Life Cycle Management of Power Transformers: Results and Discussion of Case Studies

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ABSTRACT

The knowledge of a current state of running machines is of high importance for users and producers of transformers; especially the knowledge of the present state of their priority component – insulation system. The article deals with methodology of creating and utilization of the information about the condition of insulation system of transformers database as a tool for the transformer life management. The post-mortem analysis of the insulation systems condition of transformers that have already grown old and are intended for liquidation were used a source for the database. The procedure of sampling is described. Analytically determined values of degree of polymerization (DP) and tensile strength (R) are accompanied with information from running history of a transformer (especially DGA and 2FAL values). Individual case studies, whose results are shown in the article, are realized in most cases for transformers with the highest voltage 400 kV but they differ in type (power transformers, autotransformer), manufacturer (4 providers) and also in construction. The study deals with generalization of reciprocal relationships of analysed quantities for typical representatives of individual machine groups as well as with the impact of non-standard events during the running of particular transformer.

Index Terms - **Aging, degree of polymerization, furans, insulating system, reliability, service life, tensile strength, transformer.**

1 INTRODUCTION

THE goal of this work is the gradual creation of database of important information about a state of transformers operationally insulating system. The windings of transformers that have already grown old and are intended for liquidation are methodically used for his purpose. Described work is focused on observation of changes in paper insulation's utility characteristic, degree of polymerization DP and tensile strength R (MPa), depending on the operating conditions and age of a device. At same time these information are confronted with a content of furanic substances and CO, CO_2 that are products of cellulosic materials' disintegration in oil filling of a device, if they are available.

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Theoretical and partly also empirical relationships between levels of these substances that are contained in oil and the degree of polymerization DP are known in publications. For practical application of relational recalculation in real practice it is necessary to look into factors that are affecting the content of furans and their variability which follows from operating interventions in oil filling, operating conditions and operational utilization of a transformer. As unlike the content of furanic substances the direct monitoring of DP is not possible with the devices during their running, the effort to prove expected relations and mutual relationships in the aging process in transformers leads us to monitoring of the state of paper insulations (using DP and tensile strength R) in transformers meant for disposal or in overhauled transformers and to seeking relationships with their construction, operating history, results of DGA and content of furanic substances.

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Observed indicators of the aging of insulation system's paper components seem from this point of view as basic important information even though such a complex problem like residual service life of transformers cannot be solved by these indicators completely. The reason behind it is mainly the fact that critical localities of insulation system are inaccessible during the whole operating life and the localities which are relatively accessible do not provide enough information on real state of insulation in crucial localities. Therefore the meaning of extensive analyses performed on insulations of demounted devices is cognition of mutual relationships between the state of insulation from relatively accessible places and the state of insulation from other places of the system.

2 PROBLEMS OF ESTIMATE OF THE PAPER INSULATION'S STATE, CHOSEN METHOD

Systematic observation of the state of paper parts in insulations system of transformers meant to disposal or of overhauled transformers following the set of other information from the operating life of a device (operating history, interventions in oil filling, DGA, content of degradation products in oil, furans) has two aspects in this case:

- Achieved database is a source of data for a verification of the method which is related with an estimation of residual service life of running transformers, if there is possibility of obtaining a sample of paper insulation from assessed transformers (prearranged sample that is possible to take or a sample from terminal conductors during a necessary inspecting interventions into the inner environment of a device).
- Simultaneously these data are at disposal for use according to the needs of operators for comparison of available data from running devices with parameters of transformers whose state of paper insulation was analytically proved and whose comparable data from their running history are known. The significance of this use grows especially in the case that integral sample of paper insulation is not available during the running of an assessed device.

Essential condition for an estimation of residual service life of a device is determination of criterial quantity and value determining the end of secure and reliable running of a device. From the point of view of operating capability we classify the position of insulation system of a device as dominant. The quantity of degree of polymerization DP was chosen as a criterial, this quantity proportionally determines degradation changes in binding structure of cellulose. Generally recognized physical limit of analytical quantity DP is 200, the decrease bellow this value represent theoretical end of service life of device's paper insulation.

