Interpretation of Gas-In-Oil Analysis Using New IEC Publication 60599 and IEC TC 10 Databases

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Michel Duval
IREQ, Canada

Alfonso dePablo
RYMOIL, Spain

New IEC Publication 60599, concerning the interpretation of dissolved gas-in-oil analysis, was issued in 1999 [1] by Working Group 13 [2], as a result of the revision of IEC TC 10 of the previous IEC Publication 599, issued in 1978 [3].

The main body of Publication 60599 contains an in-depth description of the five main types of faults usually found in electrical equipment in service. The familiar gas ratios have been retained for the diagnoses, but with new code limits, while additional gas ratios are suggested for specific fault cases. More precise definitions of normal and alarm gas concentrations in service are indicated. In the Annexes, examples of typical (normal) gas concentration values observed in service are given for six different types of equipment.

Extensive databases of faulty equipment inspected in service and of typical normal values related to various types and ages of equipment and types of faults have been used for the revision of Publication 60599. These databases are presented in this paper for the benefit of the maintenance personnel involved in the interpretation of DGA results in service.

Publication 60599 contains an in-depth description of the five main types of faults usually found in electrical equipment in service.

Identification of Faults in Service

Classification of Faults

Classification of faults in Publication 60599 is according to the main types of faults that can be reliably identified by visual inspection of the equipment after the fault has occurred in service:

1. partial discharges (PD) of the cold plasma (corona) type with possible X-wax formation, and of the sparking type inducing small carbonized punctures in paper;
2. discharges of low energy (D1), evidenced by larger punctures in paper, tracking, or carbon particles in oil;
3. discharges of high energy (D2), with power follow-through, evidenced by extensive carbonization, metal fusion, and possible tripping of the equipment;
4. thermal faults below 300 °C if paper has turned brownish (T1), above 300 °C if paper has carbonized (T2);
5. thermal faults above 700 °C (T3), evidenced by oil carbonization, metal coloration, or fusion.

The number of characteristic faults is thus reduced from nine in the previous IEC Publication 599 to five in new IEC Publication 60599.

IEC TC 10 Database of Faulty Equipment Inspected in Service

The IEC TC 10 database of faulty equipment inspected in service is presented in Annex 1. Faulty equipment in this Annex were removed from service, visually inspected by experienced engineers and maintenance experts, and the fault clearly identified. Relevant DGA results were available in all these cases for correlation purposes.

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Identification of Faults in Service Using New IEC Publication 60599

The three basic gas ratios of IEC 599 (C_2H_2/C_2H_4, CH_4/H_2, C_2H_4/C_2H_6) are also used in IEC 60599 for the identification of the characteristic faults. The ratio limits have been made more precise, however, using the data of Annex 1, in order to reduce the number of unidentified cases from around 30% in IEC 599 to practically 0%, using Tables II and III of IEC 60599.

Unidentified cases occurred in IEC 599 when ratio codes calculated from actual DGA results would not correspond to any of the codes associated with a characteristic fault. Graphical methods that allow one to follow more easily and more precisely these cases, as well as the evolution of faults with time, are also described. A more detailed version of the Triangle method, updated from a previously published version [4], is included.

In addition to the three basic interpretation ratios, two new gas ratios have been introduced in IEC 60599 for specific diagnoses: the C_2H_2/H_2 ratio, to detect possible contamination from the OLTC compartment (when > 3), and the O_2/N_2 ratio, to detect abnormal oil heating/oxidation (when < 0.3). The limit below which the CO_2/CO ratio indicates a possible involvement of paper in the fault has been made more precise (< 3). Finally, other sources of gas, not related to a fault in service (mainly, H_2) are indicated.

Typical (Normal) Concentration Values in Service

Definitions

Typical (normal) values of gas concentrations are calculated in Publication 60599 as follows. First, all the DGA results concerning a specific type of equipment on a particular network are gathered. Then, for each characteristic gas considered, the cumulative number of DGA analyses where the gas concentration is below a given value is calculated, then plotted as a function of gas concentration. Using the plotted curve, the gas concentration corresponding to a given percentage of the total cumulative number of analyses (for instance, 90%) is the 90% typical (normal) concentration value for that gas and equipment type. The term "typical" value has been preferred in IEC 60599 to avoid possible misunderstandings between manufacturers and their customers.

