Międzynarodowa konferencja transformatorowa

PTPiREE

TRANSFORMATOR'17

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DGA Tools: Duval Triangles and Pentagons

C. Beauchemin, TJH2b Analytical Services Inc.

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TJ H 2 b

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

- H_2
- CH_4
- C_2H_6
- C_2H_4
- C_2H_2
- CO
- CO_2
- N_2
- O_2

– Other gas (C_3) are sometime also used

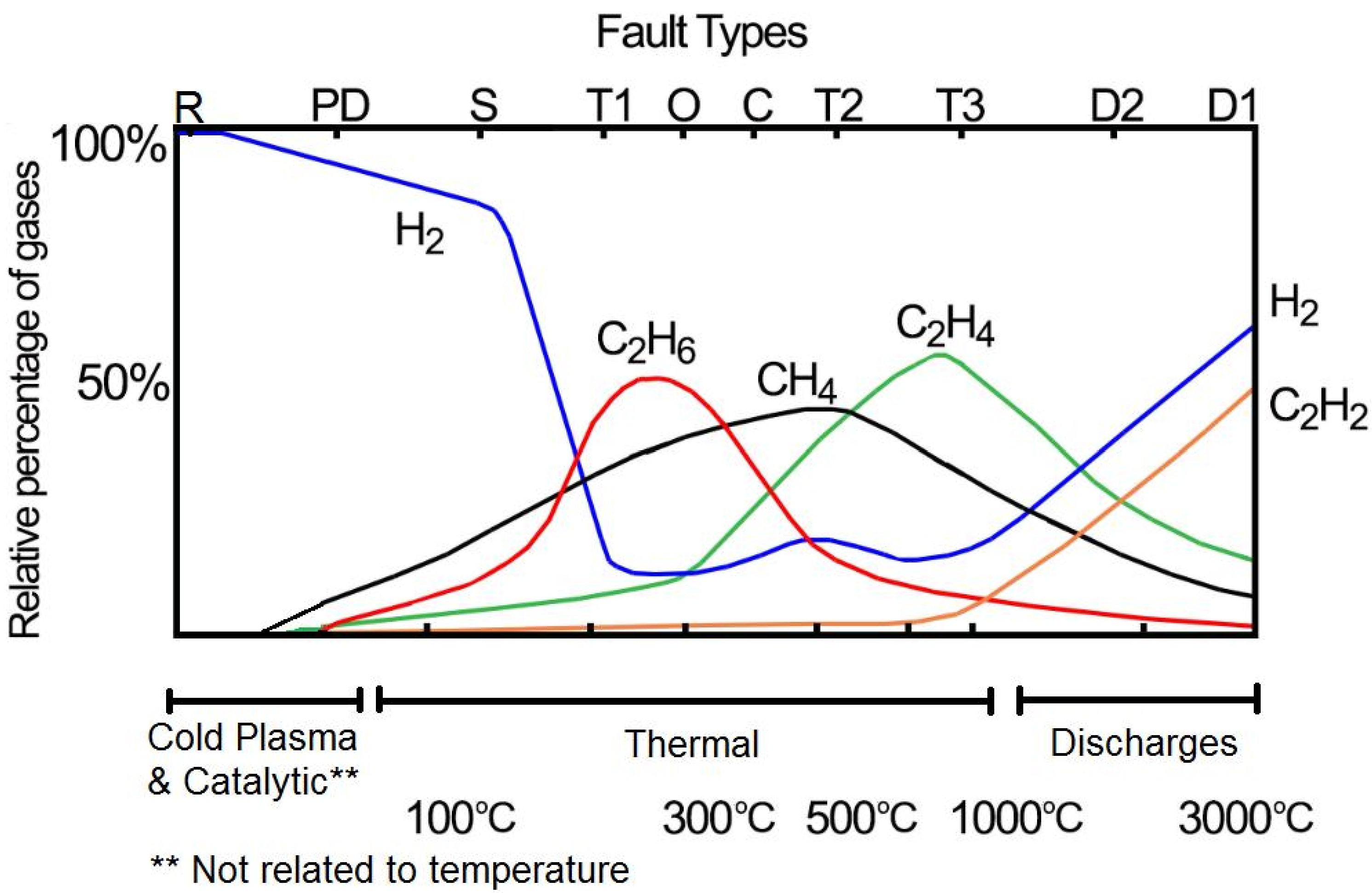
How to correlate gas to fault ?

- 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 IEEEE



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

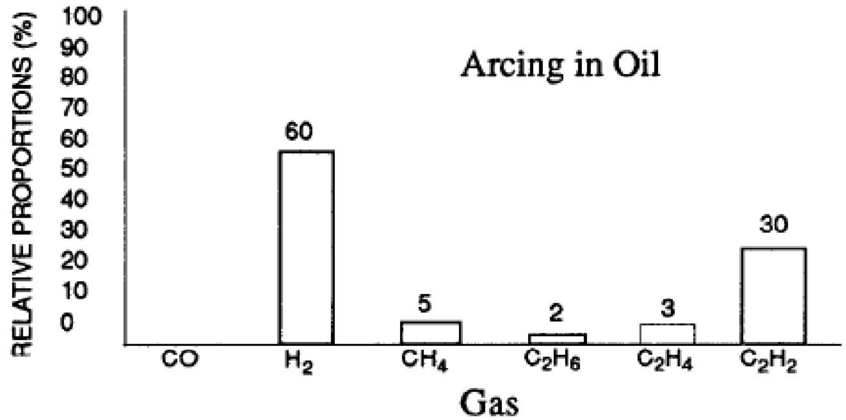
DGA Interpretation History

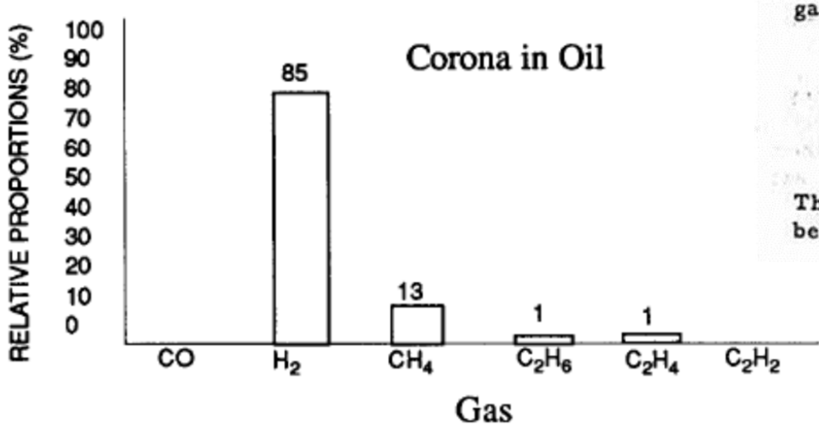
- Several methods introduced in the 1970 & 1980
  - Statistic threshold
  - Rogers
  - Halstead
  - LCIE
  - Laborelec
  - GE
  - Church
  - Dörnenberg
  - Potthoff
  - Shanks
  - Trilinear Plot
  - IEC
  - Duval
  - ....

DGA Interpretation

- Specific Gas
  - IEEE C57.104 Key Gas
  - LCIE Sheme
  - Potthoff Scheme

Key Gas Method





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

Statistical Methods: IEC 60599

Table A.2 – Ranges of 90 % typical concentration values observed in power transformers (all types)

Transformer sub-type	H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
No OLTC	60-150	540-900	5 100-13 000	40-110	50-90	60-280	3-50
Communicating OLTC	75-150	400-850	5 300-12 000	35-130	50-70	110-250	80-270

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

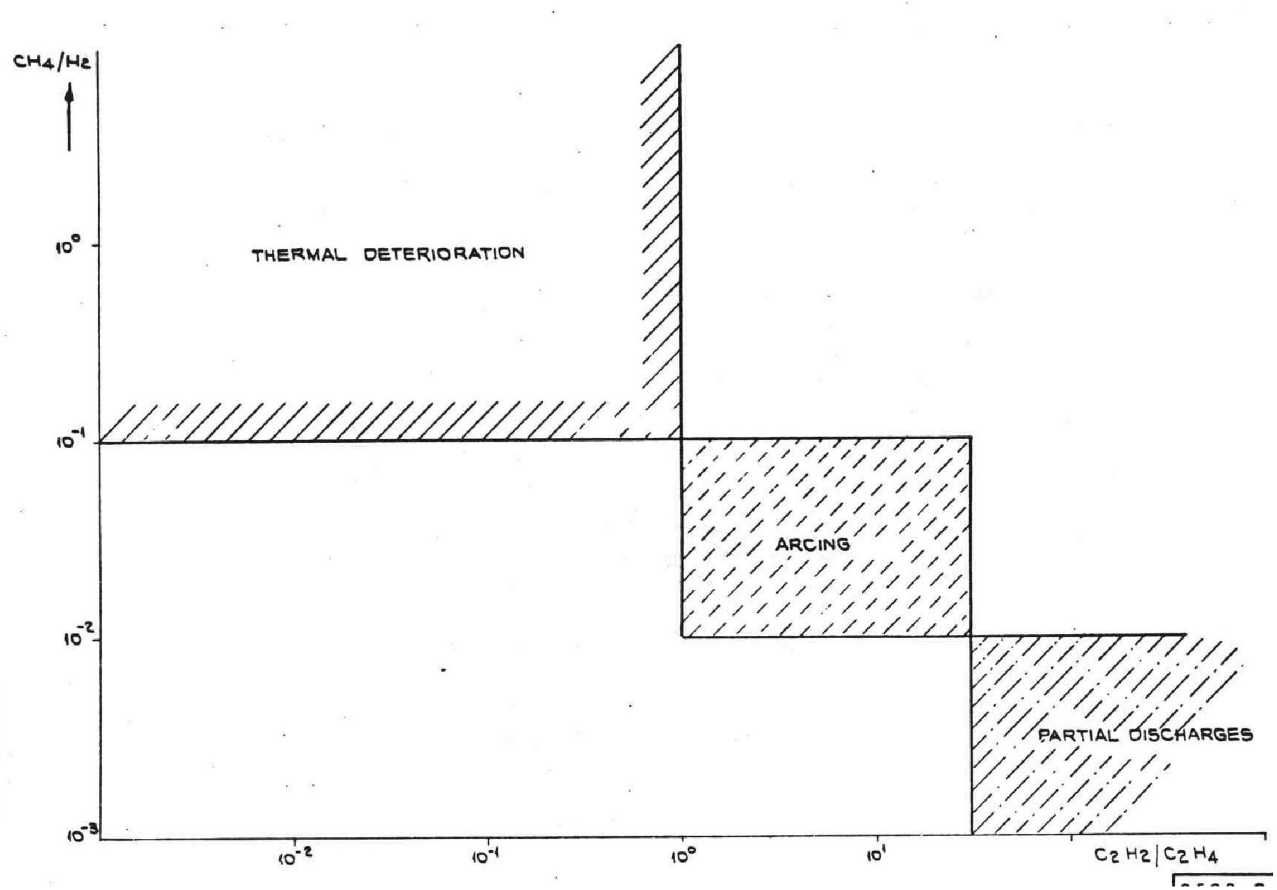
Example of Look-Up Table: Early Rogers

$\frac{CH_4}{H_2}$	$\frac{C_2H_6}{CH_4}$	$\frac{C_2H_4}{C_2H_6}$	$\frac{C_2H_2}{C_2H_4}$	Diagnosis
0	0	0	0	If CH_4/H_2 0.1 - Partial discharge, otherwise o.k.
0	0	0	1	Flash-over.
0	0	1	0	Conductor overheating.
0	0	1	1	Arc with power - persistent sparking.
0	1	0	0	Overheating 250-300°.
0	1	0	1	Tap changer, selector.
0	1	1	1	--
0	1	1	1	--
1	0	0	0	Overheating - below 150°.
1	0	1	0	Circulating current - bad contact.
1	0	1	1	--
1	0	1	1	--
1	1	0	0	Overheating 200-300°.
1	1	0	1	--
1	1	1	0	--
1	1	1	1	--

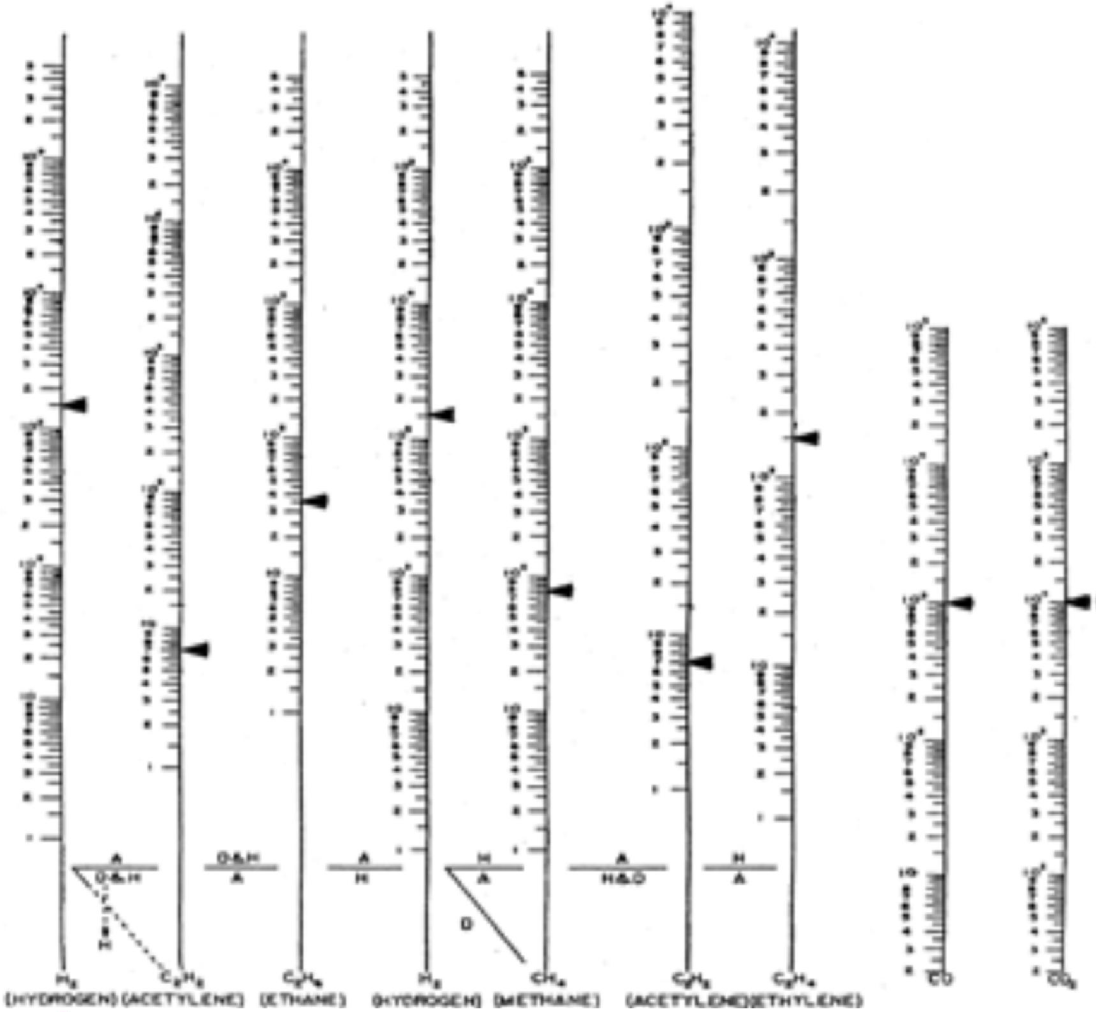
Graphical Method

- 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 - Key Gas
  - - Doernenberg - GE
  - - Duval - IEC

Example of Early Graphical Method: Doernenberg



Example of Early Graphical Method: Shanks



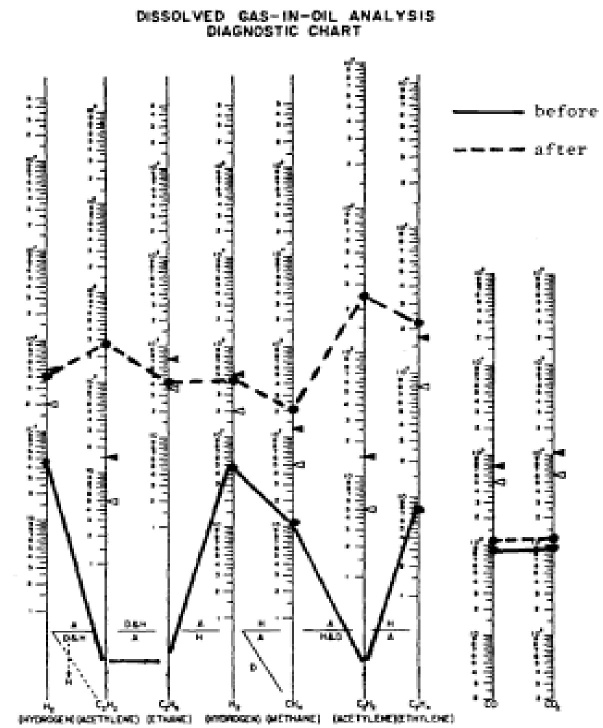


FIG. 4—A Church nomograph plot of the data in Table 3.

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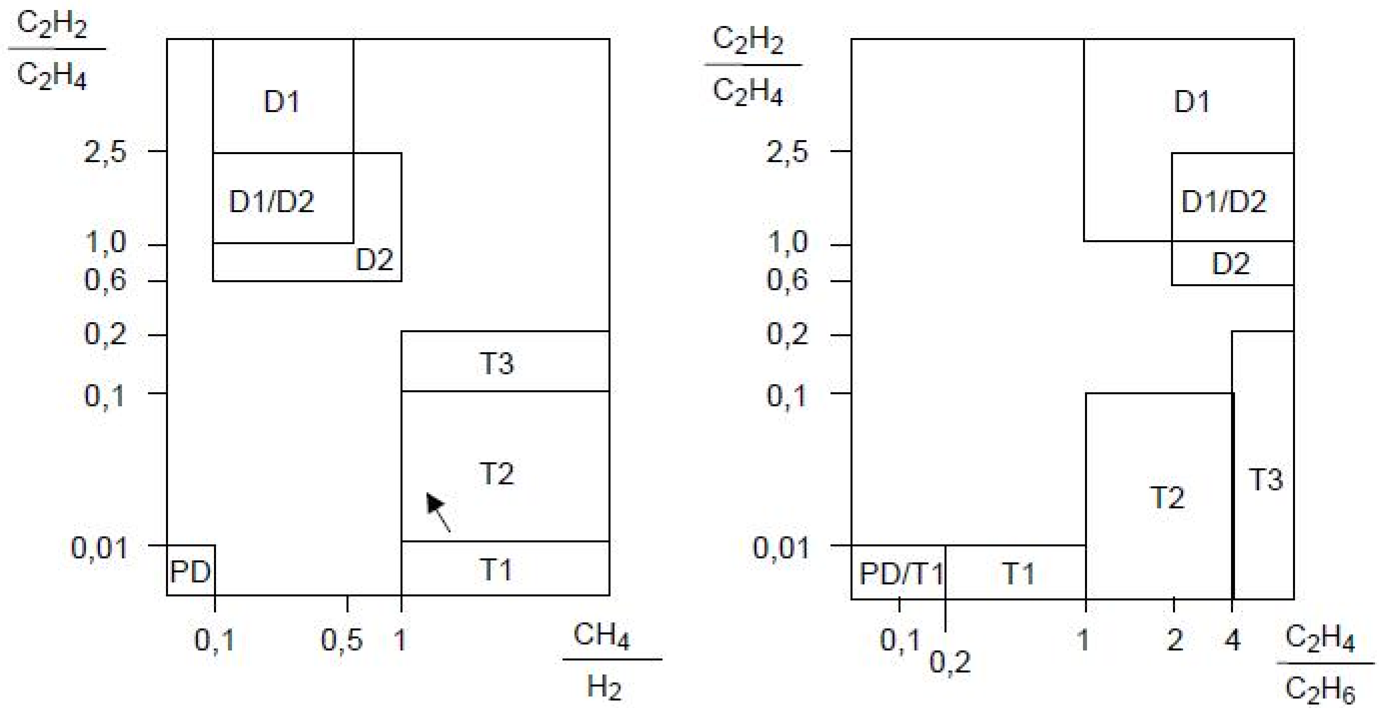
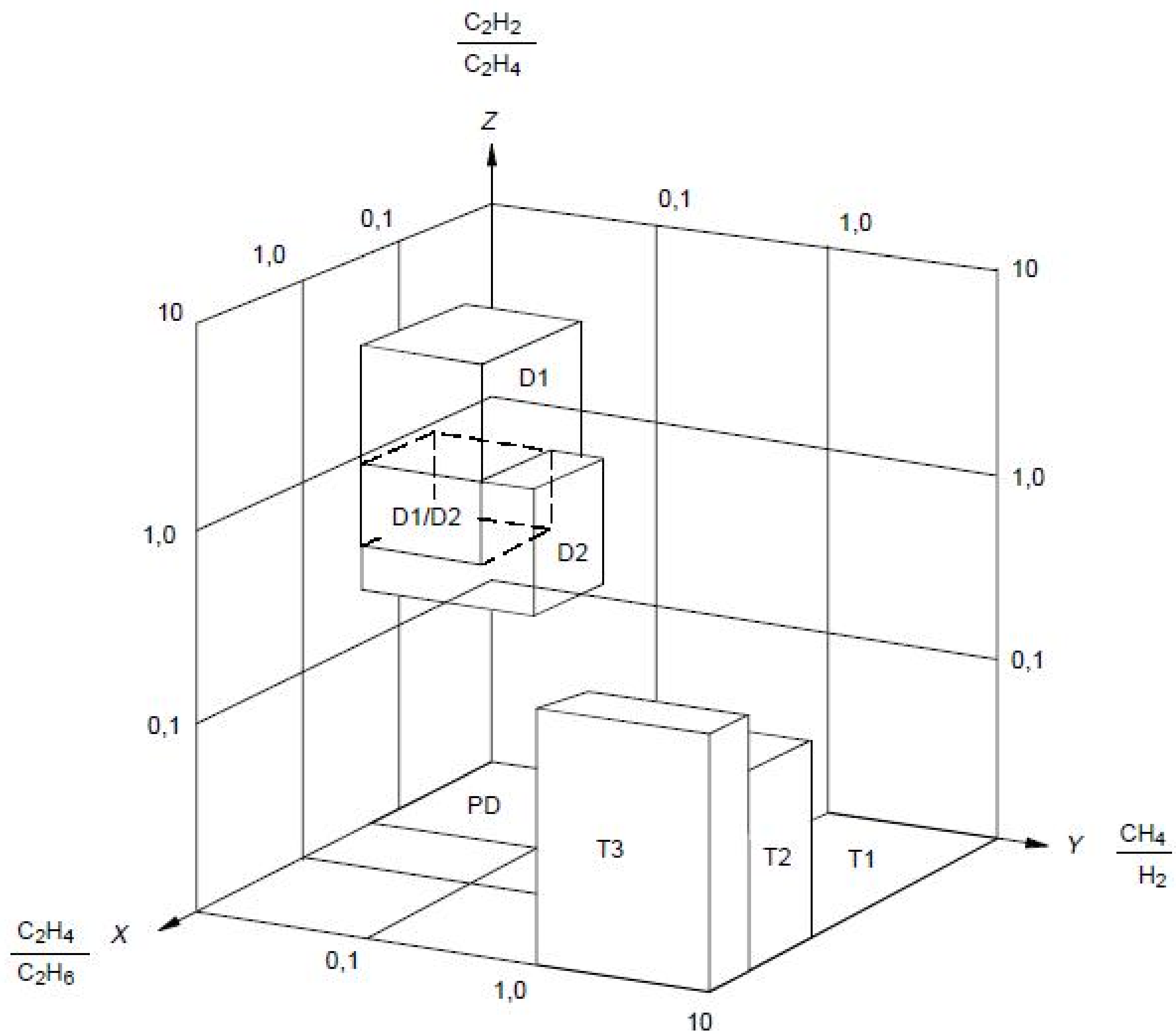
Example of Graphical Method: IEC 60599



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 know description: (Euclid, 323 – 283 BC): any three points not in a line define a triangle (second oldest geometry axiom)
- A complete field of mathematic (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

  $$\%A + \%B + \%C = 100\%$$

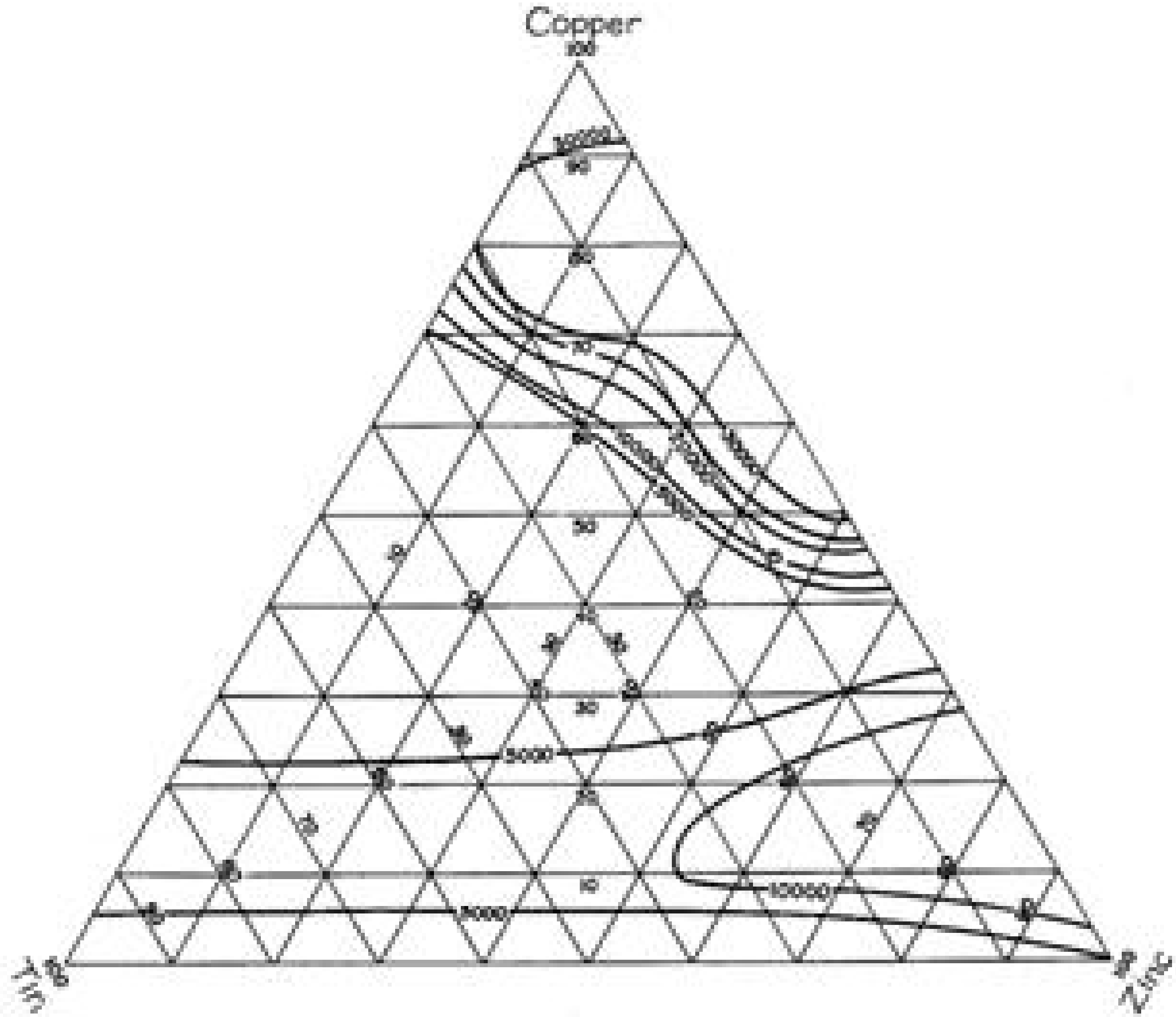
- As a result, a point could be defined by… any two variables

Why use a Trilinear graphs?

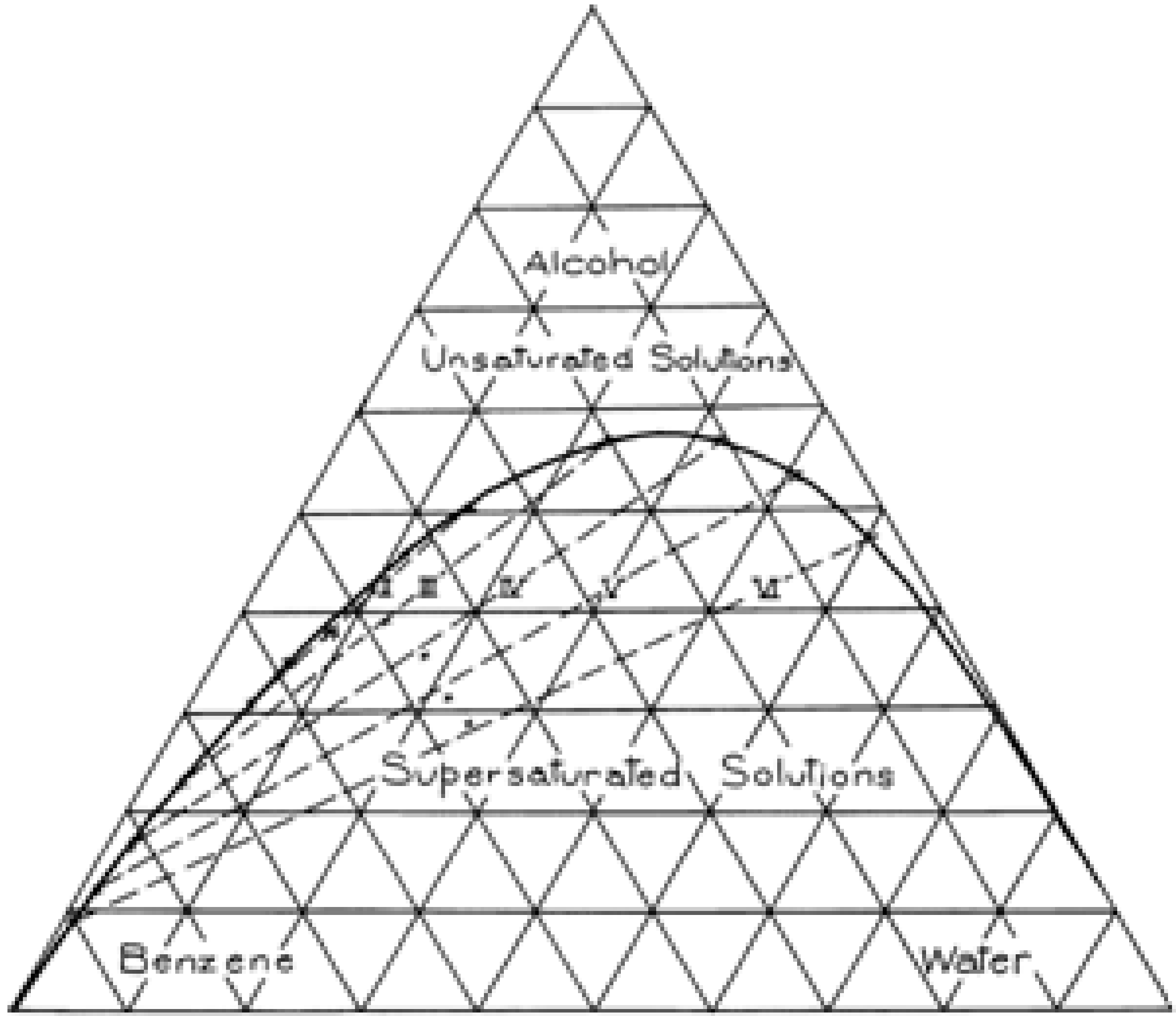
- Any quantifiable property of a 3 components system could be plotted on a trilinear graphs instead of using two XY graphs or long look-up tables

- Here a few examples:

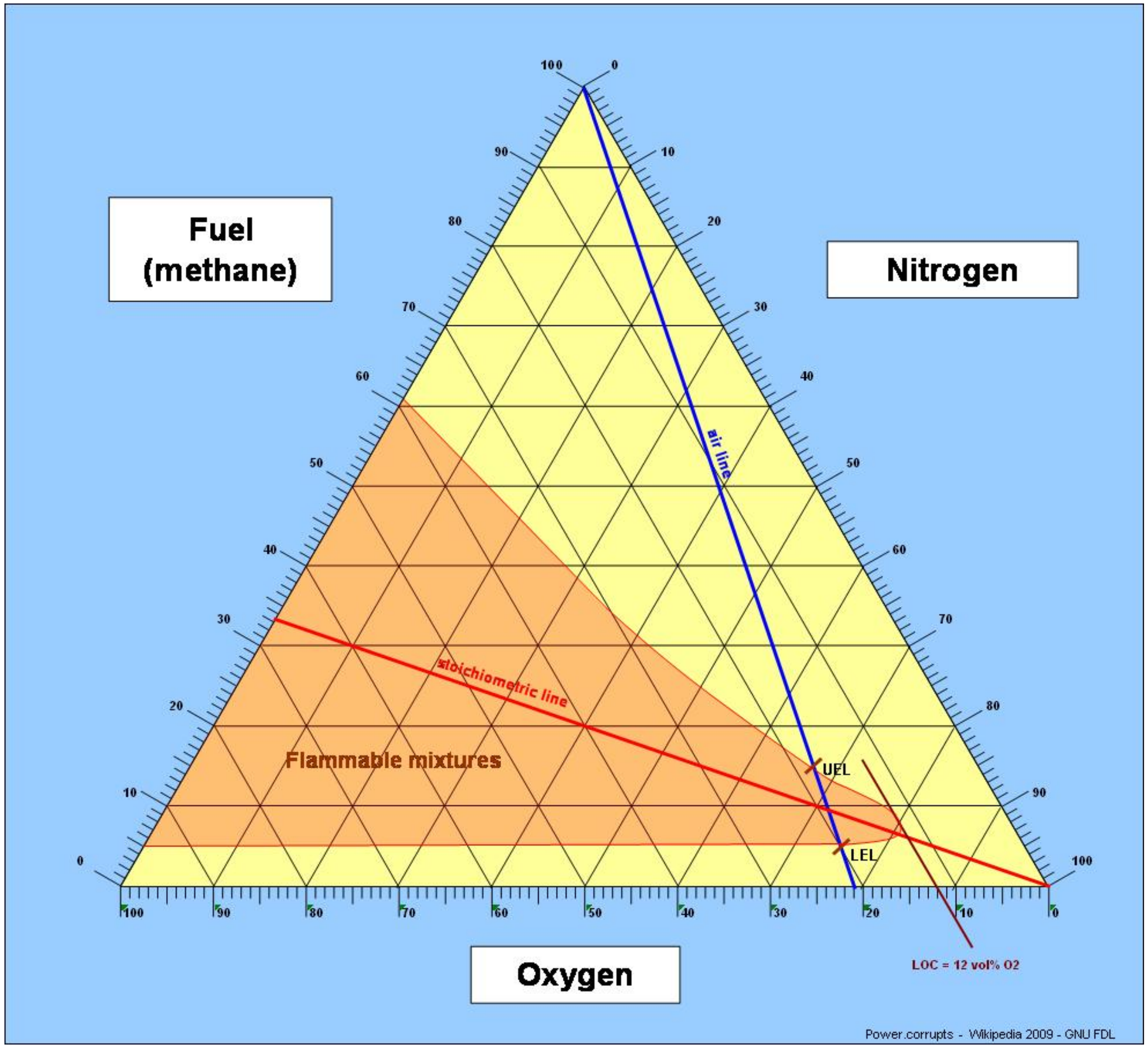
Property of Cu – Zn – Sn Mixture



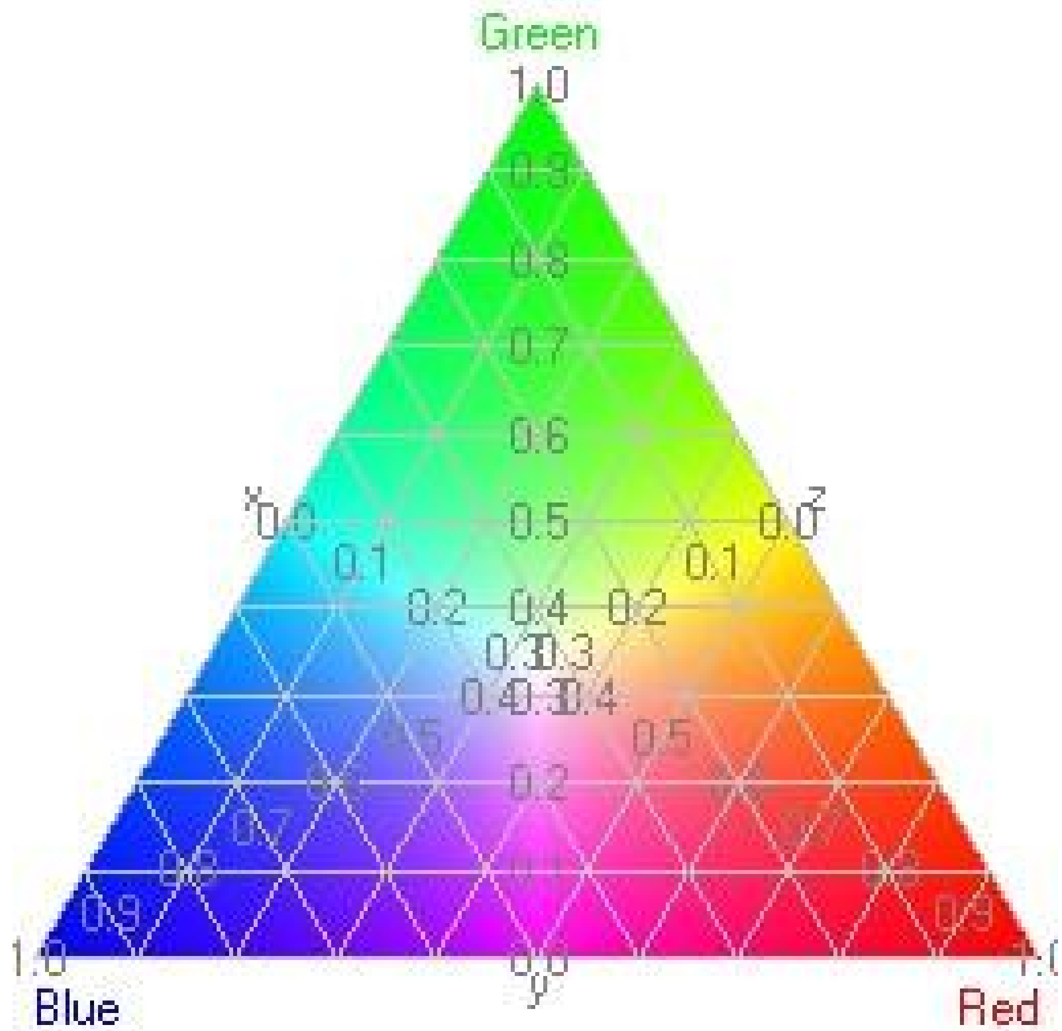
Solubility Chart



Flammability Chart



Color Chart

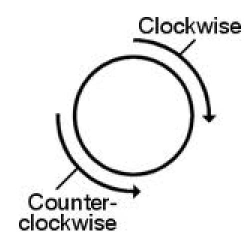


How to Read a Trilinear Graph

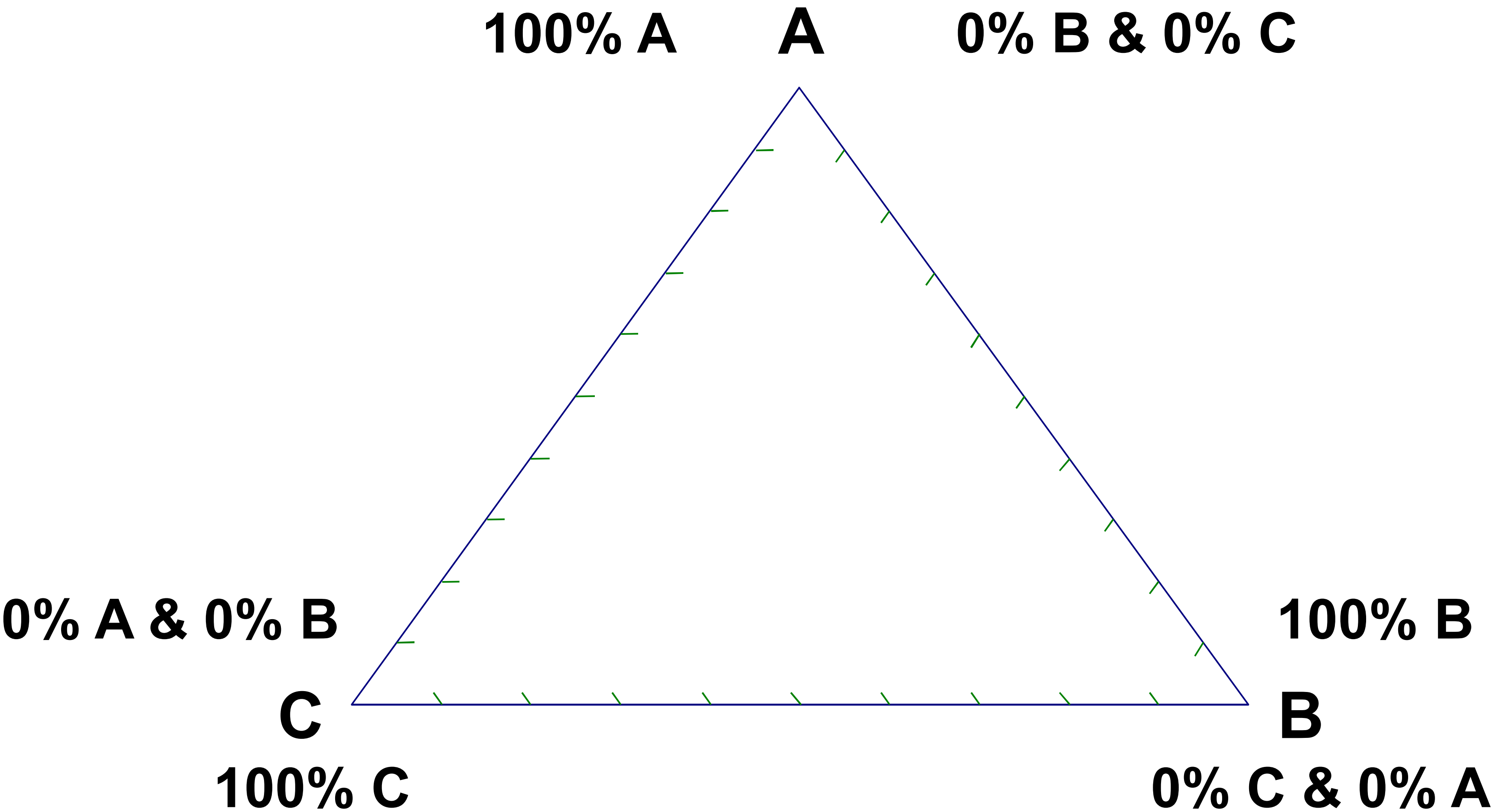
- Each corner is 100% of one variable
- The adjacent variable at that corner is 0%
- BTW, the other one too !!
- The progression around the triangle is

0 ↔ 100 0 ↔ 100 0 ↔ 100%

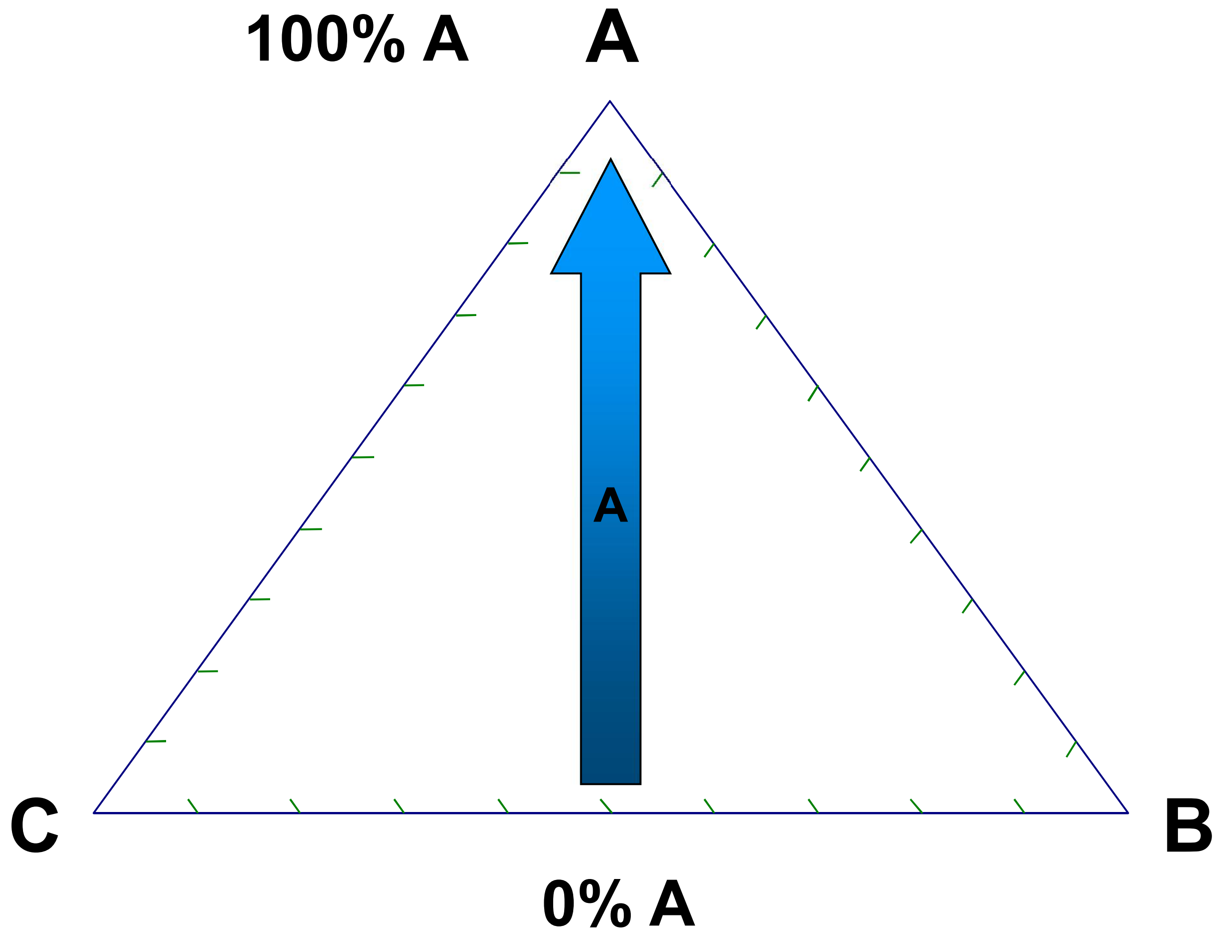
- Progression could be clockwise or counter clockwise