The determining factor is a complexity of an environment in which the degradation is taking place. Specifically it is existence of localities of critical aging within the insulation system (in winding) which are difficultly perceptible by levels of general degradation factors. Therefore it is necessary to seek a method for an estimation of device's residual service life that would at least partially proceed from specific and relatively available information. Proposed method of estimation of presumable residual service life uses practically the comparison between two specific findings:

- **Integral sample:** Analytically determined DP values of a sample of aged paper insulation of assessed device. Sample is taken after a sufficiently long period of running and it is taken from the free space within a device (usually from neutral terminal or from accessible paper barrier, preferably though from a prearranged sample). Such sample we call integral sample and analyzed value of DP is called integral quantity and it provides information about overall environment's degradation effect on paper insulation systems in a device.

- **Twelve analytical data:** A set of analytically determined DP values of aged paper insulation's samples from transformers meant for disposal or for general renovation of their insulation systems. Samples are taken from ca. 12 systematically selected locations in winding, integral sample has to be taken too. Set of values of DP provides information about frequency of occurrence of critically degraded locations in winding and about the state of its paper insulation. Integral sample provides matched value to these samples which is image of overall effect of degradation processes in a device. Relationship between value achieved from integral sample and average of at least three lowest values from the set of 12 analytical data is called relational coefficient. Rate of probability of this coefficient depends on the number of analyses of liquidated insulation systems.

Method of an estimation of probable residual lifespan itself consist in application of fitting relational coefficient on really analysed integral quantity – DP value from assessed device and subsequent calculation of aging period until reaching of limit of DP using relations (1) to (3), on condition that the ageing process has exponential character:

$$DP_i = DP_0 \cdot e^{\frac{-t_i}{\tau}} \qquad (1)$$

DP_i - value of DP which is gained by insulation during aging (after period t_i)

DP_0 - starting value of insulation (DP of new paper)

τ - time constant of function.

Then applies:

$$\tau = t_i / [\ln(DP_0 / DP_i)] \qquad (2)$$

$$t_i = \tau \cdot \ln(DP_0 / DP_i) \qquad (3)$$

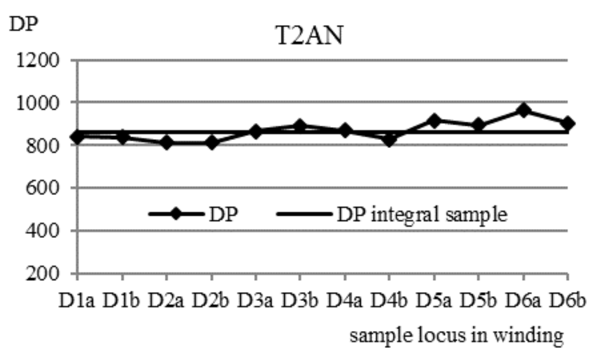
The procedure of applying aforesaid method we can call methodology of estimation of probable residual service life of device and it includes:

- sampling of integral sample from assessed device and its analysis,
- application of suitable relational coefficient that was achieved from insulation systems of devices of comparable parameters, constructional arrangement and operating conditions,
- following calculation of a time until reaching limits of a state of paper insulation using exponential relationships.

Specifically the methodical procedure can be best illustrated on an example. We take an integral sample of aged insulation that is a sample from a free space of general aging, after for instance 15 years of running from a device whose residual service life we want to estimate. We analytically evaluate its DP value (for example 500) and with exponentially relationships we can determine the period during which the integral sample would reach the aging limit of DP = 200 (35 years from estimated starting DP_0 = 1000). This way residual service life will be calculated for example (35 – 15) = 20 years. That is however time of reaching the aging limit of integral sample. From experience we know that values inside a winding of a device can be considerably lower. Therefore we determine probable values in winding up to DP = 357 by application of suitable relational coefficient (for example 1.4) that was discovered in devices with comparable parameters and operating degradation conditions. Recalculated probable residual service life decreases than on considerably lower value (23.5 – 15) = 8.5 years.

Observation of amount and development rate of gaseous degradation products (DGA with emphasis on CO, CO_2) and content of furanic substances in oil as a follow-up to operating history of a device should always be an inseparable part of methodical processes, for two basic reasons:

- indirect informative estimation of intensity of aging processes and with it the level of aging of insulation systems in transformers also from the amount and development rate of degradation products,
- opportunity of utilization of these information for more qualified selection of relational coefficient by comparing parameters of development of degradation products in assessed transformer with parameters of development in transformers whose state of paper insulation has already been proved at the end of their operating existence.