If all gas concentration values from a DGA analysis are below typical values, the probability of having a failure, although not null, is low; the equipment is considered healthy and gas ratios should not be calculated, since any fault indication resulting from this calculation would have no significance.

Choosing a normality percentage is a compromise between reducing premature failure costs and increasing preventive maintenance costs. It is generally set at 90% for power transformers and instrument transformers and at 95% for bushings and cables. Calculating the actual probability of failure in service (PFS) improves further the economics of equipment monitoring, but necessitates good records of abnormal events on the equipment.

Users with sufficiently large DGA data banks are encouraged to calculate the typical values of their particular network and specific equipment population.

IEC TC 10 Database of Typical (Normal) Concentration Values in Service

The IEC TC 10 database contains typical values observed in several tens of thousands of transformers operating on more than 15 individual networks worldwide. These data have been gathered by WG 13 members from their own networks or from previous CIGRE 15 surveys. They are presented in Tables I – IV, following Annex 2.

Typical examples of the influence of equipment sub-type, age, and fault-type can be found in Table V. A typical example of how PFS values compare to 90% and 95% values is given in Table VI. In this example, PFS values would correspond more exactly to between 93% and 98% values.

Typical Values in New IEC Publication 60599

For simplification purposes, only ranges of typical values are given in IEC 60599, as informative examples of values observed in the field and in the absence of in-house calculated values. These ranges of typical values are indicated at the end of Tables I – IV of Annex 2 of this paper. These values should not be considered as limit values, but only as values above which increased DGA monitoring is recommended.

No information is given in IEC 60599 concerning the influence of equipment sub-type, age, or fault-type, which can be found in Table V of Annex 2 and in reference [4] for even more specific and detailed values.

Note: Typical values in Annex A1 of IEC 60599 are presently under revision, in collaboration with IEC TC 14 (power transformers).

Alarm Values and Rates of Gas Increase

Alarm Values

Alarm values, often quoted as maximum acceptable values, are defined in IEC 60599 as values above which the probability of an incident is sufficiently high to require urgent competent decisions and/or actions.

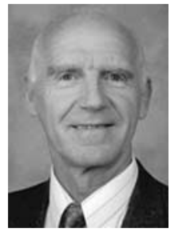
Maximum acceptable values are given for instrument transformers only in Annex A3 of IEC 60599 (values recommended by CIGRE WG 12-16). For other types of equipment, alarm values should be set by users or manufacturers. When possible, calculating PFS values will reduce subjective and personal bias when setting these values.

Rates of Gas Increase

Typical rates of gas increase are given for power transformers only in Table III of Annex A1 in IEC 60599 (these values are presently under revision, in collaboration with IEC TC 14). For other types of equipment and specific networks, in the absence of more precise information, typical rates of gas increase of more than 10% per month are generally considered necessary to pronounce the fault as active. Higher rates, such as 50% per week, are considered very serious.

References

1. IEC Publication 60599, March 1999.
2. Contributing members of WG 13: M. Duval (CA), Convenor, M. Giovannini (IT), T. Grestad (NO), H. Knab (CH), M. Kocan-Gradnik (SI), M. Martins (PO), M. Mistiaen (BE), H. Moller (DK), J.C. Noualhaguet (FR), A. dePablo (ES), B. Pahlavanpour (GB), M. Randoux (BE), A. Reygaerts (BE), V. Tumiatti (IT), M. Szebeni (HU).
3. IEC Publication 599, 1978. Out of print but available from libraries.
4. M. Duval, et al., *CIGRE Berlin Symposium*, Paper 110-14.



Michel Duval graduated from the University of Toulouse in 1966 with a B.Sc. in chemical engineering, and received a Ph.D. in polymer chemistry from the University of Paris in 1970. Since then, he has worked for Hydro Quebec's Institute of Research (IREQ) on electrical insulating oils, dissolved gas analysis, and lithium polymer batteries. A senior member of the IEEE, he holds 12 patents; has authored over 60 scientific papers, book chapters, or international standards; and is very active in several CIGRE and IEC working groups. He may be reached at IREQ, 1800 boul. Lionel Boulet, Varennes, J3X 1S1, Canada, or at duvalm@ireq.ca.