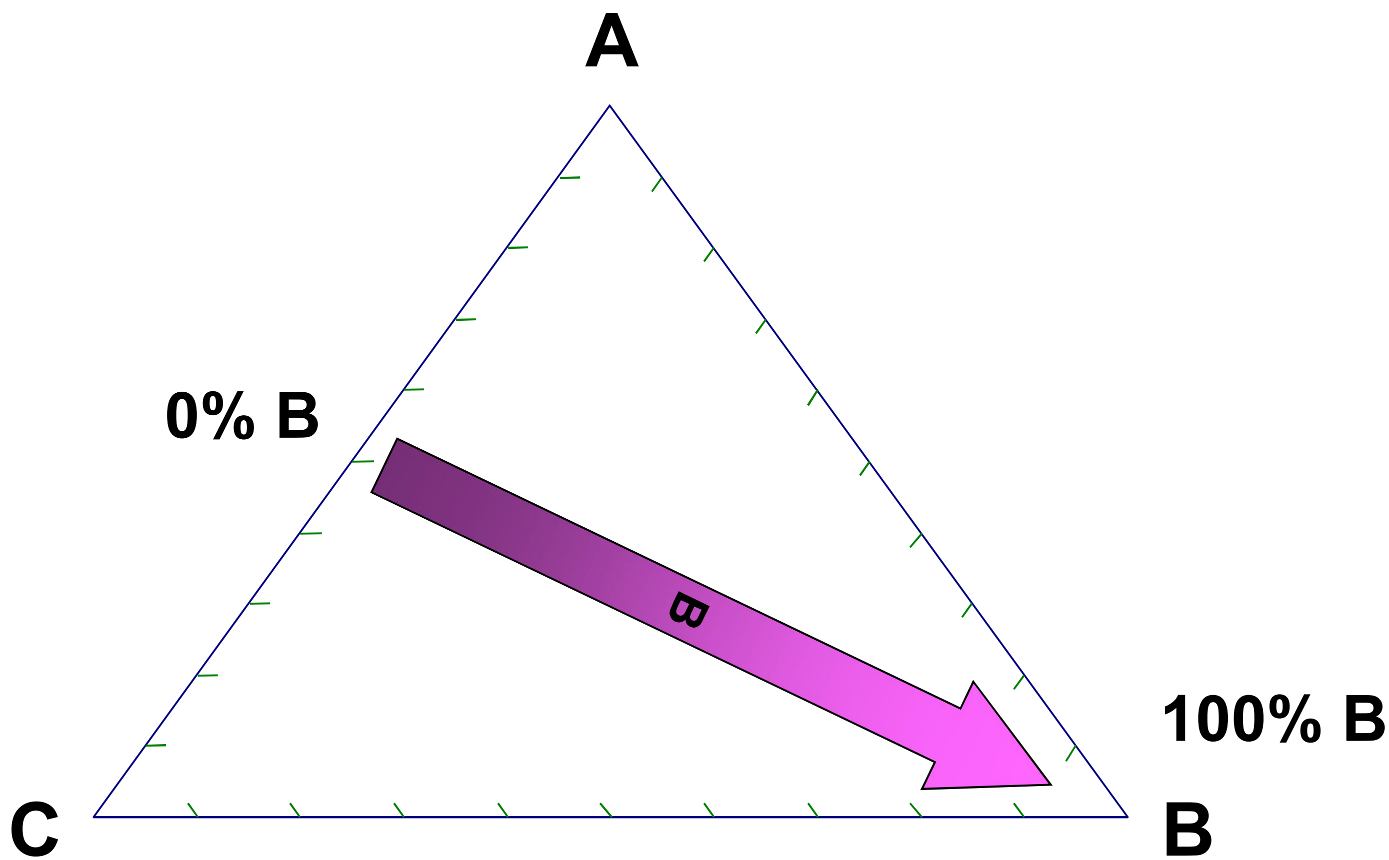
How to Read a Trilinear Graph



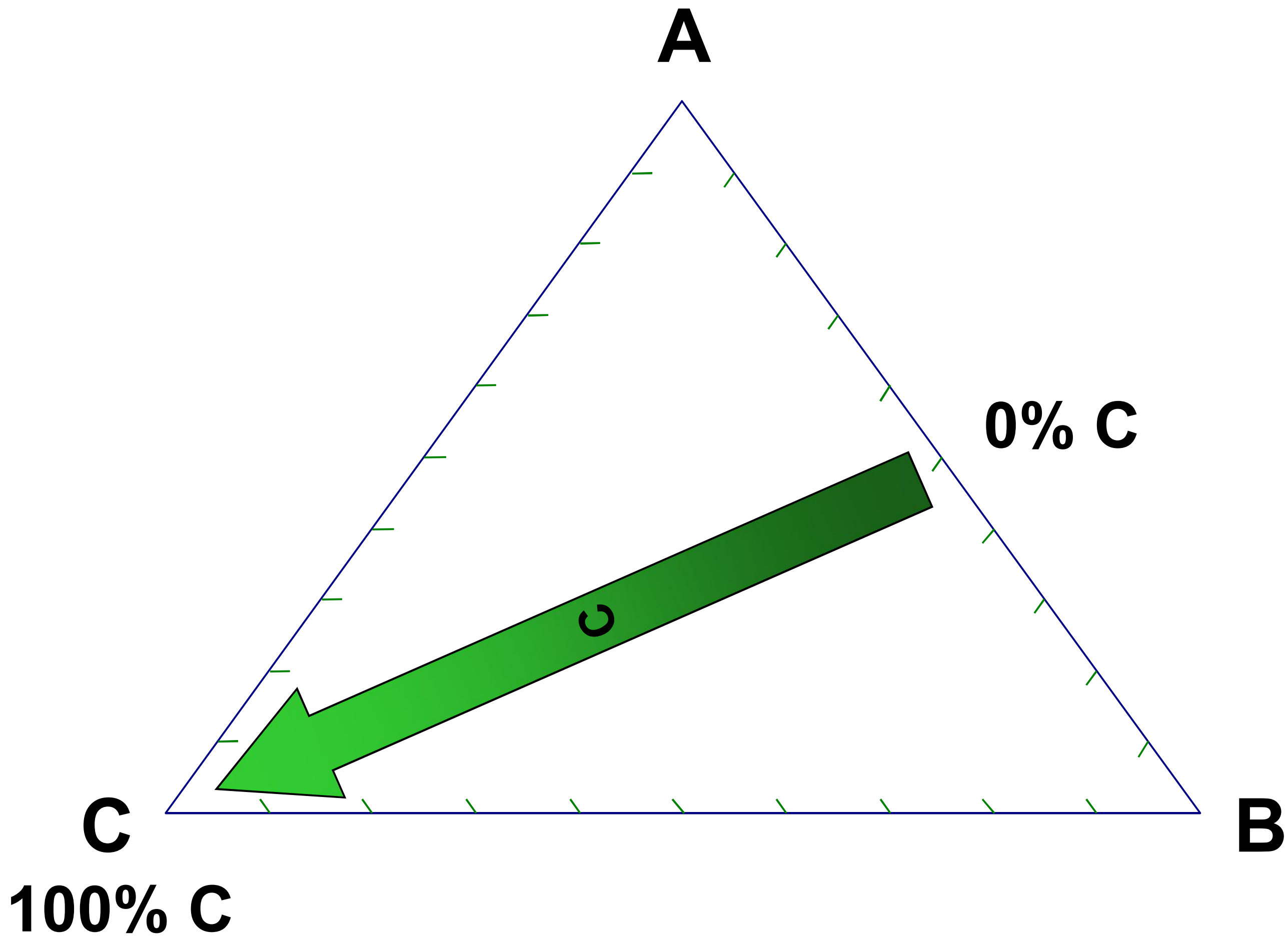
How to Read a Trilinear Graph



How to Read a Trilinear Graph



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:

H_2 a. CO b. CH_4 c. C_2H_6 d. C_2H_4 e. C_2H_2 f.

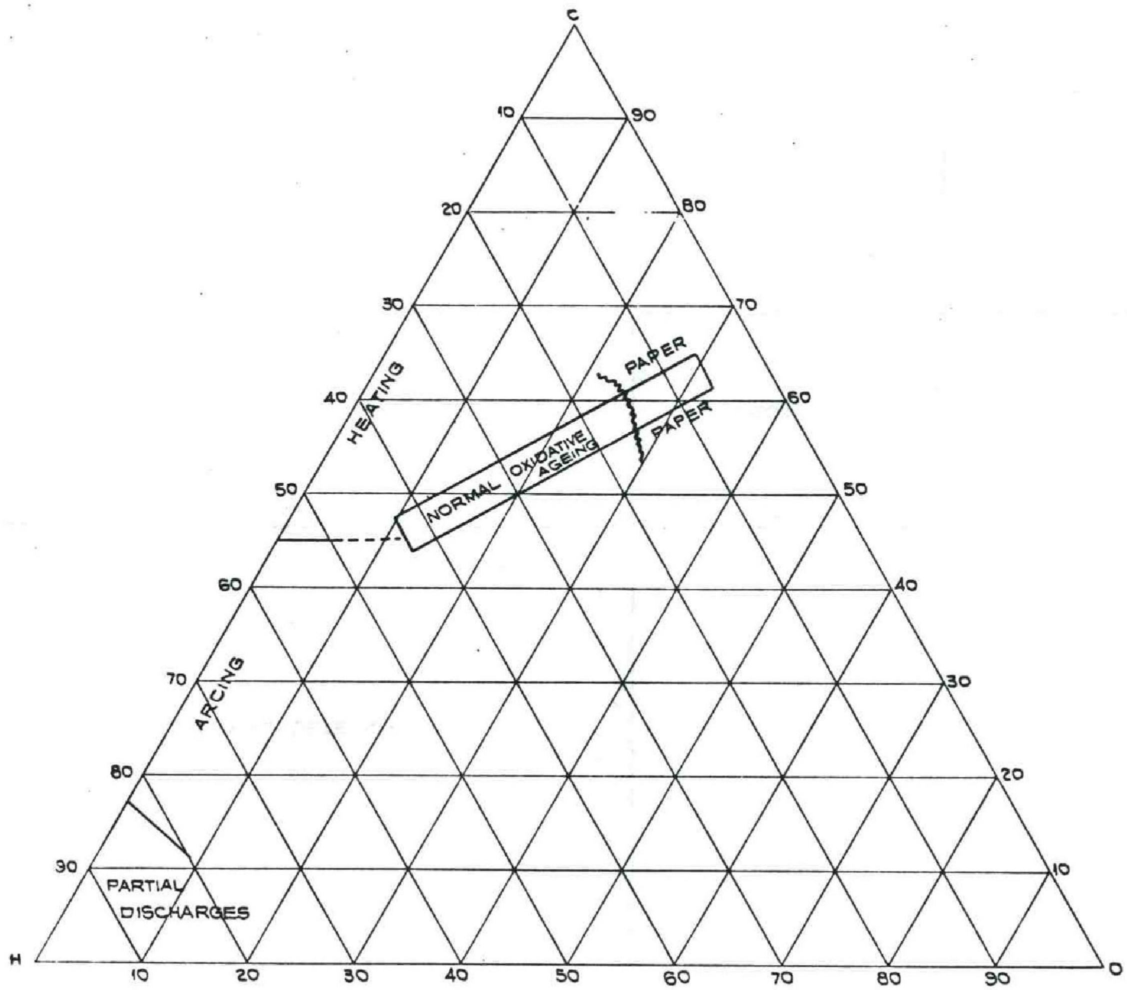
The trilinear method gives:

H_2 moles $\left[a + 2c + 3d + 2e + f\right] / \left(a + \frac{3b}{2} + 3c + 5d + 4c + 3f\right)$

O_2 moles $b/(2a + 3b + 6c + 10d + 8e + 6f)$

Carbon moles $\left[b + c + 2(d + e + f)\right] / \left(a + \frac{3b}{2} + 3c + 5d + 4e + 3f\right)$

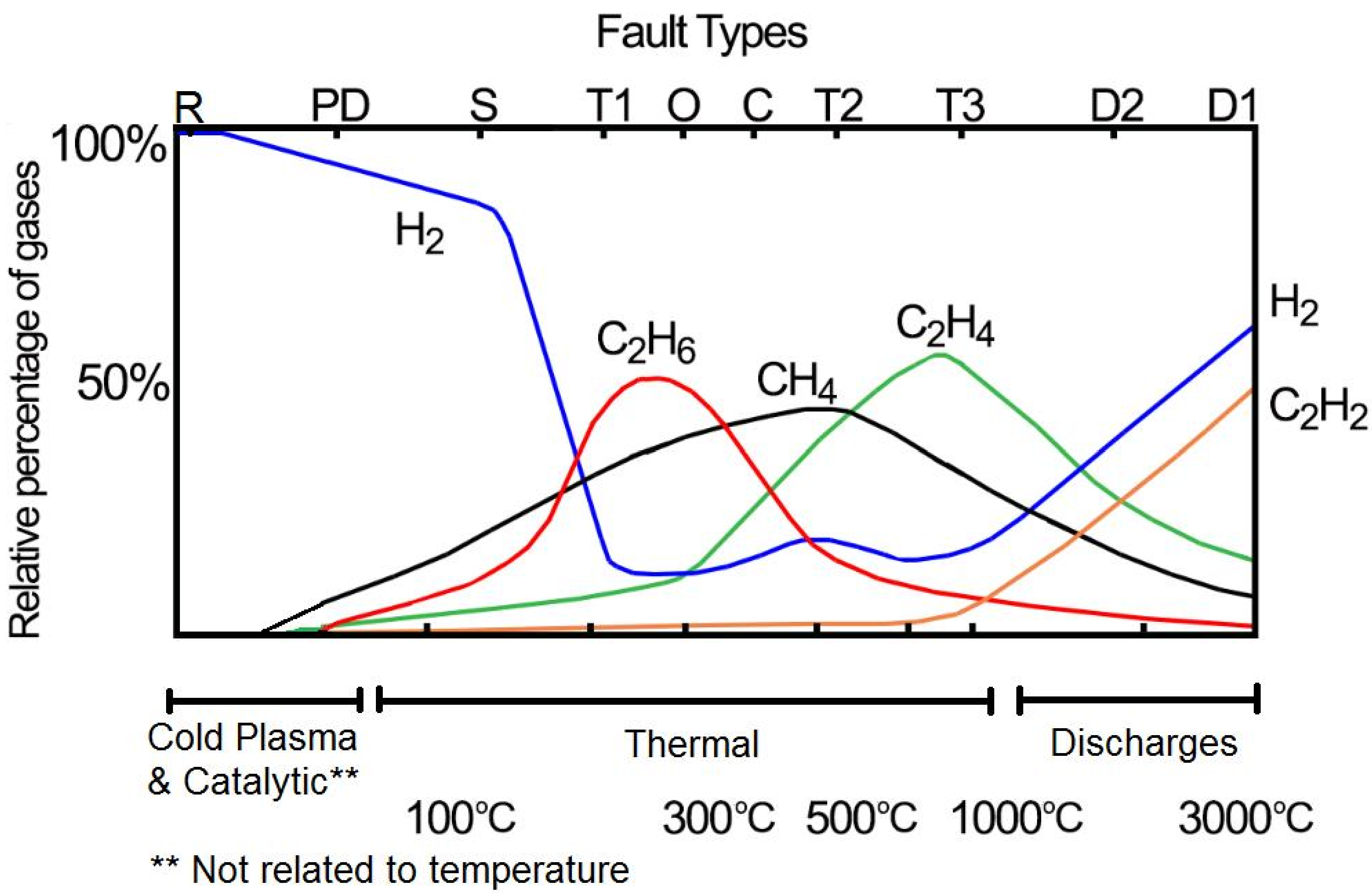
First Trilinear Graph for DGA



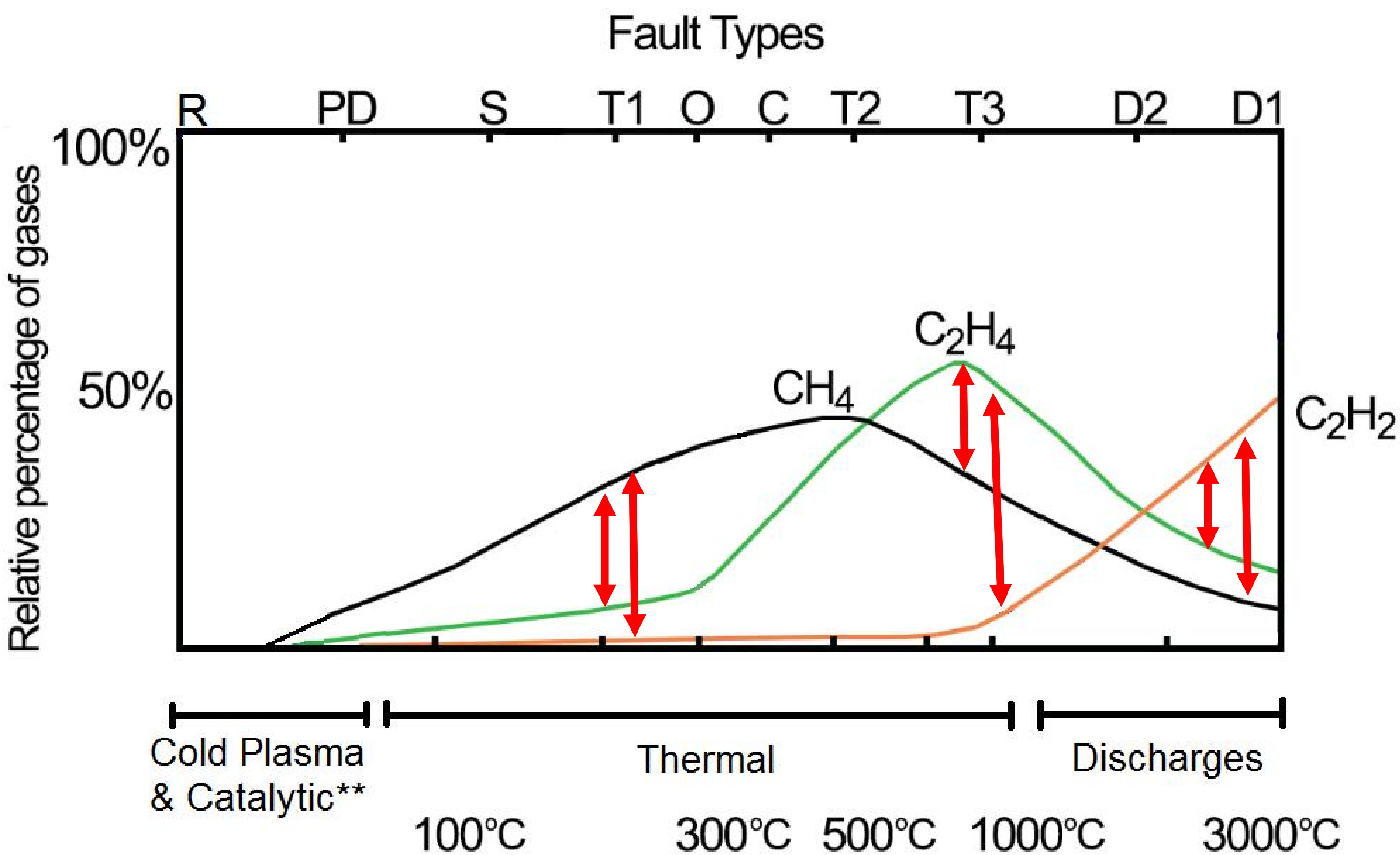
Duval Triangle (1)

- Second attempt to use trilinear graph with DGA
- Introduced in 1974 by Michel Duval
- Use 3 gas: CH_4, C_2H_4 and C_2H_2
- 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 IEEEE

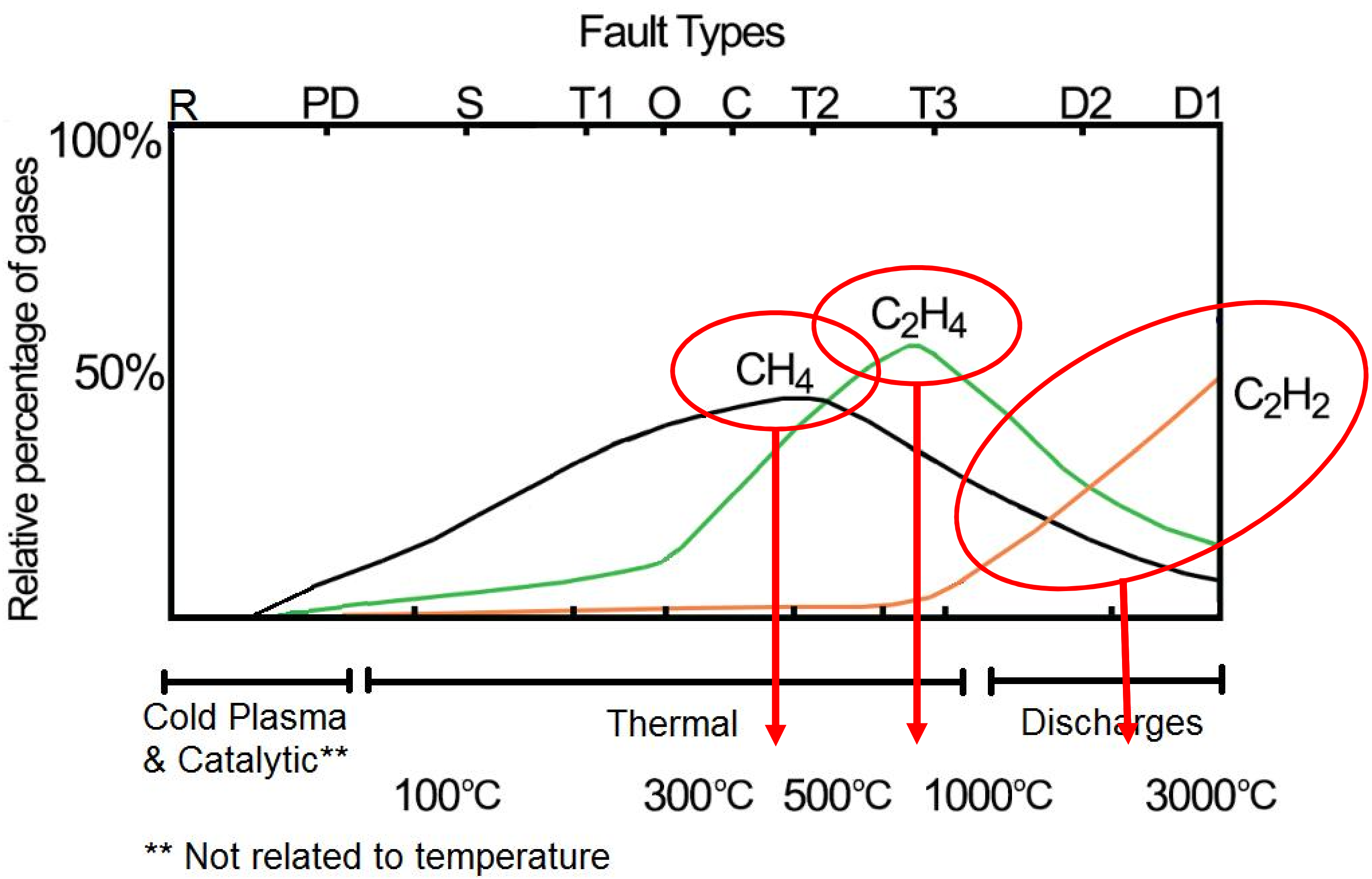


Relative Gas Generation Duval Triangle 1



** Not related to temperature

Relative Gas Generation Duval Triangle 1



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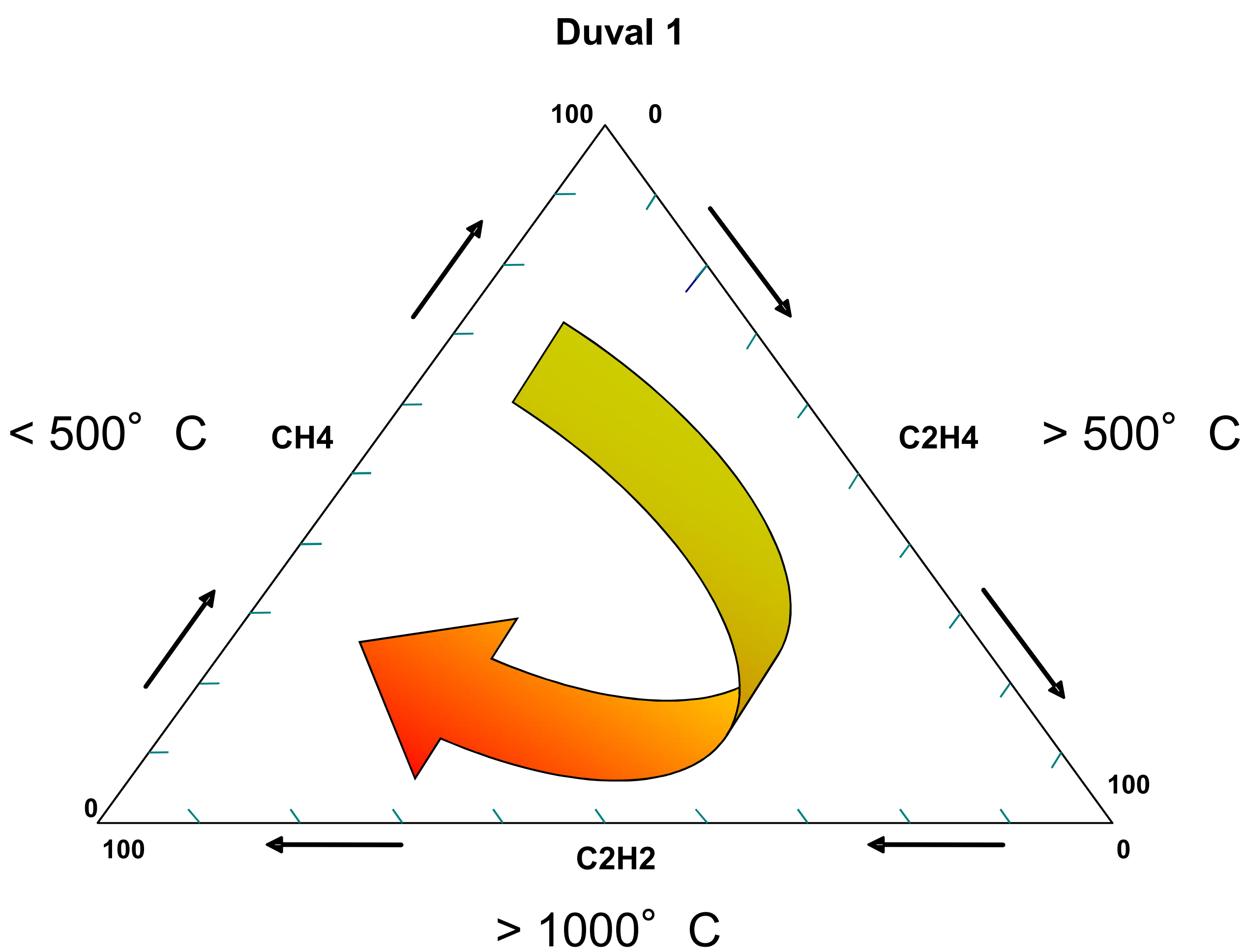
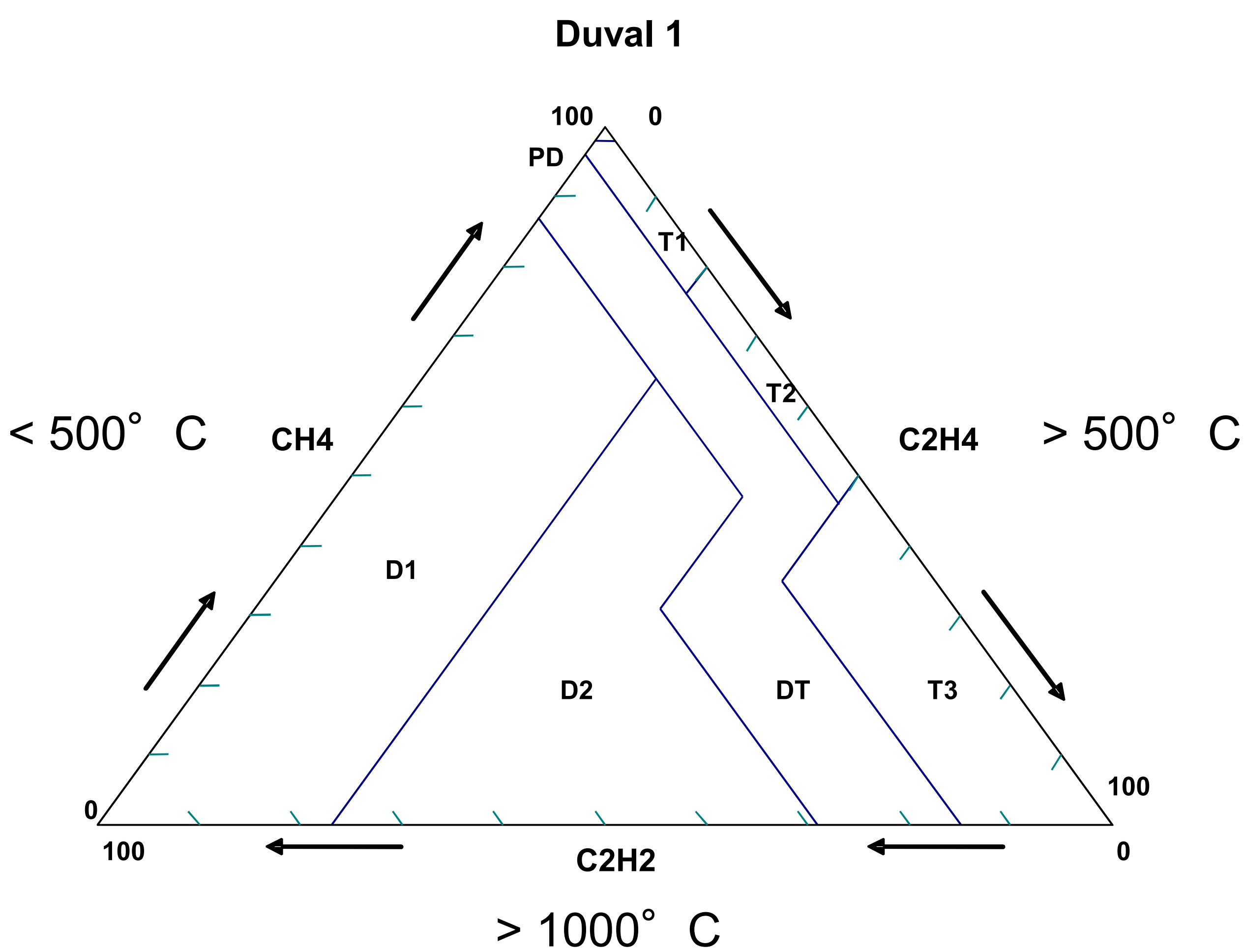
Duval Triangle 1: Temperature of gas formation



Duval Triangle 1



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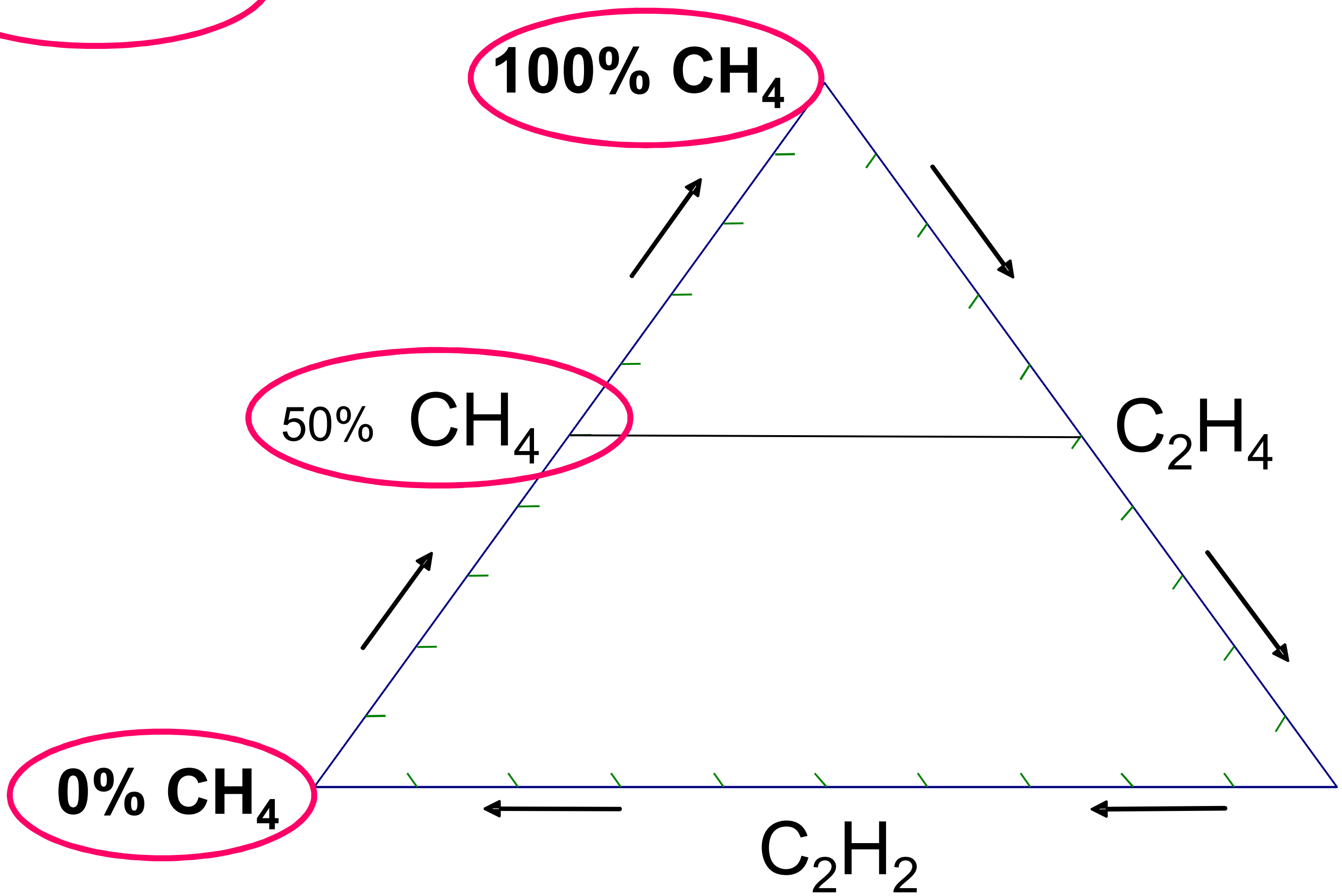
How to Place a Point in a Duval Triangle

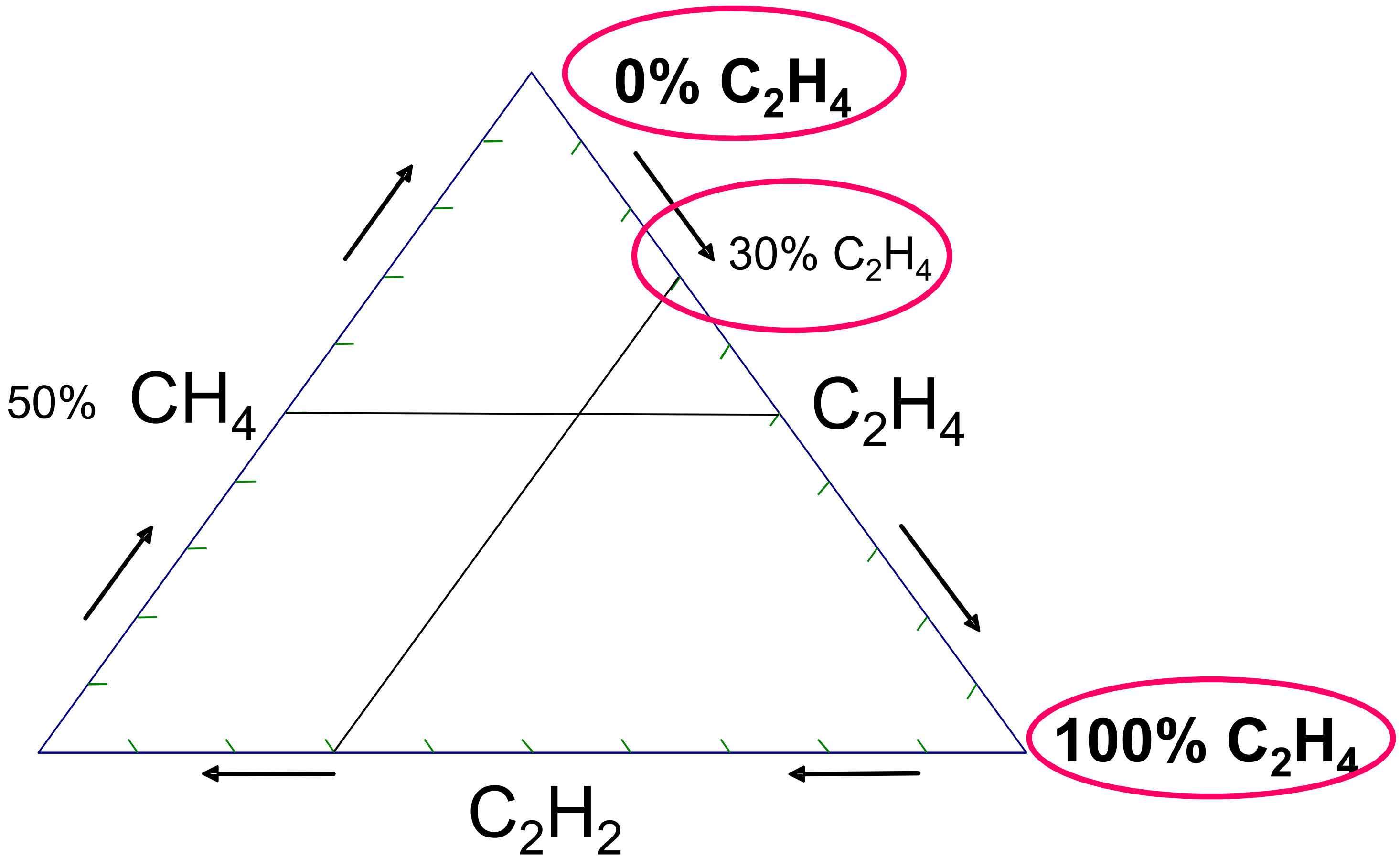
CH_4 = 50%



How to Place a Point in a Duval Triangle

CH_4 = 50%

C_2H_4 = 30%

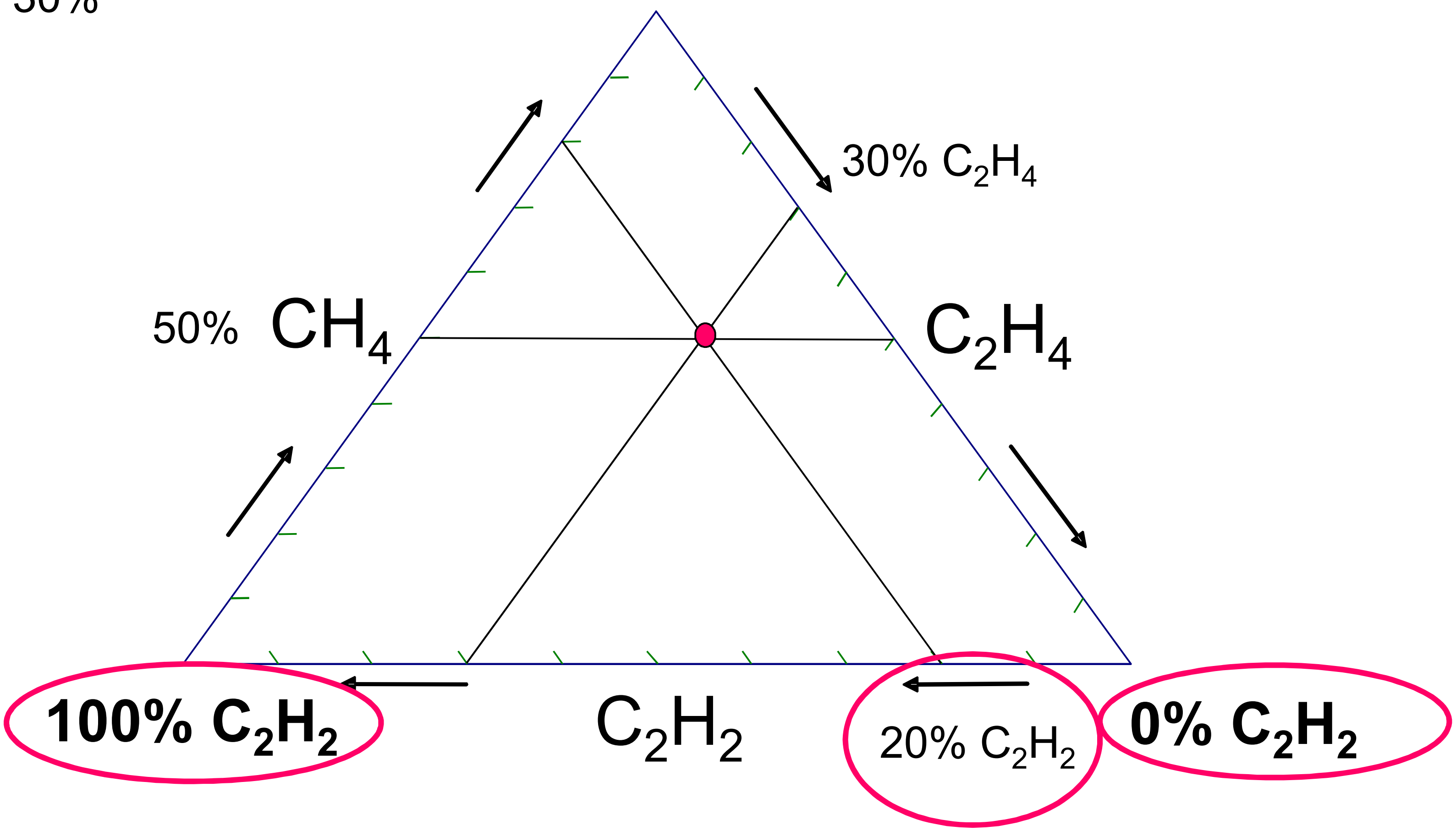


How to Place a Point in a Duval Triangle

CH_4 = 50%

C_2H_4 = 30%

C_2H_2 = 100% - $\%CH_4$ - $\%C_2H_4$ = 20%



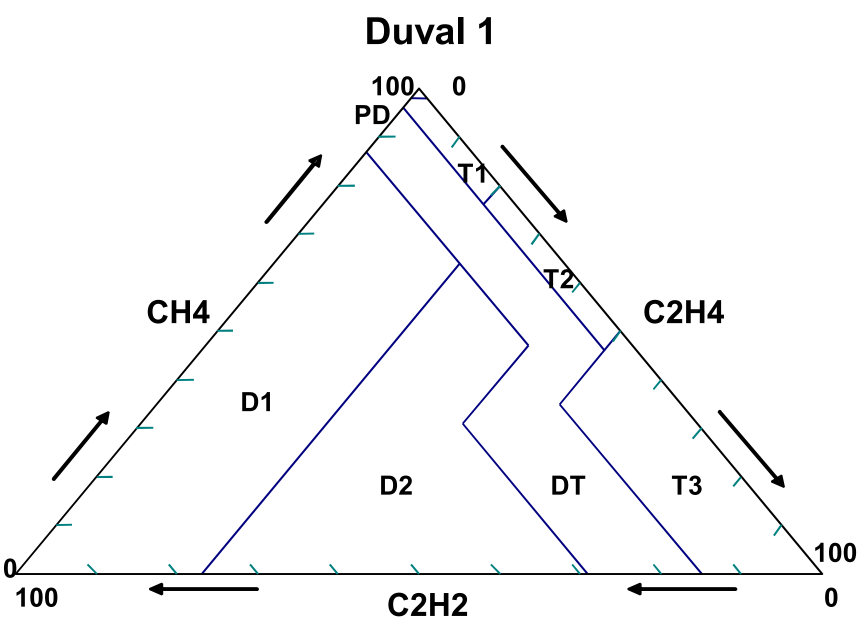
Duval Triangle 1 Zones

• PD	Partial Discharges
• T1	Low Temperature < 300 ºC
• T2	Medium Temperature 300 - 700 ºC
• T3	High Temperature > 700 ºC
• DT	Discharges with Thermal
• D1	Discharges of High Energy
• D2	Discharges of Low Energy

