DGA Tools: Duval Triangles and Pentagons

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This presentation use some material from Michel Duval and Dynamic Rating training programs
Dissolved Gas Analysis History

- Oil Filled Transformer: 1880 - 1890
- Buchholz relay: introduced in 1921
- Buchholz gas analysis: Mid 1950
- Early DGA: 1968 (CEGB)
- On-line DGA:
  - Single gas: Early 1980
  - Multi gas: Mid 1990
Dissolved Gas Analysis History

– Early on it was recognized that fault generate combustible gas.
– Combustible gas detector were used to determine if a Buchholz relay trip was caused by an internal fault or not.
– Initial analysis of individual gas indicated the presence of several light Hydrocarbon generated by fault.
Dissolved Gas Analysis History

– DGA standardised on the following gas:
  • H₂
  • CH₄
  • C₂H₆
  • C₂H₄
  • C₂H₂
  • CO
  • CO₂
  • N₂
  • O₂

– Other gas (C₃) are sometime also used
How to correlate gas to fault?

- The objective of DGA is to detect the presence of fault, and identify their nature.

- It was recognized early that some gas, or some gas ratio, could be associated with some specific type of fault.

- To be useful, DGA need interpretation methods.
Relative Gas Generation  CIGRE and IEEE

Source: IEEE C57.104 D3.2, April 2017
How to correlate gas to fault?

• Interpretation methods could be classified in 4 general classes
  – Specific gas
  – Statistic norms
  – True tables with ratio
  – Graphical

• All methods are based on the fact that different fault generate gas in different amounts
DGA Interpretation History

• Several methods introduced in the 1970 & 1980

  • Statistic threshold
  • Rogers
  • Halstead
  • LCIE
  • Laborelec
  • GE
  • Church

  • Dörnenberg
  • Potthoff
  • Shanks
  • Trilinear Plot
  • IEC
  • Duval
  • ....
DGA Interpretation

• Specific Gas
  – IEEE C57.104 Key Gas
  – LCIE Scheme
  – Potthoff Scheme
Key Gas Method

Arcing in Oil

Corona in Oil

A number of schemes have been put forward; the simplest is to relate gases with fault types, e.g.

- Hydrogen - Partial discharges
- Hydrogen, Methane, Ethane, Ethylene - Heating of oil
- Acetylene - Arcing
- Carbon monoxide - Heating of paper or cork

The main difficulty with schemes of this nature is that these gases will be found to a greater or lesser degree in practically all samples.
DGA Interpretation

• Statistical methods
  – IEEE C57.104
  – IEC 60599
Statistical Methods

• Use population curve to determine some “acceptable” levels
• Look at absolute gas concentrations
• Could be adjusted for population characteristics
• Typical 90% and 95% percentile value used as “Normal – Abnormal” limits
• Introduced by CEGB in 1972
• Adopted by IEEE and IEC
Table A.2 – Ranges of 90 % typical concentration values observed in power transformers (all types)

<table>
<thead>
<tr>
<th>Transformer sub-type</th>
<th>$H_2$</th>
<th>$CO$</th>
<th>$CO_2$</th>
<th>$CH_4$</th>
<th>$C_2H_6$</th>
<th>$C_2H_4$</th>
<th>$C_2H_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No OLTC</td>
<td>60-150</td>
<td>540-900</td>
<td>5 100-13 000</td>
<td>40-110</td>
<td>50-90</td>
<td>60-280</td>
<td>3-50</td>
</tr>
<tr>
<td>Communicating OLTC</td>
<td>75-150</td>
<td>400-850</td>
<td>5 300-12 000</td>
<td>35-130</td>
<td>50-70</td>
<td>110-250</td>
<td>80-270</td>
</tr>
</tbody>
</table>

NOTE 1 – The values listed in this table were obtained from individual networks. Values on other networks may differ.

NOTE 2 – "Communicating OLTC" means that some oil and/or gas communication is possible between the OLTC compartment and the main tank or between the respective conservators. These gases may contaminate the oil in the main tank and affect the normal values in these types of equipment. "No OLTC" refers to transformers not equipped with an OLTC, or equipped with an OLTC not communicating with or leaking to the main tank.

NOTE 3 – In some countries, typical values as low as 0,5 μl/l for $C_2H_2$ and 10 μl/l for $C_2H_4$ have been reported.
DGA Interpretation

• Ratio Methods
  – Rogers
  – Dörnenberg
  – IEC
Ratio Methods

- Look at ratio between gases rather than absolute value
- Reduce “noise” in DGA results
- Up to four ratios
- Use look-up table for diagnostic
  - Rogers
  - Dörnenberg
  - IEC
## Example of Look-Up Table: Early Rogers

<table>
<thead>
<tr>
<th>CH₄/H₂</th>
<th>CH₄</th>
<th>C₂H₆</th>
<th>C₂H₄</th>
<th>C₂H₂</th>
<th>Diagnosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>If CH₄/H₂ 0.1 - Partial discharge, otherwise o.k.</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>Flash-over.</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Conductor overheating.</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>Arc with power - persistent sparking.</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Overheating 250-300°C.</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>Tap changer, selector.</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>--</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>--</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Overheating - below 150°C.</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>Circulating current - bad contact.</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>--</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>--</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Overheating 200-300°C.</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>--</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>--</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>--</td>
</tr>
</tbody>
</table>
Graphical Method

• Look at single or multiple ratios, or gases values
• Plot value in a graphical system
• Determine fault by pattern or location on the graph
  - Church
  - Doernenberg
  - Duval
  - Key Gas
  - GE
  - IEC
Example of Early Graphical Method: Doernenberg
Example of Early Graphical Method: Shanks
Example of Graphical Method: IEC 60599
Example of Graphical Method: IEC 60599
Diagnostic Method: Duval Triangles

Duval Triangles History
The Origin of the Triangle figure

- Lost in the night of time
- Oldest known description: (Euclid, 323 – 283 BC): any three points not in a line define a triangle (second oldest geometry axiom)
- A complete field of mathematics (Trigonometry)
- Widely used in land survey and to remove the faint of heart from Engineering School
The Origin of Modern Triangle Graphs (Trilinear)

- Trilinear graph have been in use for a long time
- J. Williard Gibbs is credited with the first documented use of trilinear coordinates graph (for thermodynamics) in 1873.
- In 1881 Robert Thurston published a paper using trilinear coordinates to express the properties of Copper-Zinc-Tin alloys using contours map
How to Read a Trilinear Graph

• Widely used in several fields
• Not as intuitive as XY graphs
• Surface is not infinite, contrary to XY graphs
• Use positive values
• The 3 variable are interlocked
  \[ \%A + \%B + \%C = 100\% \]
• As a result, a point could be defined by… any two variables
Why use a Trilinear graphs?