Annex 1. IEC TC 10 Database of Faulty Equipment Inspected in Service

Table 1. Abbreviations Used for Equipment Type	
Abbr.	Equipment type
P	Power transformer without communicating OLTC
U	Power transformer with communicating OLTC
R	Reactor
I	Instrument transformer
B	Bushing
C	Cable

Table 2. Fault Identified as Partial Discharges (PD) by Inspection of the Equipment									
Equip.	Inspection	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	Ref.
U	Low energy partial discharges and x-wax formation	32930	2397	-	-	157	313	560	2
I	Corona and x-wax formation	37800	1740	8	8	249	56	197	4
I	X-wax deposition	92600	10200	-	-	-	6400	103151	4
B	Partial discharges inducing displacement of insulation and bolt	8266	1061	-	-	22	107	498	10
I	Partial discharges	9340	995	7	6	60	60	620	15
I	X-wax deposits	36036	4704	10	5	554	6	347	19
I	X-wax deposits	33046	619	-	2	58	51	1	19
I	X-wax deposits	40280	1069	1	1	1060	1	-	19
I	Heavy x-wax deposits	26788	18342	-	27	2111	704	-	19

Table 3. Fault Identified as Discharges of Low Energy (D1) by Inspection of the Equipment									
Equip.	Inspection	H_2	CH_4	$C2H_2$	C_2H_4	C_2H_6	CO	CO_2	Ref.
P	Loosening of potential ring on bushing, with marks of sparking and tracking	78	20	28	13	11		784	2
P	Sparking between HV braided connection and isolated copper tube	305	100	541	161	33	440	3700	3
S	Selector breaking current in selector tank	35	6	482	26	3	200	2240	3
U	Continuous sparking between metal cups and earthed bolts in winding	543	120	1880	411	41	76	2800	3
P	Tracking to HV bushing	1230	163	692	233	27	130	115	4
P	Tracking in bushing	645	86	317	110	13	74	114	4
R	Tracking to the ground in glue of central beam	60	10	4	4	4	780	7600	4
P	Sparking on tank walls to the bushing	95	10	39	11	-	122	467	4
S	500 OLTC normal operations	6870	1028	5500	900	79	29	388	8
S	3600 OLTC normal operations	10092	5399	37565	6500	530	42	413	8
	Poor shielding contact (electrical problem)	650	81	270	51	170	380	2000	10
C	Traces of discharges in paper of cone junction of HV cable	210	22	7	6	6	19	74	13
R	Sparking from bushing to tank	385	60	159	53	8	465	1250	14
R	Sparking from bushing to tank	4230	690	1180	196	5	438	791	14
R	Tracking in paper	7600	1230	1560	836	318	4970	4080	14
P	Low energy arcing on bushing	595	80	244	89	9	524	2100	14
R	Low energy in core	120	25	40	8	1	500	1600	14
S	Contamination from OLTC	8	-	101	43	-	192	4067	14
R	Tracking in insulation	6454	2313	6432	2159	121	3628	225	14
R	Tracking from windings to beam	2177	1049	705	440	207	4571	3923	14
R	Sparking / Tracking in insulation	1790	580	619	336	321	956	4250	14
P	Sparking from core to ground	1330	10	182	66	20	231	1820	14
U	Contamination from OLTC	4	1	52	7	2	93	519	14
U	Defective OLTC operation	1900	285	7730	957	31	681	732	14
B	Low energy arcing in bushing	57	24	30	27	2	540	2518	14
B	Low energy discharge in oil, signs of tracking along inner porcelain	1000	500	500	400	1	200	1000	18