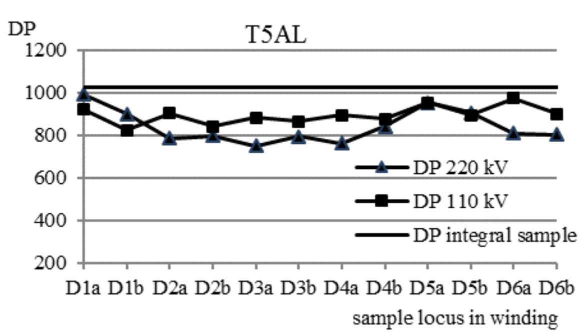


Figure 1. Comparison of typical transformer from producer "U" with defective transformer from producer "U", application of relational coefficient in practice.

2.1 EXAMPLE OF RELATIONAL COEFFICIENTS CALCULATION, APPLICATION IN PRACTICE

Transformer T2AN is typical representative of transformers from producer "U" (see Table 1, Table 2):

DP of the integral sample 860

Average of three lowest values from the set of 12 analytical data from 400 kV winding 809

Relational coefficient 860/809 = 1.06

It generally holds true for transformers from producer "U" that relation coefficients are approximately 1. Transformer T5AL (see Table 1) is to a certain extent different from this trend.

DP of the integral sample 1027

Average of three lowest values from the set of 12 analytical data from 220 kV winding 766

Relational coefficient for 220kV winding 1027/766 = 1.34

Average of three lowest values from the set of 12 analytical data from 110 kV winding 843

Relational coefficient for 110kV winding 1027/843 = 1.22

The device T5AL has paper insulation with high DP values which is typical for transformers from producer "U". In the case of this device more distinct inequality in aging of samples than it is usual in transformers of this producer showed up. Lowered DP values occur especially in 220 kV

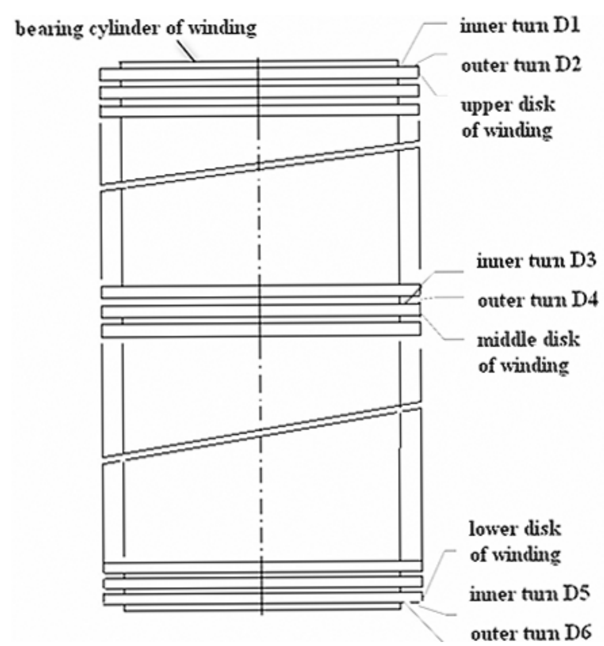


Figure 2. Diagram of sampling of conductors from a coil of winding in transformer.

D1a, D1b, D2a, D2b are samples from the first upper disk of winding (under the roof of tank); D3a, D3b, D4a, D4b are samples from middle disk of winding (in the middle of the building height of winding); D5a, D5b, D6a, D6b are samples from the last lower disk of winding (at the bottom of a tank).
a - inner papers of wrap (from the centre of conductor, in contact with metal)
b - upper papers of insulation wrap of conductor (in contact with oil)
1, 3, 5… inner turn of relevant disk (in direction from the axis of winding)
2, 4, 6… outer turn of relevant disk (in direction from the axis of winding)
NV is designation of a sample which gives us global information about aging of insulation system (integral sample). It is always taken from the place in free oil area of a tank, usually from neutral terminal or from accessible paper barrier, preferably though from a prearranged sample. Such sample can be taken during running of a device as an initial one for application of methodical procedure of residual service life's estimation.

winding in upper part of winding on the outer turn of the disk (D2a and D2b, see Figure 2) and in the middle part of winding on the inner and outer turn (D3a, D3b, D4a), see chapter 3. T5AL was characterized by high value of CO and transformer had problems with hermetization and cooling.