- Any quantifiable property of a 3 components system could be plotted on a trilinear graphs instead of using two XY graphs or long look-up tables

- Here a few examples:
Property of Cu – Zn – Sn Mixture
Solubility Chart
Flammability Chart
Color Chart
How to Read a Trilinear Graph

• Each corner is 100% of one variable
• The adjacent variable at that corner is 0%
• BTW, the other one too!!
• The progression around the triangle is

   0 100 0 100 0 100%

• Progression could be clockwise or counter clockwise
How to Read a Trilinear Graph

- 100% A
- 0% B & 0% C

- 0% A & 0% B
- 100% C

- 100% B
- 0% C & 0% A
How to Read a Trilinear Graph

- At point A: 100% A
- At point B: 0% A
- At point C: Unknown proportion of A
How to Read a Trilinear Graph

0% B

100% B
How to Read a Trilinear Graph
Early Use of Trilinear Graph in DGA Interpretation

- Early attempt for DGA interpretation
- Based on molar ratio of Carbon, Hydrogen and Oxygen in the Combustible gas mixture
- Complex computation to obtain ratios
- Was not adopted widely
Early DGA Interpretation Attempt with Triangle

Let the concentrations be:

\[ \begin{align*}
&H_2 \ a. \quad CO \ b. \quad CH_4 \ c. \quad C_2H_6 \ d. \quad C_2H_4 \ e. \quad C_2H_2 \ f. \\
\end{align*} \]

The trilinear method gives:

\[ \\
\text{H}_2 \text{ moles} & \quad \left[ a + 2c + 3d + 2e + f \right] / \left( a + \frac{3b}{2} + 3c + 5d + 4c + 3f \right) \\
\text{O}_2 \text{ moles} & \quad b / (2a + 3b + 6c + 10d + 8e + 6f) \\
\text{Carbon moles} & \quad \left[ b + c + 2(d + e + f) \right] / \left( a + \frac{3b}{2} + 3c + 5d + 4e + 3f \right)
\]
First Trilinear Graph for DGA
Duval Triangle (1)

• Second attempt to use trilinear graph with DGA
• Introduced in 1974 by Michel Duval
• Use 3 gas: CH4, C2H4 and C2H2
• Compute 3 ratios (% of gas in mixture)
• Each type of fault is assigned a zone
• Related to Gas Formation Temperature
Relative Gas Generation  CIGRE and IEEE
Relative Gas Generation  Duval Triangle 1

**Relative percentage of gases**

- **Fault Types**
  - R
  - PD
  - S
  - T1
  - O
  - C
  - T2
  - T3
  - D2
  - D1

- **Relative percentage of gases**
  - 100%
  - 50%

- **Temperature Ranges**
  - Cold Plasma & Catalytic
    - 100°C
  - Thermal
    - 300°C
    - 500°C
    - 1000°C
  - Discharges
    - 3000°C

- **Gases**
  - CH₄
  - C₂H₄
  - C₂H₂

**Not related to temperature**

- **Notes**
  - **TJ**
  - H₂b

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Relative Gas Generation  Duval Triangle 1

**Cold Plasma & Catalytic**

**Not related to temperature**
Duval Triangle 1: Temperature of gas formation

- Temperature ranges:
  - < 500°C
  - > 500°C
  - > 1000°C

- Gas composition:
  - C2H2
  - CH4
  - C2H4
Duval Triangle 1

< 500°C  CH4  > 500°C

< 1000°C  C2H2  > 1000°C

PD  D1  D2  T1  T2  DT  T3  C2H4
How to Place a Point in a Duval Triangle

\[ \text{CH}_4 = 50\% \]

100\% CH₄

50\% CH₄

0\% CH₄

C₂H₂

C₂H₄
How to Place a Point in a Duval Triangle

CH$_4$ = 50%

C$_2$H$_4$ = 30%

0% C$_2$H$_4$

30% C$_2$H$_4$

100% C$_2$H$_4$
How to Place a Point in a Duval Triangle

CH₄ = 50%
C₂H₄ = 30%

C₂H₂ = 100% - %CH₄ - %C₂H₄ = 20%
Duval Triangle 1 Zones

- **PD** Partial Discharges
- **T1** Low Temperature $<$ 300 °C
- **T2** Medium Temperature 300 - 700 °C
- **T3** High Temperature $>$ 700 °C
- **DT** Discharges with Thermal
- **D1** Discharges of High Energy
- **D2** Discharges of Low Energy
Duval Triangle 1 and IEC 60599

- Same fault designations as IEC 60599
- IEC use 5 Hydrocarbon
- IEC use 3 ratios of 2 gas
- IEC use Look-up table
- IEC use also a two graphs representation
Duval Compared to IEC 60599

<table>
<thead>
<tr>
<th>Case</th>
<th>Characteristic fault</th>
<th>( \text{C}_2\text{H}_2 / \text{C}_2\text{H}_4 )</th>
<th>( \text{CH}_4 / \text{H}_2 )</th>
<th>( \text{C}_2\text{H}_6 / \text{C}_2\text{H}_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD</td>
<td>Partial discharges (see notes 3 and 4)</td>
<td>NS(^1)</td>
<td>&lt;0.1</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>D1</td>
<td>Discharges of low energy</td>
<td>&gt;1</td>
<td>0.1 - 0.5</td>
<td>&gt;1</td>
</tr>
<tr>
<td>D2</td>
<td>Discharges of high energy</td>
<td>0.8 - 2.5</td>
<td>0.1 - 1</td>
<td>&gt;2</td>
</tr>
<tr>
<td>T1</td>
<td>Thermal fault ( t &lt; 300 \degree \text{C} )</td>
<td>NS(^1)</td>
<td>&gt;1 but NS(^1)</td>
<td>&lt;1</td>
</tr>
<tr>
<td>T2</td>
<td>Thermal fault ( 300 \degree \text{C} &lt; t &lt; 700 \degree \text{C} )</td>
<td>&lt;0.1</td>
<td>&gt;1</td>
<td>1 - 4</td>
</tr>
<tr>
<td>T3</td>
<td>Thermal fault ( t &gt; 700 \degree \text{C} )</td>
<td>&lt;0.2(^2)</td>
<td>&gt;1</td>
<td>&gt;4</td>
</tr>
</tbody>
</table>