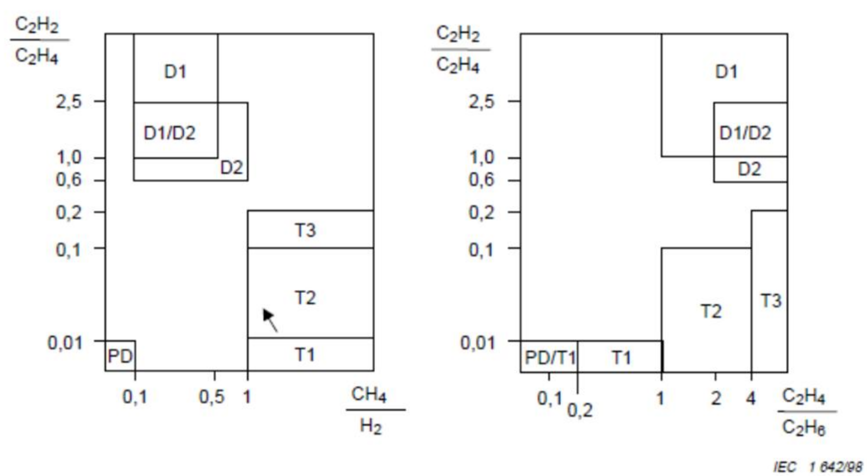
Duval Triangle 1 and IEC 60599

- 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



Case	Characteristic fault	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
PD	Partial discharges (see notes 3 and 4)	NS[1)]	<0,1	<0,2
D1	Discharges of low energy	>1	0,1 – 0,5	>1
D2	Discharges of high energy	0,6 – 2,5	0,1 – 1	>2
T1	Thermal fault t < 300 °C	NS[1)]	>1 but NS[1)]	<1
T2	Thermal fault 300 °C < t < 700 °C	<0,1	>1	1 – 4
T3	Thermal fault t > 700 °C	<0,2[2)]	>1	>4



Duval 1

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

University of New South Wales Study on 92 Cases

Method	Faults Code	Number of predictions (P)	Number of correct predictions (R)	% Successful prediction (S)	Consistency (C)
Roger	F_1	10	5	50%	45%
	F_2	13	13	39%	
	F_3	13	12	55%	
	F_4	9	8	57%	
	F_5	4	3	23%	
IEC	F_1	6	5	50%	60%
	F_2	26	26	79%	
	F_3	19	18	82%	
	F_4	9	9	64%	
	F_5	6	3	23%	
Nomograph	F_1	15	2	20%	74%
	F_2	24	23	70%	
	F_3	19	18	82%	
	F_4	20	14	100%	
	F_5	14	13	100%	

Method	Faults Code	Number of predictions (P)	Number of correct predictions (R)	% Successful prediction (S)	Consistency (C)
Doernenburg	F_1	3	2	20%	40%
	F_2	15	15	45%	
	F_3	9	8	36%	
	F_4	7	6	43%	
	F_5	8	7	54%	
Duval	F_1	10	10	100%	88%
	F_2	32	30	91%	
	F_3	26	22	100%	
	F_4	10	7	50%	
	F_5	14	13	100%	
Key Gas	F_1	11	10	100%	78%
	F_2	46	33	100%	
	F_3	11	10	45%	
	F_4	9	7	50%	
	F_5	13	2	92%	

F1 = Low Temperature
F2 = High Temperature
F3 = Arcing
F4 = Partial Discharge
F5 = Normal

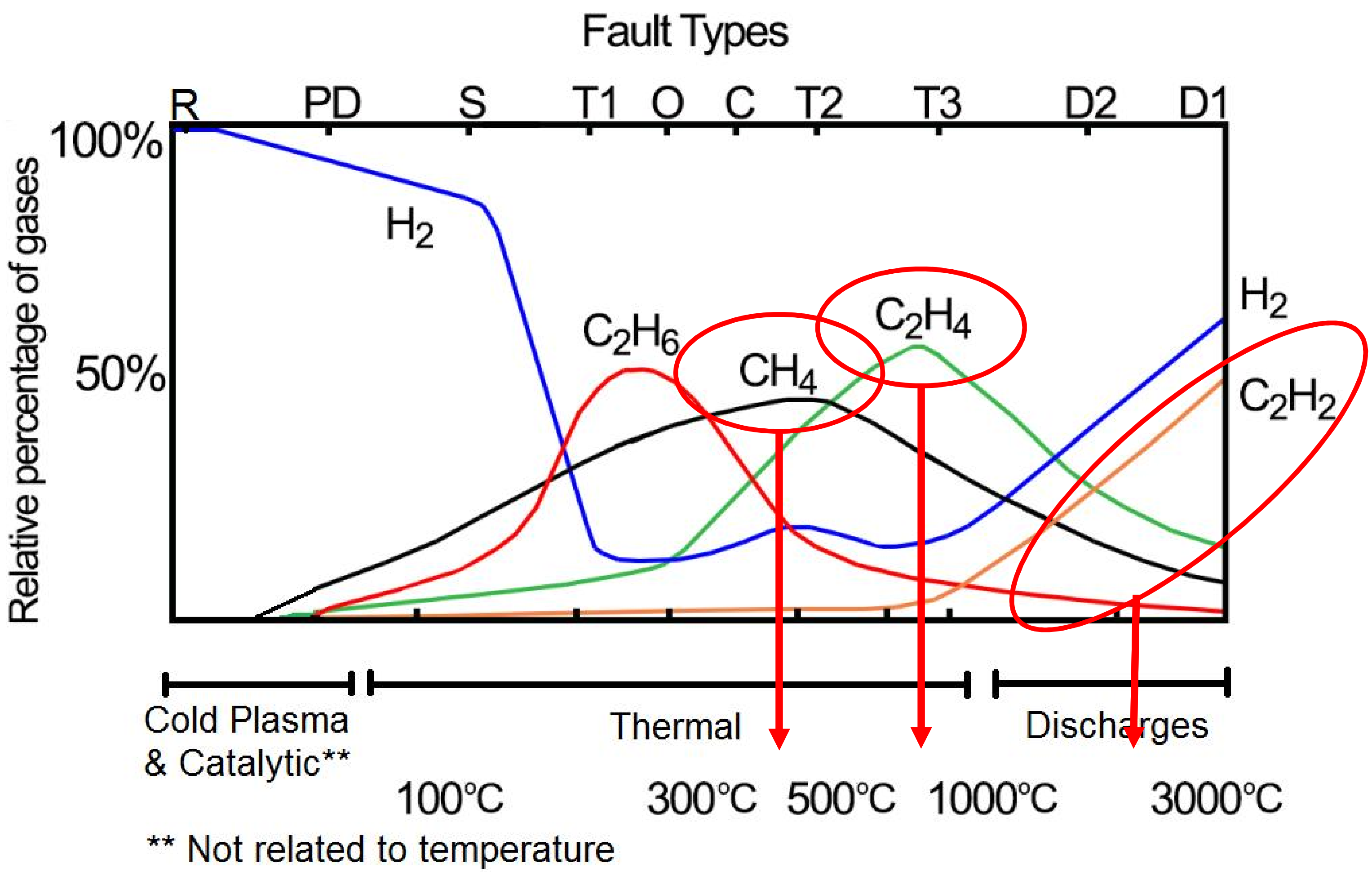
University of New South Wales Study on 92 Cases

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.

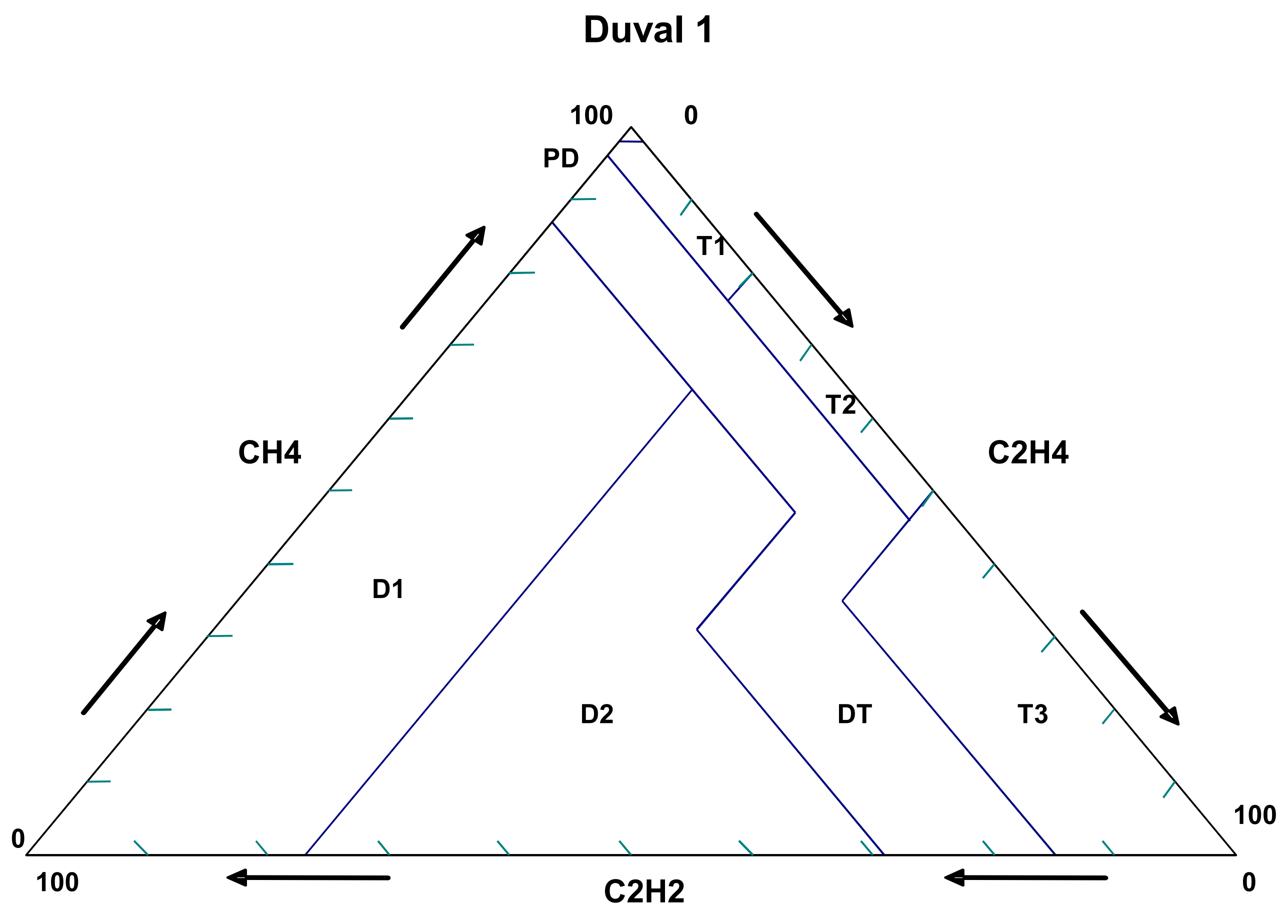
Duval Triangles 4 and 5

- 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

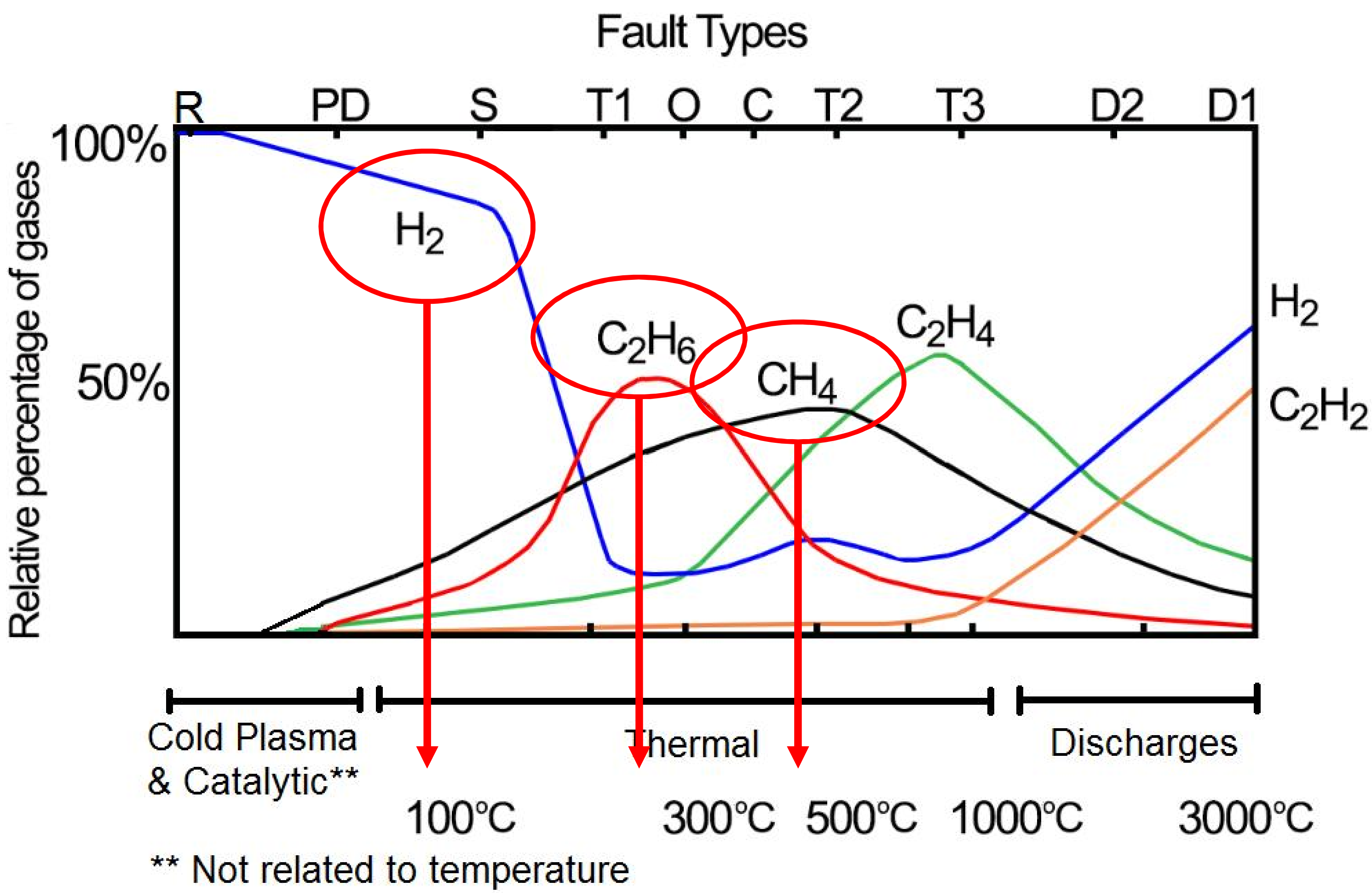
Relative Gas Generation Duval Triangle 1



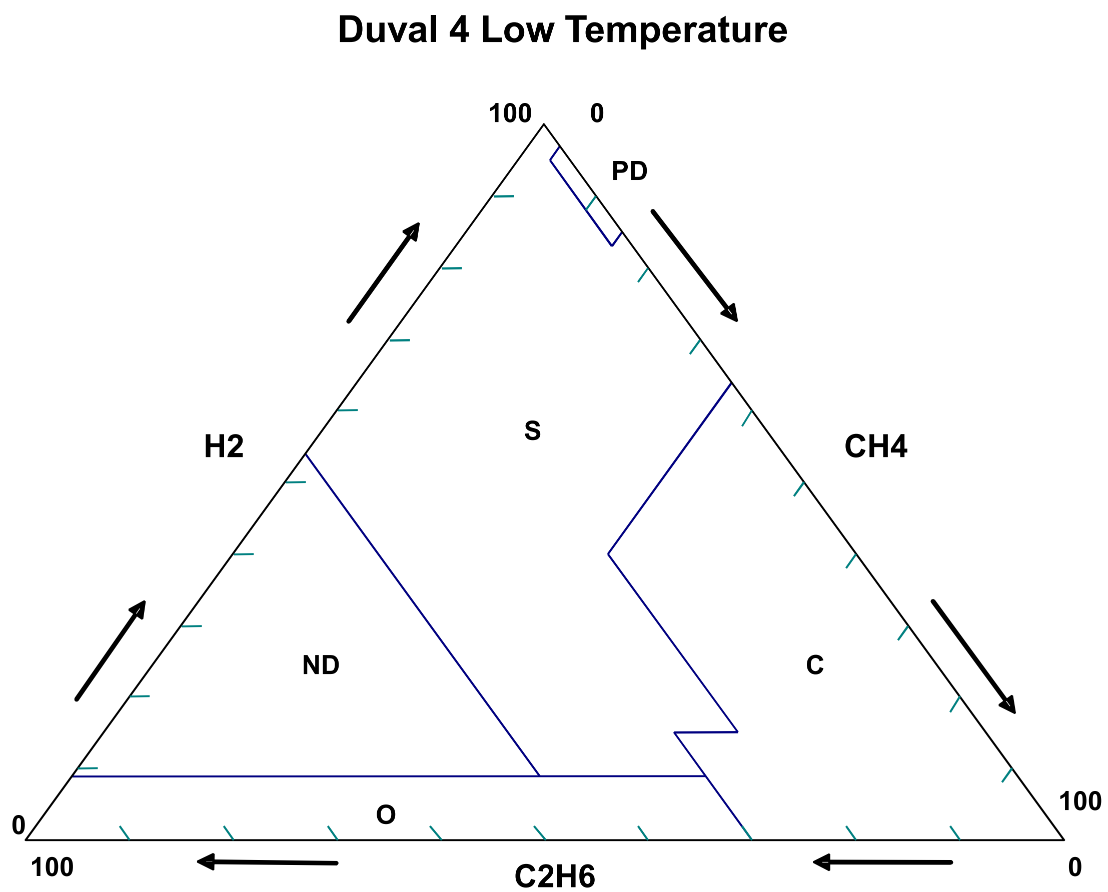
Duval Triangle 1



Relative Gas Generation Duval Triangle 4

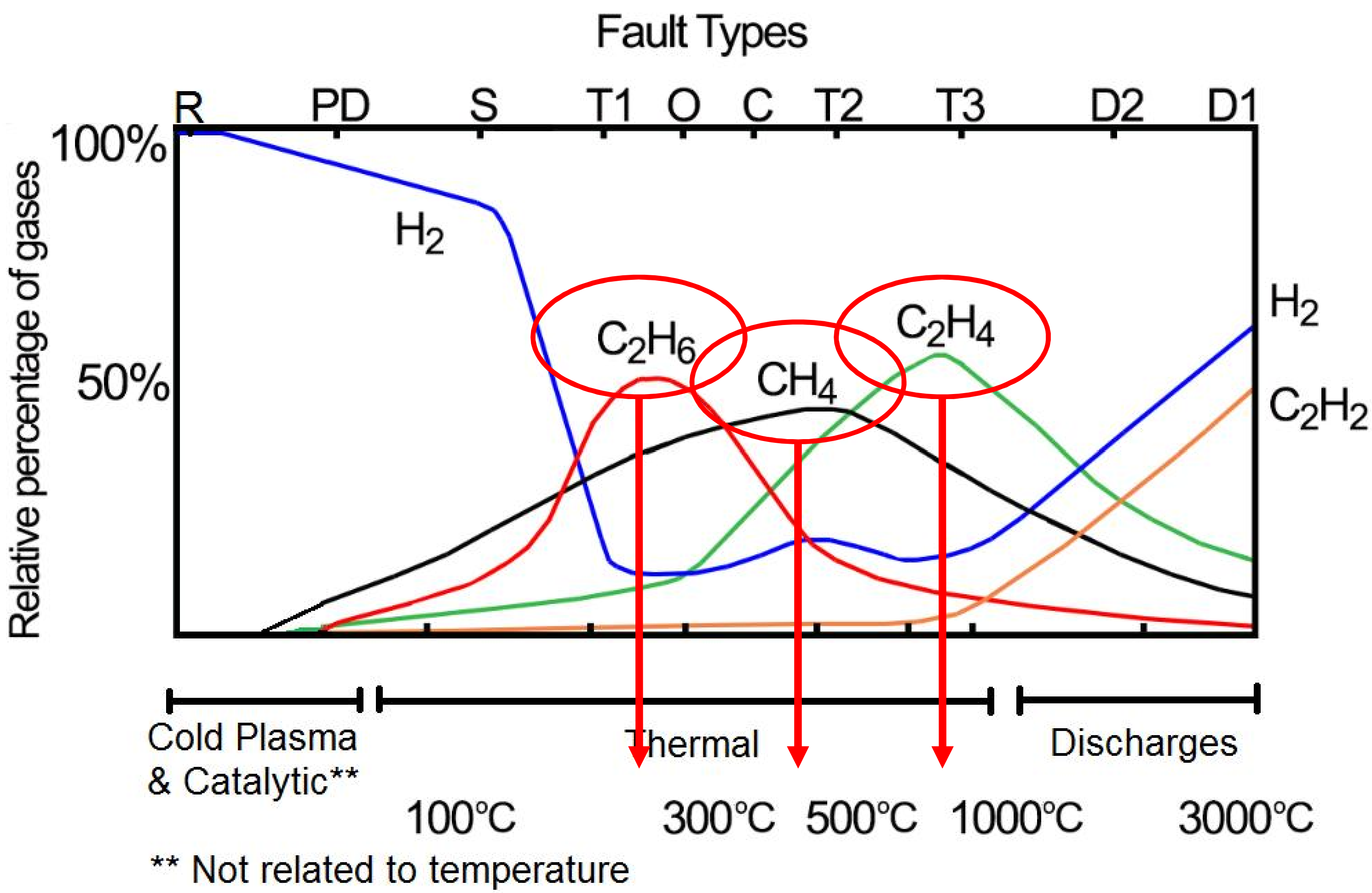


Duval Triangle 4 for Low Energy Faults

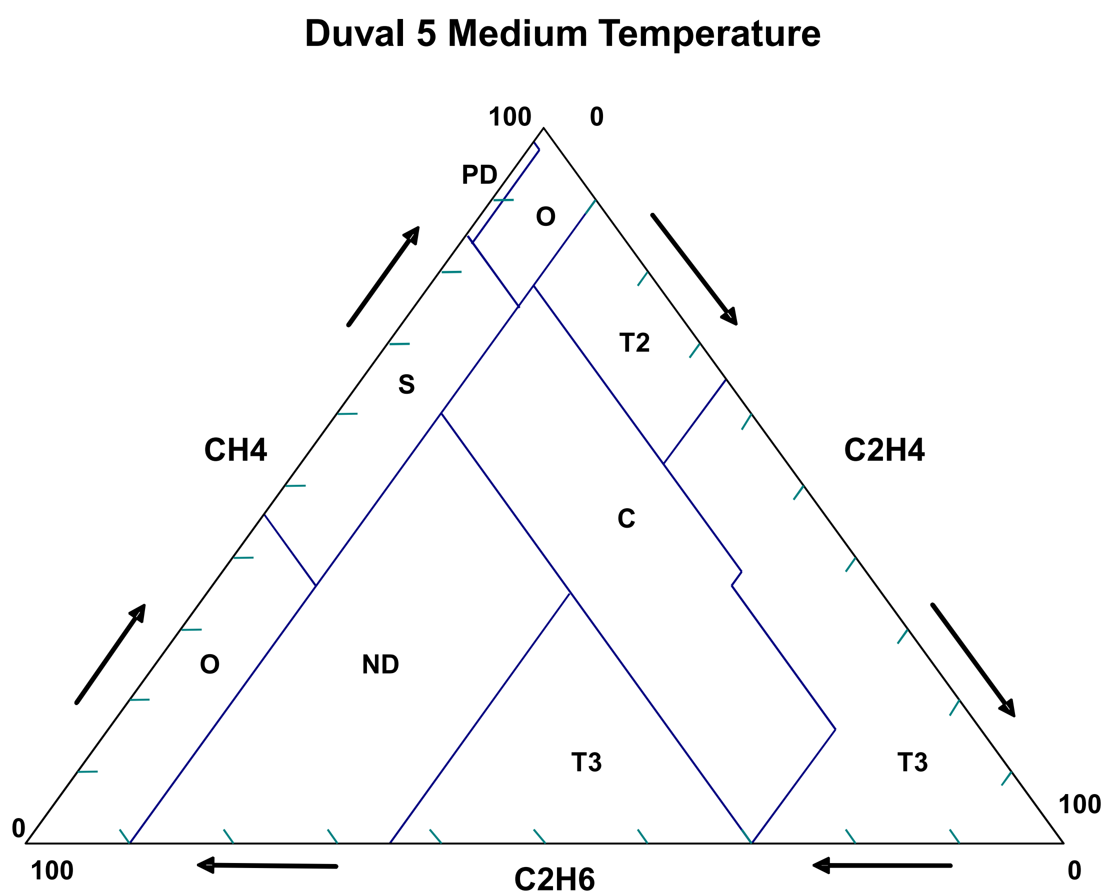


For PD, T1 and T2 of Triangle 1 only

Relative Gas Generation Duval Triangle 5



Duval Triangle 5 for Low Energy Faults



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 < 250C
- ND Not Determined (use Duval 1)
- T2 Medium Temperature 300 - 700 ºC
- T3 High Temperature > 700 ºC

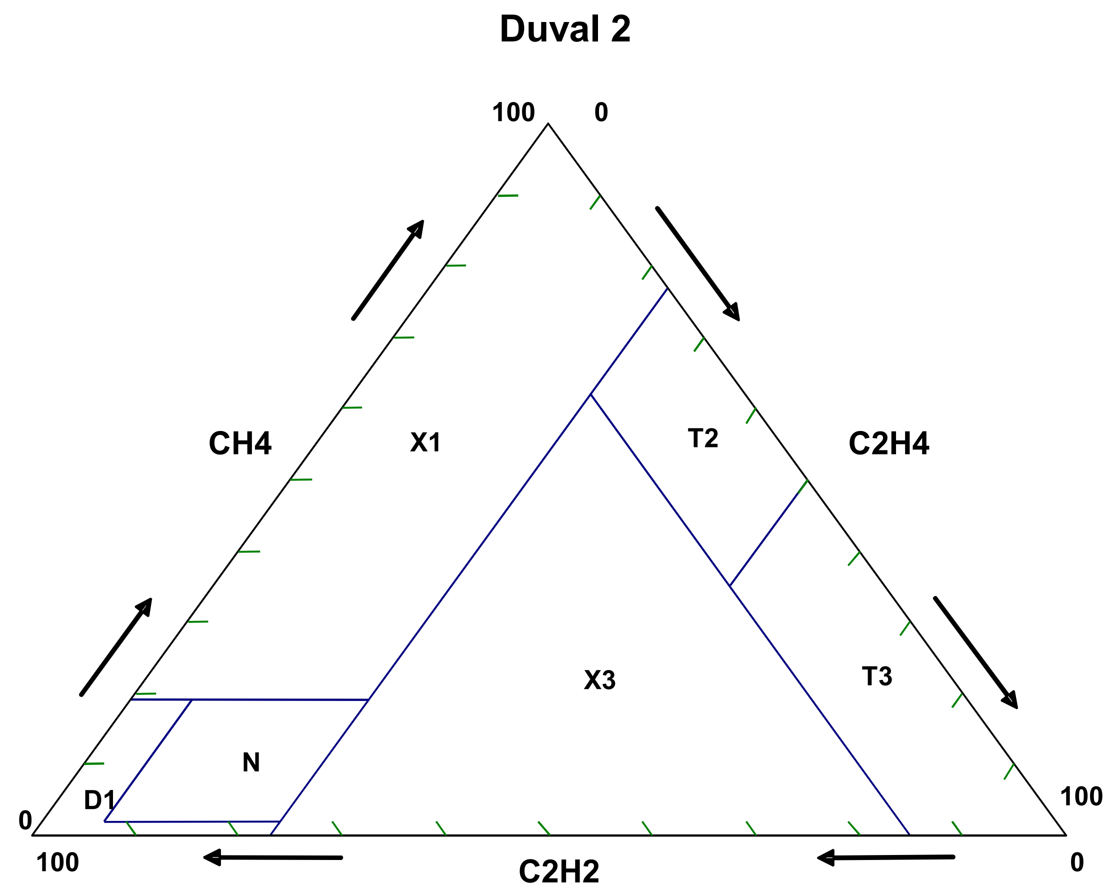
Duval Triangle 4 and 5

- 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



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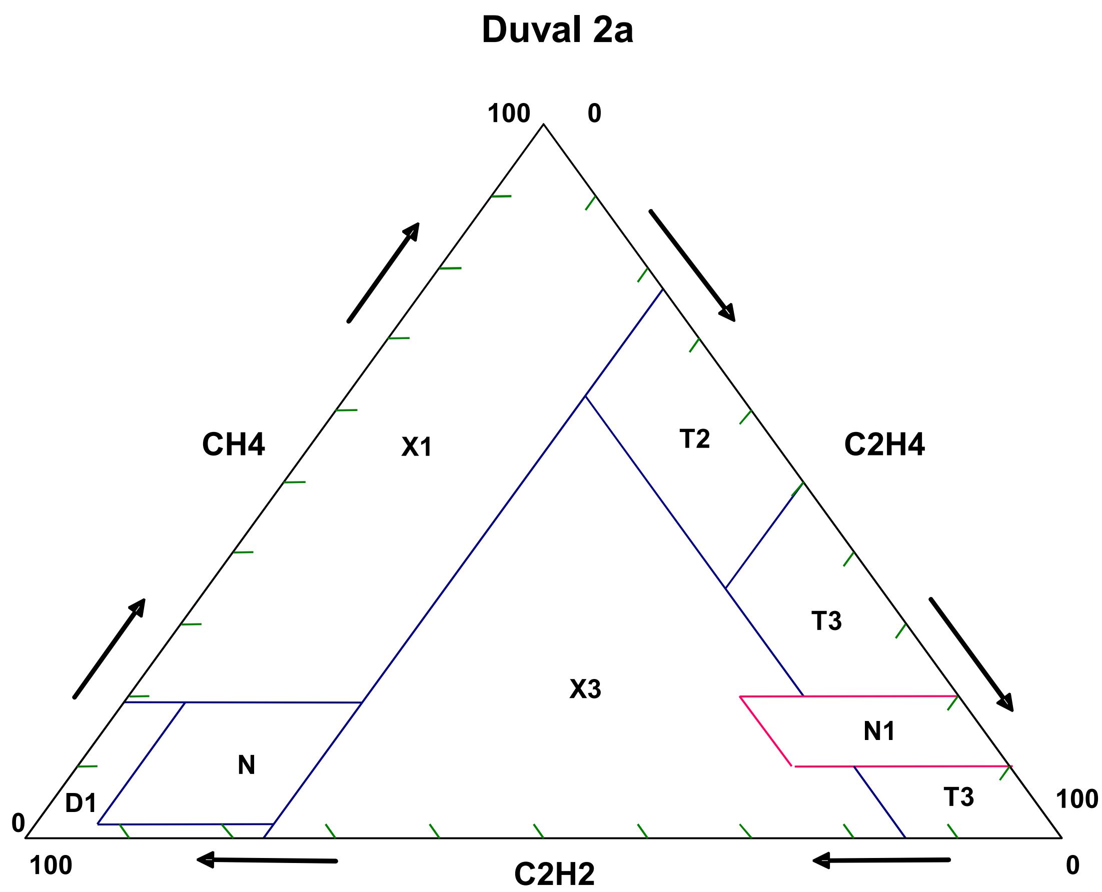
Duval Triangle 2

- N Normal Operation
- T2 Medium Temperature 300 - 700 ºC with Coking
- T3 High Temperature > 700 ºC, with Heavy Coking
- D1 Abnormal Arcing
- X1 Abnormal Arcing/Thermal
- X3 T2 or T3 or possible Abnormal Arcing/Coking

Duval Triangle 2a to 2e

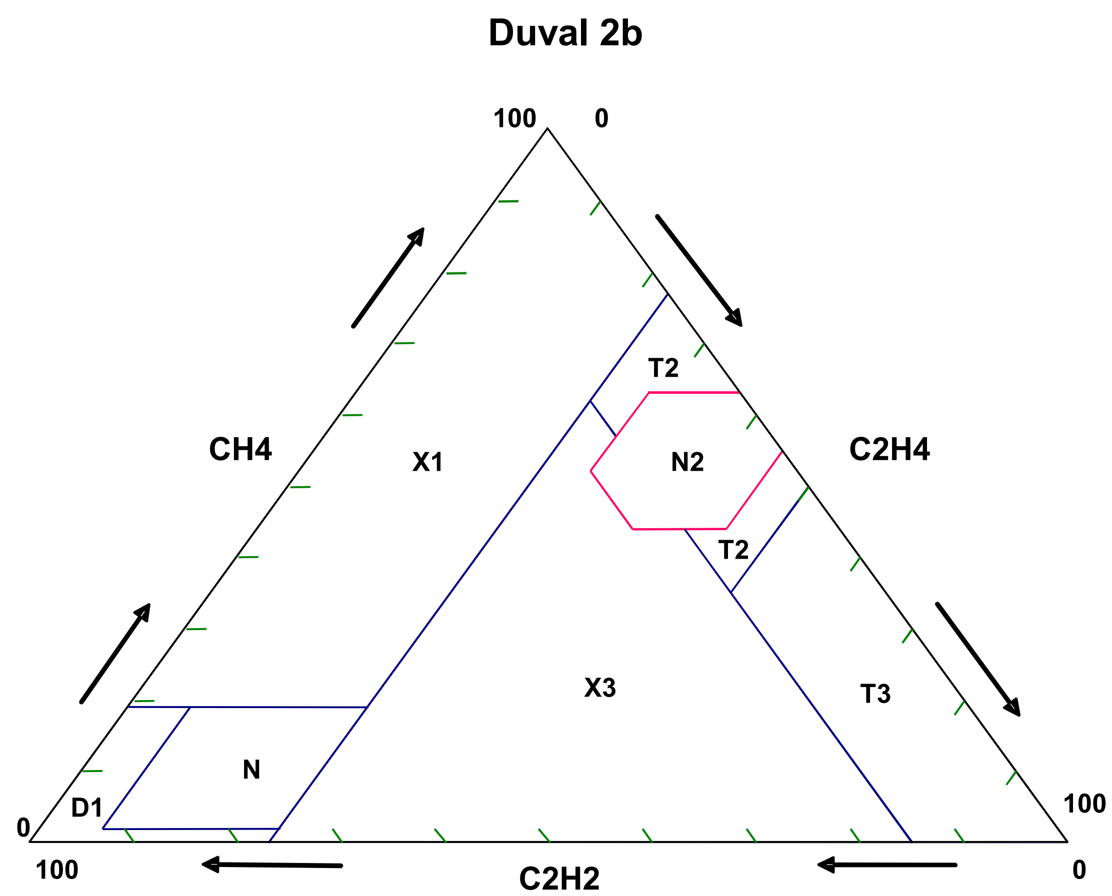
- Proposed to IEEE C57.139 in 2012
- Use same triangle zones as Triangle 2
- Add extra Normal zones (N1 to N5)
- OLTC Model specific
- OLTC application specific (High Powers)
- Mostly apply to MR OLTC

Duval Triangle 2 Type a: MR OilTaps® M & D

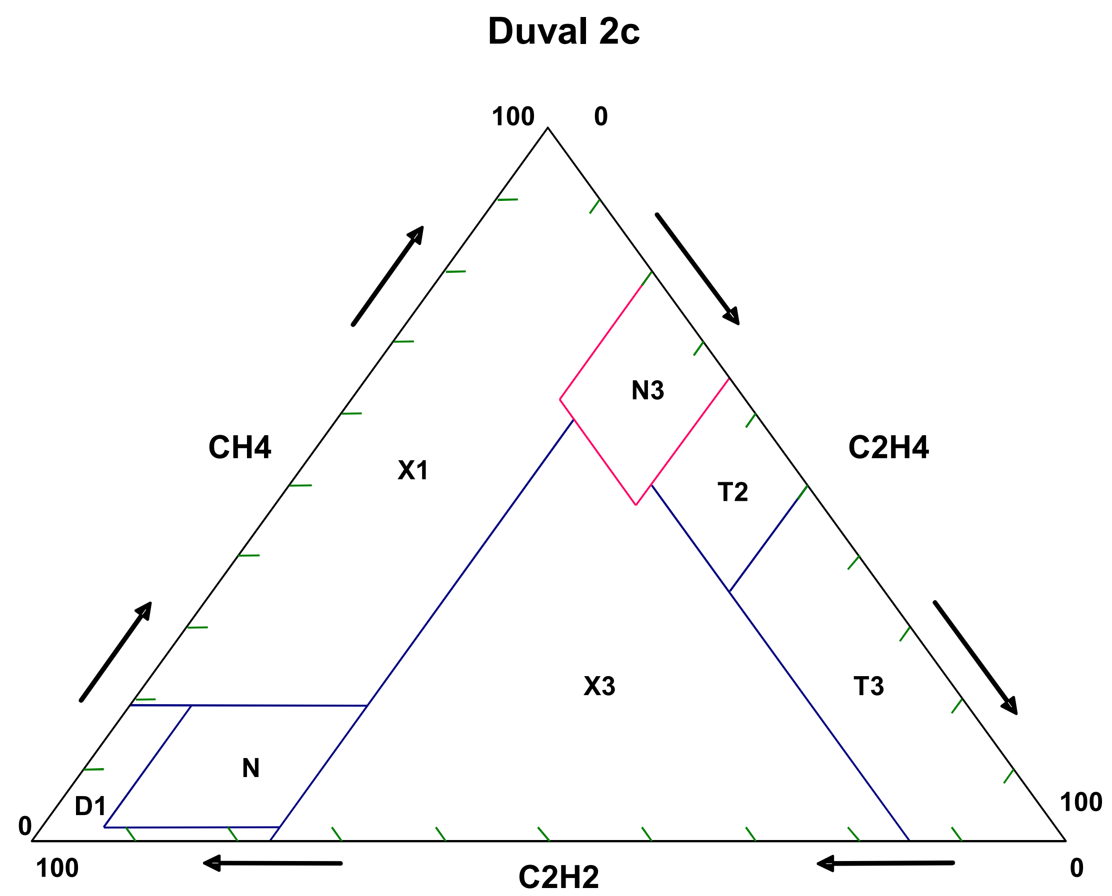


TJ | H2b

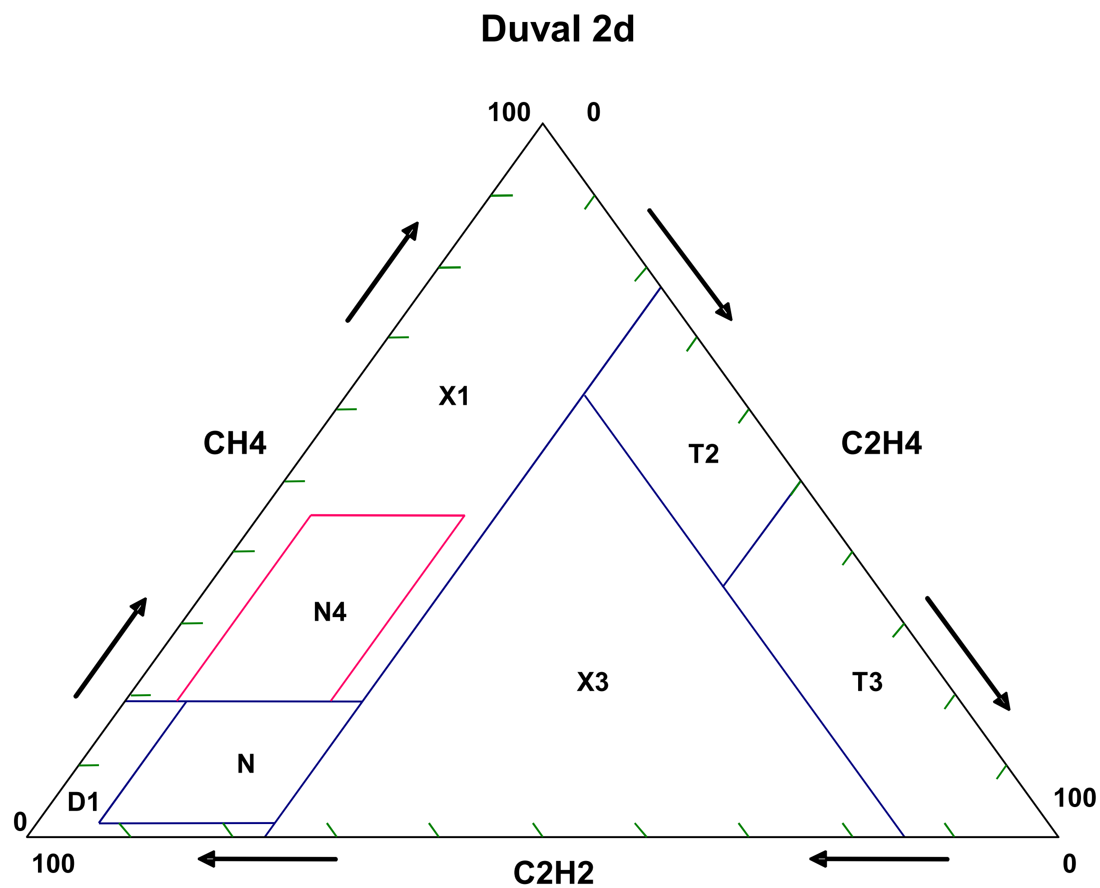
Duval Triangle 2 Type b: MR VacuTaps® VR



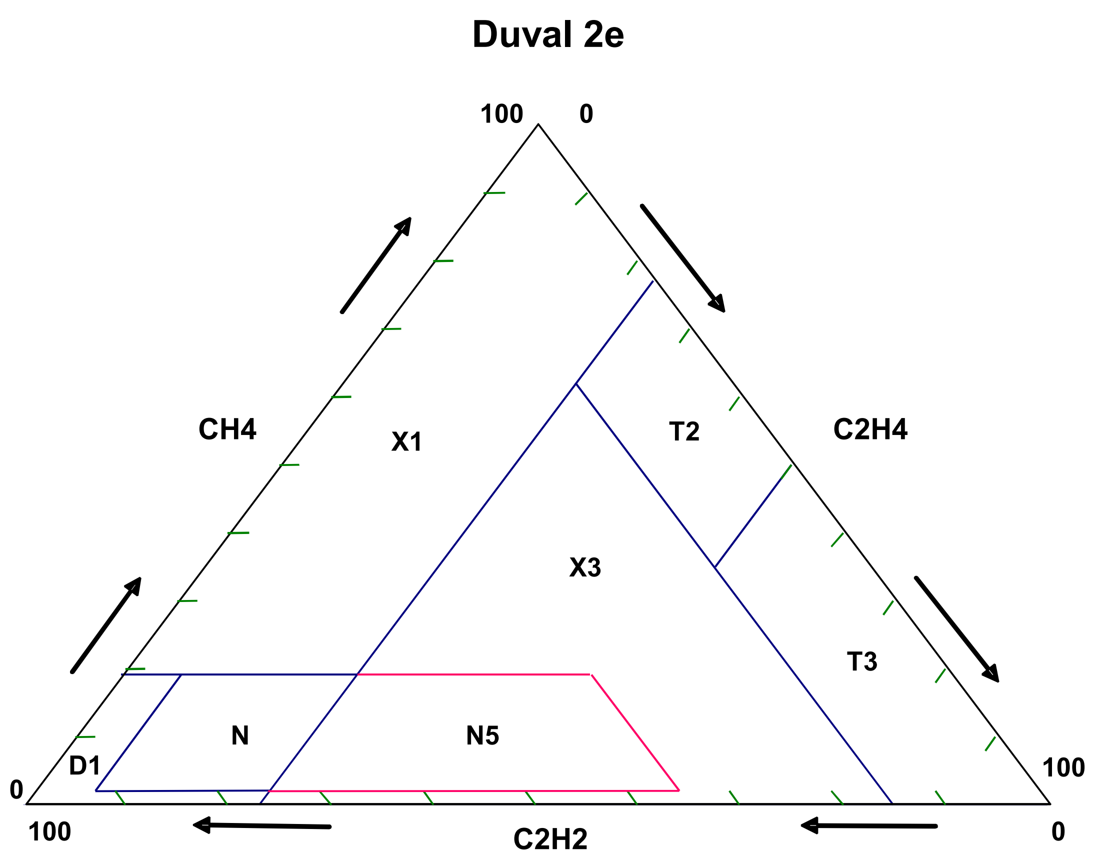
Duval Triangle 2 Type c: MR VacuTaps® VV



