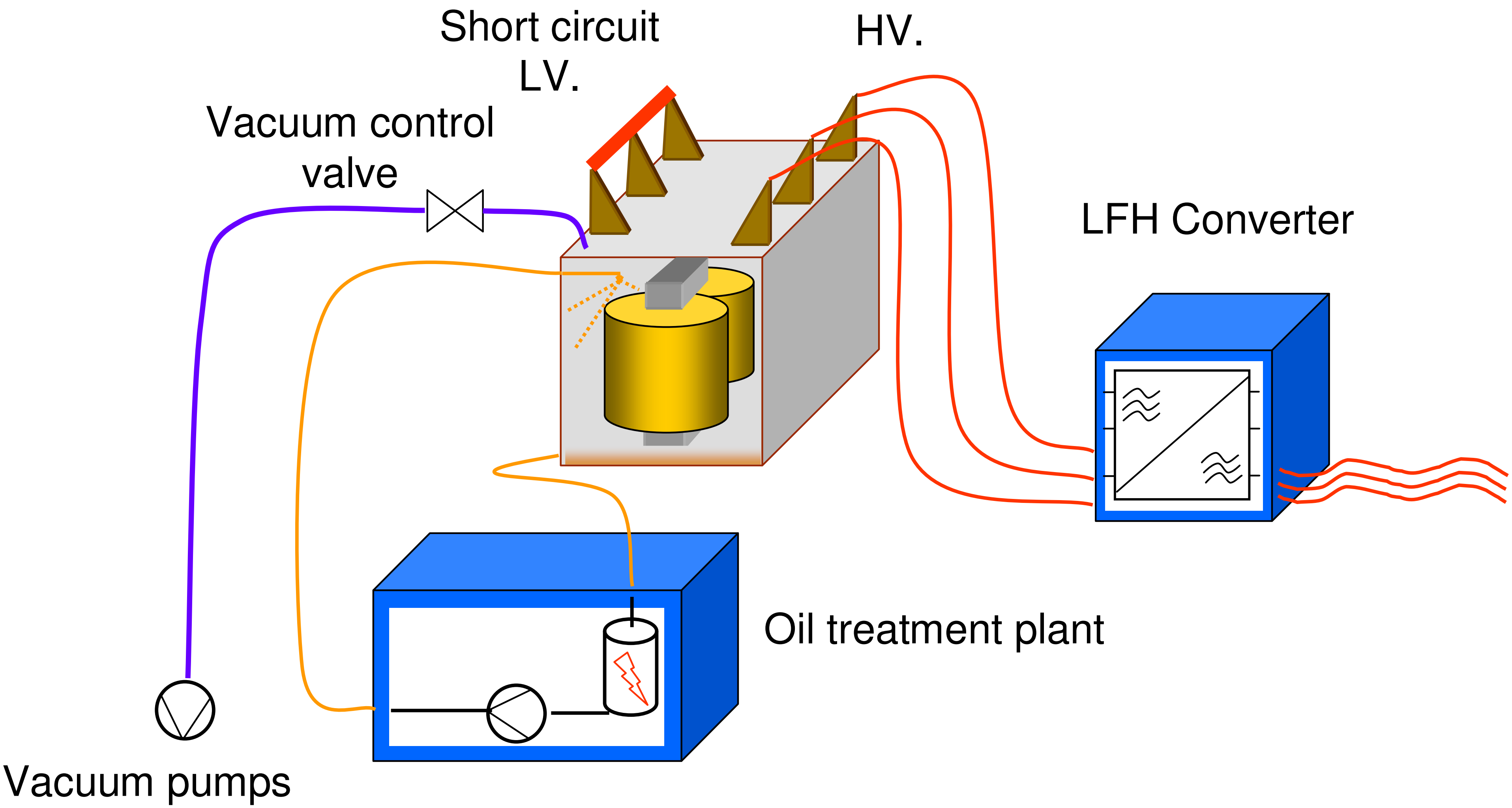
LFH And Hot Oil Spray



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Field Dryout Example

Ester Fluid Retro-fill
Biodegradable Dielectric Insulating Fluid

- **BIOTEMP® is a superior dielectric insulating fluid combining…**
  - **99% biodegradability with non hazardous and non toxic waste**
  - **High fire point, i.e., 360℃ vs. 180℃ for mineral oil**
  - **Much greater ability to hold moisture, i.e., 10 times more than mineral oil**
- Highest oxidation stability for a vegetable-based insulating fluid, outperforming the competition in all standard oxidation stability tests currently available

- With **BIOTEMP®**, ABB aims at offering **a complete and sustainable solution** for both distribution and power transformer applications **associating environmental friendliness** (high biodegradability), **safety** (superior fire resistance), **reliability and efficiency** (high overload capacity)

Reminders
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- Please be sure to complete the workshop evaluation
- Professional Development Hours (PDHs) and
  Continuing Education Credits (CEUs):
  - You will receive a link via e-mail to print certificates for all the workshops you have attended during Automation & Power World 2011.
  - BE SURE YOU HAVE YOUR BADGE SCANNED for each workshop you attend. If you do not have your badge scanned you will not be able to obtain PDHs or CEUs.

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