\(^1\) NS: Not specified
\(^2\) For values of \( \text{C}_2\text{H}_2 / \text{C}_2\text{H}_4 \) lower than 0.01, take 0.01

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**Legend**
- PD: Partial discharges
- D1: Discharges of low energy
- D2: Discharges of high energy
- T1: Thermal fault \( t < 300 \degree \text{C} \)
- T2: Thermal fault \( 300 \degree \text{C} < t < 700 \degree \text{C} \)
- T3: Thermal fault \( t > 700 \degree \text{C} \)

**Note:**
- For values of \( \text{C}_2\text{H}_2 / \text{C}_2\text{H}_4 \) lower than 0.01, take 0.01
Duval Triangle 1

• Widely used today
• Part of IEC 60599 (appendix B)
• Will be part of future revised C57.104
• A study by U of New South Wales (Australia) indicate a success rate of 88%
• Limited to mineral oil transformer
University of New South Wales Study on 92 Cases

<table>
<thead>
<tr>
<th>Method</th>
<th>Faults Code</th>
<th>Number of predictions (P)</th>
<th>Number of correct predictions (R)</th>
<th>% Successful prediction (S)</th>
<th>Consistency (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roger</td>
<td>F1</td>
<td>10</td>
<td>5</td>
<td>50%</td>
<td>45%</td>
</tr>
<tr>
<td></td>
<td>F2</td>
<td>13</td>
<td>13</td>
<td>39%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F3</td>
<td>13</td>
<td>12</td>
<td>55%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F4</td>
<td>9</td>
<td>8</td>
<td>57%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F5</td>
<td>4</td>
<td>3</td>
<td>23%</td>
<td></td>
</tr>
<tr>
<td>IEC</td>
<td>F1</td>
<td>6</td>
<td>5</td>
<td>50%</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td>F2</td>
<td>26</td>
<td>26</td>
<td>79%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F3</td>
<td>19</td>
<td>18</td>
<td>82%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F4</td>
<td>9</td>
<td>9</td>
<td>64%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F5</td>
<td>6</td>
<td>3</td>
<td>23%</td>
<td></td>
</tr>
<tr>
<td>Nomograph</td>
<td>F1</td>
<td>15</td>
<td>2</td>
<td>20%</td>
<td>74%</td>
</tr>
<tr>
<td></td>
<td>F2</td>
<td>24</td>
<td>23</td>
<td>70%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F3</td>
<td>19</td>
<td>18</td>
<td>82%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F4</td>
<td>20</td>
<td>14</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F5</td>
<td>14</td>
<td>13</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Doemenburg</td>
<td>F1</td>
<td>3</td>
<td>2</td>
<td>20%</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>F2</td>
<td>15</td>
<td>15</td>
<td>45%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F3</td>
<td>9</td>
<td>8</td>
<td>36%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F4</td>
<td>7</td>
<td>6</td>
<td>43%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F5</td>
<td>8</td>
<td>7</td>
<td>54%</td>
<td></td>
</tr>
<tr>
<td>Duval</td>
<td>F1</td>
<td>10</td>
<td>10</td>
<td>100%</td>
<td>88%</td>
</tr>
<tr>
<td></td>
<td>F2</td>
<td>32</td>
<td>30</td>
<td>91%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F3</td>
<td>26</td>
<td>22</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F4</td>
<td>10</td>
<td>7</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F5</td>
<td>14</td>
<td>13</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Key Gas</td>
<td>F1</td>
<td>11</td>
<td>10</td>
<td>100%</td>
<td>78%</td>
</tr>
<tr>
<td></td>
<td>F2</td>
<td>46</td>
<td>33</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F3</td>
<td>11</td>
<td>10</td>
<td>45%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F4</td>
<td>9</td>
<td>7</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F5</td>
<td>13</td>
<td>2</td>
<td>92%</td>
<td></td>
</tr>
</tbody>
</table>

F1 = Low Temperature
F2 = High Temperature
F3 = Arcing
F4 = Partial Discharge
F5 = Normal
The results are summarized in table 11. It can be seen that the Duval Triangle method is the most consistent method followed by the Key Gas, Nomograph, IEC Ratio, Roger Ratio and lastly the Doernenburg method. Note the low consistency value (<50%) with some of the methods. We also find that those methods that take into account the limit value of fault gases before doing diagnosis have better success in predicting the normal condition and methods that have no limit value of faults gases always fail to predict the normal condition. This affects the consistency result.
Duval Triangles 4 and 5

- Introduced in 2008
- For mineral oil Transformer
  - With PD, T1 or T2 in Duval 1
  - **DO NOT** use for T3, D1, D2
  - Use with DT with precaution
- To refine/confirm low energy faults
- Different gas and zones than in Triangle 1
- Use H2, CH4, C2H4 and C2H6
Relative Gas Generation  Duval Triangle 1

** Relative percentage of gases**

- **H₂**, **C₂H₆**, **C₂H₄**, **CH₄**, **C₂H₂**

**Fault Types**
- R, PD, S, T1, O, C, T2, T3, D2, D1

**Temperature Ranges**
- Cold Plasma & Catalytic: 100°C
- Thermal: 300°C
- Discharges: 500°C, 1000°C, 3000°C

**Note:** Not related to temperature

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Duval Triangle 1
Duval Triangle 4 for Low Energy Faults

For PD, T1 and T2 of Triangle 1 only
Relative Gas Generation  Duval Triangle 5

Fault Types

H₂
C₂H₆
CH₄
C₂H₄
H₂
C₂H₂

Cold Plasma & Catalytic**

100°C  300°C  500°C  1000°C  3000°C

** Not related to temperature
Duval Triangle 5 for Low Energy Faults

Duval 5 Medium Temperature

For T2 and T3 of Triangle 1 only
### Duval Triangles 4 and 5 for Low Energy Faults