Duval Triangle 2 Type d: OilTaps® R & V



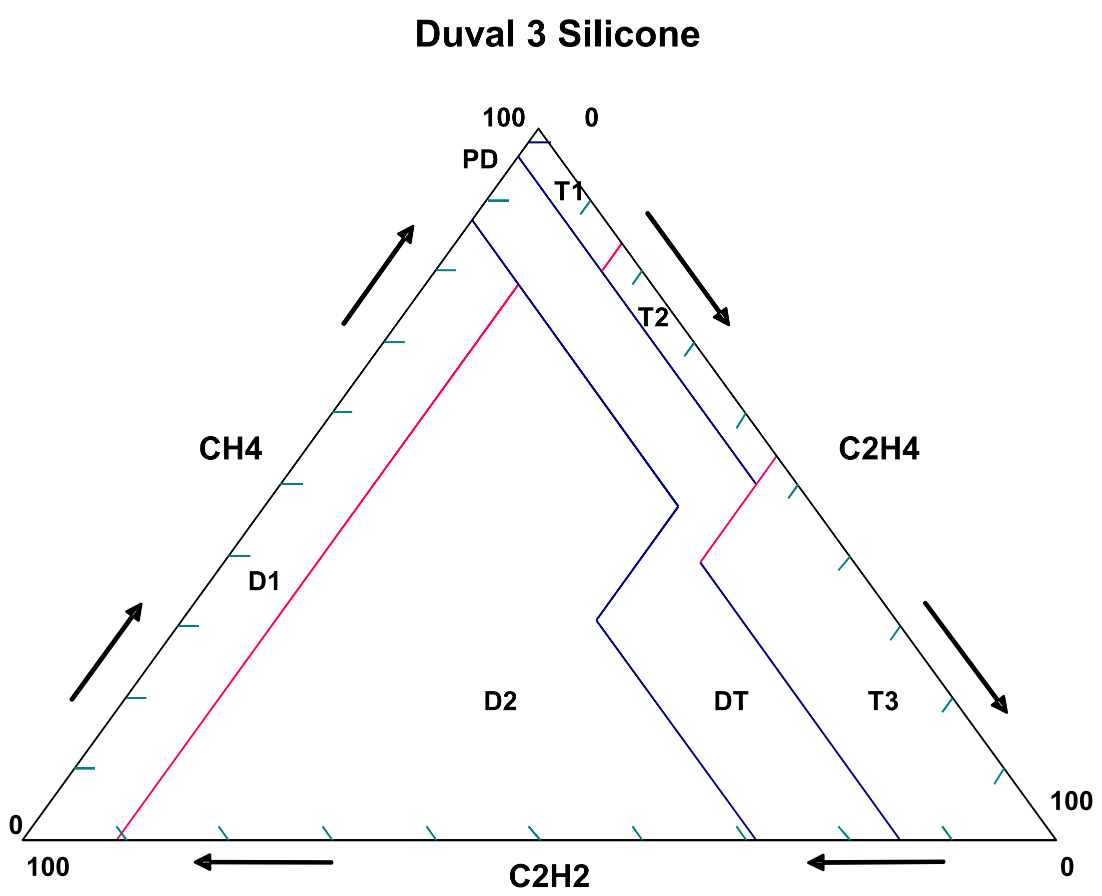
Triangle 2 Type e: MR OilTap G®; ABB few UZD®, some UZB®



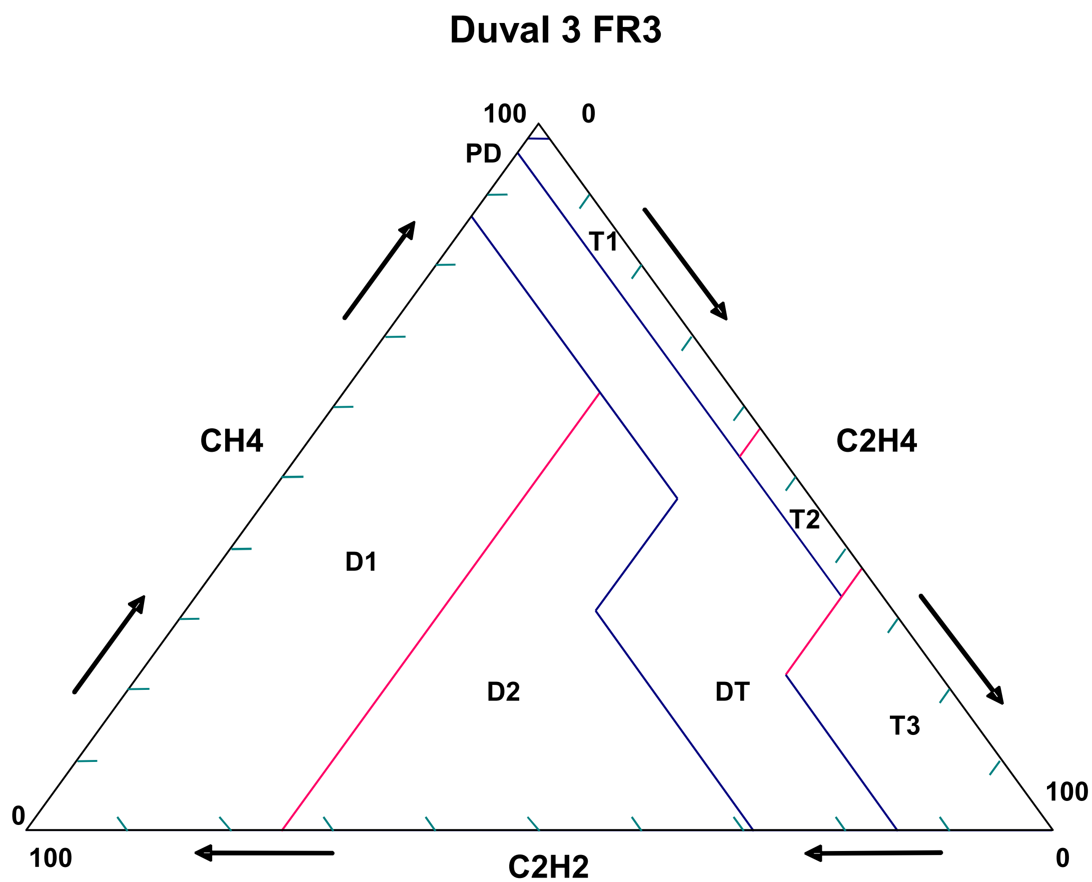
Duval Triangle 3

- 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

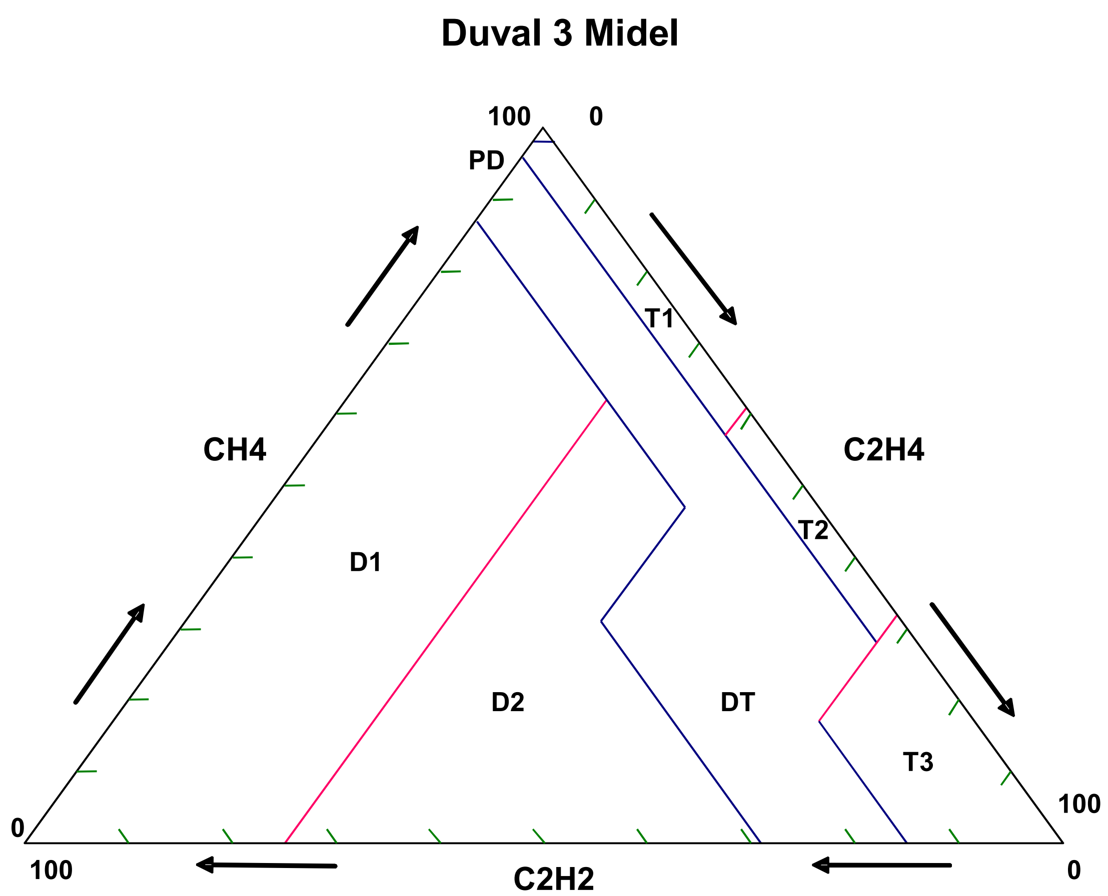
Duval 3 Silicone Oil



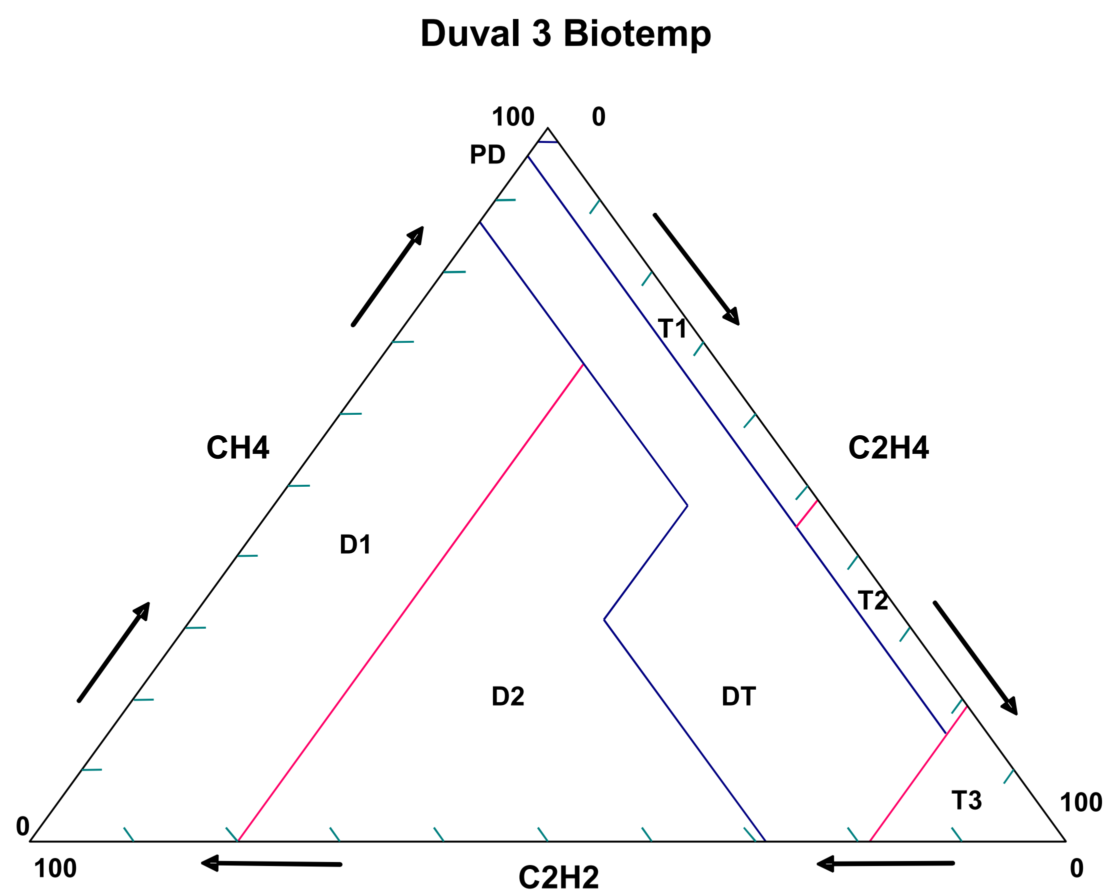
Duval 3 FR3®



Duval Triangle 3 Midel®



Duval Triangle 3 Biotemp®

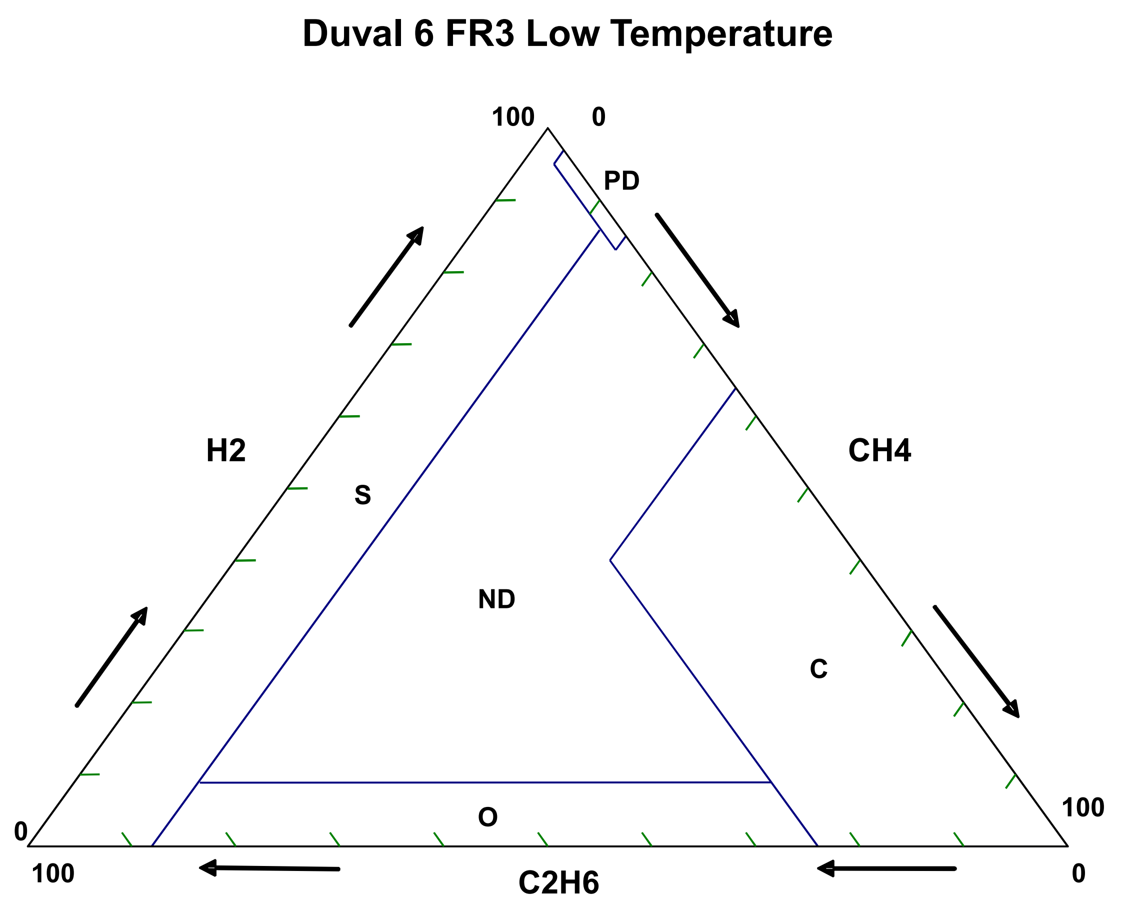


TJ | H 2 b

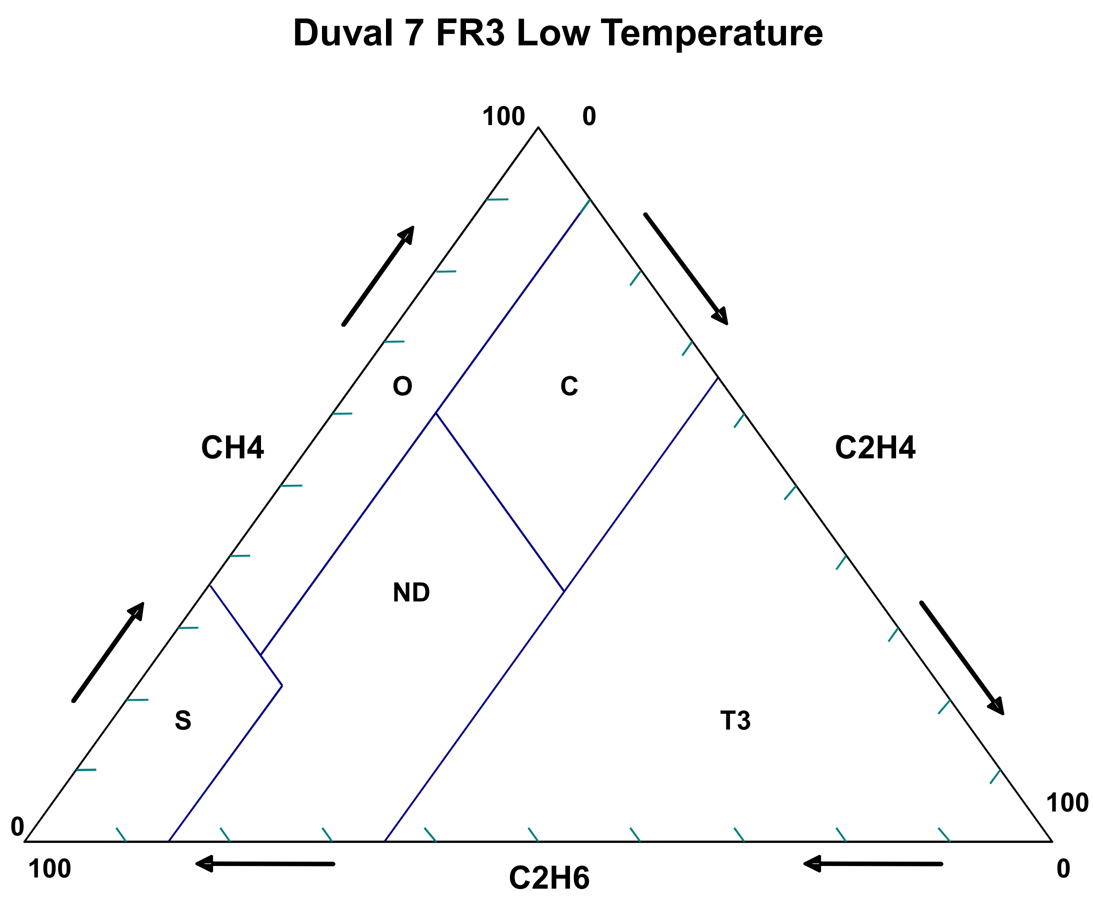
Duval Triangles 6 and 7 for Low Energy Faults in FR3

- 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



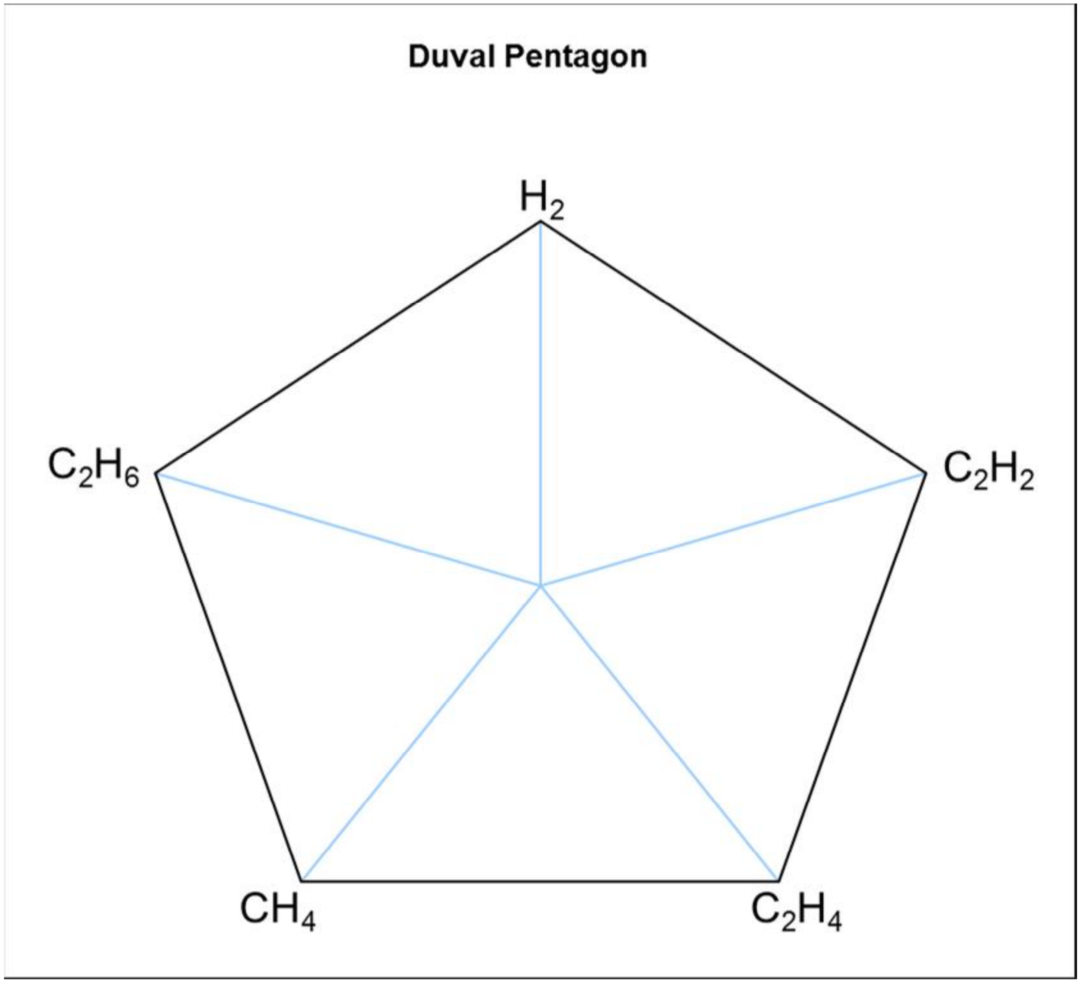
Duval Triangle 7 for Low Energy Faults in FR3



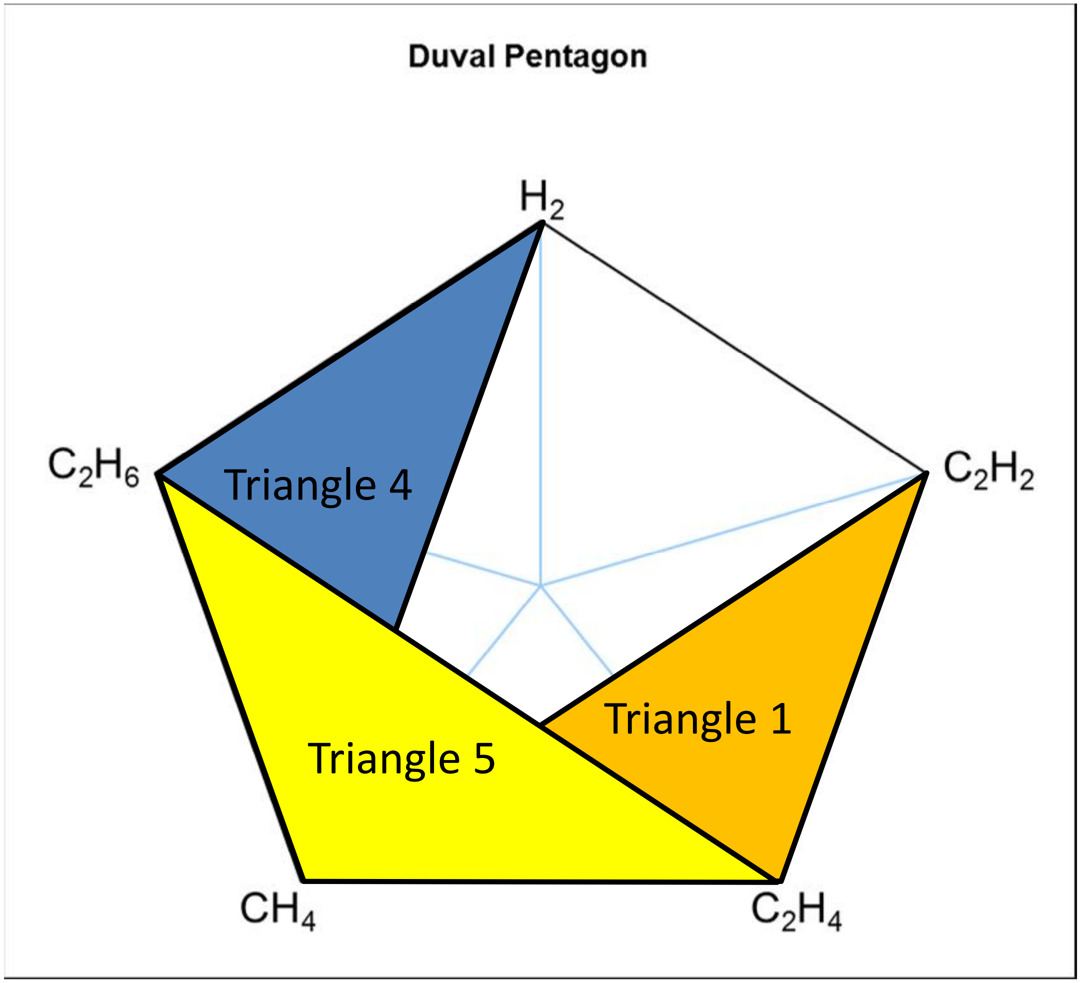
Duval Pentagon 1 and 2

- 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

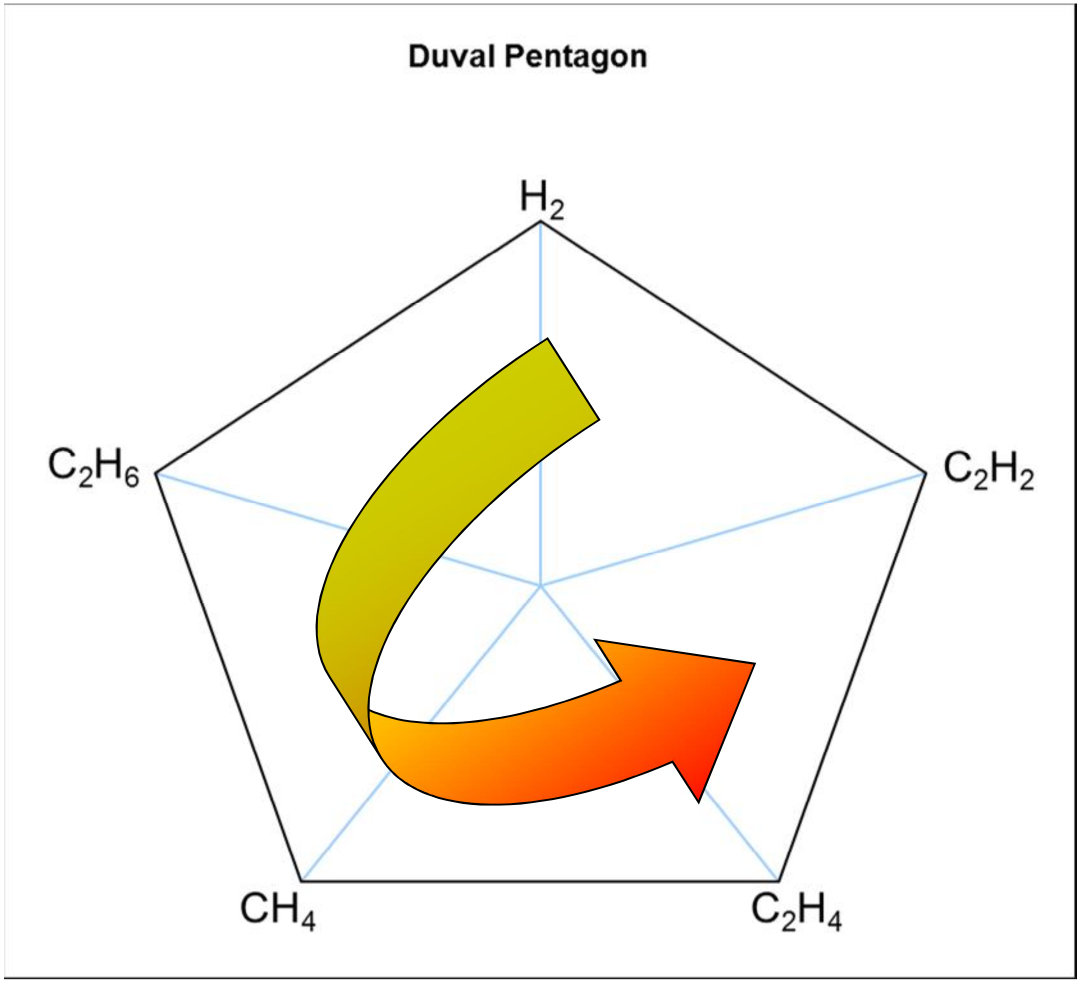
Duval Pentagons: H_2, C_2H_6, CH_4, C_2H_4 and C_2H_2



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

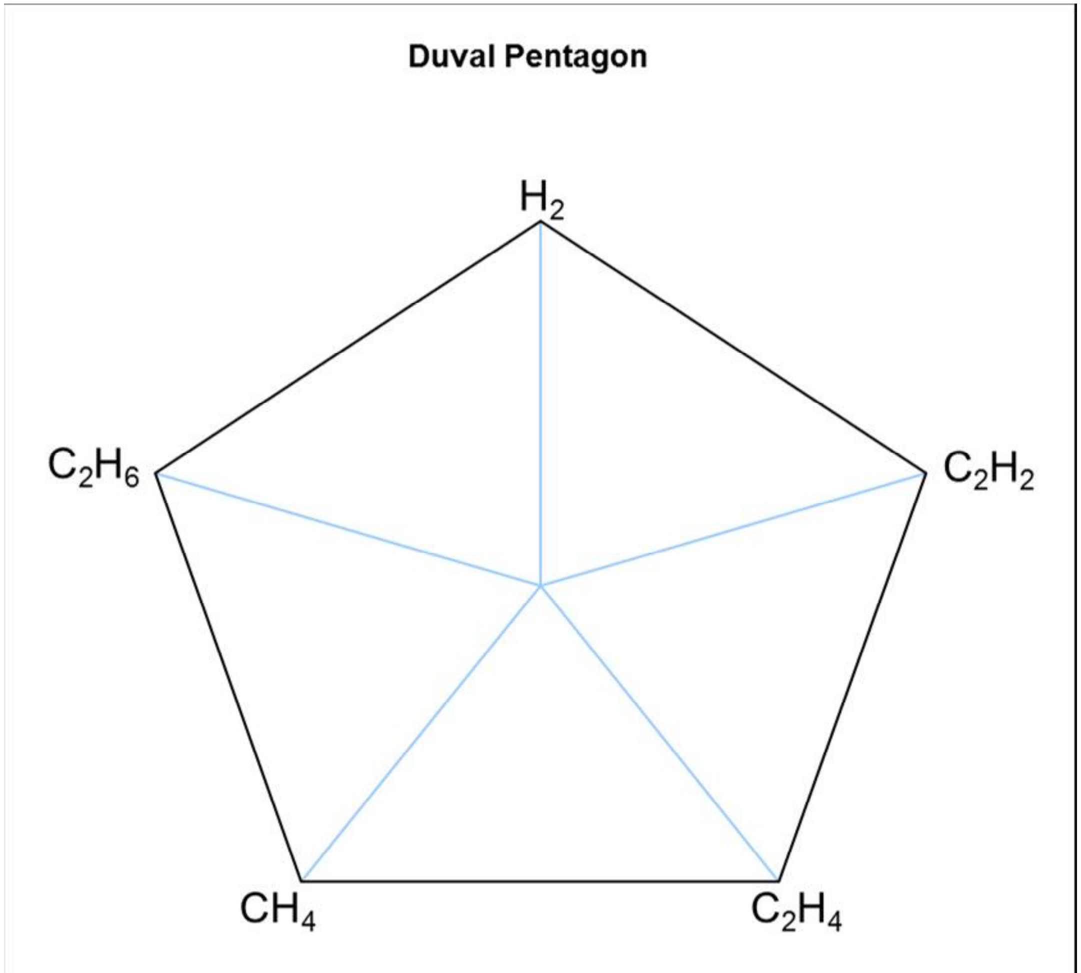
C_2H_6 = 57 ppm

CH_4 = 35 ppm

C_2H_4 = 25 ppm

C_2H_2 = 0 ppm

Total = 192 ppm



Duval Pentagons: place % H_2

Gas

H_2 = 75 ppm

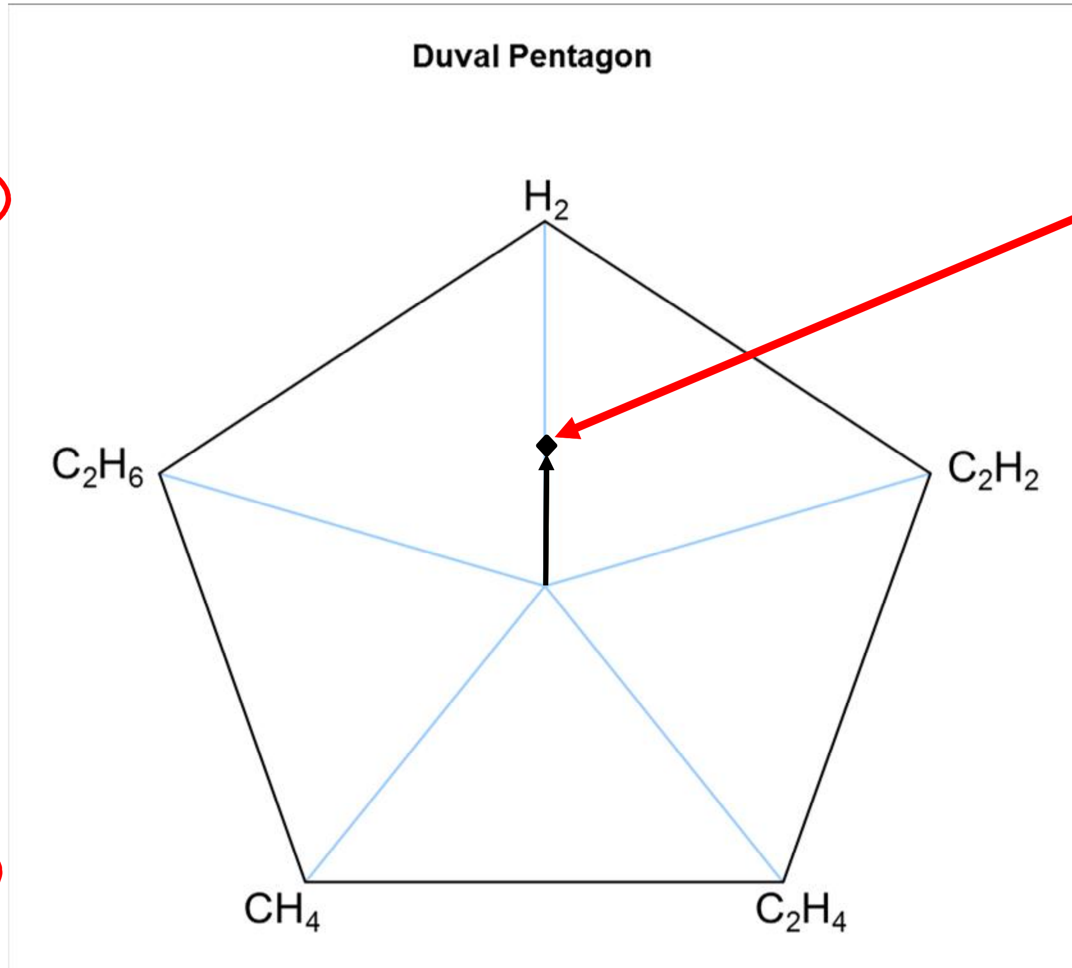
C_2H_6 = 57 ppm

CH_4 = 35 ppm

C_2H_4 = 25 ppm

C_2H_2 = 0 ppm

Total = 192 ppm



% of Total

39 %

Duval Pentagons: place % C_2H_6

Gas

H_2 = 75 ppm

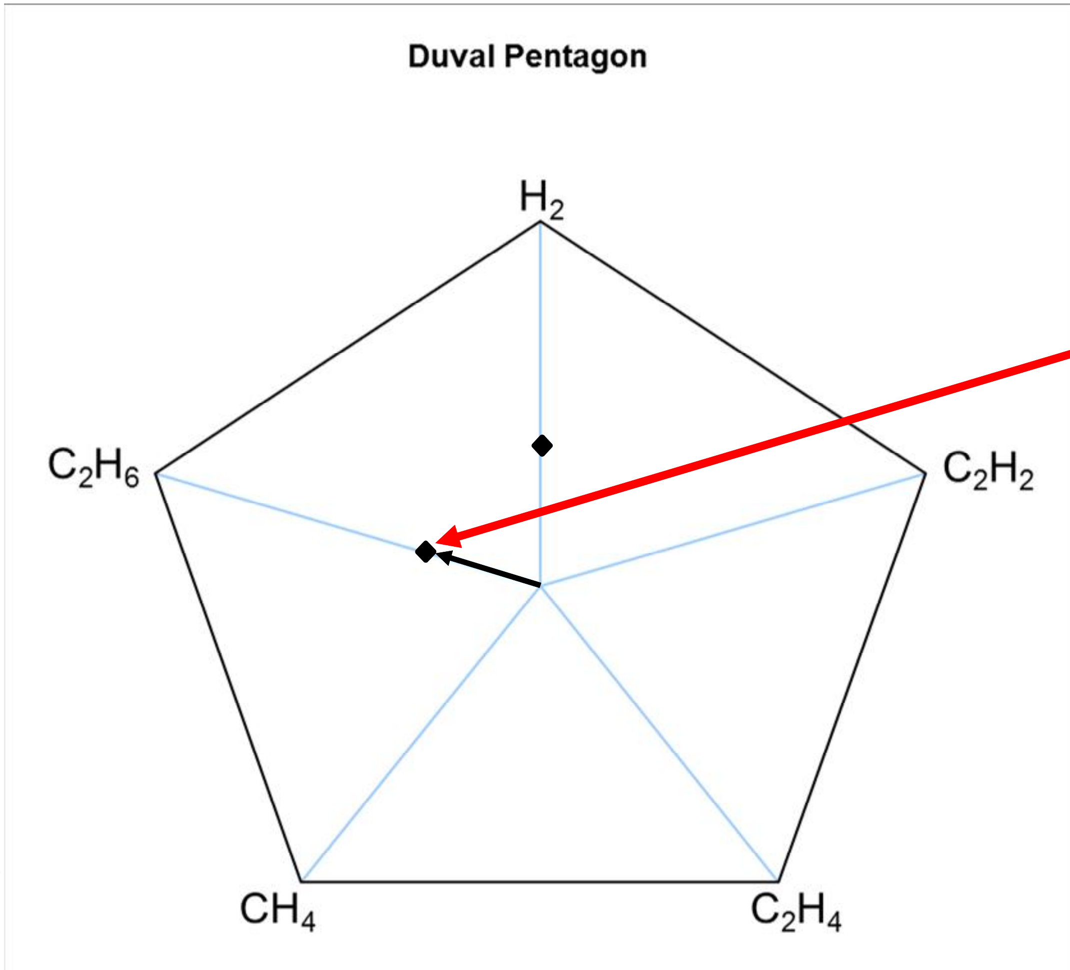
C_2H_6 = 57 ppm

CH_4 = 35 ppm

C_2H_4 = 25 ppm

C_2H_2 = 0 ppm

Total = 192 ppm



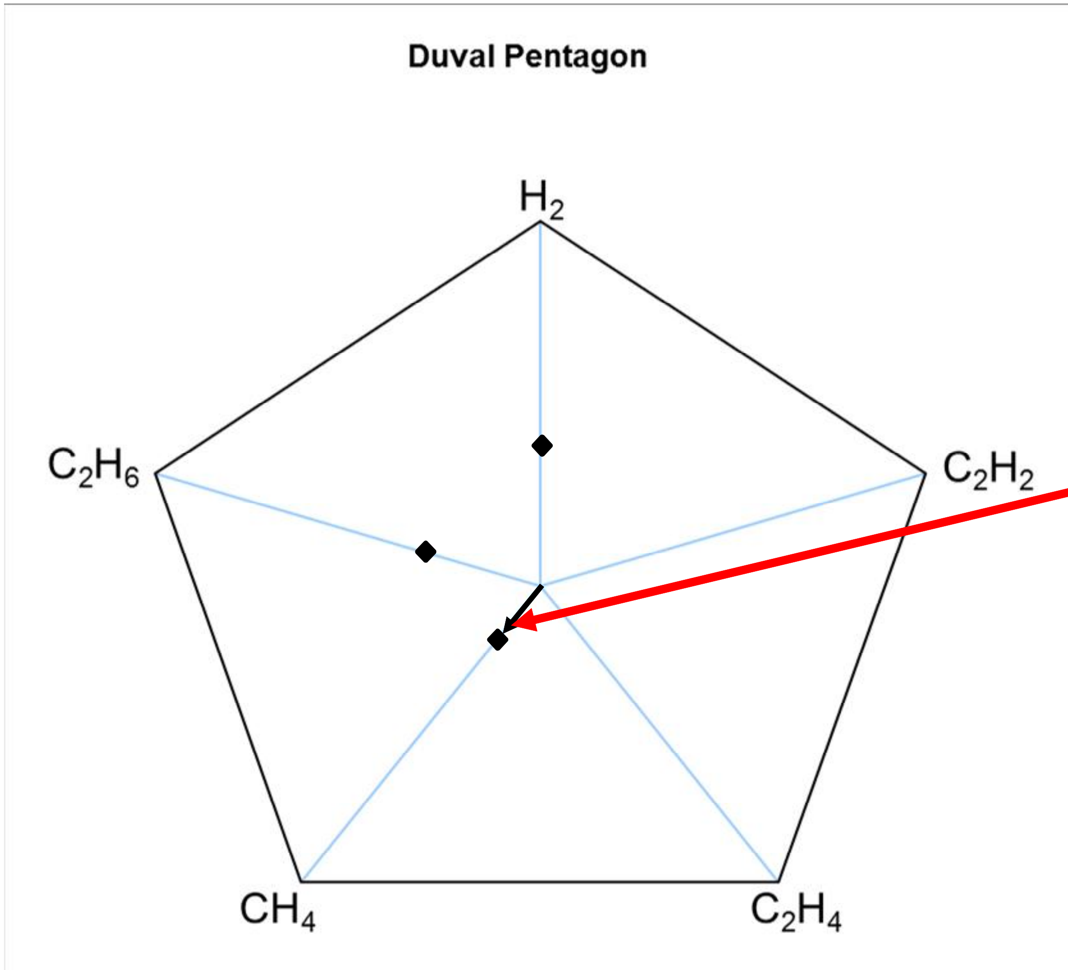
% of Total

39 %

30 %

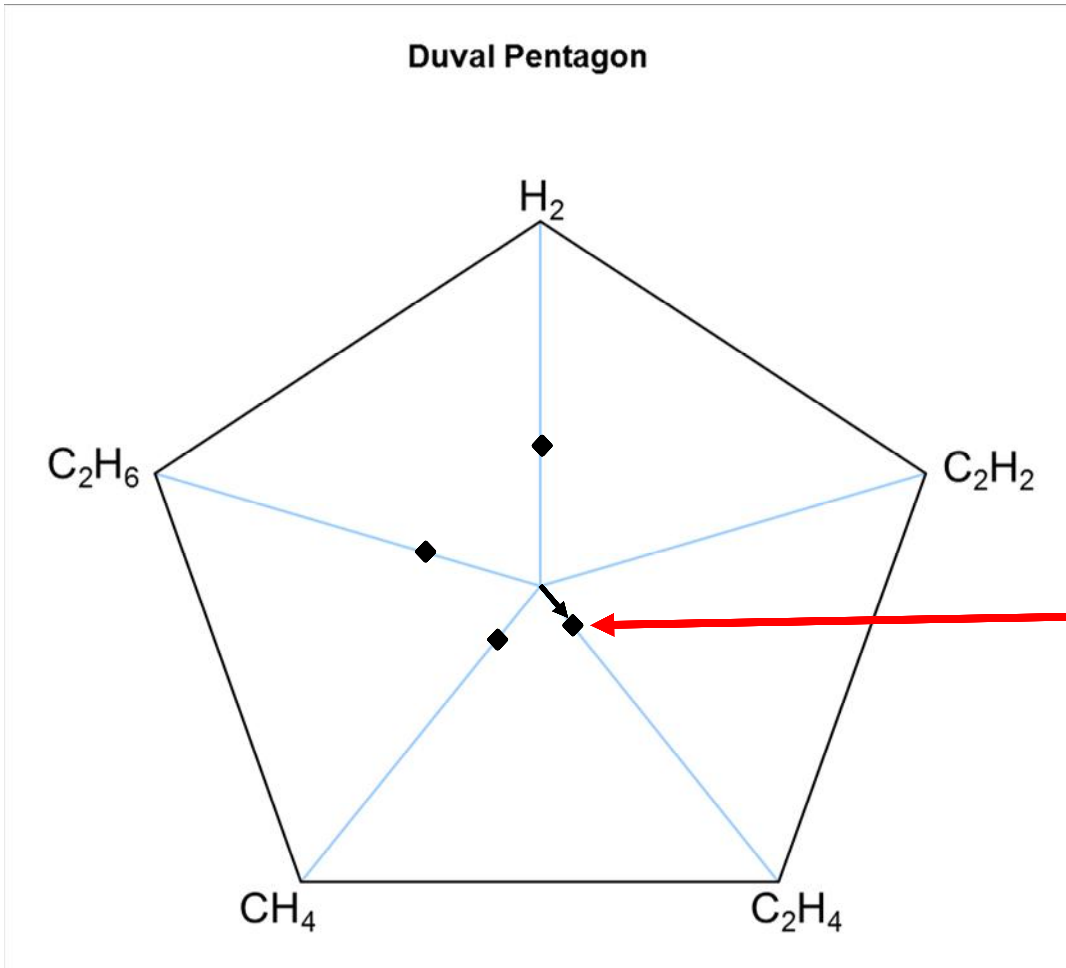
Duval Pentagons: place % CH_4

Gas	% of Total
H_2 = 75 ppm	39 %
C_2H_6 = 57 ppm	30 %
CH_4 = 35 ppm	**18 %**
C_2H_4 = 25 ppm	
C_2H_2 = 0 ppm	
Total = 192 ppm	