Table 4. Fault Identified as Discharges of High Energy (D2) by Inspection of the Equipment									
	Inspection	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	Ref.
P	Flahover from LV to ground, external	440	89	757	304	19	299	1190	4
S	Arc in selector switch	210	43	187	102	12	167	1070	4
U	Short circuit in distribution windings	2850	1115	3675	1987	138	2330	4330	4
U	Short circuit from LV to ground, internal	7020	1850	4410	2960	-	2140	1000	4
P	Short circuit from LV to connector	545	130	239	153	16	660	2850	4
P	Arcing from windings to porcelain	7150	1440	1760	1210	97	608	2260	4
U	Tertiary windings damaged by arcing	620	325	244	181	38	1480	2530	4
R	Arcing in wet cellulose	120	31	94	66	-	48	271	4
P	Short circuit in windings	755	229	460	404	32	845	5580	4
R	Arcing from windings to ground (inadvertent piece leftover)	5100	1430	1010	1140	-	117	197	4
U	Short circuit in windings	13500	6110	4040	4510	212	8690	1460	4
P	Bushing swollen, tank opened	1570	1110	1830	1780	175	135	602	4
P	Arcing to magnetic circuit (ground)	3090	5020	2540	3800	323	270	400	4
P	Short circuit between conductors	1820	405	634	365	35	1010	8610	4
R	Arcing inside windings	535	160	680	305	16	172	338	4
U	Flash-over between dislocated connection and HV bushing turret	13	3	6	3	1	4	51	9
U	Flash-over due to lightning overvoltage with burnt insulation and leads	137	67	104	53	7	196	1678	9
S	Arcing on selector switch ring	1084	188	769	166	8	38	199	9
U	Arcing between connections to tap changer, burnt areas on windings	34	21	56	49	4	95	315	9
I	Arcing in static shield connections	7940	2000	5390	3120	355	1130	285	10
C	Very short HV high energy discharge, followed by tracking	150	130	30	55	9	120	200	13
R	Arcing from bushing to tank	8200	3790	5830	4620	250	31	85	14
P	Arcing in windings	260	215	277	334	35	130	416	14
P	Arcing in windings	75	15	26	14	7	105	322	14
R	Arcing in windings	530	345	250	266	85	3900	20000	14
P	Arcing in oil	60	5	21	21	2	188	2510	14
R	Arcing in wndings	90	28	32	31	8	1380	11700	14
R	Arcing in wndings	220	77	240	170	22	1800	13800	14
R	Arcing in wndings	5900	1500	2300	1200	68	750	335	14
U	Arcing in wndings	420	250	800	530	41	300	751	14
R	Arcing from bushing to tank	2800	2800	3600	3500	234	92	718	14
R	Arcing in bushing	99	170	190	200	20	140	1160	14
U	Arcing in oil duct	310	230	760	610	54	150	631	14
U	Arcing in oil duct	800	160	600	260	23	490	690	14
P	Arcing from bushing to tank	1500	395	323	395	28	365	576	14
P	Arcing from windings to core	20000	13000	57000	29000	1850	2600	2430	14
R	Arcing in windings (molten metal)	305	85	130	197	25	813	8380	14
R	Arcing in windings	1900	530	434	383	35	1890	7570	14
R	Arcing in windings	110	62	250	140	90	680	6470	14
P	Arcing in oil (turret)	3700	1690	3270	2810	128	22	86	14
P	Arcing in oil (turret)	2770	660	763	712	54	522	1490	14
R	Arcing from bushing to tank	245	120	167	131	18	829	4250	14
P	Arcing from HV to tank	1170	255	325	312	18	5	1800	14
R	Arcing from bushing to tank	4419	3564	2025	2861	668	909	9082	14
R	Arcing in bushing	810	580	490	570	111	1100	6800	14
R	Arcing in bushing insulation	5000	1200	1100	1000	83	140	265	14
U	Arcing in OLTC and windings	10000	6730	10400	7330	345	1980	3830	14
U	Arcing in oil from copper bus to tank	1570	735	1740	1330	87	711	4240	14

Table 5. Fault Identified as Thermal Faults < 700 C (T1 and T2) by Inspection of the Equipment									
Equip.	Inspection	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	Ref.
P	High circulating currents between conductors with winding damage	1270	3450	8	1390	520	483	44500	3
P	Circulating currents in LV windings and core	3420	7870	33	6990	1500	573	4640	3
I	Thermal runaway inside thick insulation with puncture / carbonization of paper	360	610	9	260	259	12000	74200	5
I	Thermal runaway in thick paper insulation	1	27	1	4	49	53	254	5
U	Blackened area within windings, interturn fault, open circuit parallel path	3675	6392	5	7691	2500	101	833	9
P	Vertical bar buses burnt out, carbonization of paper strips	48	610	-	10	29	1900	970	10
P	Carbonized windings during heat run tests	12	18	-	4	4	559	1710	12
P	Circulating currents in magnetic tank shunt during heat run tests	66	60	-	7	2	76	90	12
U	Overheating of core to ground and insulation shields (narrow oil ducts)	1450	940	61	322	211	2420	3560	14
B	Hot spot with carbon formation	-	18900	330	540	410	3900	710	14
I	Hot spot in paper	960	4000	6	1560	1290	15800	50300	14
I	Hot spot in paper	24700	61000	1560	42100	26300	14400	30400	14
P	Overheating of conductor < 200 °C	14	44	1	7	124	128	2746	16
R	Low temperature overheating of clamping beams of yokes by stray flux	2031	149	-	3	20	556	3008	17
R	Idem, with carbonization of beams	480	1075	-	1132	298	464	1000	17
B	Thermodielectric failure	40000	400	6	600	70	800	218	18