- **PD**: Partial Discharge
- **S**: Stray gassing
- **C**: Hot Spot with Paper Carbonization
- **O**: Overheating $< 250^\circ \text{C}$
- **ND**: Not Determined (use Duval 1)
- **T2**: Medium Temperature $300 - 700 \, ^\circ \text{C}$
- **T3**: High Temperature $> 700 \, ^\circ \text{C}$
Duval Triangle 4 and 5

- New type of fault give a better description of low energy phenomena
- Less cases classified as PD
- Distinguish between Stray gassing (S) and low temperature oil overheating (O)
- Identify possible paper carbonisation (C)
Duval Triangle 2

- Introduced in 2008
- Developed to offer DGA interpretation for OLTC
- Apply to non-vacuum OLTC that generate gas in normal operation
- Same gases as Triangle 1
- Generic application
Duval Triangle 2: OLTC

![Duval Triangle 2 Diagram](image-url)
Duval Triangle 2

- **N**: Normal Operation
- **T2**: Medium Temperature 300 - 700 °C with Coking
- **T3**: High Temperature > 700 °C, with Heavy Coking
- **D1**: Abnormal Arcing
- **X1**: Abnormal Arcing/Thermal
- **X3**: T2 or T3 or possible Abnormal Arcing/Coking
Duval Triangle 2a to 2e

- Proposed to IEEE C57.139 in 2012
- Use same triangle zones as Triangle 2
- Add extra Normal zones (N1 to N5)
- OLTC Model specific
- OLTC application specific (High Powers)
- Mostly apply to MR OLTC
Duval Triangle 2 Type α: MR OilTaps® M & D
Duval Triangle 2 Type b: MR VacuTaps® VR
Duval Triangle 2 Type c: MR VacuTaps® VV
Duval Triangle 2 Type d: OilTaps® R & V
Triangle 2 Type e: MR OilTap G®; ABB few UZD®, some UZB®
Duval Triangle 3

- Introduced in 2008
- For non mineral oil Transformer
  - FR3 ®
  - Silicone
  - Midel ®
  - Biotemp ®
- Same gases and zones as in Triangle 1
- Zone borders adjusted for D1/D2, T1/T2 and T2/T3
Duval 3 Silicone Oil

Duval 3 Silicone

CH4

C2H4

C2H2

D1

D2

D3

T1

T2

T3

PD

0

100

0

100

0

100

0

100

0
Duval Triangle 3 Midel®

Duval 3 Midel

- CH₄
- C₂H₂
- C₂H₄

PD

D1

D2

DT

T1

T2

T3
Duval Triangle 3 Biotemp®
Duval Triangles 6 and 7 for Low Energy Faults in FR3

- Introduced in 2008
- For FR3 Transformer
  - With PD, T1 or T2 (Triangle 3 FR3)
  - DO NOT use for T3, D1, D2 and DT
- To refine/confirm low energy faults
- Different gas and zones than Triangle 3
- Use H2, CH4, C2H4 and C2H6
Duval Triangle 6 Low Energy Faults in FR3
Duval Triangle 7 for Low Energy Faults in FR3

Duval 7 FR3 Low Temperature

- CH4
- O
- C
- ND
- S
- T3
- C2H4
- C2H6
Duval Pentagon 1 and 2

- Introduced in 2014
- For Mineral Oil Transformer
- Combine Triangle 1, 2 and 3
- Use H2, C2H6, CH4, C2H4 and C2H6
- Pentagon 1
  - “Classic” designation fault zones
- Pentagoe 2
  - “Modern” designation fault zones
Duval Pentagons: $H_2$, $C_2H_6$, $CH_4$, $C_2H_4$ and $C_2H_2$
Duval Pentagons: Combine Triangles 1, 4 and 5
Duval Pentagons: Energy levels
Duval Pentagons: place % of gas on each axis

Gas

- $H_2 = 75$ ppm
- $C_2H_6 = 57$ ppm
- $CH_4 = 35$ ppm
- $C_2H_4 = 25$ ppm
- $C_2H_2 = 0$ ppm
- Total = 192 ppm
Duval Pentagons: place $\% \text{H}_2$

Gas

- $\text{H}_2 = 75 \text{ ppm}$
- $\text{C}_2\text{H}_6 = 57 \text{ ppm}$
- $\text{CH}_4 = 35 \text{ ppm}$
- $\text{C}_2\text{H}_4 = 25 \text{ ppm}$
- $\text{C}_2\text{H}_2 = 0 \text{ ppm}$

Total = 192 ppm

% of Total

- $39 \%$
Duval Pentagons: place % $C_2H_6$

Gas

- $H_2 = 75$ ppm
- $C_2H_6 = 57$ ppm
- $CH_4 = 35$ ppm
- $C_2H_4 = 25$ ppm
- $C_2H_2 = 0$ ppm

Total = 192 ppm

% of Total

- $H_2 = 39\%$
- $C_2H_6 = 30\%$
Duval Pentagons: place % CH₄

Gas

H₂ = 75 ppm
C₂H₆ = 57 ppm
CH₄ = 35 ppm
C₂H₄ = 25 ppm
C₂H₂ = 0 ppm
Total = 192 ppm

% of Total

H₂ = 39 %
C₂H₆ = 30 %
CH₄ = **18 %**
Duval Pentagons: place % $\text{C}_2\text{H}_4$

- $\text{H}_2 = 75 \text{ ppm}$
- $\text{C}_2\text{H}_6 = 57 \text{ ppm}$
- $\text{CH}_4 = 35 \text{ ppm}$
- $\text{C}_2\text{H}_4 = 25 \text{ ppm}$
- $\text{C}_2\text{H}_2 = 0 \text{ ppm}$

Total = 192 \text{ ppm}

% of Total
- $\text{H}_2 = 39 \%$
- $\text{C}_2\text{H}_6 = 30 \%$
- $\text{CH}_4 = 18 \%$
- $\text{C}_2\text{H}_4 = 13 \%$

TRANSFORMATOR'17
Duval Pentagons: place % $\text{C}_2\text{H}_2$

<table>
<thead>
<tr>
<th>Gas</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}_2$ = 75 ppm</td>
<td>39 %</td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_6$ = 57 ppm</td>
<td>30 %</td>
</tr>
<tr>
<td>$\text{CH}_4$ = 35 ppm</td>
<td>18 %</td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_4$ = 25 ppm</td>
<td>13 %</td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_2$ = 0 ppm</td>
<td>0 %</td>
</tr>
</tbody>
</table>