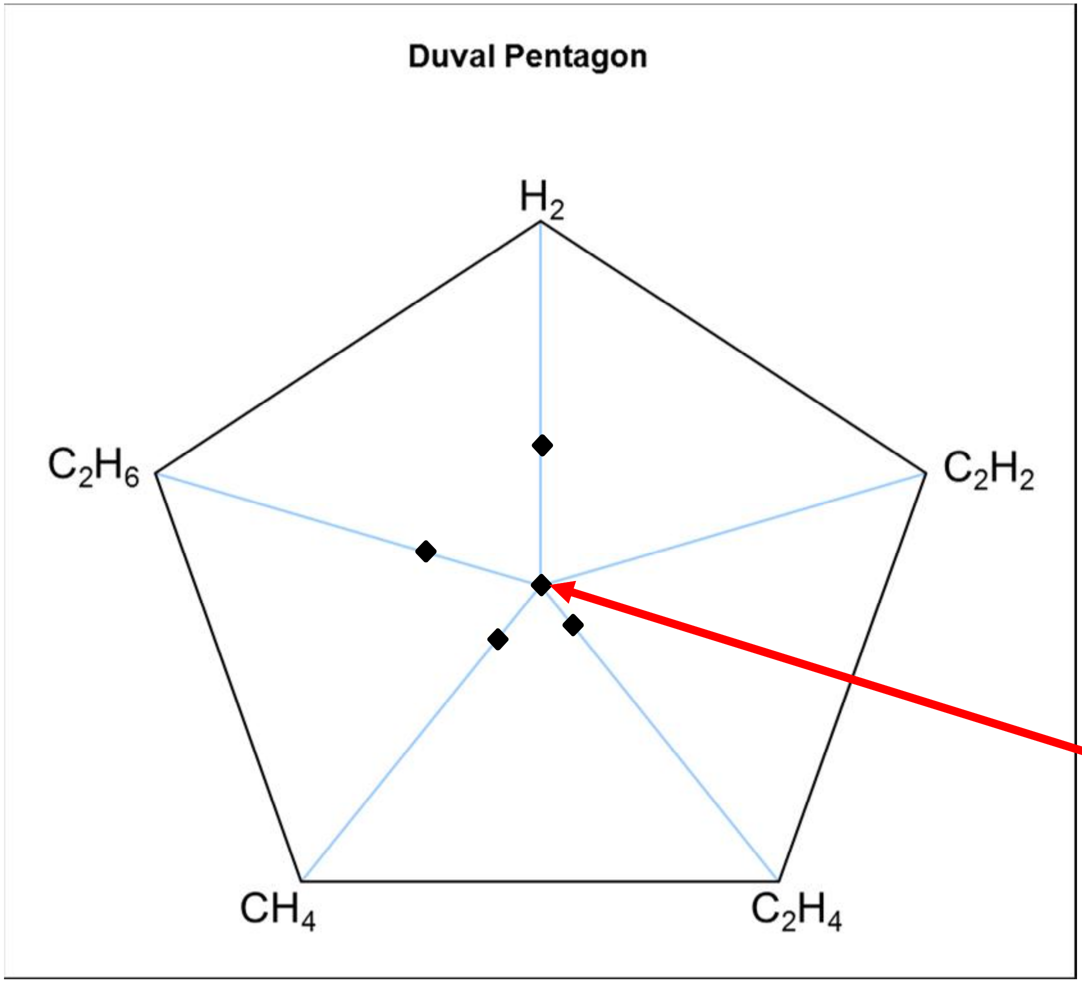
Duval Pentagons: place % C_2H_4

Gas	% of Total
H_2 = 75 ppm	39 %
C_2H_6 = 57 ppm	30 %
CH_4 = 35 ppm	18 %
C_2H_4 = 25 ppm	**13 %**
C_2H_2 = 0 ppm	
Total = 192 ppm	

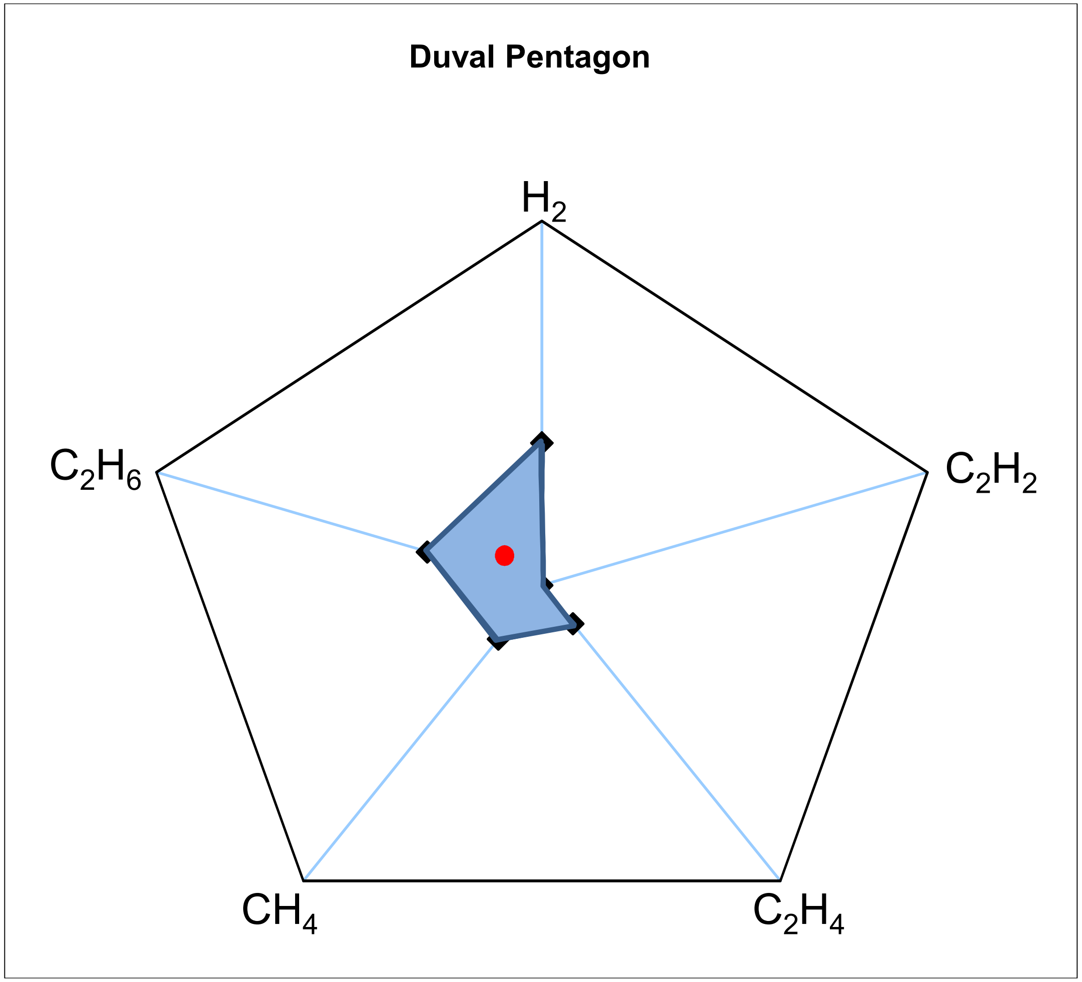


Duval Pentagons: place % C_2H_2

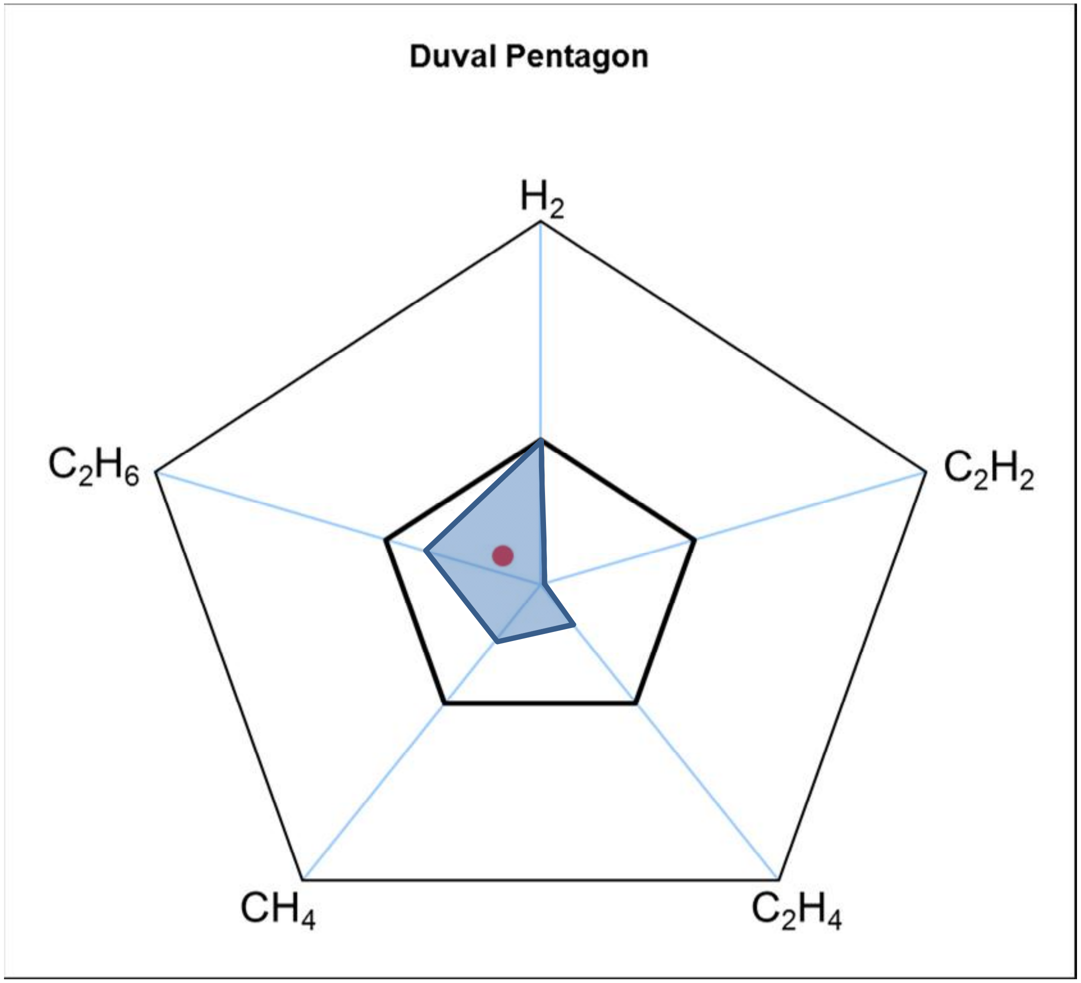
Gas	% of Total
H_2 = 75 ppm	39 %
C_2H_6 = 57 ppm	30 %
CH_4 = 35 ppm	18 %
C_2H_4 = 25 ppm	13 %
C_2H_2 = 0 ppm	0 %
Total = 192 ppm	



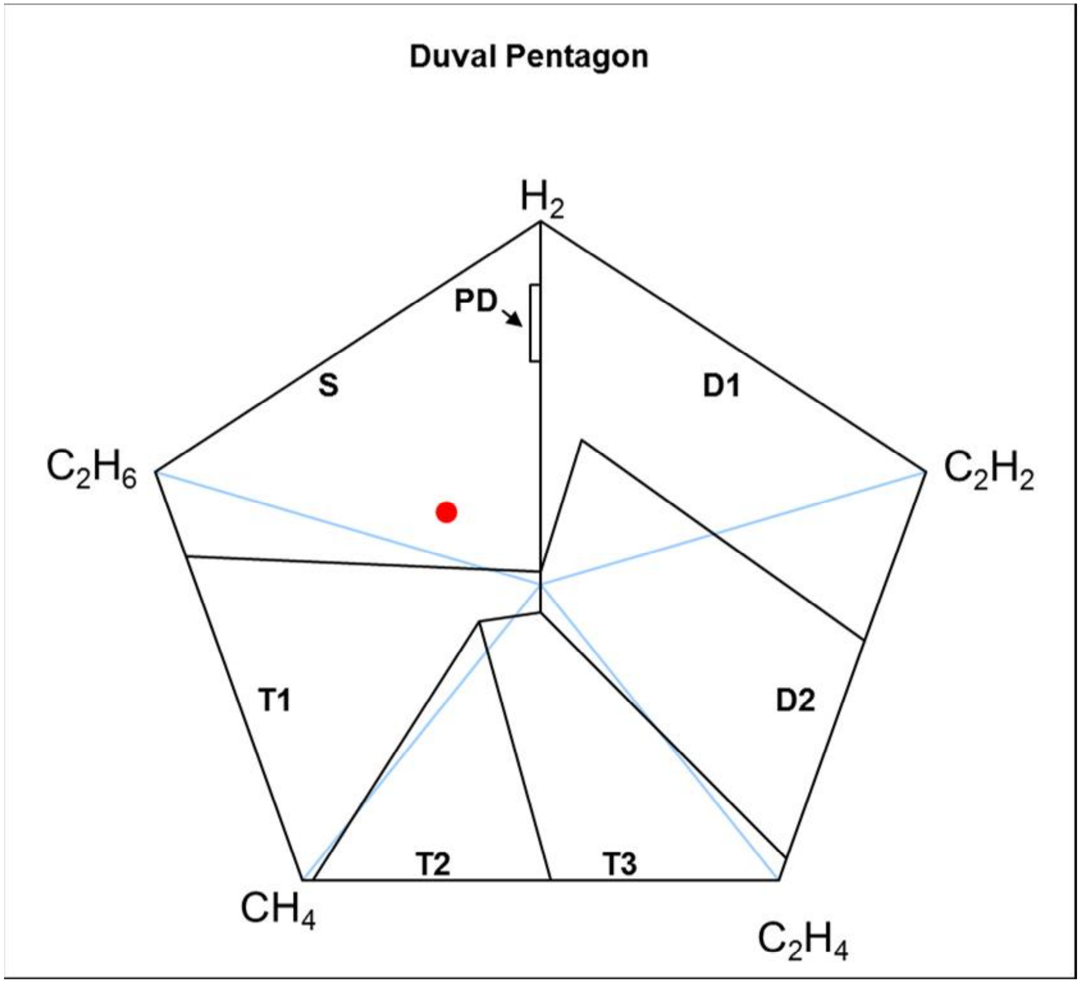
Duval Pentagons: Compute Centroid



Duval Pentagons: Select inner 40%



Duval Pentagons: Add Zones



Reference

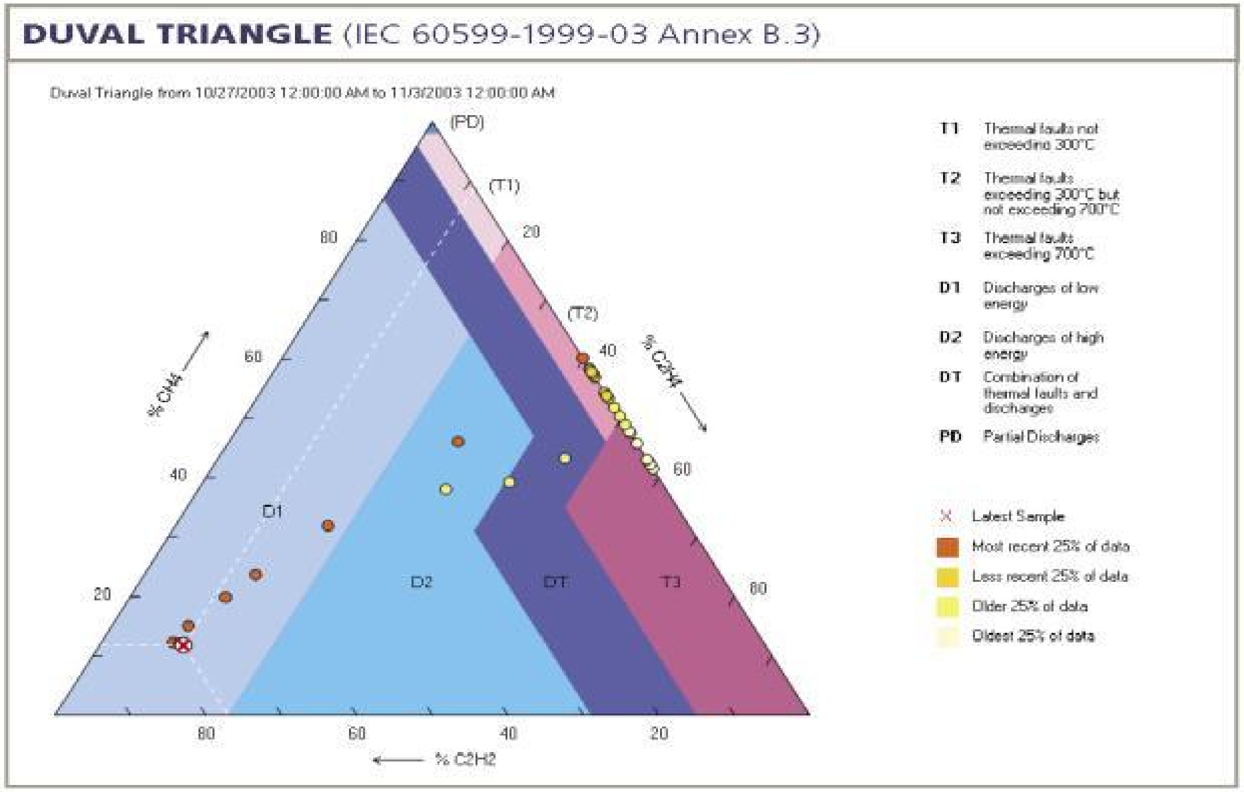
DEIS FEATURE ARTICLE

The Duval Pentagon—A New Complementary Tool for the Interpretation of Dissolved Gas Analysis in Transformers

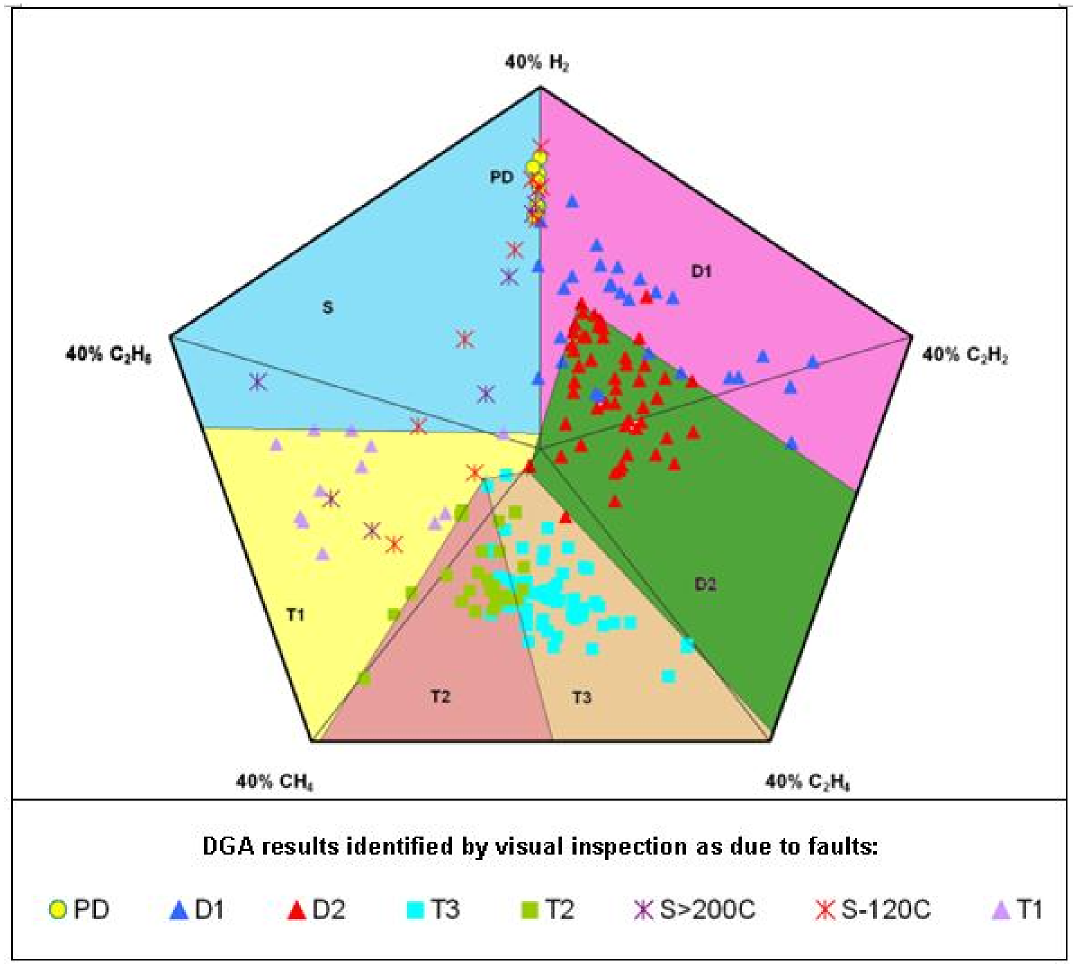
Michel Duval and Laurent Lamarre
IREQ, Varennes, QC, Canada

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

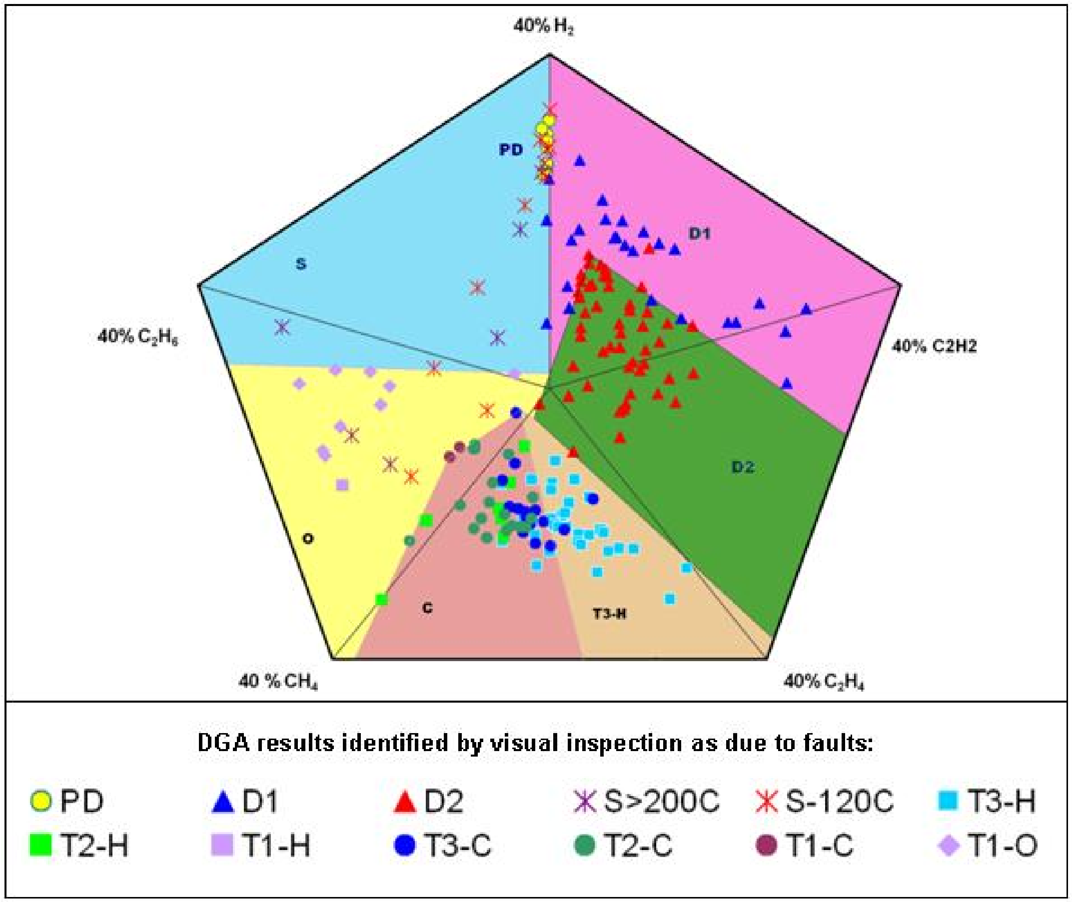
Using the Triangle Method



Duval Pentagon 1 Typical faults

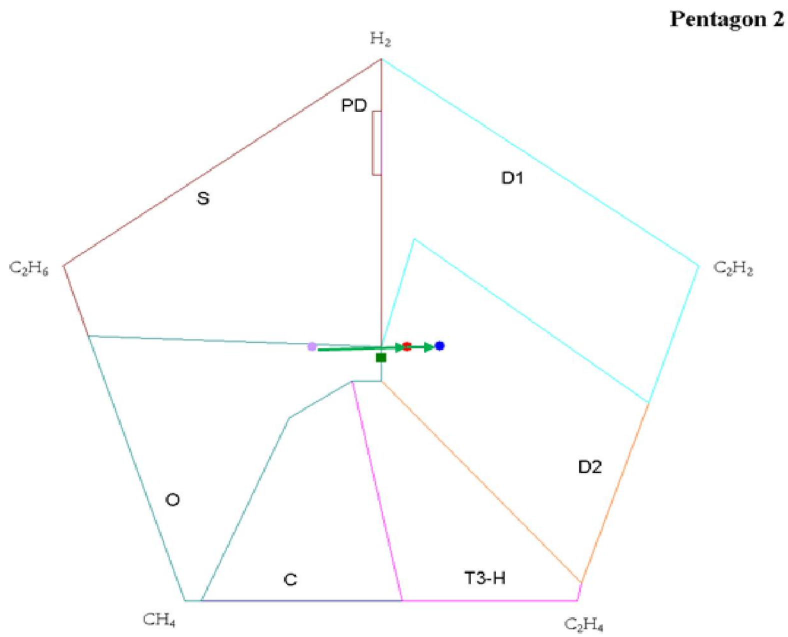


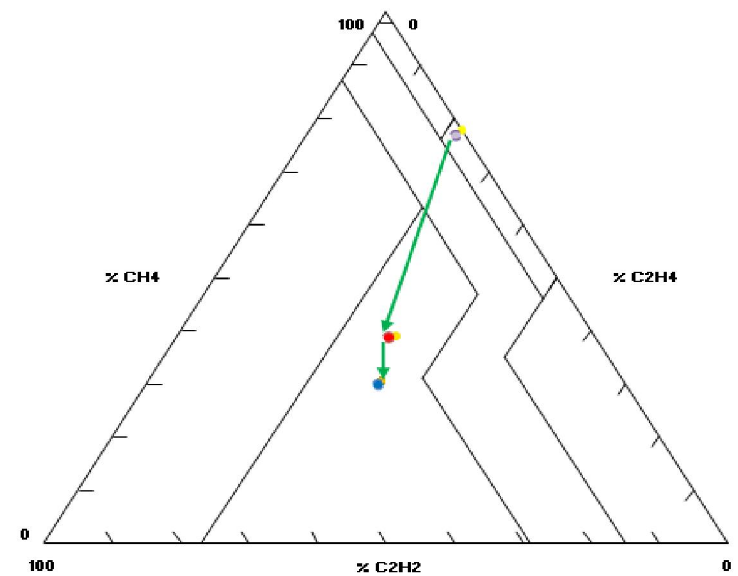
Duval Pentagon 2 Typical faults



DGA Example

	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	Tr1	Pent2	
Before failure	800	700	0	200	400	T2	O	●
At failure	2800	1950	1450	1600	400	D2	D2	●
Delta	2000	1250	1450	1400	0	D2	D2	●

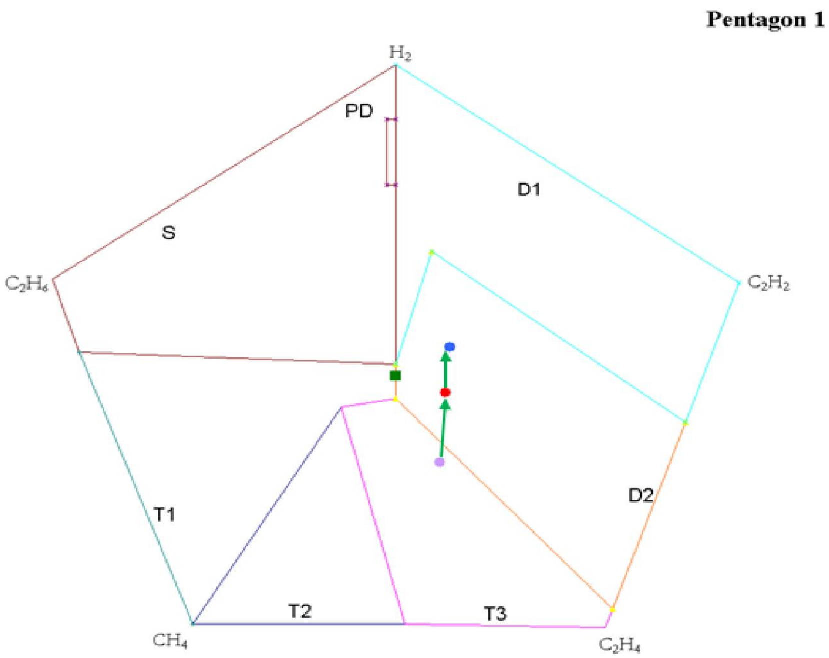


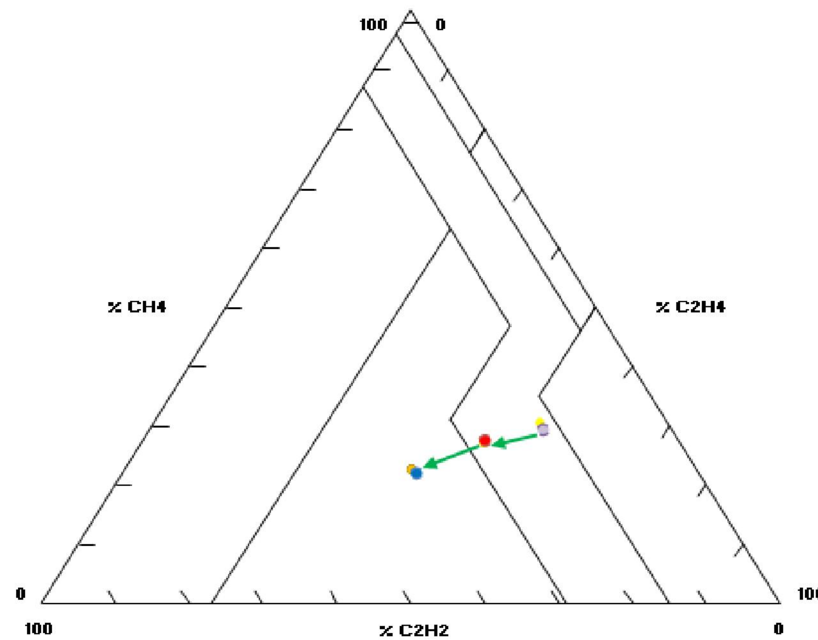


Arcing on windings and hot spot on lead found by inspection

DGA Example

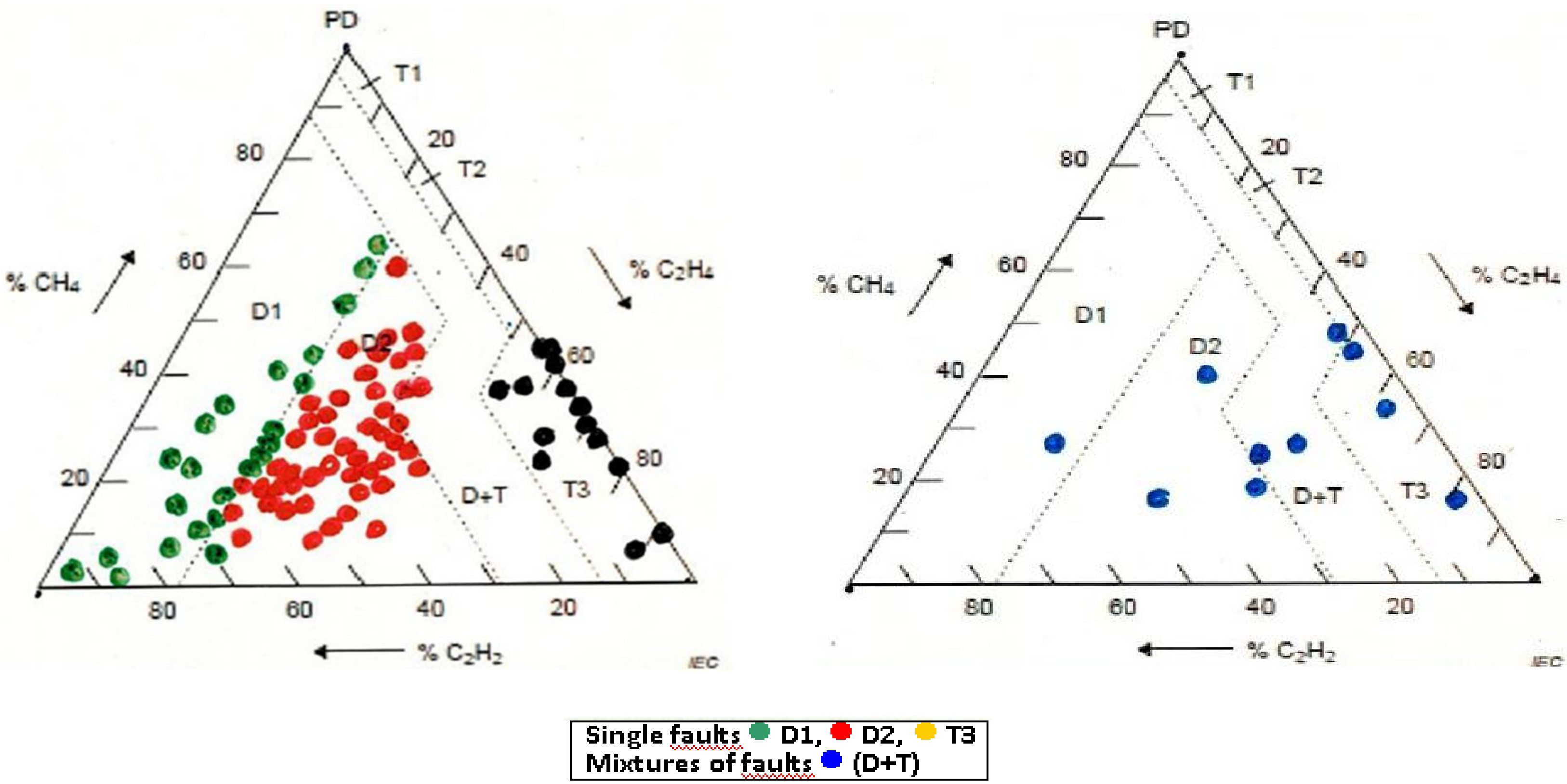
	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	Tr1	Pent2	
Before failure	200	350	200	600	100	DT	T3-H	●
At failure	1120	700	690	1200	180	DT	D2	●
Delta	920	350	490	600	80	D2	D2	●





Hot spot and flashover found by inspection

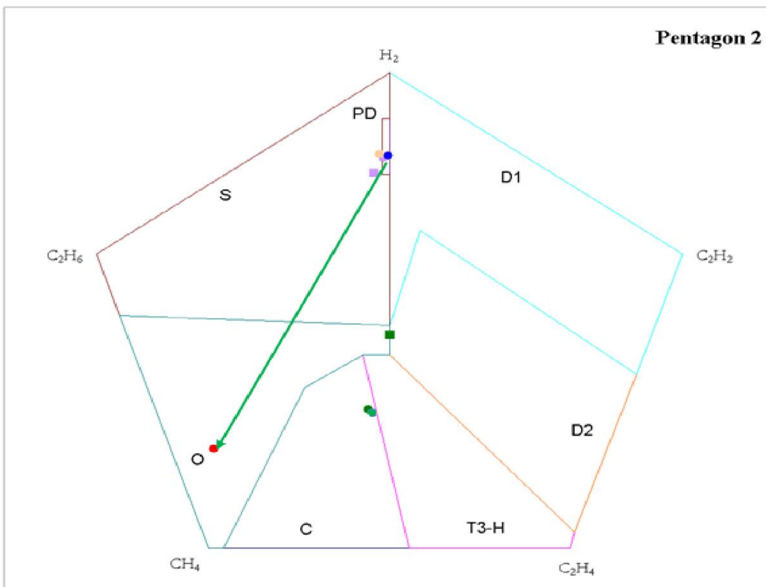
Mixtures of faults

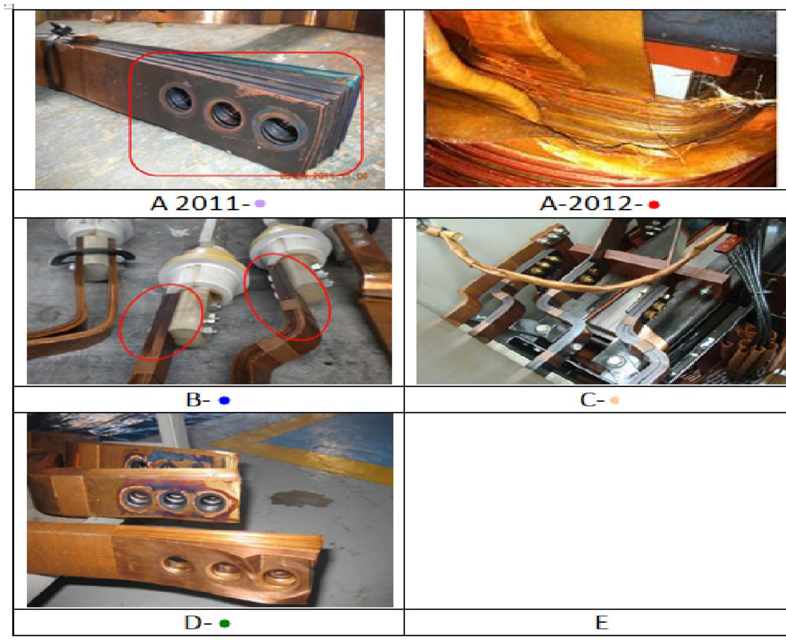


Inspected cases of single faults of IEC TC 10
and mixtures of faults of CIGRE WG47 (S.Spremic)

Mixtures of faults

	Date	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	Tr4	Pent2	
A	2011	10000	1000	0	0	200	S	PD	
	2012	0	2000	0	0	700	C/O	O	
B		15000	1500	0	0	0	PD	PD	
C		12000	1000	0	0	500	S	S	
D		300	150	0	75	0	S	C	
E		6000	600	0	0	400	S	S	

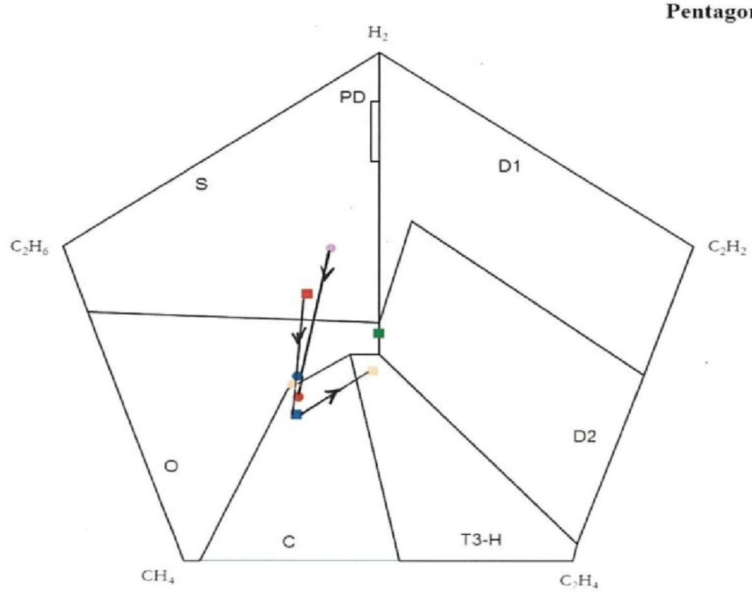




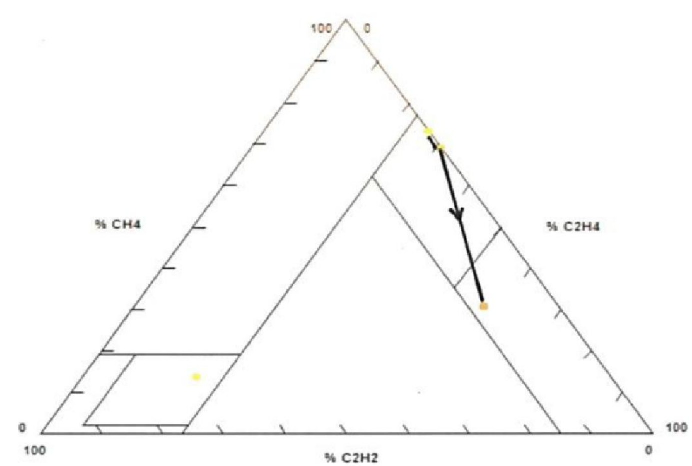
Mixtures of faults

	Date	H2	CH4	C2H2	C2H4	C2H6	
	11Ju	77	26	0	11	23	● (violet)
	12ja	114	545	0	433	511	● (red)
	13ja	307	673	0	451	601	● (blue)
	13Ap	508	1345	0	770	1058	● (orange)
URT	11No	42	27	0	10	25	■ (red)
	12Dec	150	559	0	251	256	■ (blue)
	13Feb	62	68	27	126	73	■ (orange)

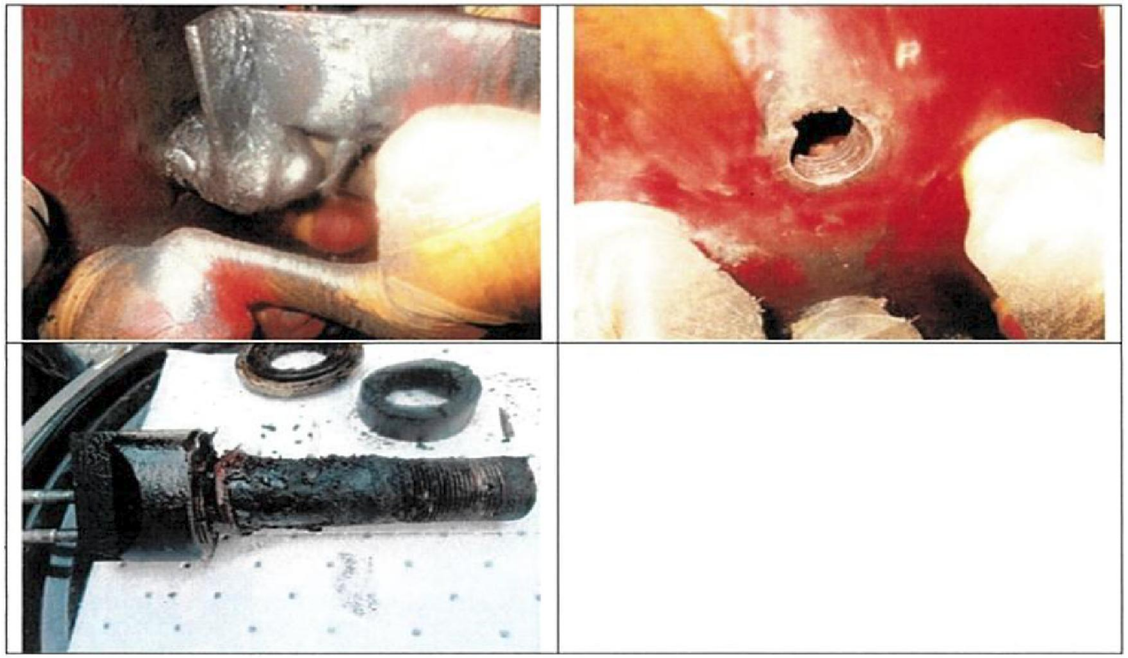
Pentagon 2



URT LTC



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**

Międzynarodowa konferencja transformatorowa

PTPiREE

TRANSFORMATOR'17

Toruń, 9-11 maja 2017 r.