Table 6. Fault Identified as Thermal Faults > 700 °C (T3) by Inspection of the Equipment									
Equip.	Inspection	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	Ref.
P	Hot spot at connection	8800	64064	-	95650	72128	290	90300	1
P	Circulating currents between yoke clamps and connecting bolts	6709	10500	750	17700	1400	290	1500	3
S	Pyrolitic carbon growth between selector contacts	1100	1600	26	2010	221	-	1430	3
P	Steel lamination eroded	290	966	57	1810	299	72	756	4
P	Circulating currents in clamping bolt	2500	10500	6	13500	4790	530	2310	4
U	Contacts of selector switch burnt	1860	4980	1600	10700	-	158	1300	4
U	Lengthy overheating of tap changer contacts	860	1670	40	2050	30	10	690	6
U	Defects on contacts of tap changer selector	150	22	11	60	9	-	-	7
P	High contact resistance of winding terminal	400	940	24	820	210	390	1700	10
P	Ground wiring burnt and ruptured by circulating current	6	2990	67	26076	29990	6	26	10
U	Burnt copper contacts in change over selector	100	200	11	670	110	100	650	11
P	Bad contact in windings	290	1260	8	820	231	228	826	14
R	Bad contact in defective weld in windings	1550	2740	184	5450	816	1140	9360	14
R	Hot spots in laminations	3910	4290	1230	6040	626	1800	11500	14
R	Hot spot in laminations (molten steel)	12705	23498	5188	34257	6047	4004	8539	14
R	Hot spot on bushing	1	8	6	100	8	300	5130	14
R	High temperature in laminations	300	700	36	1700	280	760	9250	14
P	Burnt lamination during heat run test	107	143	2	222	34	193	1330	14

Table 7. References in Tables 2 - 6 of Annex 1			
Ref.	Year	Authors	Journal / Report
1	1972	J. Rabaud et al.	Rev. Gen. Elec., 31 (11)
2	1976	J. Rabaud et al.	CIGRE TF 12-06
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10	1986	C. Sobral Viera	CIGRE Paris
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19	1992		EPRI Workshop on TCs

Annex 2. IEC TC 10 Database of Typical (Normal) Values in Service

Table 1. 90% Typical (Normal) Values for Power Transformers Without a Communicating OLTC, in ppm

Year	Company	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	Ref.
76	LCIE	134	134	-	45	157	1008	10528	1
80	Alsthom	100	200	20	200	200	1000	10000	2
81	EDF	-	225	3	110	225	785	4500	2
82	Asinel	105	125	10	166	71	2000	18000	2
85	Chili	100	50	15	50	65	500	5000	2
88	Asinel	100	70	10	170	70	1000	10000	2
89	Hydro Quebec (HQ)	150		8	220				3
92	LCIE	-	224	5	112	224	2150	6720	4
92	Vattenfall	200	50	3	200	50	1000	20000	4
93	HQ (electrical)	85		70	35	80			8
93	HQ (thermal)	175		3	375	100			8
93	LCIE / EDF	80		4	100	200	800		4
93	Jeumont Schneider	150	-	15	100	200	1000	10000	4
93	Haeffely	125	100	20	150	100	500	6000	4
93	ABB Sweden	200	3	-	200	50	1000	20000	4
93	GEC	50	30	5					4
93	Asinel	100	70	10	170	70	1000	10000	4
95	Enel	95	280	10	150	250	700	8000	4
96	Labelec	60	40	3	60	50	540	5100	9
96	Laborelec (tight OLTC)	84	79	56	166	52	673	8068	9
96	Laborelec (no OLTC)	66	111	15	110	90	865	12670	9
99	60599 (Annex A1)	60-150	40-110	3-50	60-280	50-90	540-900	5100-13000	10