Total = 192 ppm
Duval Pentagons: Compute Centroid
Duval Pentagons: Select inner 40%
Duval Pentagons: Add Zones
The Duval Pentagon—A New Complementary Tool for the Interpretation of Dissolved Gas Analysis in Transformers

Michel Duval and Laurent Lamarre
IREQ, Varennes, QC, Canada

IEEE Electrical Insulation Magazine
November/December 2014, Vol 30, No 6
0883-7554/12/2014/IEEE
Using the Triangle Method

![Duval Triangle Diagram](image)

**DUVAL TRIANGLE** (IEC 60599-1999-03 Annex B.3)

- T1: Thermal faults not exceeding 300°C
- T2: Thermal faults exceeding 300°C but not exceeding 700°C
- T3: Thermal faults exceeding 700°C
- D1: Discharges of low energy
- D2: Discharges of high energy
- DT: Combination of thermal faults and discharges
- P6: Partial Discharges

**Notes:****
- Latest Sample
- Most recent 25% of data
- Less recent 25% of data
- Older 25% of data
- Oldest 25% of data

---

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TRANSFORMATOR’17
Duval Pentagon 1 Typical faults

DGA results identified by visual inspection as due to faults:

- PD
- D1
- D2
- T3
- T2
- S>200C
- S<120C
- T1

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Duval Pentagon 2 Typical faults

DGA results identified by visual inspection as due to faults:

- PD
- D1
- D2
- S>200C
- S-120C
- T3-H
- T2-H
- T1-H
- T3-C
- T2-C
- T1-C
- T1-O

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TRANSFORMATOR’17
DGA Example

<table>
<thead>
<tr>
<th></th>
<th>H₂</th>
<th>CH₄</th>
<th>C₂H₂</th>
<th>C₂H₄</th>
<th>C₂H₆</th>
<th>Tr₁</th>
<th>Pent₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before failure</td>
<td>800</td>
<td>700</td>
<td>0</td>
<td>200</td>
<td>400</td>
<td>T2</td>
<td>O</td>
</tr>
<tr>
<td>At failure</td>
<td>2800</td>
<td>1950</td>
<td>1450</td>
<td>1600</td>
<td>400</td>
<td>D2</td>
<td>D2</td>
</tr>
<tr>
<td>Delta</td>
<td>2000</td>
<td>1250</td>
<td>1450</td>
<td>1400</td>
<td>0</td>
<td>D2</td>
<td>D2</td>
</tr>
</tbody>
</table>

Arcing on windings and hot spot on lead found by inspection
DGA Example

<table>
<thead>
<tr>
<th></th>
<th>H₂</th>
<th>CH₄</th>
<th>C₂H₂</th>
<th>C₂H₄</th>
<th>C₂H₆</th>
<th>Tr1</th>
<th>Pent2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before failure</td>
<td>200</td>
<td>350</td>
<td>200</td>
<td>600</td>
<td>100</td>
<td>DT</td>
<td>T3-H</td>
</tr>
<tr>
<td>At failure</td>
<td>1120</td>
<td>700</td>
<td>690</td>
<td>1200</td>
<td>180</td>
<td>DT</td>
<td>D2</td>
</tr>
<tr>
<td>Delta</td>
<td>920</td>
<td>350</td>
<td>490</td>
<td>600</td>
<td>80</td>
<td>D2</td>
<td>D2</td>
</tr>
</tbody>
</table>

Hot spot and flashover found by inspection

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Mixtures of faults

Inspected cases of single faults of IEC TC 10 and mixtures of faults of CIGRE WG47 (S. Spremic)
Mixtures of faults

<table>
<thead>
<tr>
<th>Date</th>
<th>H₂</th>
<th>CH₄</th>
<th>C₂H₂</th>
<th>C₂H₄</th>
<th>C₂H₆</th>
<th>Tr4</th>
<th>Pent2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2011</td>
<td>10000</td>
<td>1000</td>
<td>0</td>
<td>0</td>
<td>200</td>
<td>S</td>
</tr>
<tr>
<td>2012</td>
<td>0</td>
<td>2000</td>
<td>0</td>
<td>0</td>
<td>700</td>
<td>C/O</td>
<td>O</td>
</tr>
<tr>
<td>B</td>
<td>15000</td>
<td>1500</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>PD</td>
<td>PD</td>
</tr>
<tr>
<td>C</td>
<td>12000</td>
<td>1000</td>
<td>0</td>
<td>0</td>
<td>500</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>D</td>
<td>300</td>
<td>150</td>
<td>0</td>
<td>75</td>
<td>0</td>
<td>S</td>
<td>C</td>
</tr>
<tr>
<td>E</td>
<td>6000</td>
<td>600</td>
<td>0</td>
<td>0</td>
<td>400</td>
<td>S</td>
<td>S</td>
</tr>
</tbody>
</table>
Mixtures of faults

<table>
<thead>
<tr>
<th>Date</th>
<th>H2</th>
<th>CH4</th>
<th>C2H2</th>
<th>C2H4</th>
<th>C2H6</th>
</tr>
</thead>
<tbody>
<tr>
<td>11Ju</td>
<td>77</td>
<td>26</td>
<td>0</td>
<td>11</td>
<td>23</td>
</tr>
<tr>
<td>12ja</td>
<td>114</td>
<td>545</td>
<td>0</td>
<td>433</td>
<td>511</td>
</tr>
<tr>
<td>13ja</td>
<td>307</td>
<td>673</td>
<td>0</td>
<td>451</td>
<td>601</td>
</tr>
<tr>
<td>13Ap</td>
<td>508</td>
<td>1345</td>
<td>0</td>
<td>770</td>
<td>1058</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>URT</th>
<th>11No</th>
<th>27</th>
<th>0</th>
<th>10</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>12Dec</td>
<td>150</td>
<td>559</td>
<td>0</td>
<td>251</td>
<td>256</td>
</tr>
<tr>
<td>13Feb</td>
<td>62</td>
<td>68</td>
<td>27</td>
<td>126</td>
<td>73</td>
</tr>
</tbody>
</table>

Pentagon 2

URT LTC

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Mixtures of faults

Inspection done in April 2013: overheating and coking at the connections of the conductor through-bushings associated to the selector reversing switch on both the main body (transformer tank) and selector compartment sides, as predicted by Pentagon 2, Triangle 1 and Triangle 5 (O/T2/C) and Triangle 2 for the selector LTC (T2).
Duval Methods

- 15 Duval Triangles
- 2 Pentagons
- 112 Zones
- 20 Diagnostics
- 5 Insulating Fluids
- 2 Type of equipment
  - Transformer
  - OLTC
- 8 Models of OLTC
Today DGA Interpretation Methods

- Since 1970
- Transformer / OLTC / CT / PT / Bushing
- Mineral / Ester / Silicone
- 7 Gases
- 4 Different interpretation methodologies
- More than 100 gas level limits
- More than 20 ratios
- More than 40 faults conditions
- More than 10 rates of rise
Conclusion

Yes, life is complicated!!
However, new software tools exist to make your life simpler and sort out all these possibilities
Experts are also there to help you!