DGA Tools: Duval Triangles and Pentagons

C. Beauchemin, TJH2b Analytical Services Inc.

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

TJ H2b

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

TJ | H 2 b

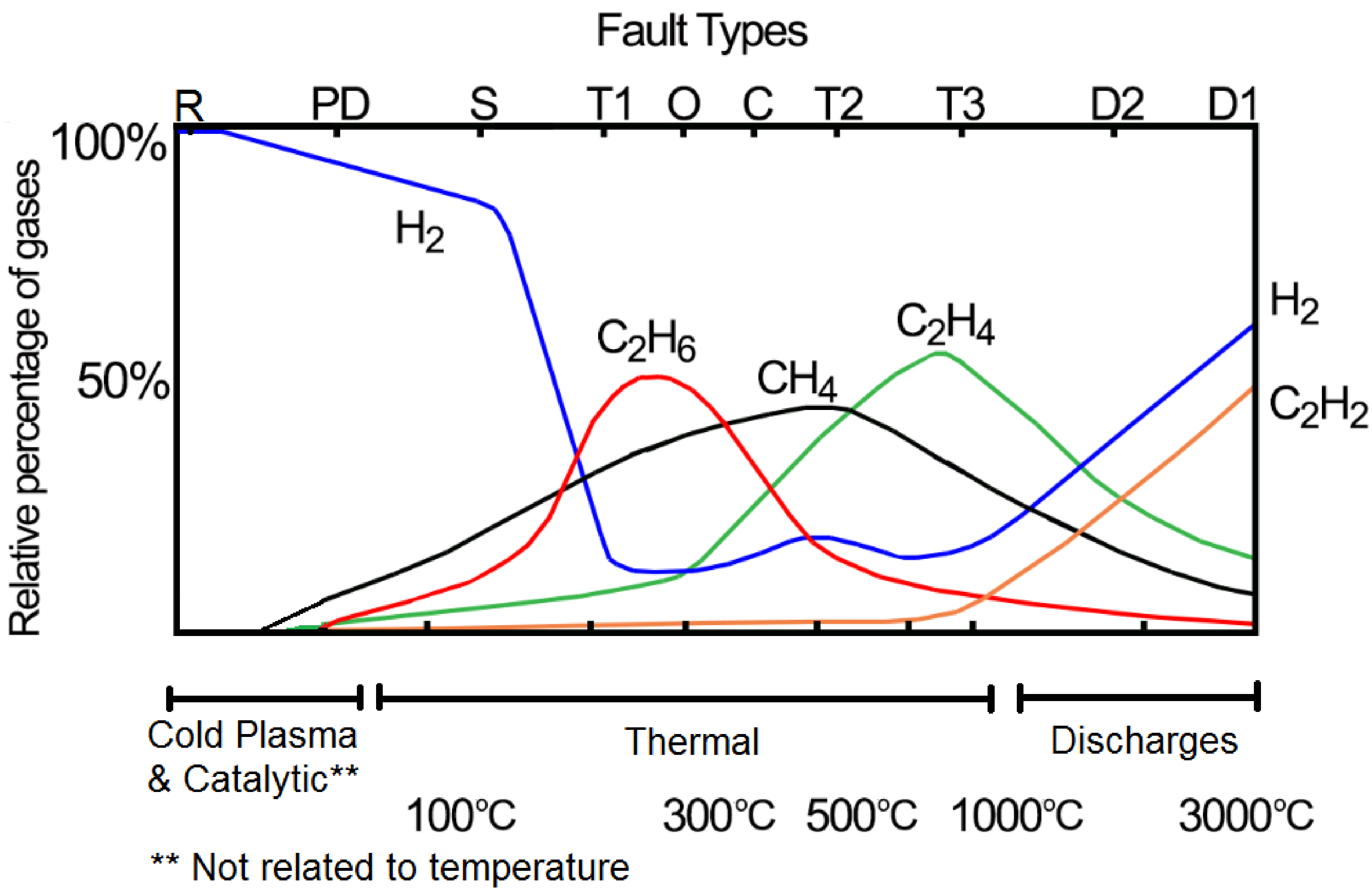
How to correlate gas to fault ?

- 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 IEEEE



Source: IEEE C57.104 D3.2, April 2017

How to correlate gas to fault ?

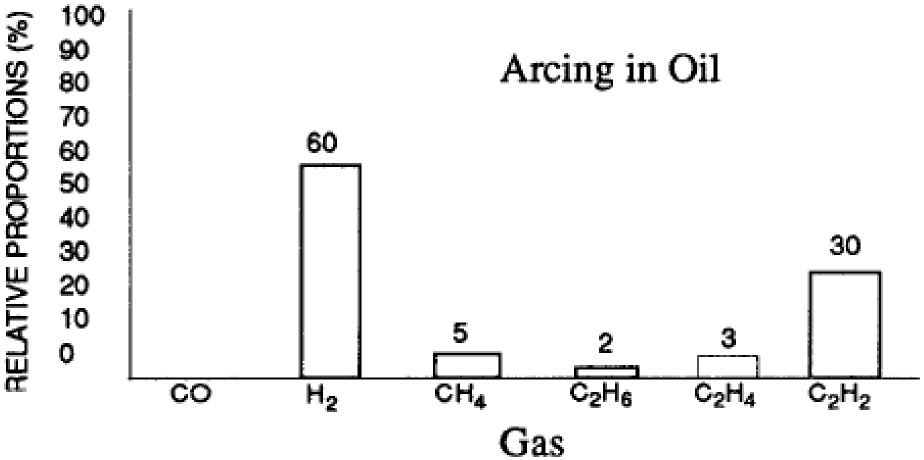
- Interpretation methods could be classified in 4 general classes
  - Specific gas
  - Statistic norms
  - True tables with ratio
  - Graphical
- All methods are based on the fact that different fault generate gas in different amounts

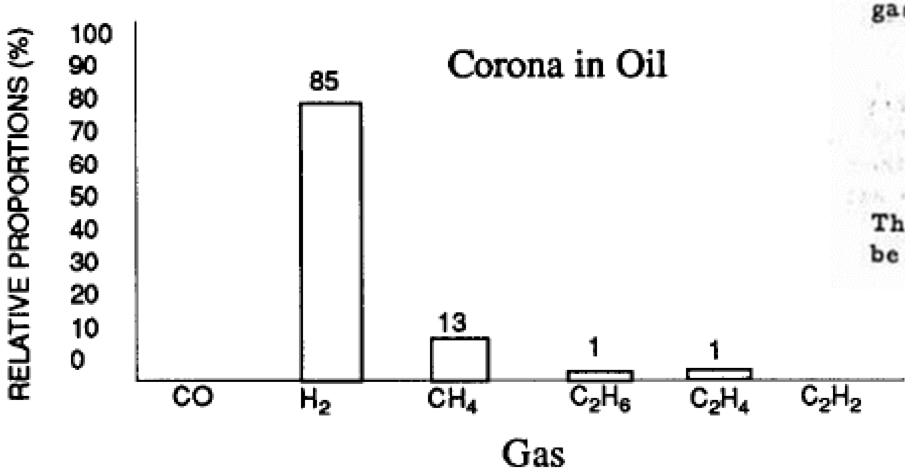
DGA Interpretation History

- Several methods introduced in the 1970 & 1980
  - Statistic threshold
  - Rogers
  - Halstead
  - LCIE
  - Laborelec
  - GE
  - Church
  - Dörnenberg
  - Potthoff
  - Shanks
  - Trilinear Plot
  - IEC
  - Duval
  - ....

TJ | H 2 b

Key Gas Method





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.

TJ | H_2b

Statistical Methods: IEC 60599

Table A.2 – Ranges of 90 % typical concentration values observed in power transformers (all types)

Transformer sub-type	H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
No OLTC	60-150	540-900	5 100-13 000	40-110	50-90	60-280	3-50
Communicating OLTC	75-150	400-850	5 300-12 000	35-130	50-70	110-250	80-270

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.

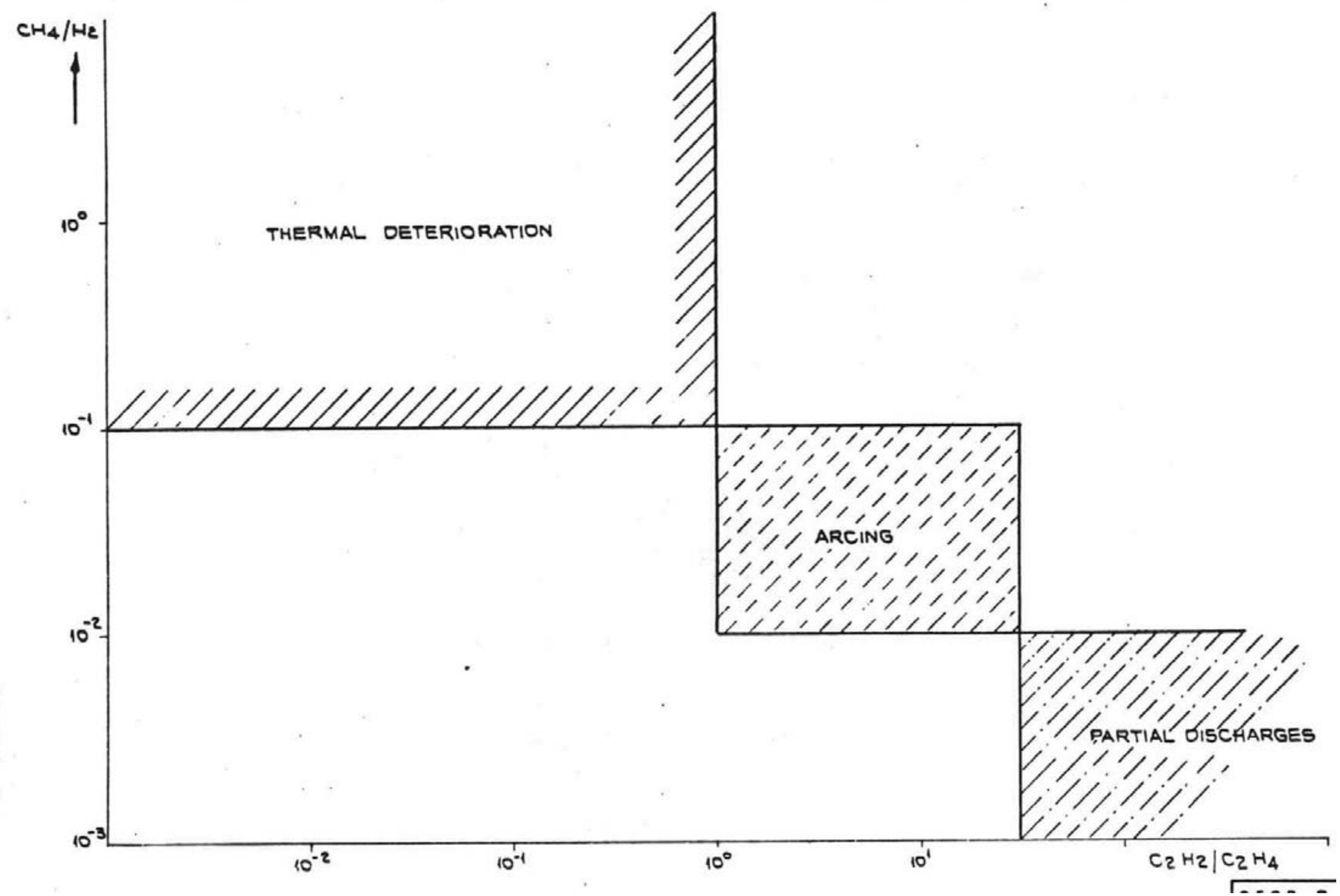
NOTE 3 – In some countries, typical values as low as 0,5 µl/l for C_2H_2 and 10 µl/l for C_2H_4 have been reported.

Example of Look-Up Table: Early Rogers

CH_4/H_2	C_2H_6/CH_4	C_2H_4/C_2H_6	C_2H_2/C_2H_4	Diagnosis
0	0	0	0	If CH_4/H_2 0.1 - Partial discharge, otherwise o.k.
0	0	0	1	Flash-over.
0	0	1	0	Conductor overheating.
0	0	1	1	Arc with power - persistent sparking.
0	1	0	0	Overheating 250-300°.
0	1	0	1	Tap changer, selector.
0	1	1	1	--
0	1	1	1	--
1	0	0	0	Overheating - below 150°.
1	0	1	0	Circulating current - bad contact.
1	0	1	1	--
1	0	1	1	--
1	1	0	0	Overheating 200-300°.
1	1	0	1	--
1	1	1	0	--
1	1	1	1	--

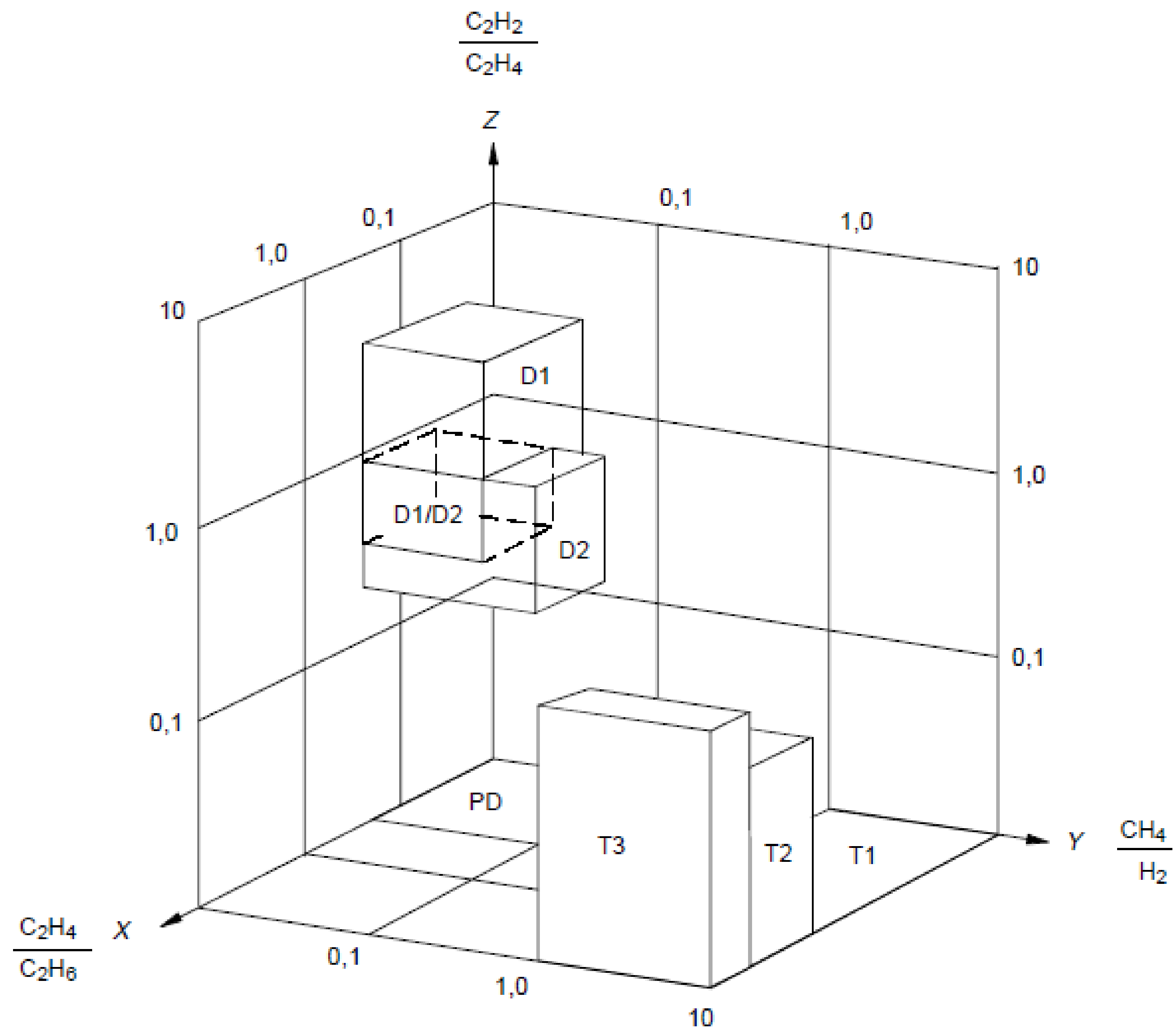
TJ | H 2 b

Example of Early Graphical Method: Doernenberg



TJ | H 2 b

Example of Graphical Method: IEC 60599



Duval Triangles History

The Origin of the Triangle figure

- Lost in the night of time
- Oldest know description: (Euclid, 323 – 283 BC): any three points not in a line define a triangle (second oldest geometry axiom)
- A complete field of mathematic (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

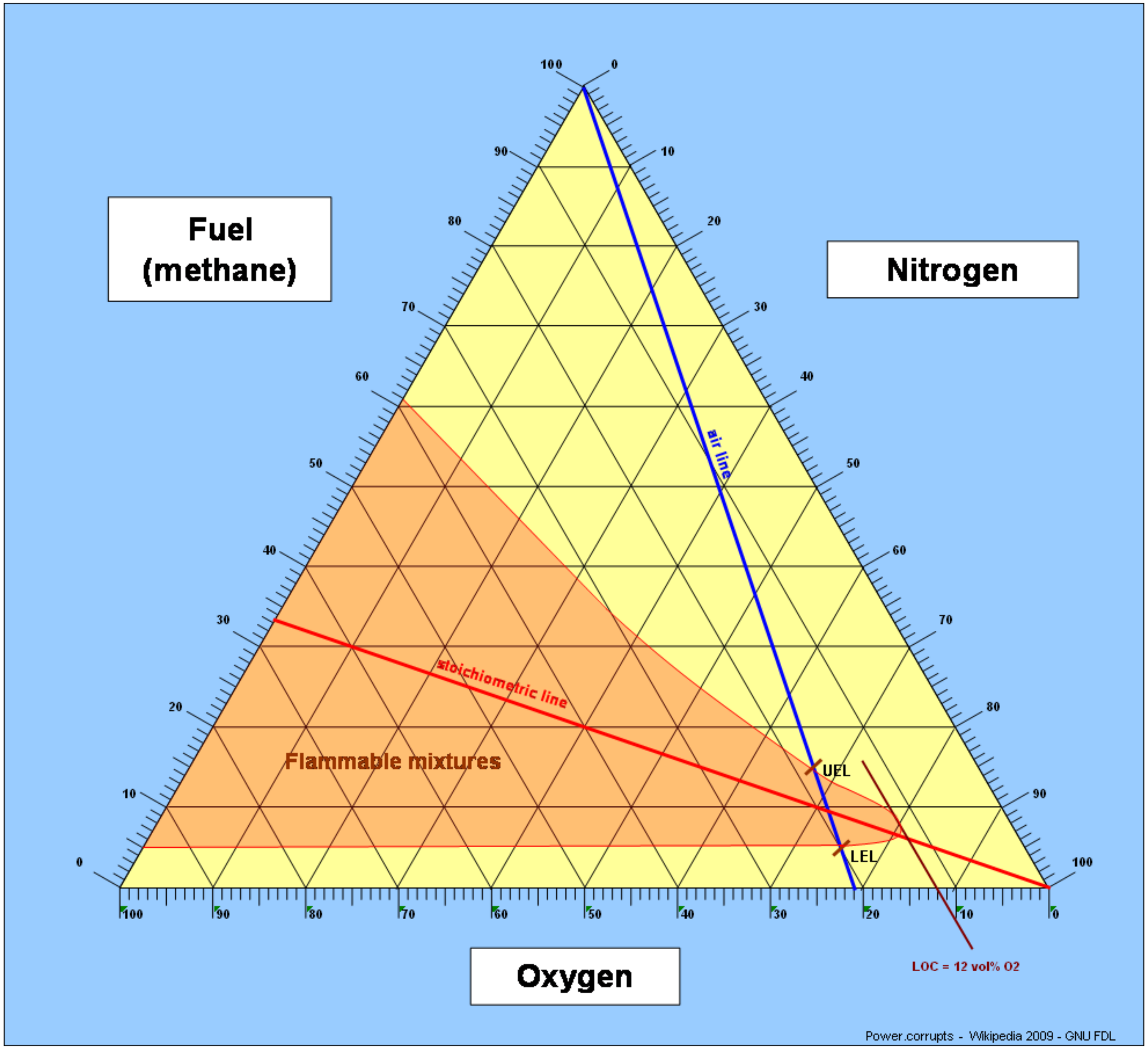
Why use a Trilinear graphs?

- 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:

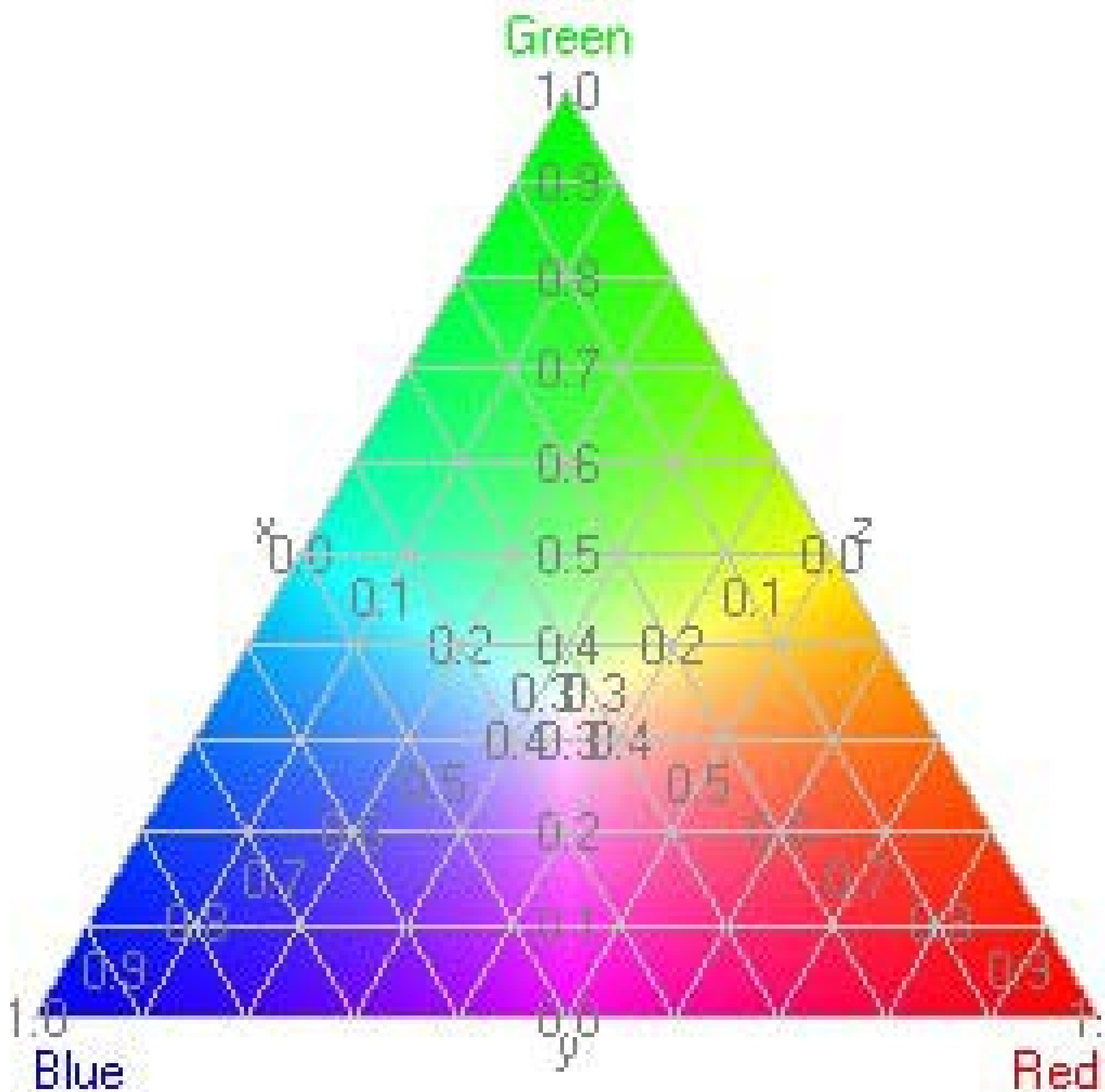
TJ | H 2 b

Flammability Chart



TJ | H 2 b

Color Chart

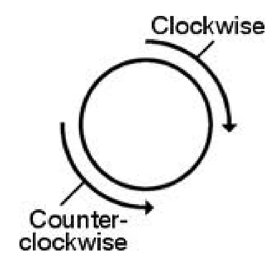

Green
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.2
x
0.0
0.1
0.2
z
0.0
0.1
0.2
0.5
0.5
y
0.0
1.0
Blue
Red

How to Read a Trilinear Graph

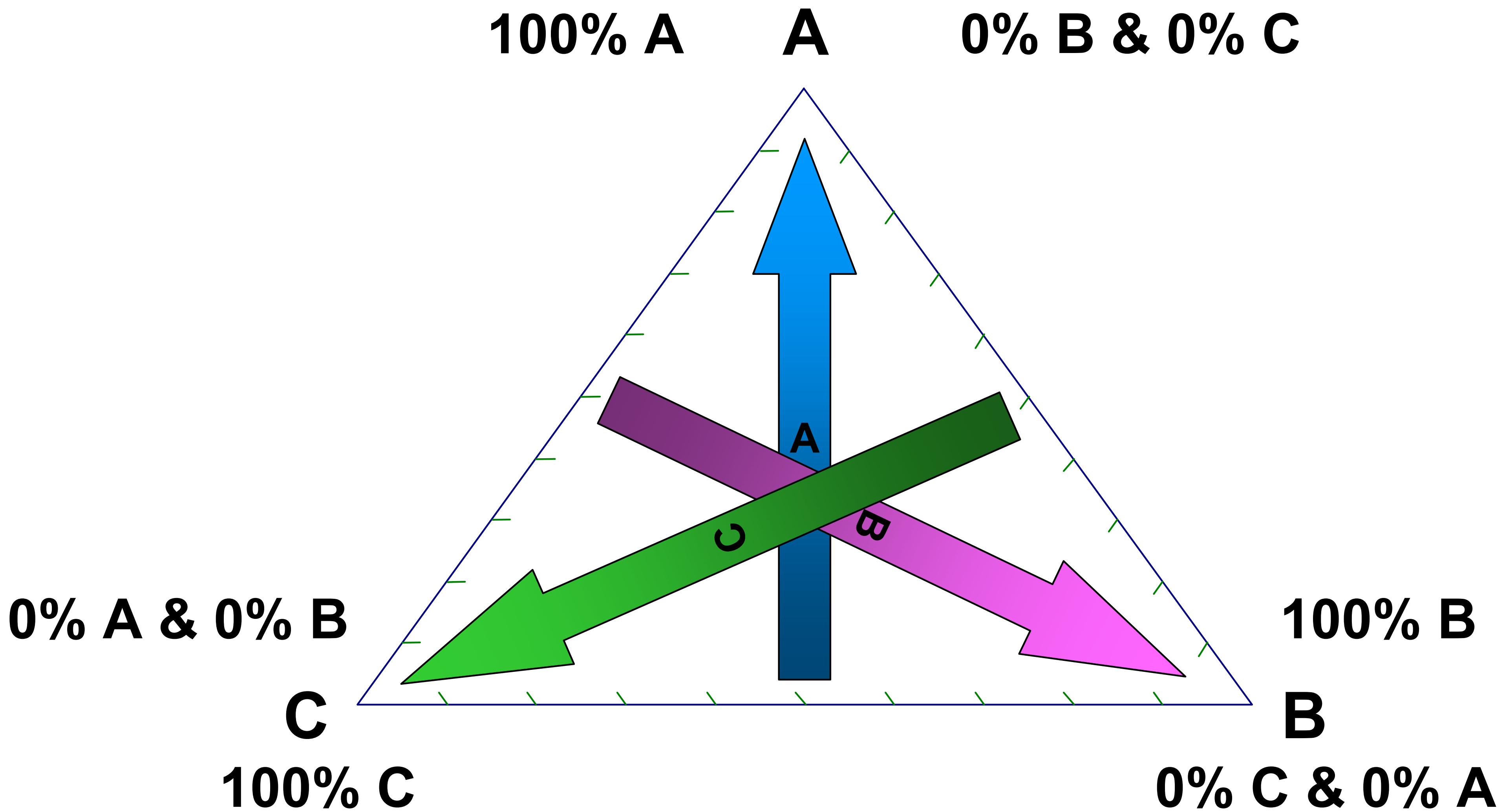
- Each corner is 100% of one variable
- The adjacent variable at that corner is 0%
- BTW, the other one too !!
- The progression around the triangle is

0 ↔ 100 0 ↔ 100 0 ↔ 100%

- Progression could be clockwise or counter clockwise



How to Read a Trilinear Graph



TJ | H_2b

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:

H_2 a. CO b. CH_4 c. C_2H_6 d. C_2H_4 e. C_2H_2 f.

The trilinear method gives:

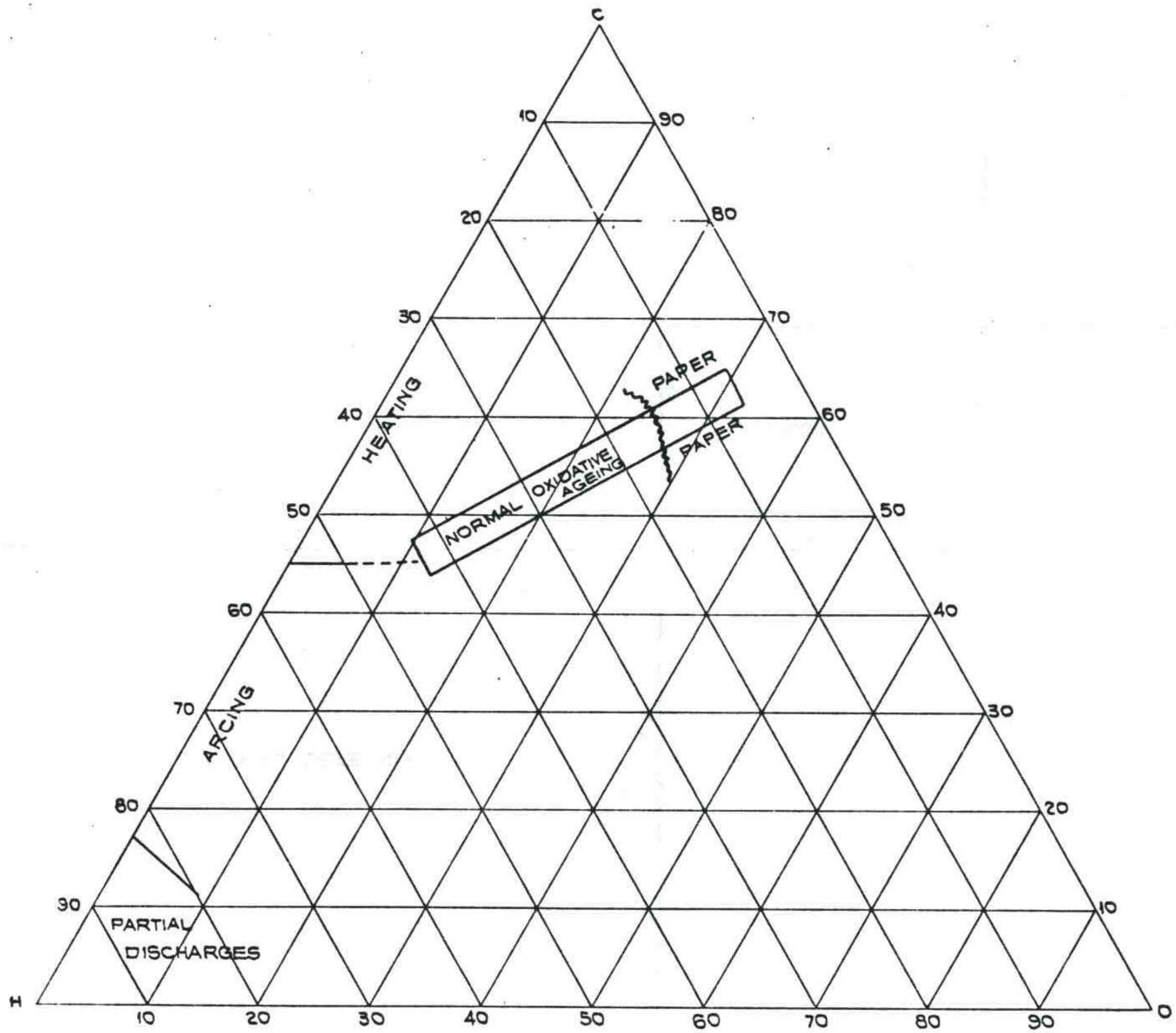
H_2 moles $\left[a + 2c + 3d + 2e + f\right] / \left(a + \frac{3b}{2} + 3c + 5d + 4c + 3f\right)$

O_2 moles $b/(2a + 3b + 6c + 10d + 8e + 6f)$

Carbon moles $\left[b + c + 2(d + e + f)\right] / \left(a + \frac{3b}{2} + 3c + 5d + 4e + 3f\right)$

TJ | H 2 b

First Trilinear Graph for DGA

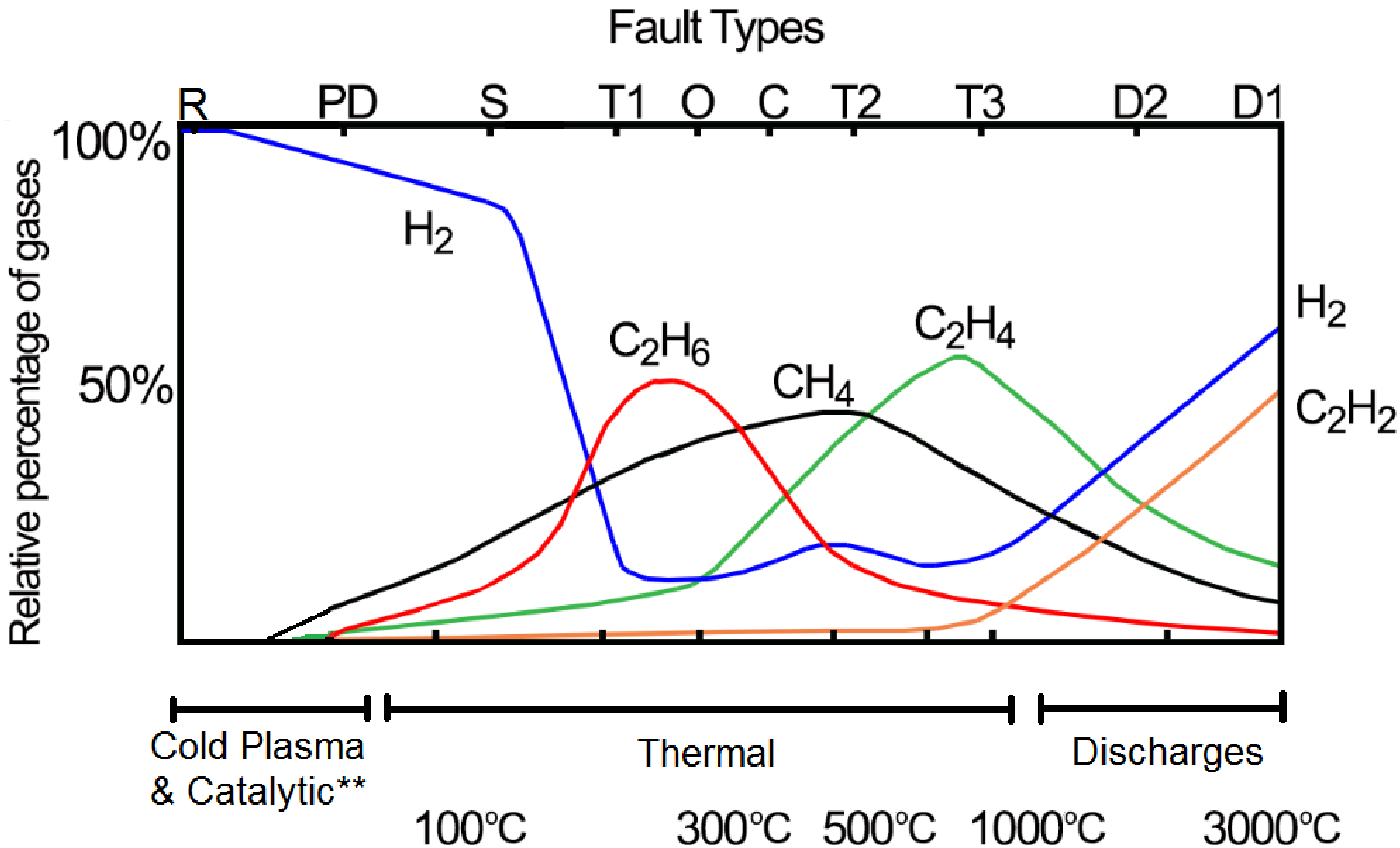


Duval Triangle (1)

- 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

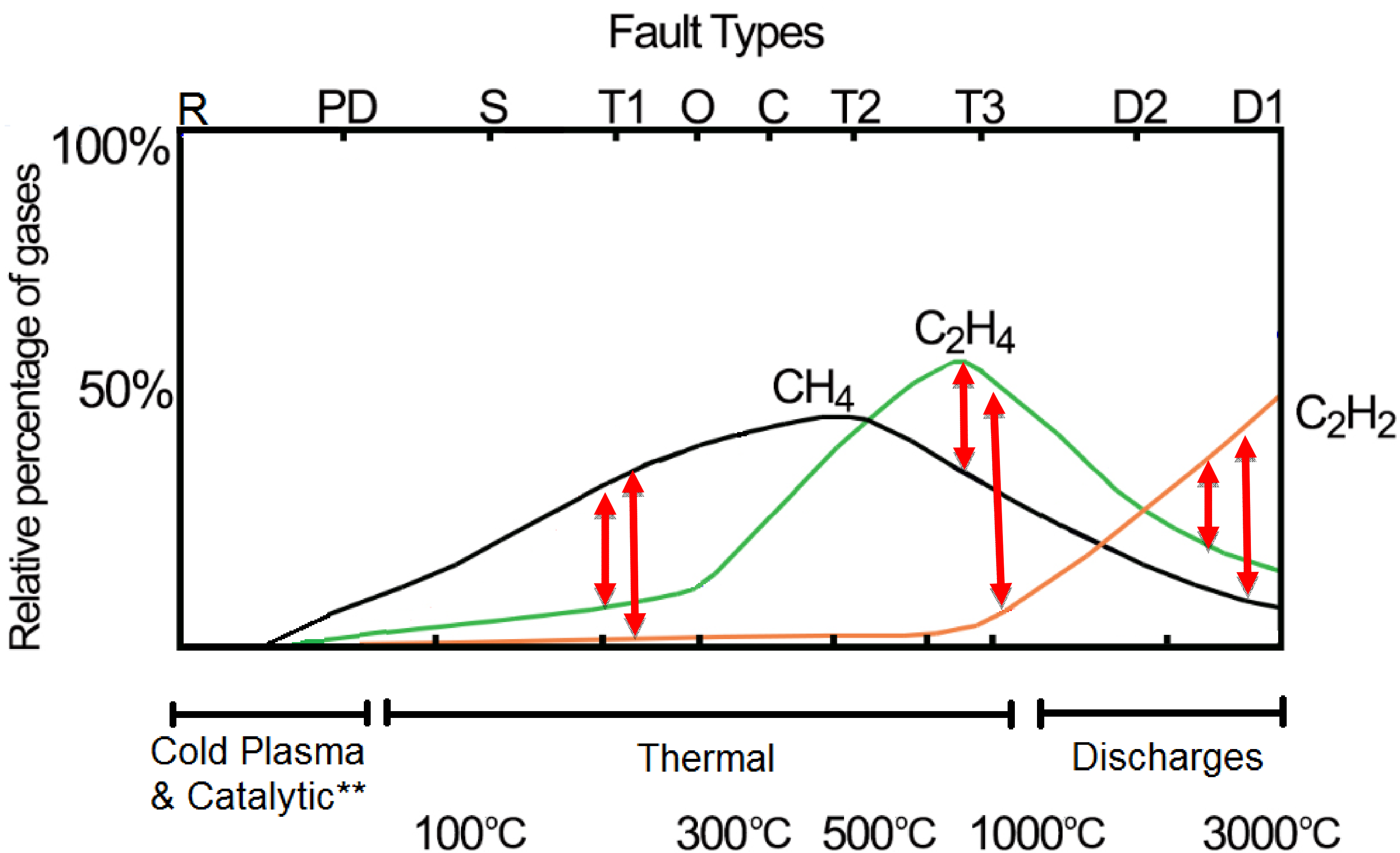
TJ | H 2 b

Relative Gas Generation CIGRE and IEEEE



** Not related to temperature

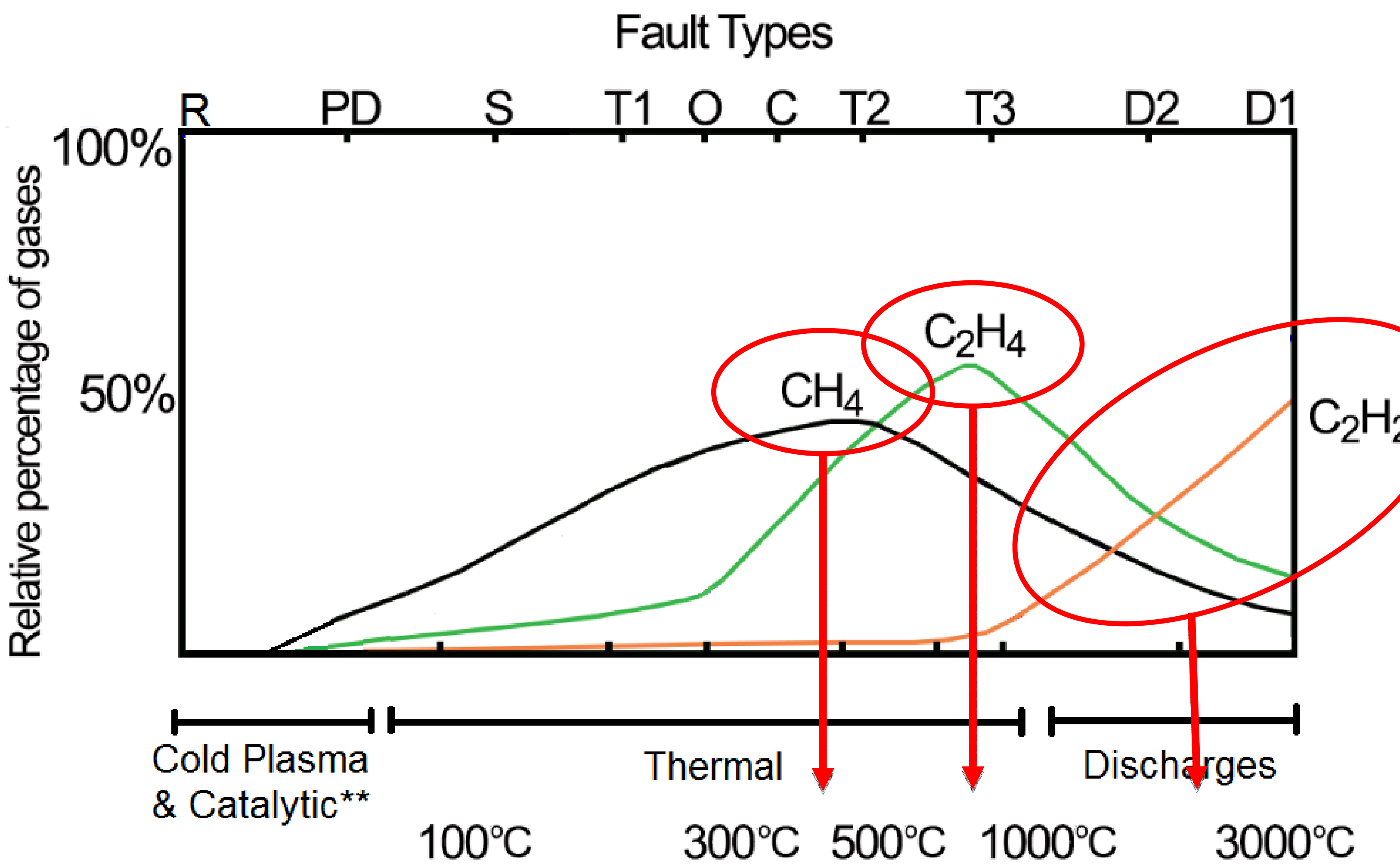
Relative Gas Generation Duval Triangle 1