2.2 PROCEDURE OF SAMPLING, GENERAL PRINCIPLES

Sampling locations are labelled according to their geometrical position and the code of sampling locations is apparent from enclosed picture Figure 2.

- in three phased transformers we use coil of middle phase, if possible, for sampling; in one phased transformers (with more coils) it would be object of consideration,
- sample of conductor means at least one whole turn,
- the coil of both higher and lower voltage should be used for sampling,
- samples of conductors can be folded or even cut to pieces ca. half meter long for transport, but they always have to be reliably and unchangeably marked with identification label (in the case of cutting to pieces with several labels),
- identification label should include basic information about sample and source transformer (code of sampling location, number of a device, last operating station, date of liquidation etc.).

For purposes of the study the degree of polymerization DP and the tensile strength R were evaluated for paper insulation samples, see the procedure of sampling listed above. The samples was analyzed according to standard IEC60567 (DP) and ISO1924-2 (R) in accredited laboratory. The values of DGA and furans concentration in oil used as information additional to the case studies are the accredited laboratory data. The sampling and analysis were made according to standards IEC60567 (DGA) and IEC61198 (2FAL).

3 RESULTS OF THE STUDY

In this study, which creates database of information and data for above mentioned purposes, insulation systems of group of devices were analysed post-mortem in the course of several years. Constitution of this group is shown in Table 1.

3.1 COMPARISON BETWEEN DP AND R OF ALL UP TO NOW ANALYSED TRANSFORMERS

Enclosed graphs and tables (see Table 1, Table 2, Figure 3 and Figure 4) provide an opportunity to compare trends of DP and R in all obtained results from the set of analysis of insulation system which were performed on transformers meant for disposal or on overhauled transformers. There are obviously evident two biggest groups of transformers, which differ in producer and constructional design (see Table 1, Figure 3, among others the type of cooling), in the summarizing graphs of so far available DP results from transformers meant to disposal or from overhauled transformers. We can generally observe from the course of DP alongside the winding that the higher rate of aging prevails in upper insulation papers of conductor (in the contact with oil, coded name "b"). Differences between inner wraps (in contact with metal, coded name "a") and outer paper wraps (in contact with oil, coded name "b") in devices in transmission system are less obvious and in the upper half of a winding are DP values almost the same for inner conductors as for outer conductors. This difference is more obvious alongside whole winding on power transformer.

Table 1. Constitution of the group of devices analyzed post-mortem.

Code of device	Parameters of device	Cooling, type	Code of producer	Age (years)
T1AR	400/121kV 250MVA	OFAF, hermetized autotransformer	U	29
T2AN	400/121kV 250 MVA	OFAF, hermetized autotransformer	U	30
T1BJ	420/15,75 kV 250 MVA	OFAF, hermetized power transformer	U	20
T2BJ	420/15,75 kV 250 MVA	OFAF, hermetized power transformer	U	24
T3BJ	420/15,75 kV 250 MVA	OFAF, hermetized power transformer	U	28
T4BJ	420/15,75 kV 250 MVA	OFAF, hermetized power transformer	U	27
T5BJ	420/15,75 kV 250 MVA	OFAF, hermetized power transformer	U	30
T6BJ	420/15,75 kV 250 MVA	OFAF, hermetized power transformer	U	26
T7BJ	420/15,75 kV 250 MVA	OFAF, hermetized power transformer	U	26
T3AA	400/121kV 330 MVA	OFAF, hermetized autotransformer	C	37
T4AB	400/121 kV 250 MVA	OFAF, hermetized autotransformer	L	35
T5AL	230/121kV 200 MVA	OFAF, hermetized autotransformer	U	26
T6AM	231/121kV 200 MVA	OFAF, one-phased autotransformer	C	38
T8BJ	420/15,75 kV 250 MVA	ODAF, power transformer	E	24
T9BJ	420/15,75 kV 250 MVA	ODAF, power transformer	E	25
T10BJ	420/15,75 kV 250 MVA	ODAF, power transformer	E	25
T11BJ	420/15,75 kV 250 MVA	ODAF, power transformer	E	23
T12BJ	420/15,75 kV 250 MVA	ODAF, power transformer	E	23
T13BJ	420/15,75 kV 250 MVA	ODAF, power transformer	E	24
T14BT	420/15,75 kV 250 MVA	ODAF, power transformer	E	34
T15BT	420/15,75 kV 250 MVA	ODAF, power transformer	E	34
T16BV	420/13,8 kV 254 MVA	ODAF, power transformer	E	34
T17BV	420/13,8 kV 254 MVA	ODAF, power transformer	E	34
T18BV	420/13,8 kV 254 MVA	ODAF, power transformer	E	31