Thank to Dynamic Rating and Michel Duval for permission to use their training material

To obtain a worksheet of Duval Triangles and Pentagons
Make a request to Michel Duval at: duvalm@ireq.ca
DGA Tools: Duval Triangles and Pentagons

C. Beauchemin, TJH2b Analytical Services Inc.

Initially presented at the TechCon SE Asia, Kuala Lumpur, April 10, 2017

This presentation use some material from Michel Duval and Dynamic Rating training programs
Dissolved Gas Analysis History

- Oil Filled Transformer: 1880 - 1890
- Buchholz relay: introduced in 1921
- Buchholz gas analysis: Mid 1950
- Early DGA: 1968 (CEGB)
- On-line DGA:
  - Single gas: Early 1980
  - Multi gas: Mid 1990
How to correlate gas to fault?

- The objective of DGA is to detect the presence of fault, and identify their nature.

- It was recognized early that some gas, or some gas ratio, could be associated with some specific type of fault.

- To be useful, DGA need interpretation methods.
Relative Gas Generation  CIGRE and IEEE

Source: IEEE C57.104 D3.2, April 2017
How to correlate gas to fault?

- Interpretation methods could be classified in 4 general classes
  - Specific gas
  - Statistic norms
  - True tables with ratio
  - Graphical
- All methods are based on the fact that different fault generate gas in different amounts
DGA Interpretation History

• Several methods introduced in the 1970 & 1980
  
  • Statistic threshold
  • Rogers
  • Halstead
  • LCIE
  • Laborelec
  • GE
  • Church

  • Dörnenberg
  • Potthoff
  • Shanks
  • Trilinear Plot
  • IEC
  • Duval
  • ....
Key Gas Method

**Arcing in Oil**

<table>
<thead>
<tr>
<th>Gas</th>
<th>Relative Proportions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0</td>
</tr>
<tr>
<td>H₂</td>
<td>60</td>
</tr>
<tr>
<td>CH₄</td>
<td>5</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>2</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>3</td>
</tr>
<tr>
<td>C₂H₂</td>
<td>30</td>
</tr>
</tbody>
</table>

**Corona in Oil**

<table>
<thead>
<tr>
<th>Gas</th>
<th>Relative Proportions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0</td>
</tr>
<tr>
<td>H₂</td>
<td>85</td>
</tr>
<tr>
<td>CH₄</td>
<td>13</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>1</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>1</td>
</tr>
<tr>
<td>C₂H₂</td>
<td>0</td>
</tr>
</tbody>
</table>

A number of schemes have been put forward; the simplest is to relate gases with fault types, e.g.

- Hydrogen
- Hydrogen, Methane, Ethane, Ethylene
- Acetylene
- Carbon monoxide

Partial discharges
- Heating of oil
- Arcing
- Heating of paper or cork

The main difficulty with schemes of this nature is that these gases will be found to a greater or lesser degree in practically all samples.
Table A.2 – Ranges of 90 % typical concentration values observed in power transformers (all types)

<table>
<thead>
<tr>
<th>Transformer sub-type</th>
<th>$H_2$</th>
<th>$CO$</th>
<th>$CO_2$</th>
<th>$CH_4$</th>
<th>$C_2H_6$</th>
<th>$C_2H_4$</th>
<th>$C_2H_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No OLTC</td>
<td>60-150</td>
<td>540-900</td>
<td>5 100-13 000</td>
<td>40-110</td>
<td>50-90</td>
<td>60-280</td>
<td>3-50</td>
</tr>
<tr>
<td>Communicating OLTC</td>
<td>75-150</td>
<td>400-850</td>
<td>5 300-12 000</td>
<td>35-130</td>
<td>50-70</td>
<td>110-250</td>
<td>80-270</td>
</tr>
</tbody>
</table>

NOTE 1 – The values listed in this table were obtained from individual networks. Values on other networks may differ.

NOTE 2 – "Communicating OLTC" means that some oil and/or gas communication is possible between the OLTC compartment and the main tank or between the respective conservators. These gases may contaminate the oil in the main tank and affect the normal values in these types of equipment. "No OLTC" refers to transformers not equipped with an OLTC, or equipped with an OLTC not communicating with or leaking to the main tank.

NOTE 3 – In some countries, typical values as low as 0,5 μl/l for $C_2H_2$ and 10 μl/l for $C_2H_4$ have been reported.
## Example of Look-Up Table: Early Rogers

<table>
<thead>
<tr>
<th>CH$_4$</th>
<th>C$_2$H$_6$</th>
<th>C$_2$H$_4$</th>
<th>C$_2$H$_2$</th>
<th>Diagnosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$</td>
<td>CH$_4$</td>
<td>C$_2$H$_6$</td>
<td>C$_2$H$_4$</td>
<td>C$_2$H$_2$</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
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<tr>
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<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Example of Early Graphical Method: Doernenberg
Example of Graphical Method: IEC 60599
Diagnostic Method: Duval Triangles

Duval Triangles History
The Origin of the Triangle figure

- Lost in the night of time
- Oldest known description: (Euclid, 323 – 283 BC): any three points not in a line define a triangle (second oldest geometry axiom)
- A complete field of mathematics (Trigonometry)
- Widely used in land survey and to remove the faint of heart from Engineering School
The Origin of Modern Triangle Graphs (Trilinear)

- Trilinear graph have been in use for a long time
- J. Williard Gibbs is credited with the first documented use of trilinear coordinates graph (for thermodynamics) in 1873.
- In 1881 Robert Thurston published a paper using trilinear coordinates to express the properties of Copper-Zinc-Tin alloys using contours map
How to Read a Trilinear Graph

- Widely used in several fields
- Not as intuitive as XY graphs
- Surface is not infinite, contrary to XY graphs
- Use positive values
- The 3 variable are interlocked
  \[ \%A + \%B + \%C = 100\% \]
- As a result, a point could be defined by… any two variables
Why use a Trilinear graphs?