** Not related to temperature

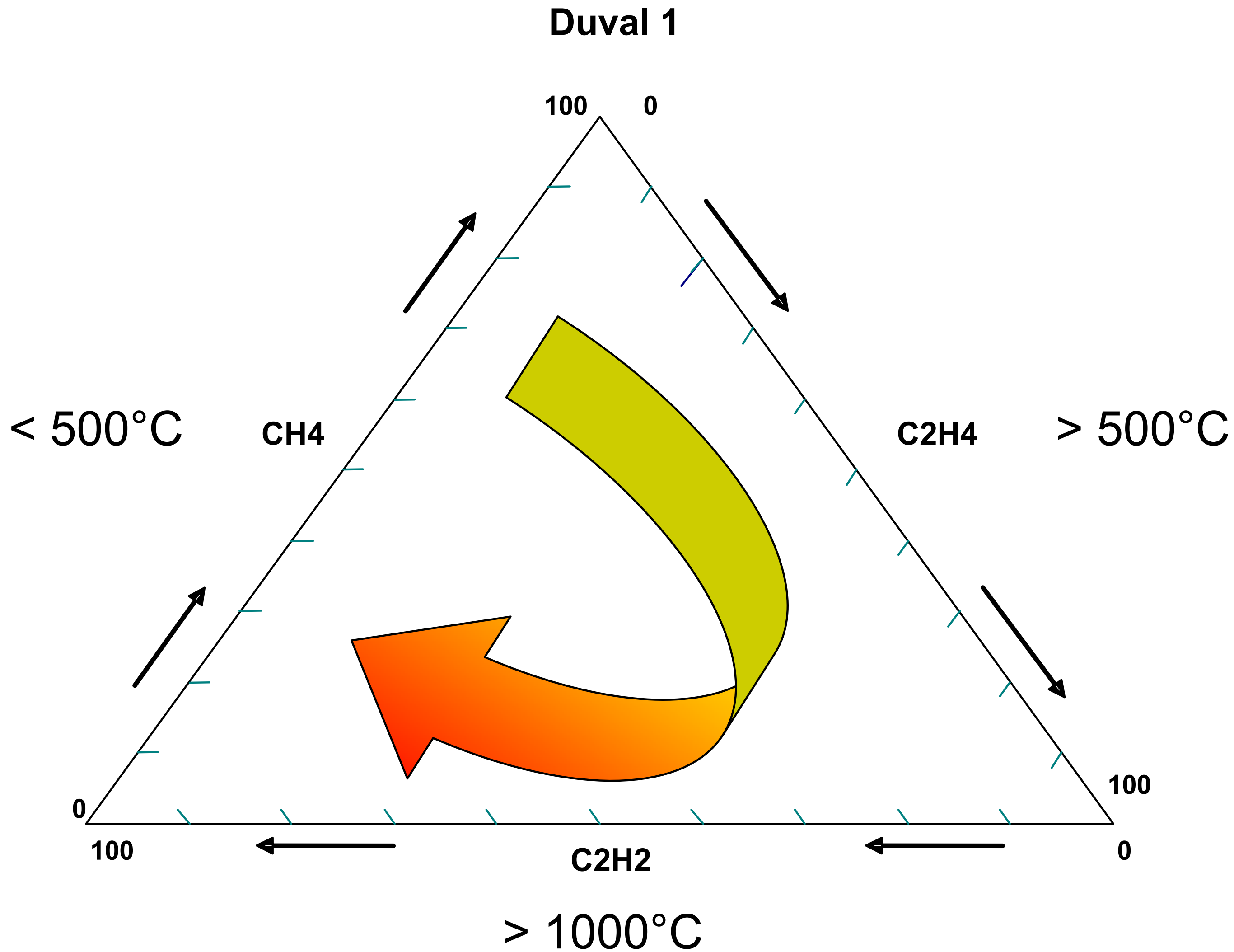
TJ H 2 b

Relative Gas Generation Duval Triangle 1

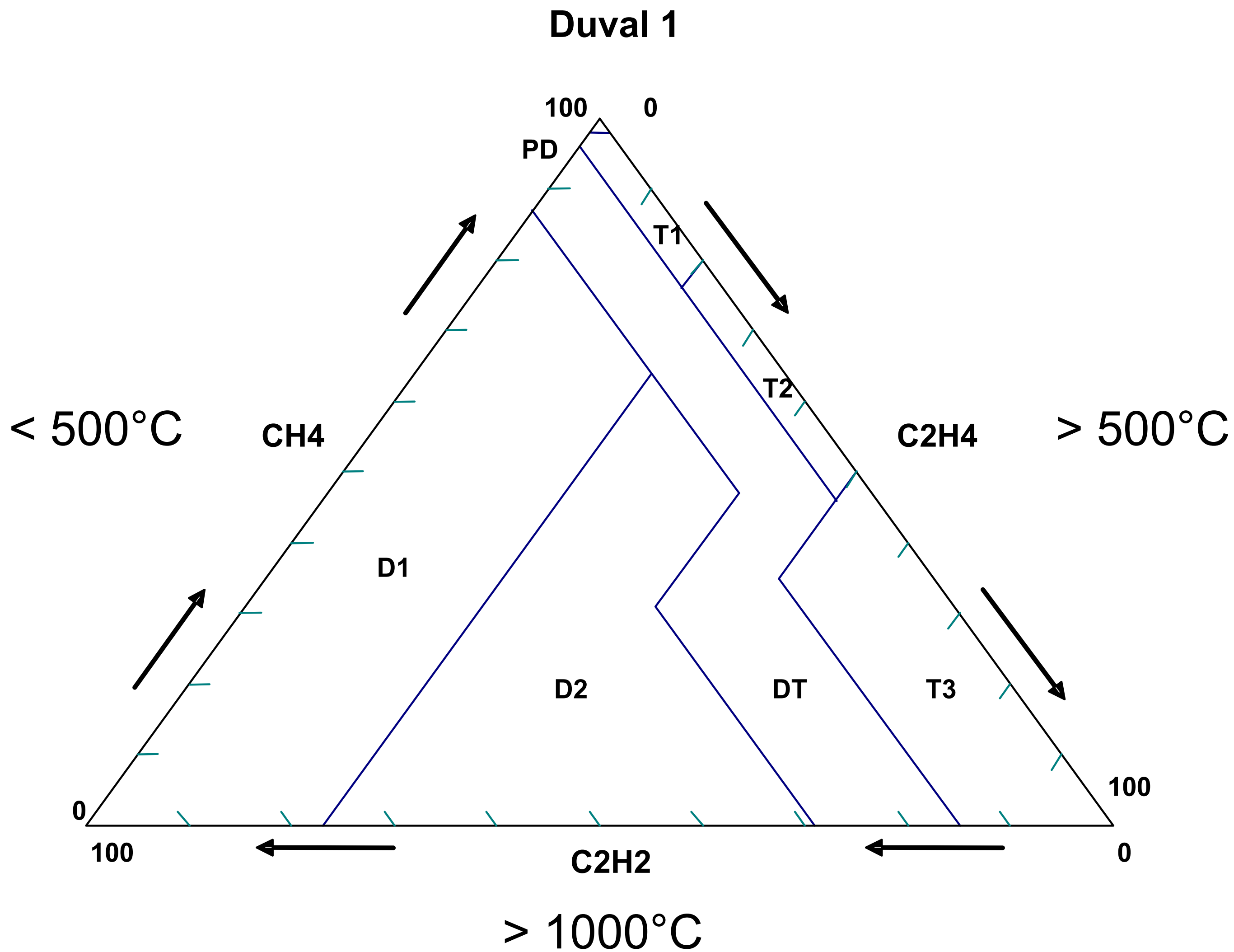


** Not related to temperature

Duval Triangle 1: Temperature of gas formation



Duval Triangle 1



Duval Triangle 1 Zones

- PD Partial Discharges
- T1 Low Temperature < 300 ºC
- T2 Medium Temperature 300 - 700 ºC
- T3 High Temperature > 700 ºC
- DT Discharges with Thermal
- D1 Discharges of High Energy
- D2 Discharges of Low Energy

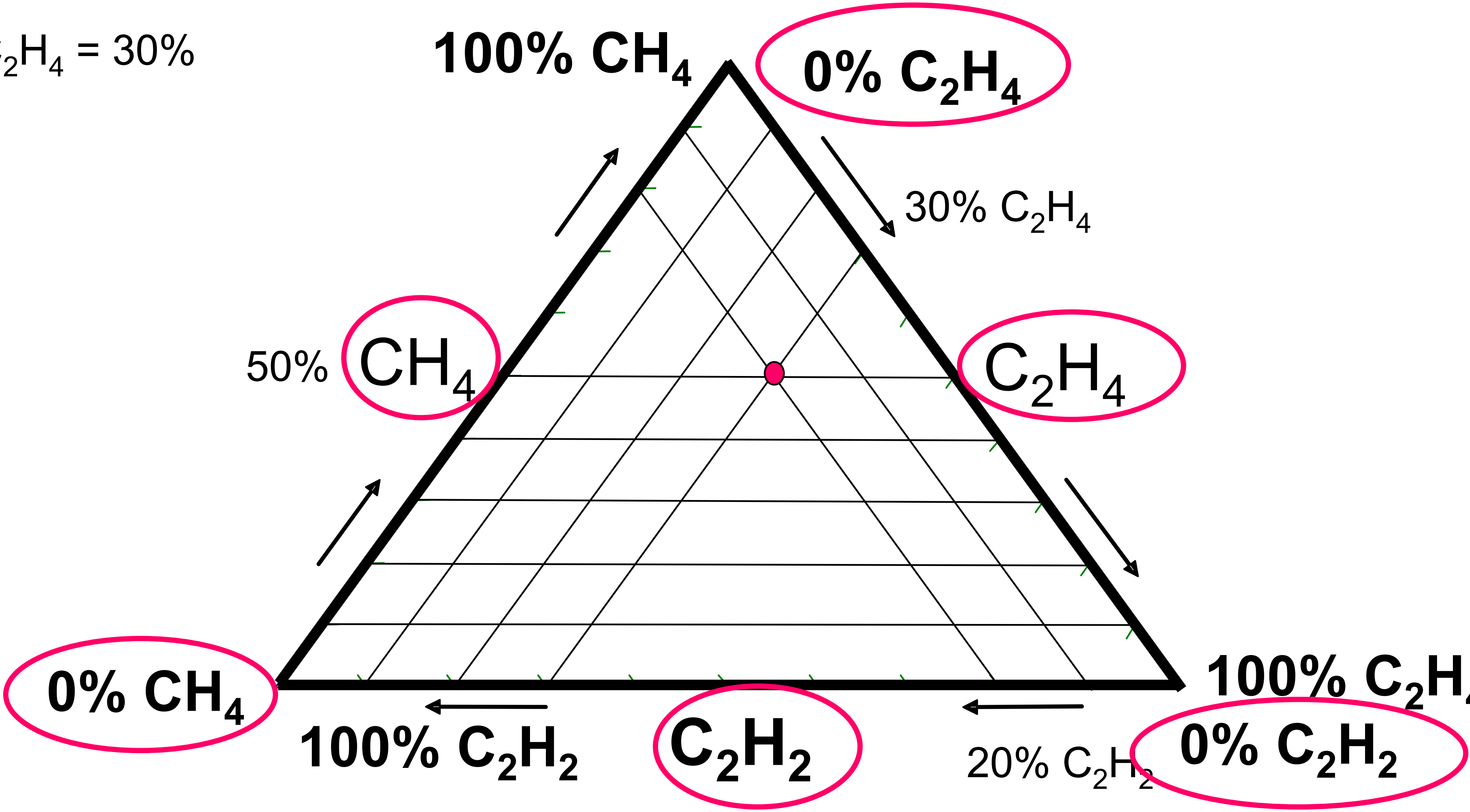
TJ | H 2 b

How to Place a Point in a Duval Triangle

CH_4 = 50%

C_2H_4 = 30%

C_2H_2 = 100% - %CH_4 - %C_2H_4 = 20%

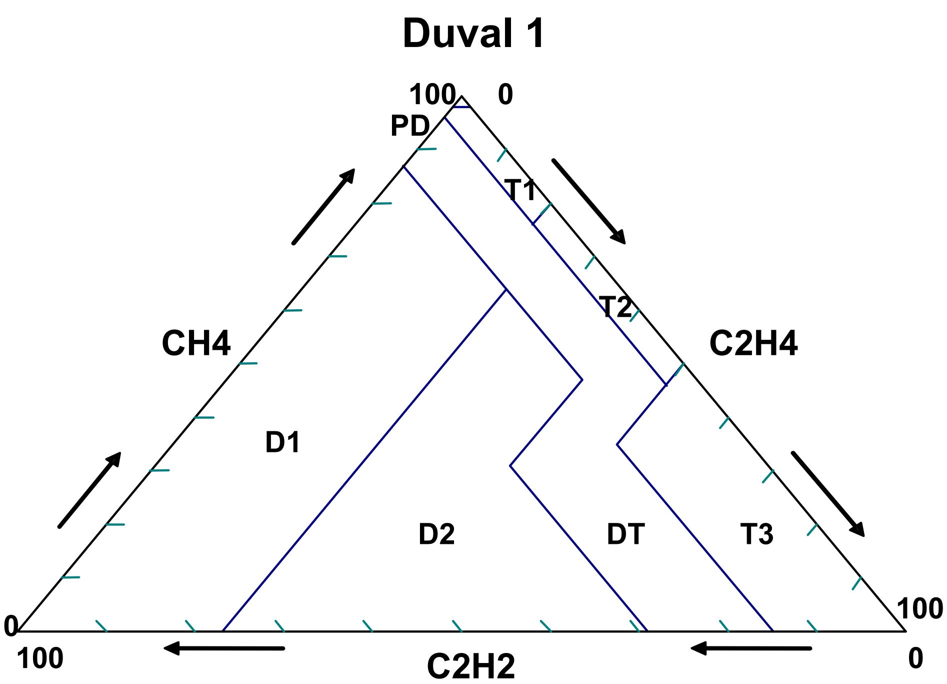


TJ H2b

Duval Triangle 1 and IEC 60599

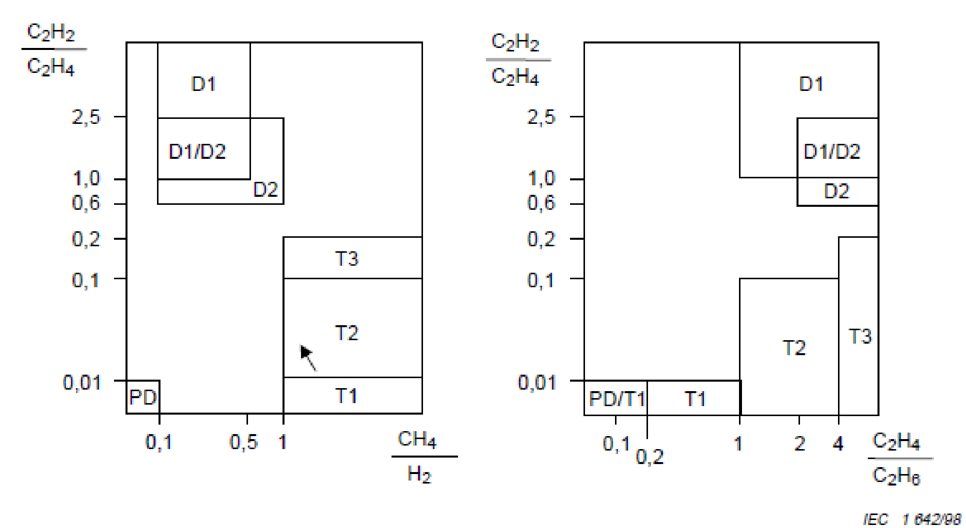
- Same fault designations as IEC 60599
- IEC use 5 Hydrocarbon
- IEC use 3 ratios of 2 gas
- IEC use Look-up table
- IEC use also a two graphs representation

Duval Compared to IEC 60599



Duval 1

Case	Characteristic fault	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
PD	Partial discharges (see notes 3 and 4)	NS[1)]	<0,1	<0,2
D1	Discharges of low energy	>1	0,1 – 0,5	>1
D2	Discharges of high energy	0,6 – 2,5	0,1 – 1	>2
T1	Thermal fault t < 300 °C	NS[1)]	>1 but NS[1)]	<1
T2	Thermal fault 300 °C < t < 700 °C	<0,1	>1	1 – 4
T3	Thermal fault t > 700 °C	<0,2[2)]	>1	>4



IEC

TJ | H 2 b

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

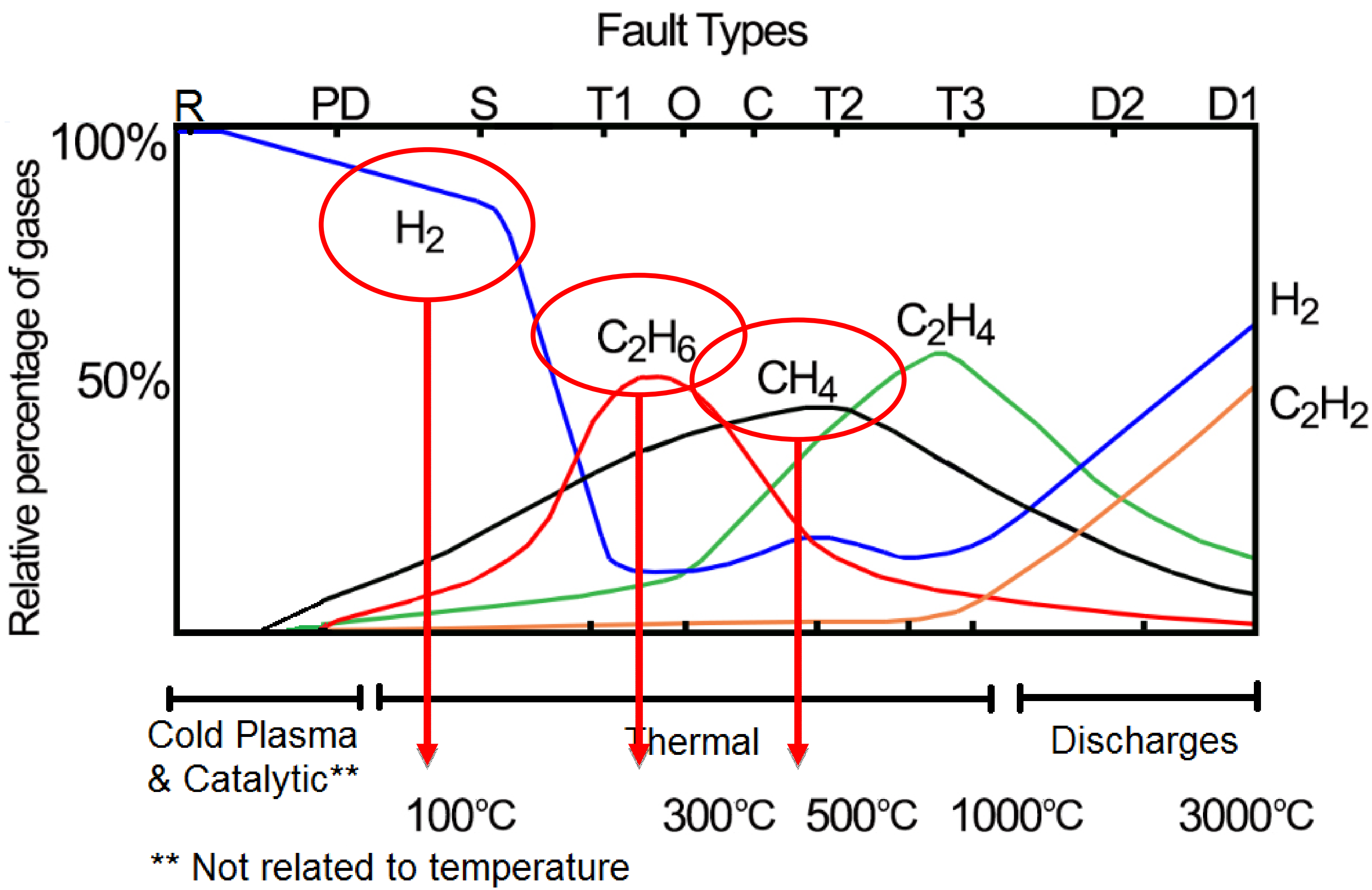
- So Variations have been added

TJ | H 2 b

Duval Triangles 4 and 5

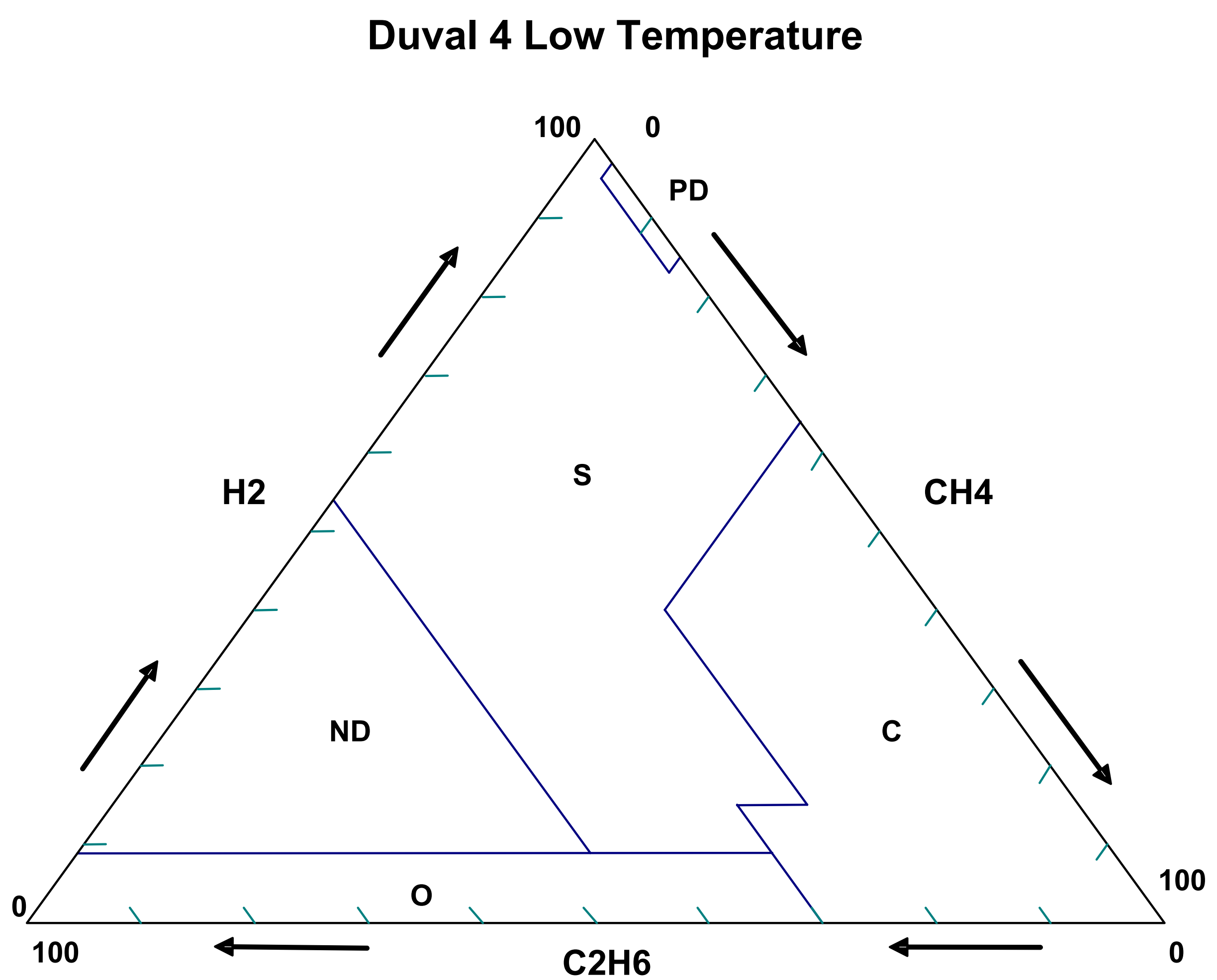
- Introduced in 2008
- For mineral oil Transformer
  - T4: With PD, T1 or T2 in Duval 1
  - T5: With T2 or T3 in Duval 1
  - **DO NOT** use for D1, D2
  - Use with DT with precaution
- To refine/confirm low energy faults
- Different gas and zones than in Triangle 1
- Use H2, CH4, C2H4 and C2H6

Relative Gas Generation Low Temperature



TJ | H 2 b

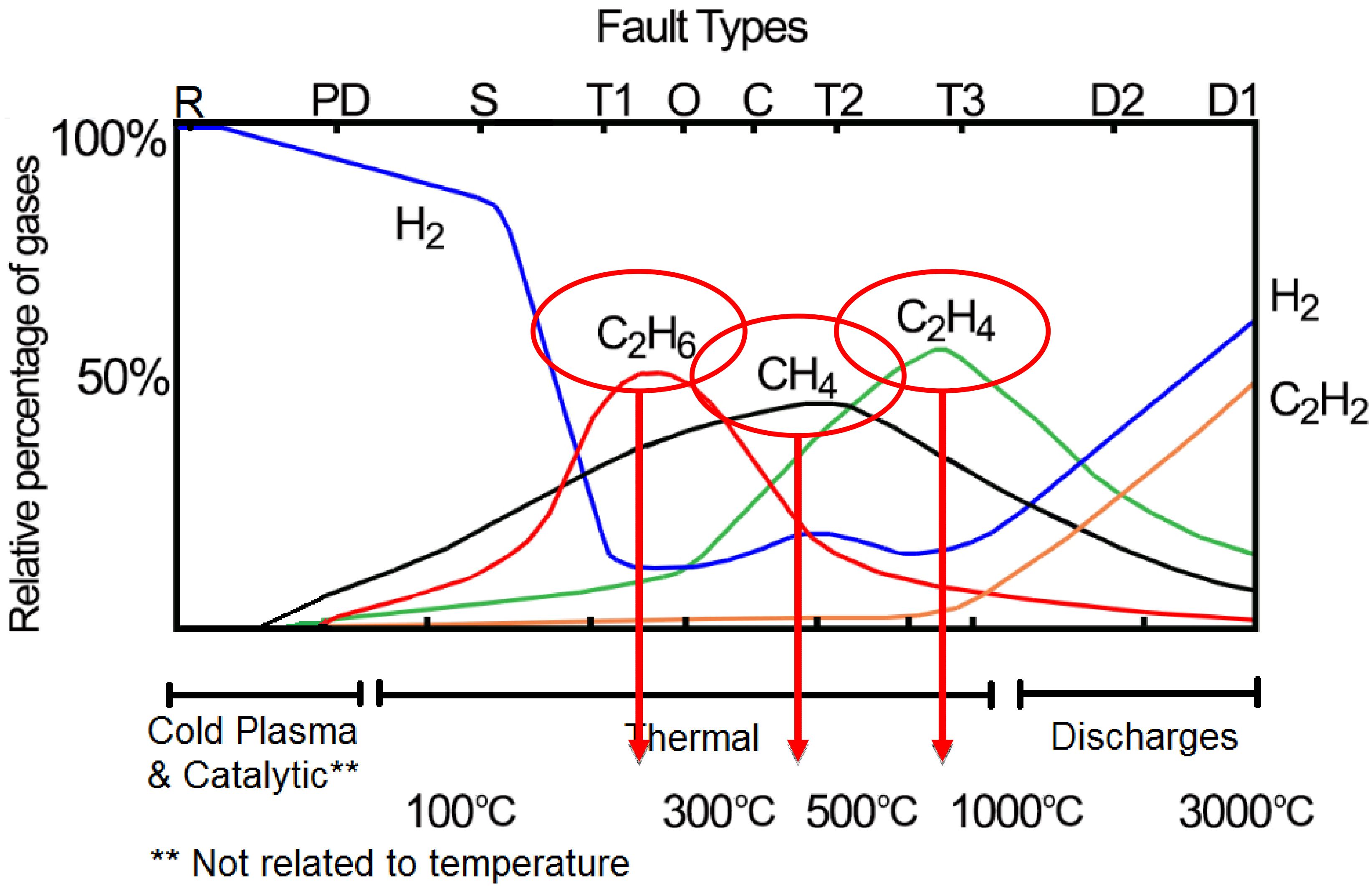
Duval Triangle 4 for Low Energy Faults



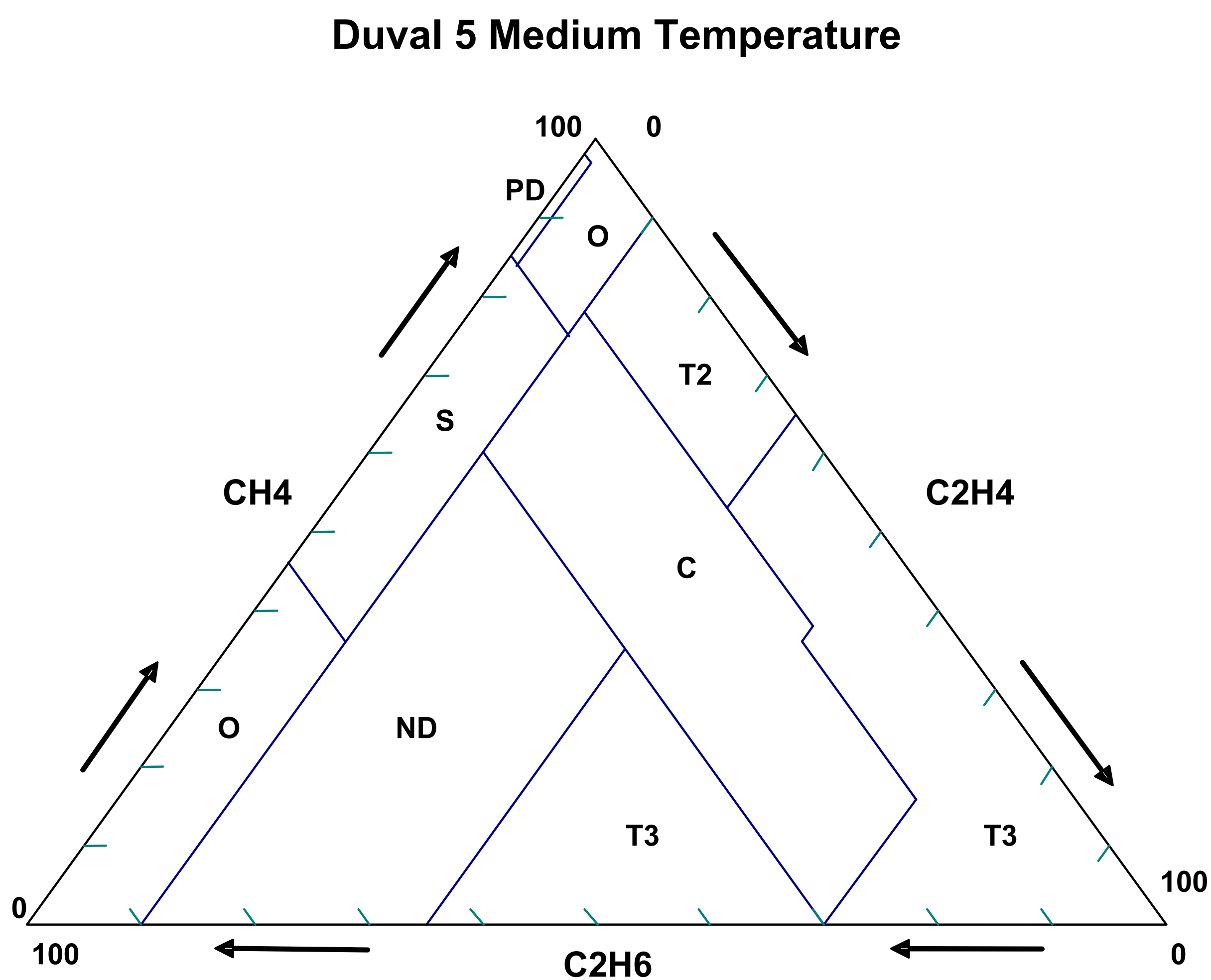
For PD, T1 and T2 of Triangle 1 only

TJ | H 2 b

Relative Gas Generation: Intermediate Temperature



Duval Triangle 5 for Low Energy Faults



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 < 250C
- ND Not Determined (use Duval 1)
- T2 Medium Temperature 300 - 700 ºC
- T3 High Temperature > 700 ºC

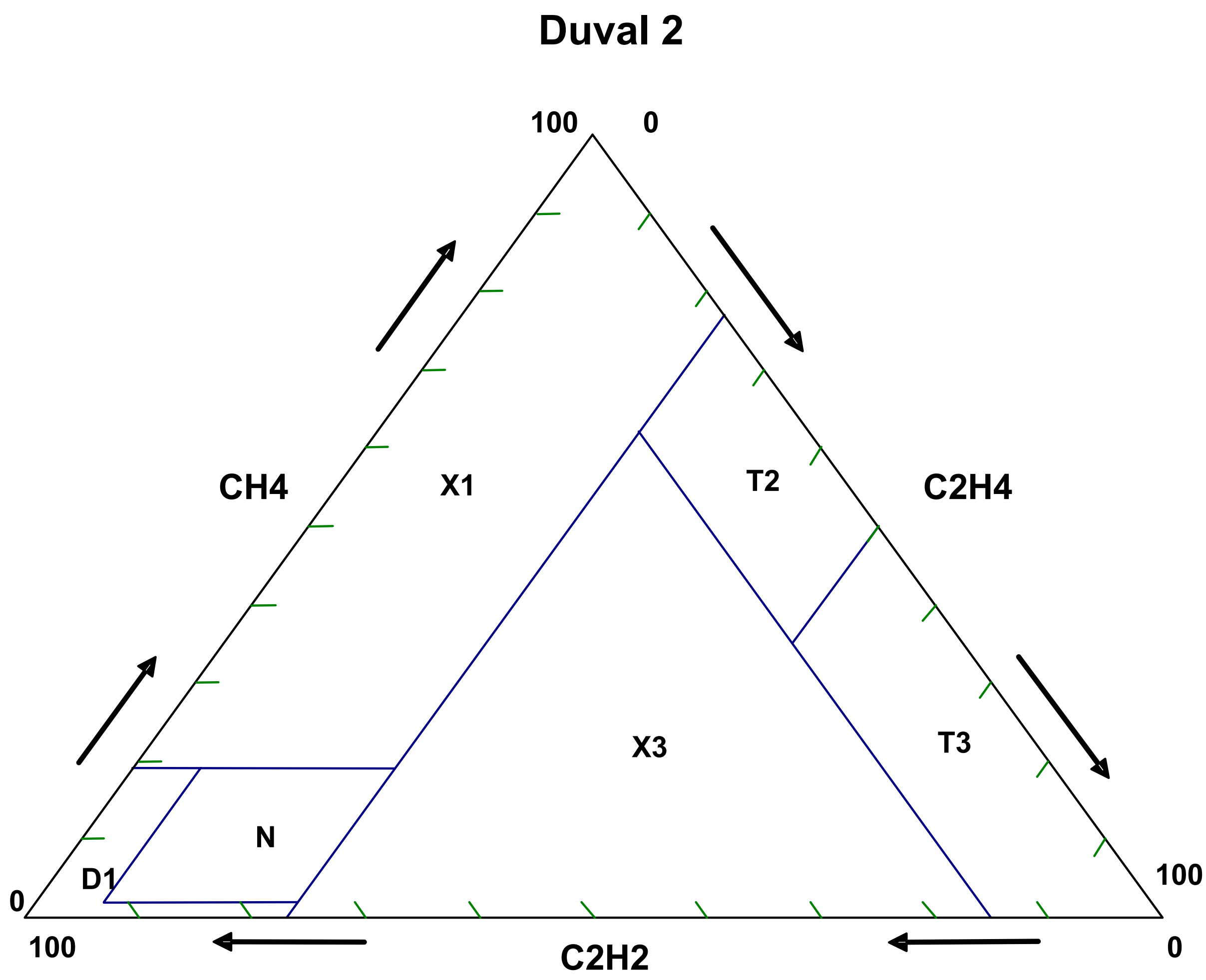
Duval Triangle 4 and 5

- 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

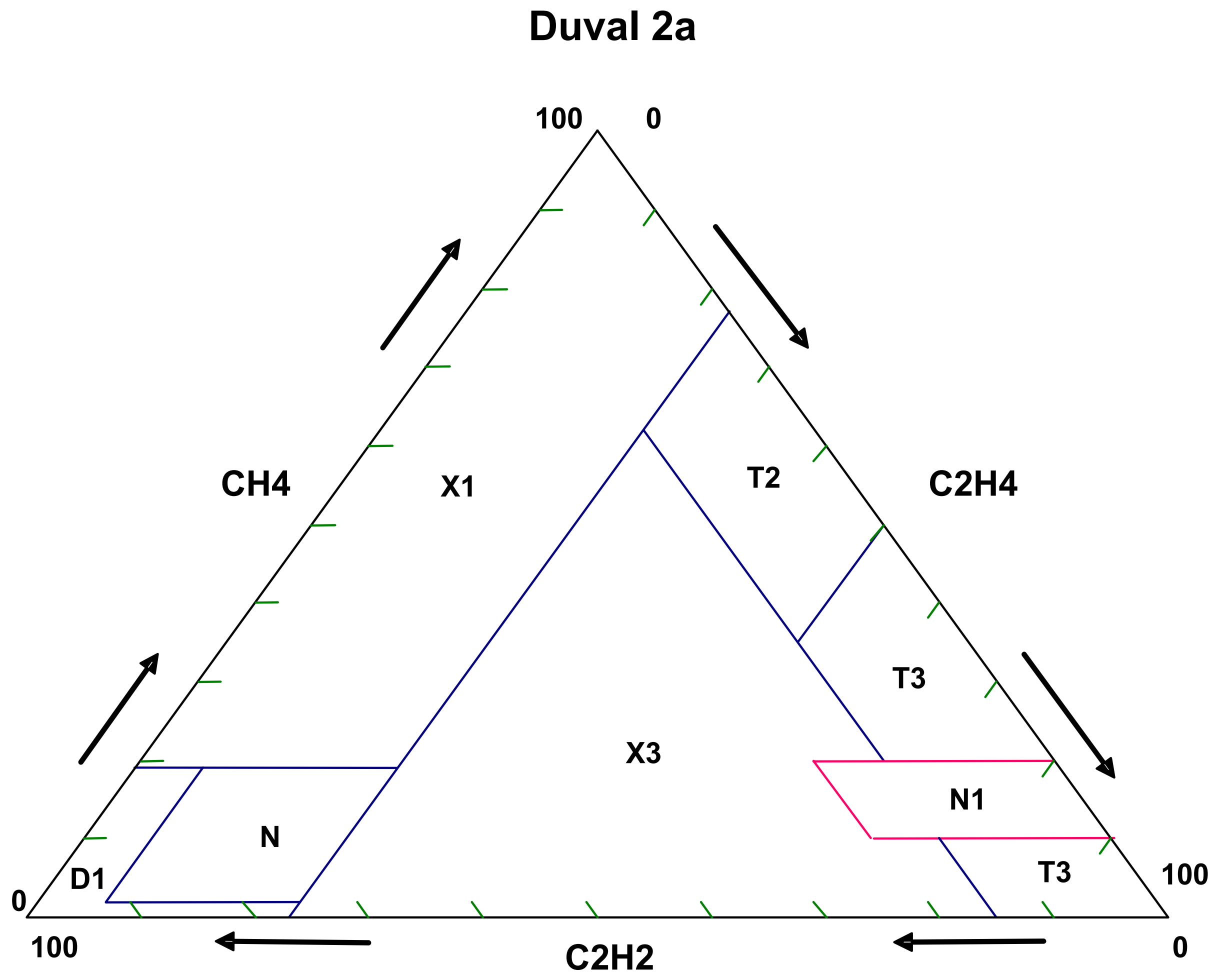
- N Normal Operation
- T2 Medium Temperature 300 - 700 ºC with Coking
- T3 High Temperature > 700 ºC, with Heavy Coking
- D1 Abnormal Arcing
- X1 Abnormal Arcing/Thermal
- X3 T2 or T3 or possible Abnormal Arcing/Coking

TJ | H 2 b

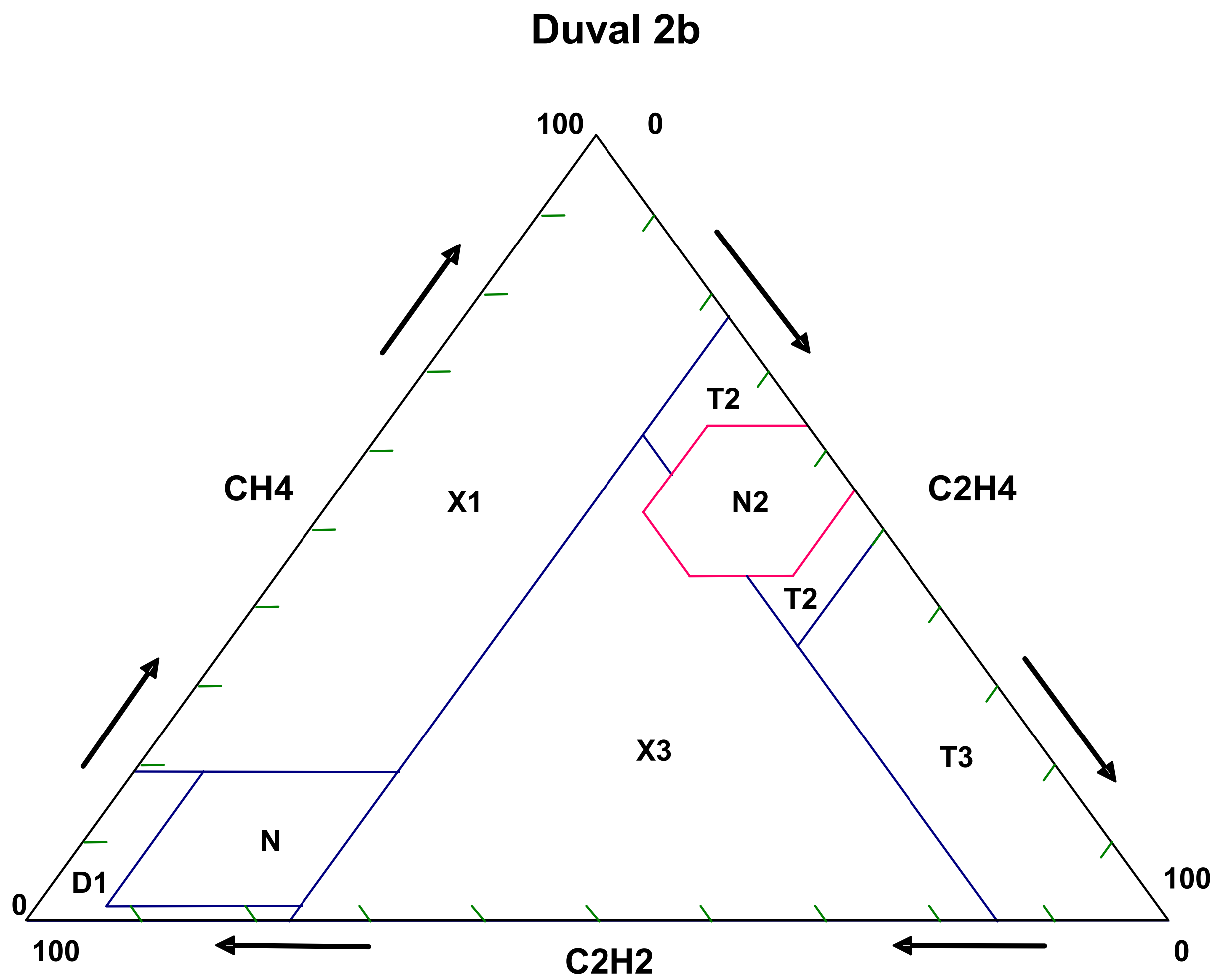
Duval Triangle 2a to 2e

- 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

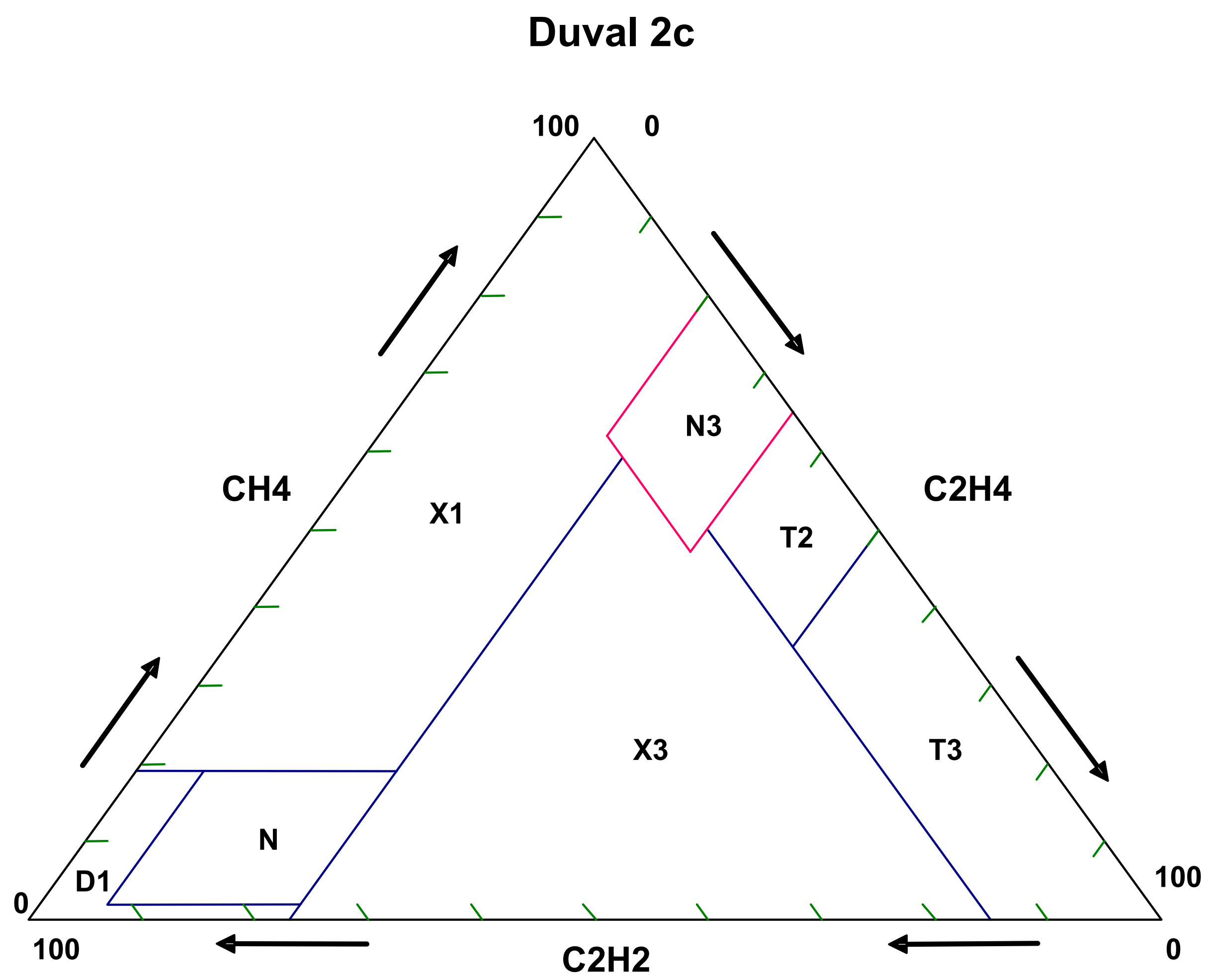
Duval Triangle 2 Type a: MR OilTaps® M & D