Table 2. 90% Typical (Normal) Values for Power Transformers with a Communicating OLTC, in ppm

Year	Company	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	Ref.
76	LCIE	235	180	336	145	270	672	4256	1
88	Asinel	250	150	150	250	150	1000	10000	2
89	Hydro Quebec (HQ)	150		150	220				3
92	Vattenfall	200	50	30	200	50	1000	20000	4
92	LCIE	134	224	154	224	550	672	3584	4
93	HQ (electrical)	250		280	150	15			8
93	HQ (thermal)	150		22	320	80			8
93	LCIE / EDF	-	150	150	200	550	800	5000	4
93	Jeumont Schneider	150	-	150	200	200	1000	10000	4
93	Enel	200	100	50	100	100	500	10000	4
93	Asinel	250	190	180	250	180	1000	10000	4
96	Labelec	75	35	80	110	50	400	5300	9
96	Laborelec	151	131	266	250	73	848	11818	9
99	60599 (Annex A1)	75-150	35-130	80-270	110-250	50-70	400-850	5300-12000	10

Table 3. 90% Typical (Normal) Values for OLTC, in ppm									
Year	Company	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	Ref.
92	LCIE	8288	1120	19712	1344	784	448	5600	4

Table 4. 90% Typical (Normal) Values for Instrument Transformers, in ppm									
Year	Company	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	Ref.
86	Asinel (CTs)	31	6	1	3	8	260	705	2
86	Asinel (VTs)	22	7	-	5	4	180	650	2
87	Kema (CTs)	80	18	1	-	20			2
87	Kema (VTs)	170	16	1	-	8			2
88	Asinel	50	10	5	10	10	1000	10000	2
89	CIGRE	120		5	10				2
89	Hydro Quebec (HQ)	150		3	8				3
91	HQ (CTs)	85		5	9				7
91	HQ (CCVTs)	70		4	30				7
91	HQ (IVTs)	135		4	30				7
91	HQ (CVTs)	1000		16	20				7
93	Labelec	6	11	1	3	7	250	800	9
93	Milan Vidmar	150	120	1	40	130	1100	4000	9
96	ABB (CT, rubber seal)	20	30	2	4	25	330	900	9
96	ABB (CT, metal seal)	300	30	2	4	25	330	900	9
99	60599 (Annex A1)	6-300	11-120	1-5	3-40	7-130	250-1100	800-4000	10

Table 5. Influence of Various Parameters on 90% Typical (Normal) Values in Power Transformers, in ppm (Typical Examples)					
Parameter	H_2	C_2H_2	C_2H_4	C_2H_6	Ref.
Transformer sub-type:					
Sealed	100	35	50		6
Breathing, transmission	150	10	280		
Breathing, generation	100	50	200		
Fault type					
Discharges	85	70	35	8	8
Thermal	175	3	375	100	8
Age, in years					
< 2	60	5	5	2	8*
2 – 5	100	100	60	15	8*
10 – 20	200	80	80	20	8*
> 20	400	150	100	30	8*
* Case of discharges in power transformers P					

Table 6. Comparison of 90% and 95% Typical Values with Values Based on Actual Probability of Failure in Service (PFS), in ppm (Typical Examples)					
Base for Calculating Typical Values	H_2	C_2H_2	C_2H_4	C_2H_6	Ref.
90 % value	85	70	35	8	8*
95 % value	220	170	90	20	8*
PFS value	100	300	100	20	8*
*Case of discharges in power transformers P					

Table 7. References Used in Annex 2			
Ref.	Year	Authors	Journal / Report
1	76	J. Rabaud et al.	CIGRE Paper 12-06
2	80-89	J. Samat et al.	CIGRE TF 15-01
3	89	M. Duval et al.	Doble Conf., p. 10-4
4	90-94	A. Molmann et al.	CIGRE TF 15-01-01
5	90	M. Duval et al.	CEIDP, p. 325
6	90	IEEE / ANSI	C 57-104
7	91	M. Duval et al.	CEIDP, p. 506
8	93	M. Duval et al.	CIGRE Symp., Paper 110-14
9	93-96		IEC TC 10 WG 13
10	99	M. Duval et al.	IEC 60599