- Any quantifiable property of a 3 components system could be plotted on a trilinear graphs instead of using two XY graphs or long look-up tables

- Here a few examples:
Flammability Chart

Fuel (methane)  Nitrogen  Oxygen

Flammable mixtures

LEL  UEL

LOC = 12 vol% O2
Color Chart
How to Read a Trilinear Graph

• Each corner is 100% of one variable
• The adjacent variable at that corner is 0%
• BTW, the other one too!!
• The progression around the triangle is
  \[ 0 \leftrightarrow 100 \leftrightarrow 0 \leftrightarrow 100 \leftrightarrow 0 \leftrightarrow 100\%
• Progression could be clockwise or counter clockwise
How to Read a Trilinear Graph

A

100% A

0% B & 0% C

B

100% B

0% C & 0% A

C

100% C

0% A & 0% B

0% A & 0% B
Early Use of Trilinear Graph in DGA Interpretation

- Early attempt for DGA interpretation
- Based on molar ratio of Carbon, Hydrogen and Oxygen in the Combustible gas mixture
- Complex computation to obtain ratios
- Was not adopted widely
Early DGA Interpretation Attempt with Triangle

Let the concentrations be:

\[ \begin{align*}
    & H_2 \quad a. \\
    & CO \quad b. \\
    & CH_4 \quad c. \\
    & C_2H_6 \quad d. \\
    & C_2H_4 \quad e. \\
    & C_2H_2 \quad f. 
\end{align*} \]

The trilinear method gives:

\[ \begin{align*}
    H_2 \text{ moles} & \quad \left[ a + 2c + 3d + 2e + f \right] / \left( a + \frac{3b}{2} + 3c + 5d + 4c + 3f \right) \\
    O_2 \text{ moles} & \quad b / \left( 2a + 3b + 6c + 10d + 8e + 6f \right) \\
    \text{Carbon moles} & \quad \left[ b + c + 2(d + e + f) \right] / \left( a + \frac{3b}{2} + 3c + 5d + 4e + 3f \right)
\]
First Trilinear Graph for DGA
Duval Triangle (1)

- Second attempt to use trilinear graph with DGA
- Introduced in 1974 by Michel Duval
- Use 3 gas: CH4, C2H4 and C2H2
- Compute 3 ratios (% of gas in mixture)
- Each type of fault is assigned a zone
- Related to Gas Formation Temperature
Relative Gas Generation  Duval Triangle 1

Fault Types

Relative percentage of gases

Cold Plasma & Catalytic**

Thermal

Discharges

100°C  300°C  500°C  1000°C  3000°C

** Not related to temperature

TJ | H₂b

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Relative Gas Generation  Duval Triangle 1

Fault Types

Relative percentage of gases

100%

50%

Cold Plasma & Catalytic**

100°C  300°C  500°C  1000°C  3000°C

Thermal

Discharges

** Not related to temperature

H b
Duval Triangle 1: Temperature of gas formation

- CH4
- C2H4
- C2H2

- < 500°C
- > 1000°C
- > 1000°C
Duval Triangle 1

\[ \begin{align*}
\text{Duval 1} & \\
\text{CH}_4 & \quad \text{C}_2\text{H}_4 & \quad \text{CH}_4
\end{align*} \]

< 500°C \quad \text{CH}_4 \quad \text{C}_2\text{H}_4 \quad > 500°C

< 1000°C \quad \text{C}_2\text{H}_2 \quad > 1000°C
Duval Triangle 1 Zones

• PD  Partial Discharges
• T1  Low Temperature  < 300 °C
• T2  Medium Temperature  300 - 700 °C
• T3  High Temperature  > 700 °C
• DT  Discharges with Thermal
• D1  Discharges of High Energy
• D2  Discharges of Low Energy
How to Place a Point in a Duval Triangle

\[ \text{CH}_4 = 50\% \]
\[ \text{C}_2\text{H}_4 = 30\% \]

\[ \text{C}_2\text{H}_2 = 100\% - \%\text{CH}_4 - \%\text{C}_2\text{H}_4 = 20\% \]
Duval Triangle 1 and IEC 60599

- Same fault designations as IEC 60599
- IEC use 5 Hydrocarbon
- IEC use 3 ratios of 2 gas
- IEC use Look-up table
- IEC use also a two graphs representation
Duval Compared to IEC 60599

<table>
<thead>
<tr>
<th>Case</th>
<th>Characteristic fault</th>
<th>$\frac{C_2H_2}{C_2H_4}$</th>
<th>$\frac{CH_4}{H_2}$</th>
<th>$\frac{C_2H_4}{C_2H_6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD</td>
<td>Partial discharges (see notes 3 and 4)</td>
<td>NS$^1$</td>
<td>&lt;0.1</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>D1</td>
<td>Discharges of low energy</td>
<td>&gt;1</td>
<td>0.1 – 0.5</td>
<td>1</td>
</tr>
<tr>
<td>D2</td>
<td>Discharges of high energy</td>
<td>0.6 – 2.5</td>
<td>0.1 – 1</td>
<td>&gt;2</td>
</tr>
<tr>
<td>T1</td>
<td>Thermal fault $T &lt; 300 \degree C$</td>
<td>NS$^1$</td>
<td>&gt;1 but NS$^{1,2}$</td>
<td>&lt;1</td>
</tr>
<tr>
<td>T2</td>
<td>Thermal fault $300 \degree C &lt; T \leq 700 \degree C$</td>
<td>&lt;0.1</td>
<td>1</td>
<td>1 – 4</td>
</tr>
<tr>
<td>T3</td>
<td>Thermal fault $T &gt; 700 \degree C$</td>
<td>&lt;0.2$^{1,2}$</td>
<td>1</td>
<td>&gt;4</td>
</tr>
</tbody>
</table>