Duval Triangle 2 Type b: MR VacuTaps® VR

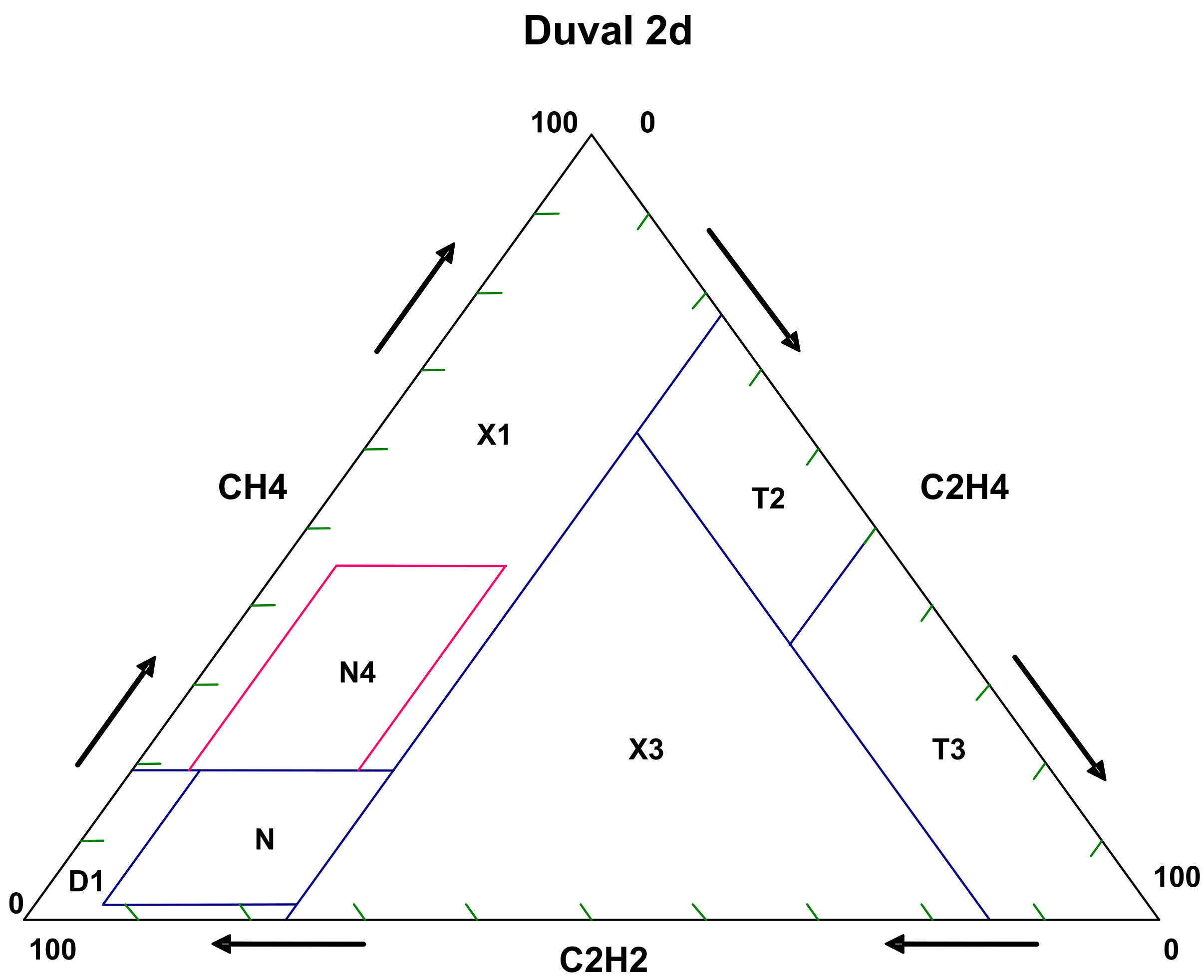


Duval Triangle 2 Type c: MR VacuTaps® VV

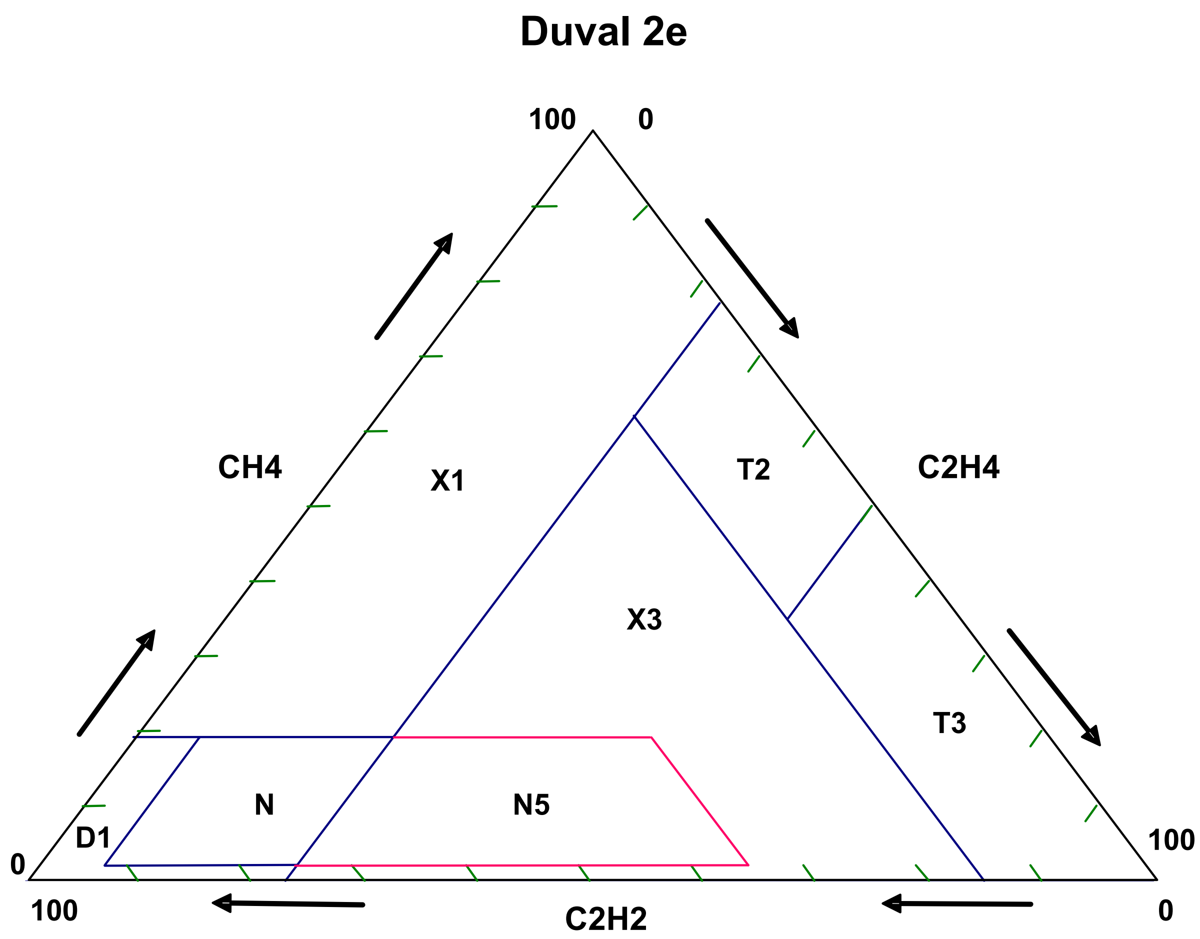


TJ | H_2b

Duval Triangle 2 Type d: OilTaps® R & V



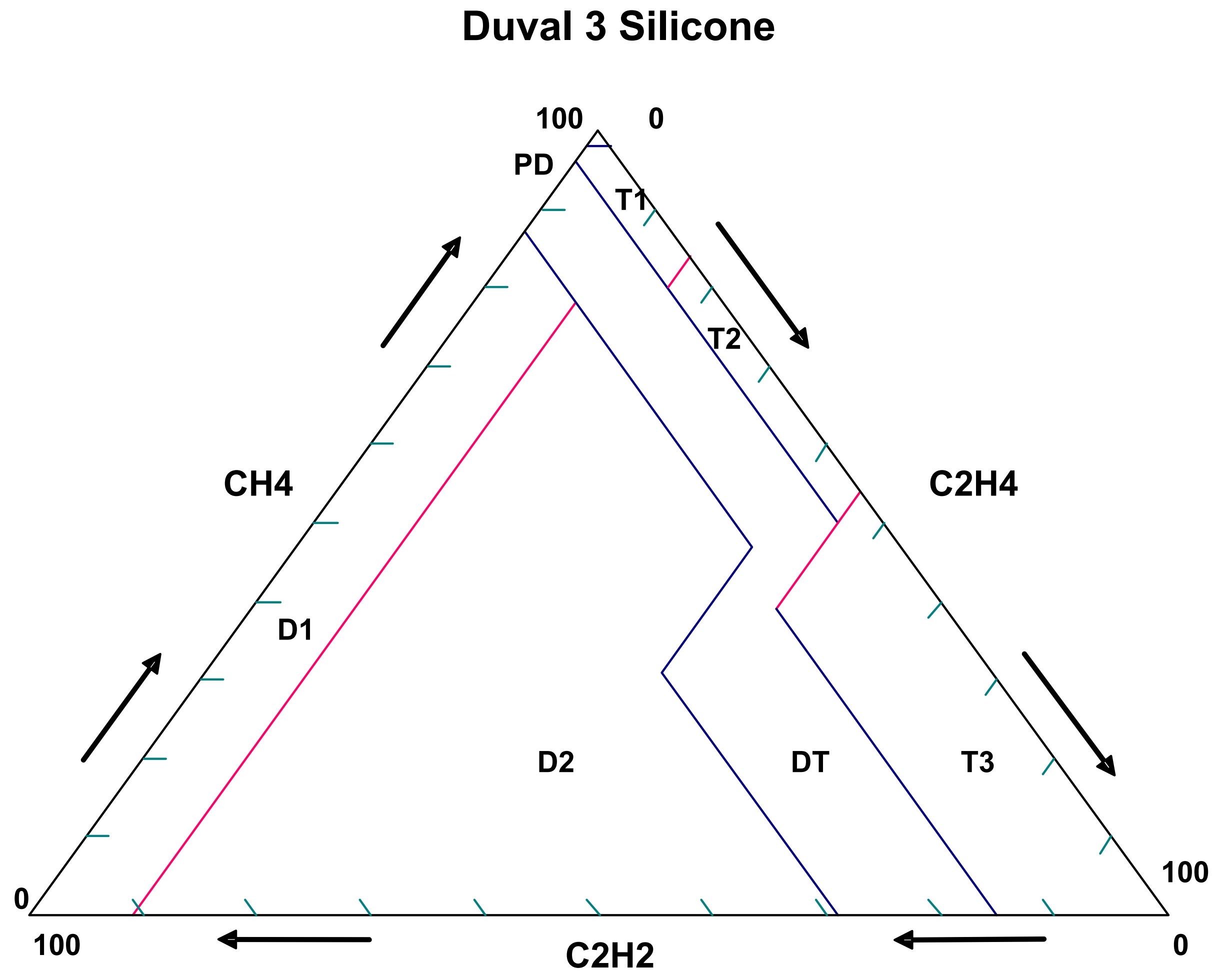
Triangle 2 Type e: MR OilTap G®; ABB few UZD®, some UZB®



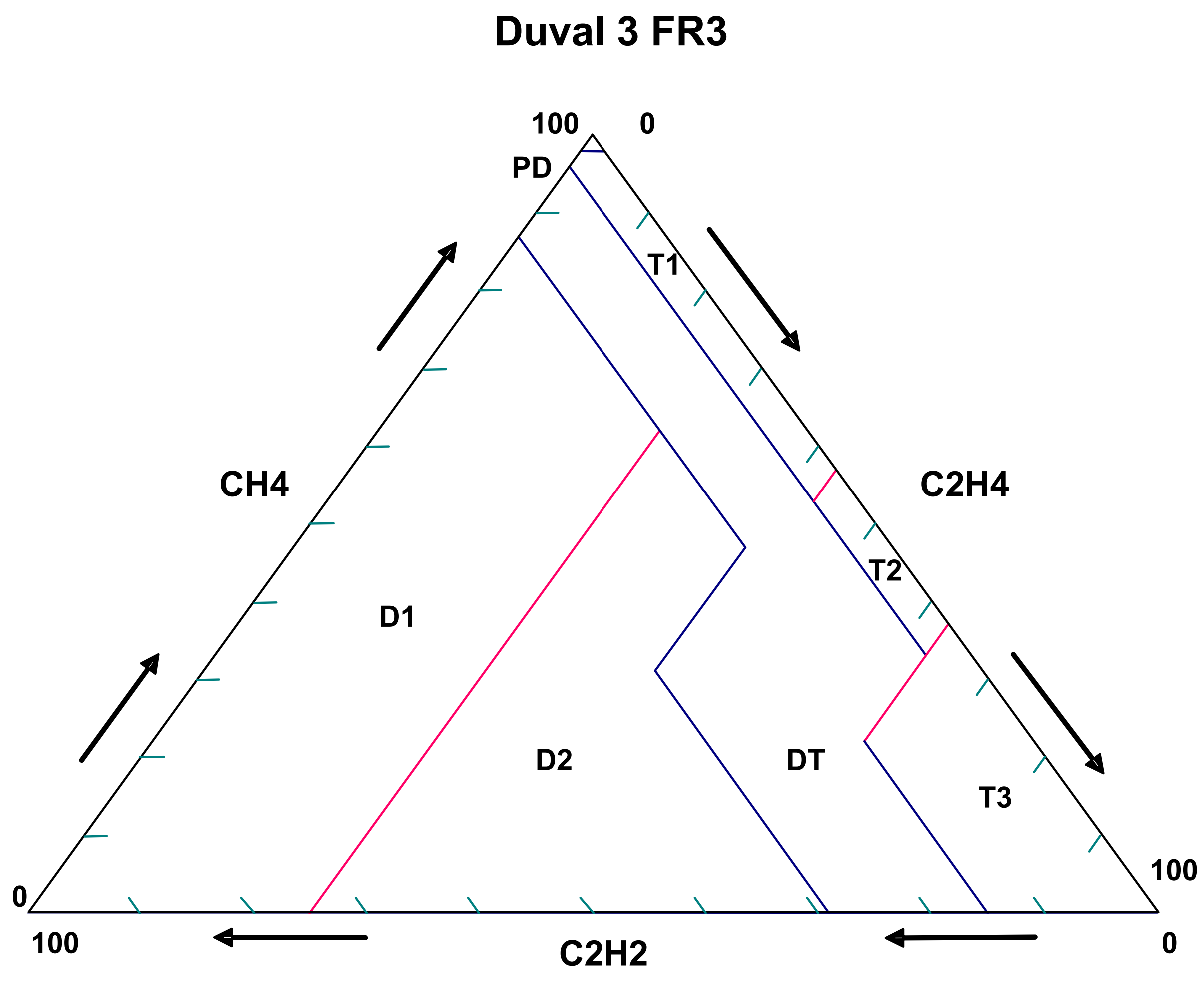
Duval Triangle 3

- 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

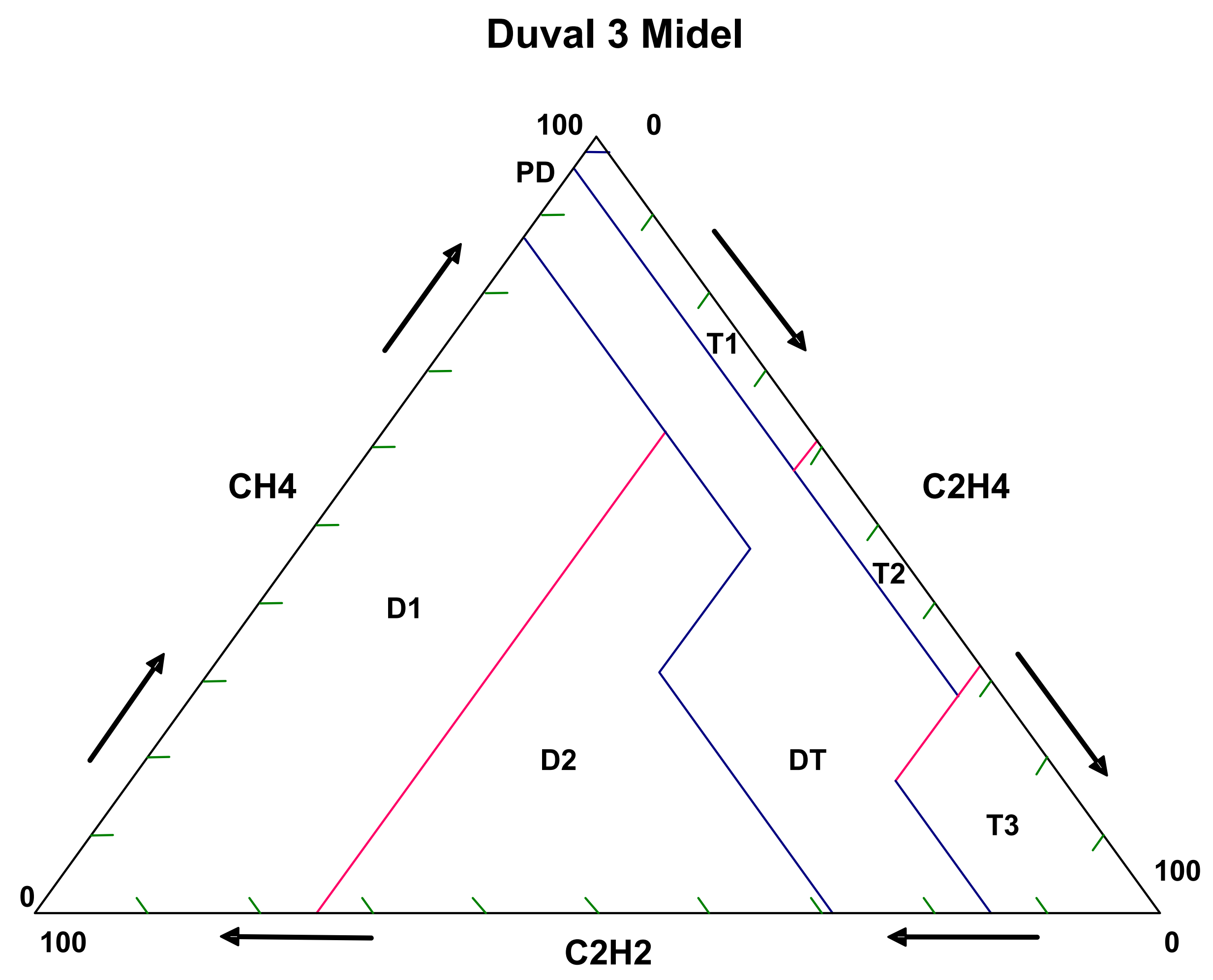


Duval 3 FR3®

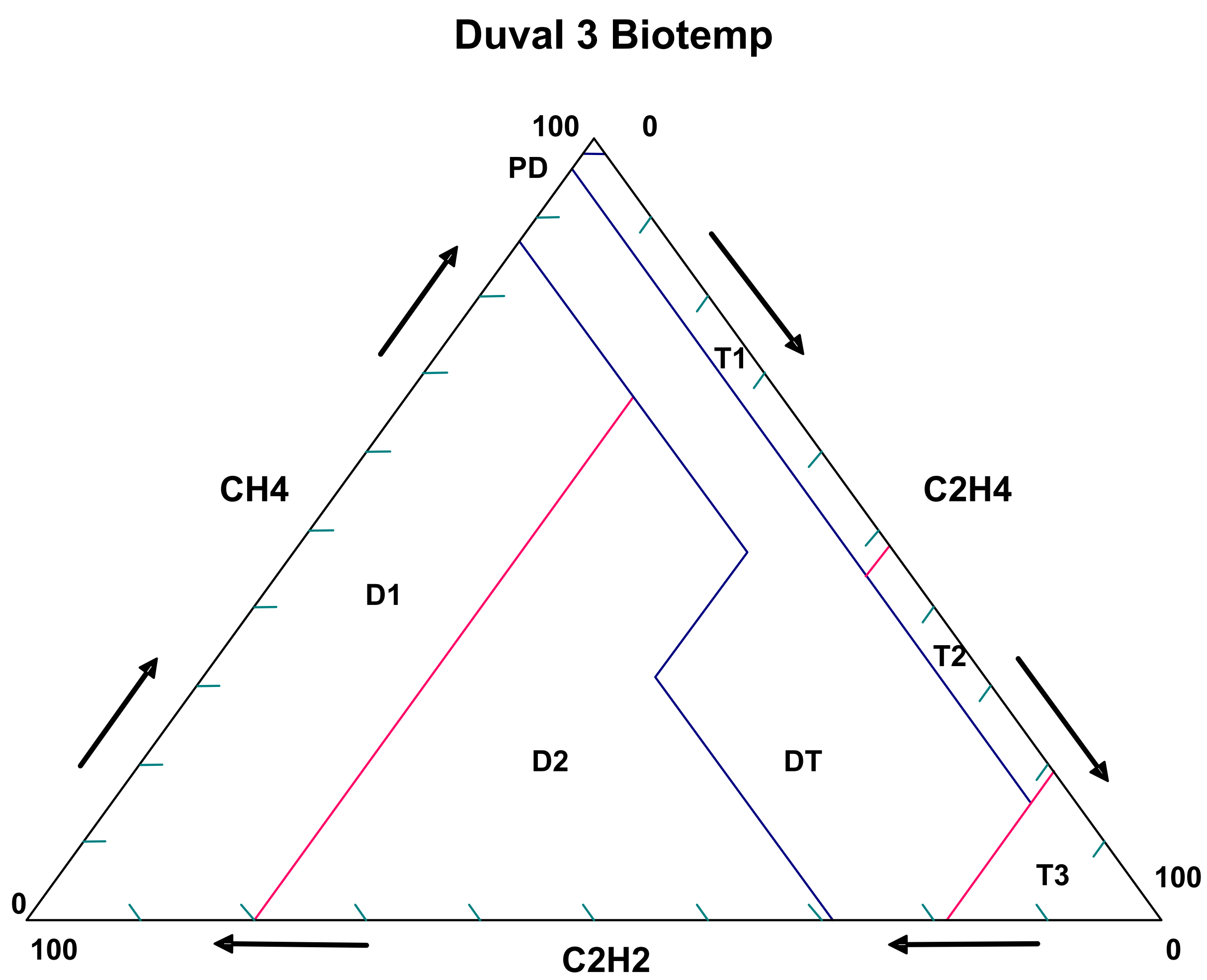


H 2 b

Duval Triangle 3 Midel®



Duval Triangle 3 Biotemp®



Duval Pentagons: Simplifying process

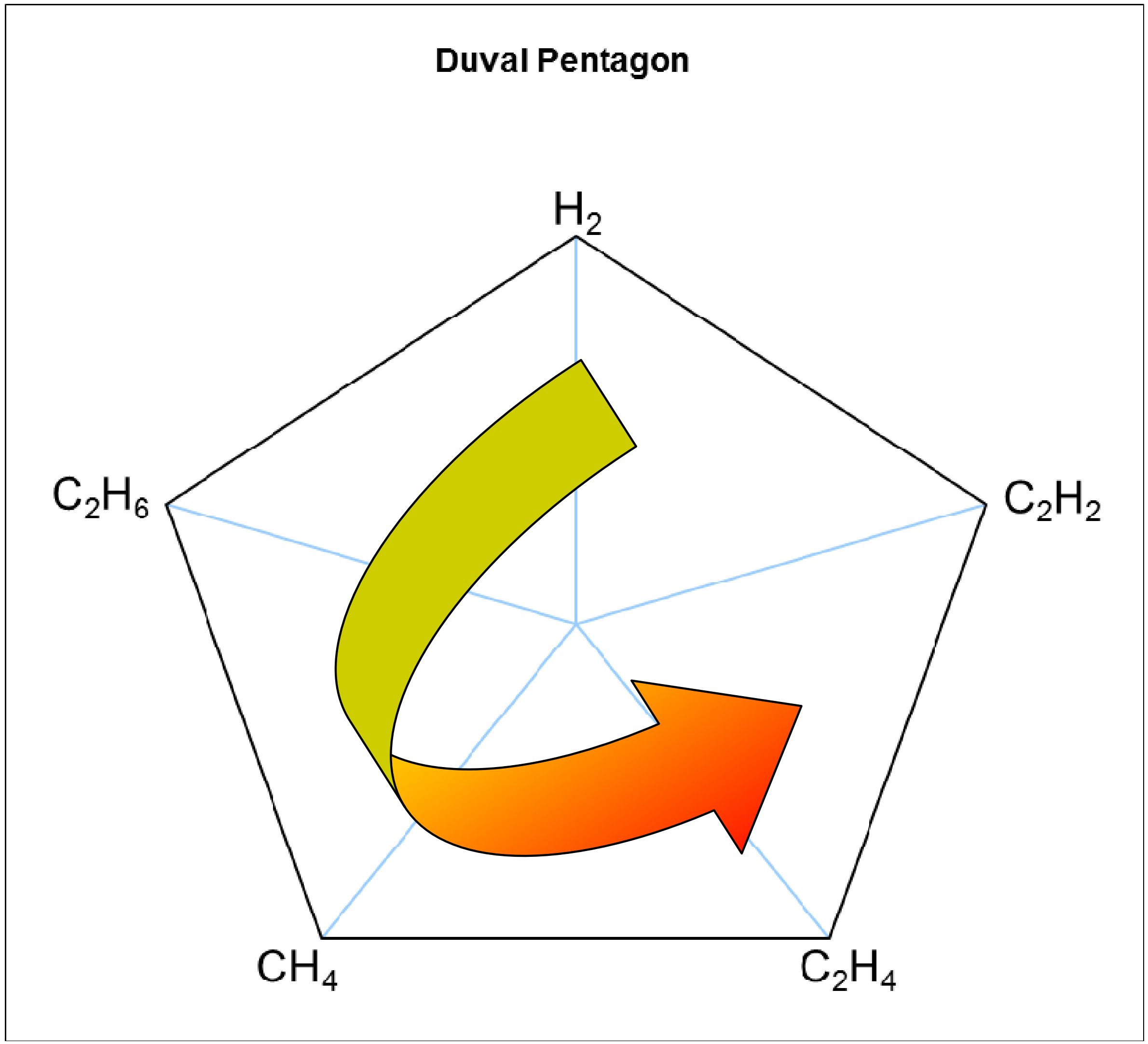
- Use of Triangle 1, 4 and 5 could be cumbersome
- It could be also confusing
- It could be misused

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

Duval Pentagon 1 and 2

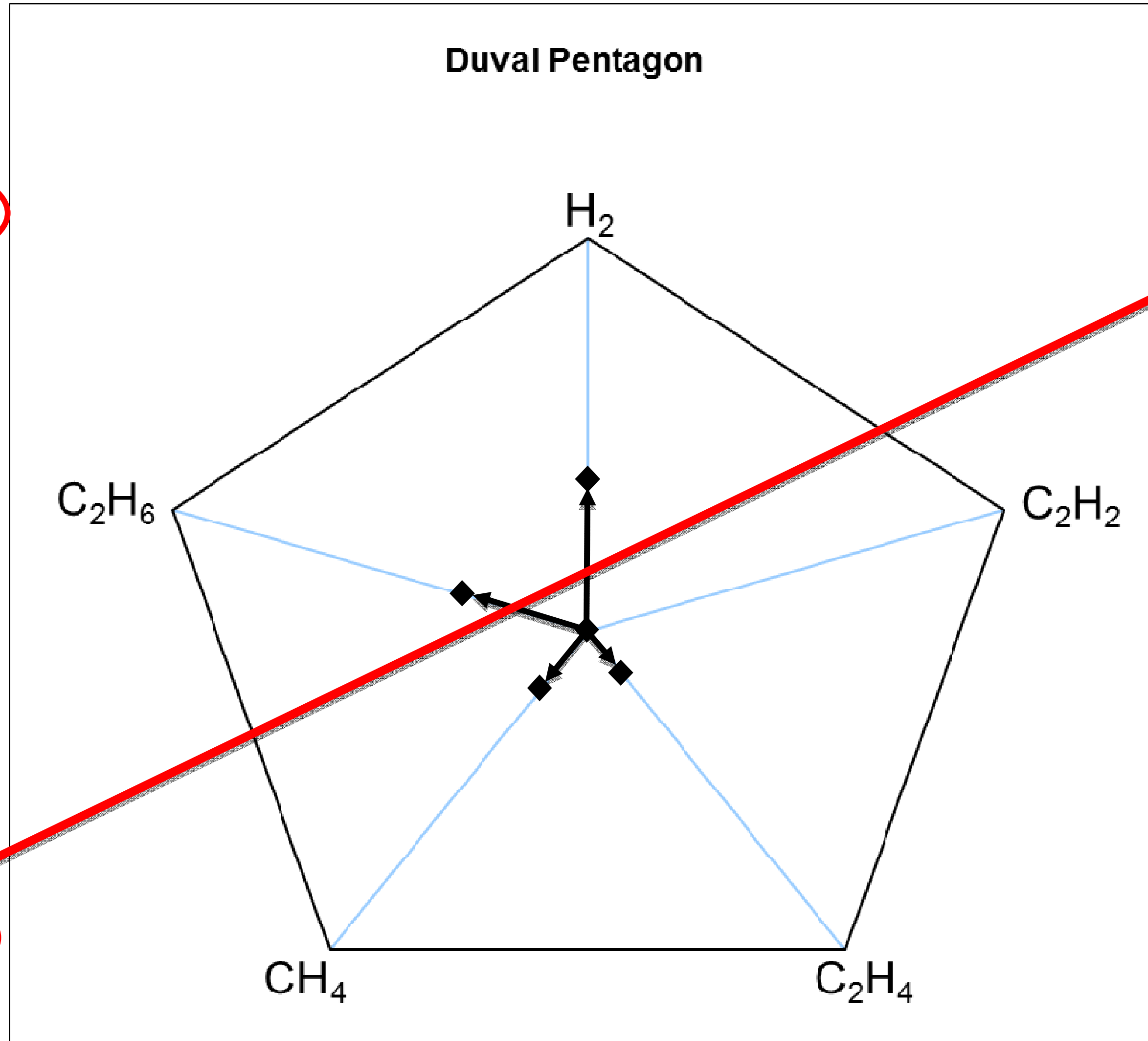
- Introduced in 2014
- For Mineral Oil Transformer
- Combine Triangle 1, 2 and 3
- Use H_2, C_2H_6, CH_4, C_2H_4 and C_2H_2
- Pentagon 1
  - "Classic" designation fault zones
- Pentagon 2
  - "Modern" designation fault zones

Duval Pentagons: H_2, C_2H_6, CH_4, C_2H_4 and C_2H_2

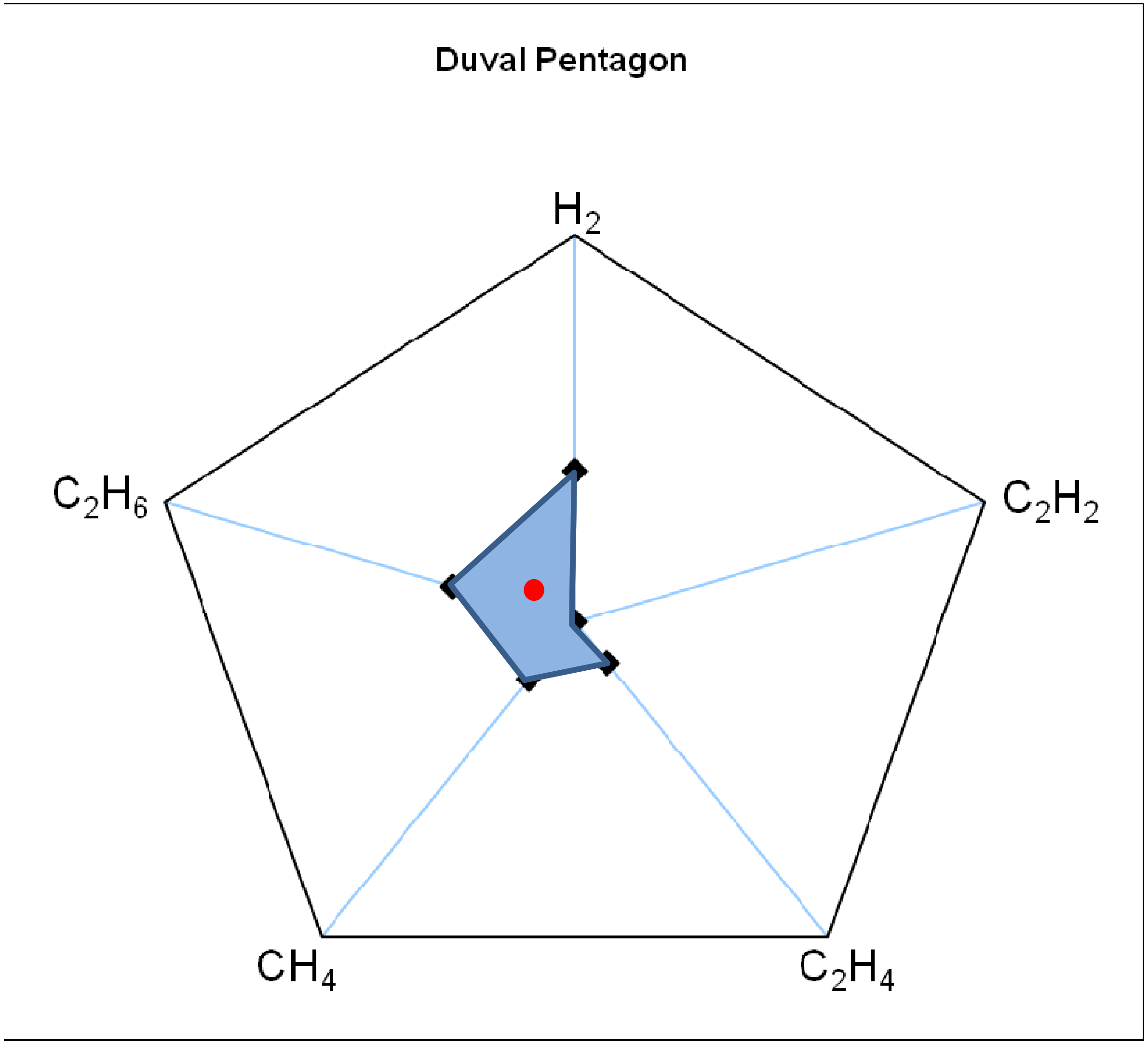


Duval Pentagons: place % of gas on each axis

Gas	% of Total
H_2 = 75 ppm	39 %
C_2H_6 = 57 ppm	30 %
CH_4 = 35 ppm	18 %
C_2H_4 = 25 ppm	13 %
C_2H_2 = 0 ppm	0 %
Total = 192 ppm	

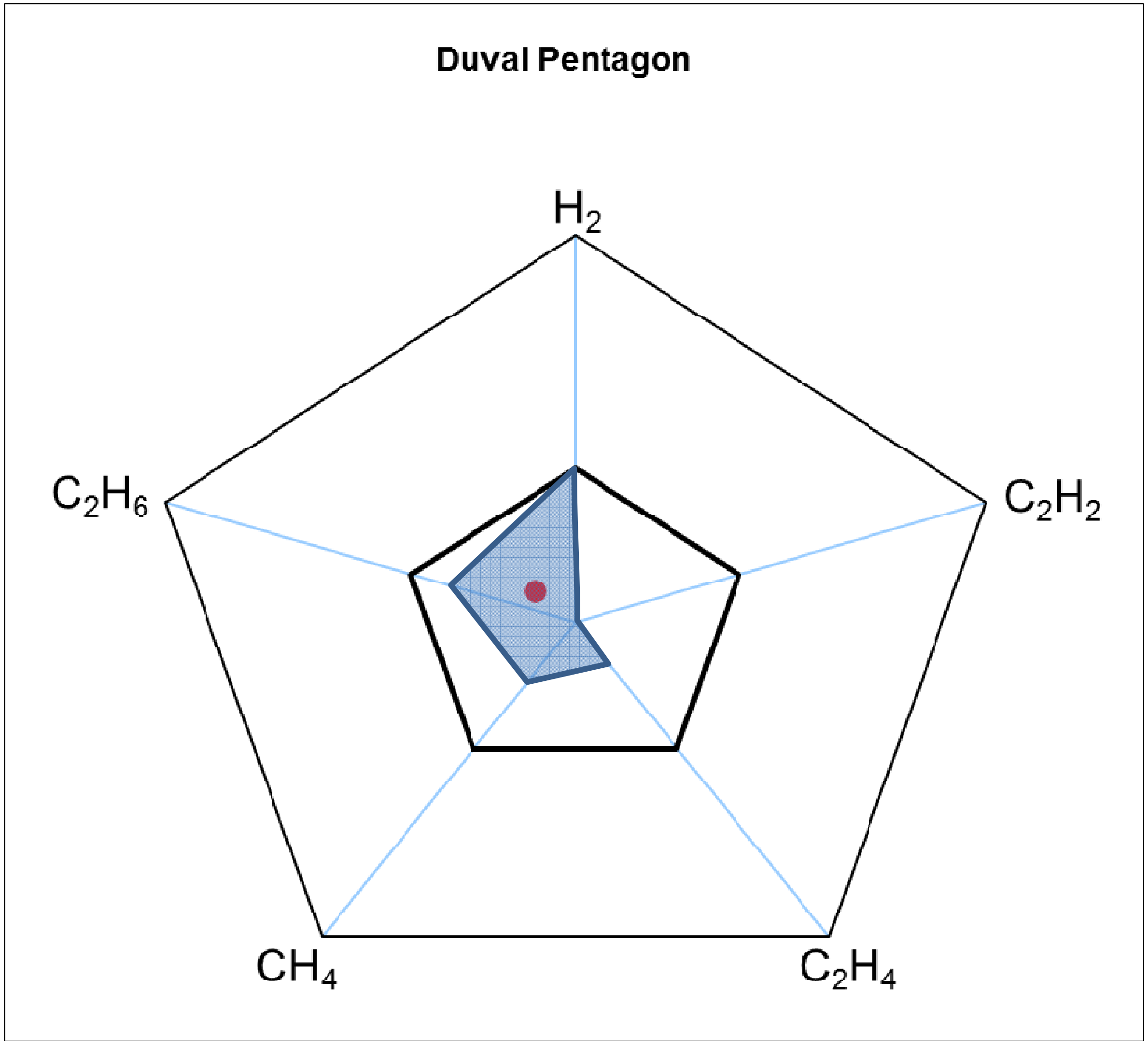


Duval Pentagons: Compute Centroid



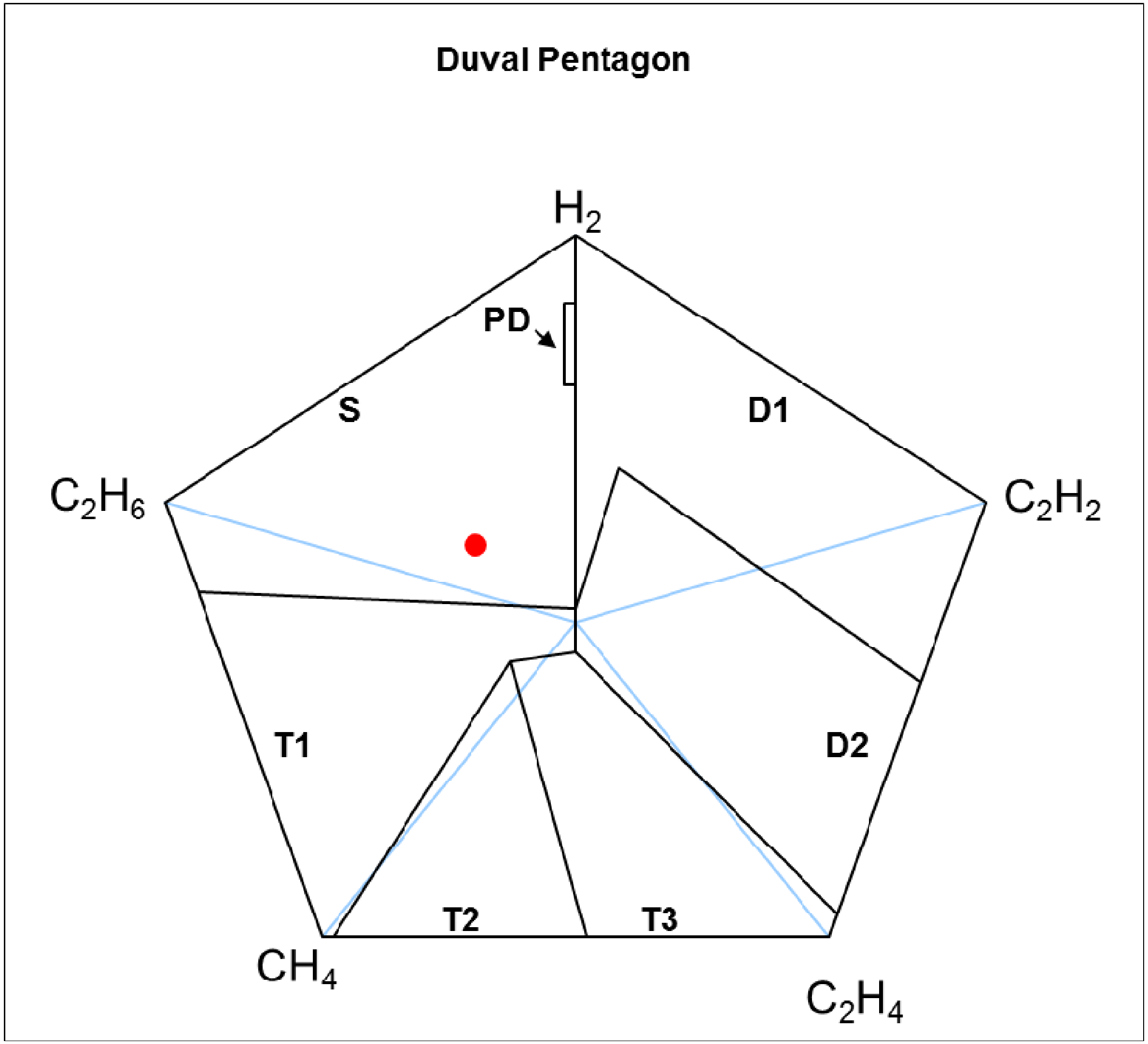
TJ | H 2 b

Duval Pentagons: Select inner 40%



TJ | H 2 b

Duval Pentagons: Add Zones



TJ | H 2 b

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

Conclusion

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**

TJ | H 2 b