Duval 1

TJ | H₂ | b

IEC
Duval Triangle 1

- Widely used today
- Part of IEC 60599 (appendix B)
- Will be part of future revised C57.104
- A study by U of New South Wales (Australia) indicate a success rate of 88%
- Limited to mineral oil transformer
Duval Triangles: Other options

• Triangle 1 issues:
  – Low energy faults (Stray gassing, low temp overheating, catalytic) almost always give a PD diagnostic
  – Applicable only to transformers
  – Applicable only to Mineral Oil

• So Variations have been added
Duval Triangles 4 and 5

- Introduced in 2008
- For mineral oil Transformer
  - T4: With PD, T1 or T2 in Duval 1
  - T5: With T2 or T3 in Duval 1
  - **DO NOT** use for D1, D2
  - Use with DT with precaution
- To refine/confirm low energy faults
- Different gas and zones than in Triangle 1
- Use H2, CH4, C2H4 and C2H6
Relative Gas Generation  Low Temperature

Fault Types

Relative percentage of gases

Cold Plasma & Catalytic**

100°C  300°C  500°C  1000°C  3000°C

** Not related to temperature

TJ H₂ b
Duval Triangle 4 for Low Energy Faults

For PD, T1 and T2 of Triangle 1 only
Relative Gas Generation: Intermediate Temperature

Fault Types

100%  50%  0%

Relative percentage of gases

100°C  300°C  500°C  1000°C  3000°C

Cold Plasma & Catalytic**
Thermal
Discharges

** Not related to temperature

TJ H 2 b
Duval Triangle 5 for Low Energy Faults

Duval 5 Medium Temperature

For T2 and T3 of Triangle 1 only
Duval Triangles 4 and 5 for Low Energy Faults

- PD Partial Discharge
- S Stray gassing
- C Hot Spot with Paper Carbonization
- O Overheating < 250°C
- ND Not Determined (use Duval 1)
- T2 Medium Temperature 300 - 700 °C
- T3 High Temperature > 700 °C
Duval Triangle 4 and 5

- New type of fault give a better description of low energy phenomena
- Less cases classified as PD
- Distinguish between Stray gassing (S) and low temperature oil overheating (O)
- Identify possible paper carbonisation (C)
Duval Triangle 2

- Introduced in 2008
- Developed to offer DGA interpretation for OLTC
- Apply to non-vacuum OLTC that generate gas in normal operation
- Same gases as Triangle 1
- Generic application
Duval Triangle 2: OLTC
Duval Triangle 2

- **N**: Normal Operation
- **T2**: Medium Temperature 300 - 700 °C with Coking
- **T3**: High Temperature > 700 °C, with Heavy Coking
- **D1**: Abnormal Arcing
- **X1**: Abnormal Arcing/Thermal
- **X3**: T2 or T3 or possible Abnormal Arcing/Coking
Duval Triangle 2a to 2e

- Proposed to IEEE C57.139 in 2012
- Use same triangle zones as Triangle 2
- Add extra Normal zones (N1 to N5)
- OLTC Model specific
- OLTC application specific (High Powers)
- Mostly apply to MR OLTC
Duval Triangle 2 Type α: MR OilTaps® M & D
Duval Triangle 2 Type b: MR VacuTaps® VR
Duval Triangle 2 Type c: MR VacuTaps® VV

D1

CH4

X1

N

C2H2

X3

T2

N3

T3

C2H4

TJ

H₂b

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Duval Triangle 2 Type d: OilTaps® R & V
Triangle 2 Type e: MR OilTap G®; ABB few UZD®, some UZB®
Duval Triangle 3

- Introduced in 2008
- For non mineral oil Transformer
  - FR3 ®
  - Silicone
  - Midel ®
  - Biotemp ®
- Same gases and zones as in Triangle 1
- Zone borders adjusted for D1/D2, T1/T2 and T2/T3
Duval 3 Silicone Oil
Duval Triangle 3 Midel®

Duval 3 Midel

CH4

C2H2

C2H4

D1

D2

D3

PD

T1

T2

T3

0

100

100

0

PD

T1

T2

T3
Duval Triangle 3 Biotemp®
Duval Pentagons: Simplifying process

• Use of Triangle 1, 4 and 5 could be cumbersome
• It could be also confusing
• It could be misused

• So, a simplified approach was proposed by Michel Duval: Combine Triangles 1, 4 and 5 in a Pentagon
Duval Pentagon 1 and 2

- Introduced in 2014
- For Mineral Oil Transformer
- Combine Triangle 1, 2 and 3
- Use $H_2$, $C_2H_6$, $CH_4$, $C_2H_4$ and $C_2H_2$
- Pentagon 1
  - “Classic” designation fault zones
- Pentagon 2
  - “Modern” designation fault zones
Duval Pentagons: $H_2$, $C_2H_6$, $CH_4$, $C_2H_4$ and $C_2H_2$
Duval Pentagons: place % of gas on each axis

Gas

- $H_2 = 75$ ppm
- $C_2H_6 = 57$ ppm
- $CH_4 = 35$ ppm
- $C_2H_4 = 25$ ppm
- $C_2H_2 = 0$ ppm
- Total = 192 ppm

% of Total

- $H_2 = 39\%$
- $C_2H_6 = 30\%$
- $CH_4 = 18\%$
- $C_2H_4 = 13\%$
- $C_2H_2 = 0\%$

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Duval Pentagons: Compute Centroid

Duval Pentagon

H₂

C₂H₆

CH₄

C₂H₄

C₂H₂
Duval Pentagons: Select inner 40%
Duval Pentagons: Add Zones
Duval Methods

- 15 Duval Triangles
- 2 Pentagons
- 112 Zones
- 20 Diagnostics
- 5 Insulating Fluids
- 2 Type of equipment
  - Transformer
  - OLTC
- 8 Models of OLTC
Today Interpretation Methods

- Since 1970
- Transformer / OLTC / CT / PT / Bushing
- Mineral / Ester / Silicone
- 7 Gases
- 4 Different interpretation methodologies
- More than 100 gas level limits
- More than 20 ratios
- More than 40 faults conditions
- More than 10 rates of rise
Yes, life is complicated!!
However, new software tools exist to make your life simpler and sort out all these possibilities
Experts are there to help you

Thank to Dynamic Rating and Michel Duval for permission to use their training material

To obtain a worksheet of Duval Triangles and Pentagons
Make a request to Michel Duval at: duvalm@ireq.ca