BJ, BT, BV - power transformer, Ax – autotransformer

Transformer T4AB defies this summarizing evaluation on first sight; it ranks among up till now vacant middle zone of DP values with its average aging value. But the variance of values especially in winding 400 kV is so big that the values of inner wraps (in contact with conductor, coded name "a") range in upper zone of little aged transformers and values of outer wraps (in contact with oil, coded name "b") range in zone of devices with DP values that signal closeness of high-risk running (see Figure 3). The state of inner wraps (coded

Table 2. DP of aged paper insulation of up to now analyzed devices.

	T5BJ	T4BJ	T3BJ	T2BJ	T1BJ	T7BJ	T6BJ	T13BJ	T12BJ	T11BJ	T10BJ	T9BJ	T8BJ	T15BT
D1a	647	781	777	580	836	668	805	400	400	248	375	430	306	367
D1b	619	802	658	617	718	687	632	316	413	448	397	403	300	290
D2a	647	750	825	587	816	614	678	333	421	471	313	396	366	243
D2b	617	708	678	566	692	691	649	340	451	454	435	370	329	276
D3a	657	750	915	617	856	711	776	422	362	316	316	492	289	-
D3b	638	699	877	593	773	711	731	395	385	323	306	437	332	-
D4a	734	786	1068	644	837	783	804	470	528	224	463	359	474	468
D4b	660	710	861	587	809	748	752	424	421	536	391	379	418	367
D5a	660	825	973	699	921	790	784	506	344	481	400	565	500	-
D5b	726	734	894	685	904	762	842	464	393	525	366	509	510	-
D6a	715	889	872	702	928	748	786	534	393	554	400	456	545	477
D6b	733	748	776	711	904	696	784	537	421	560	365	291	510	457

	T14BT	T16BV	T17BV	T18BV	T3AA	T6AM	T2AN	T1AR 400	T1AR 110	T4AB 400	T4AB 110	T5AL 220	T5AL 110
D1a	245	396	427	350	352	497	841	974	877	855	618	990	919
D1b	254	378	398	363	365	468	839	979	829	413	455	900	824
D2a	283	359	389	295	299	474	812	880	829	772	521	785	902
D2b	252	370	388	335	299	468	812	918	839	440	426	796	841
D3a	-	455	363	347	340	465	865	974	813	832	720	751	883
D3b	-	403	424	428	321	468	891	978	911	415	528	793	864
D4a	334	432	424	329	321	468	869	973	874	922	611	761	893
D4b	311	403	388	356	317	423	827	981	894	566	509	840	875
D5a	-	460	370	339	471	468	917	985	896	862	610	952	952
D5b	-	422	415	409	327	423	895	1000	862	588	555	905	895
D6a	345	444	434	367	451	456	965	988	918	826	641	809	974
D6b	346	418	415	318	299	505	905	990	862	592	668	802	899

The number behind the code of a device is the voltage of winding from which the set of samples was taken. If the value of voltage is not mentioned then the samples are always taken from the highest voltage of given device.

name "a") is on normal rate of devices from producer "U" (average DP value is 854), meanwhile average DP value for outer wraps (coded name "b") is 500. Lowest DP is 413 and highest DP value is 922. DP values are likely consequences of running device as a not hermetized one (bladder was refilled in 2004, in operation since1981) with relatively high total content of gases (Q_p), high level of oxygen and higher content of water in oil (average Q_p = 9.3 %; content of water in oil from 10 to 15 g/t). Tensile strength R (MPa) of paper wraps have values common for

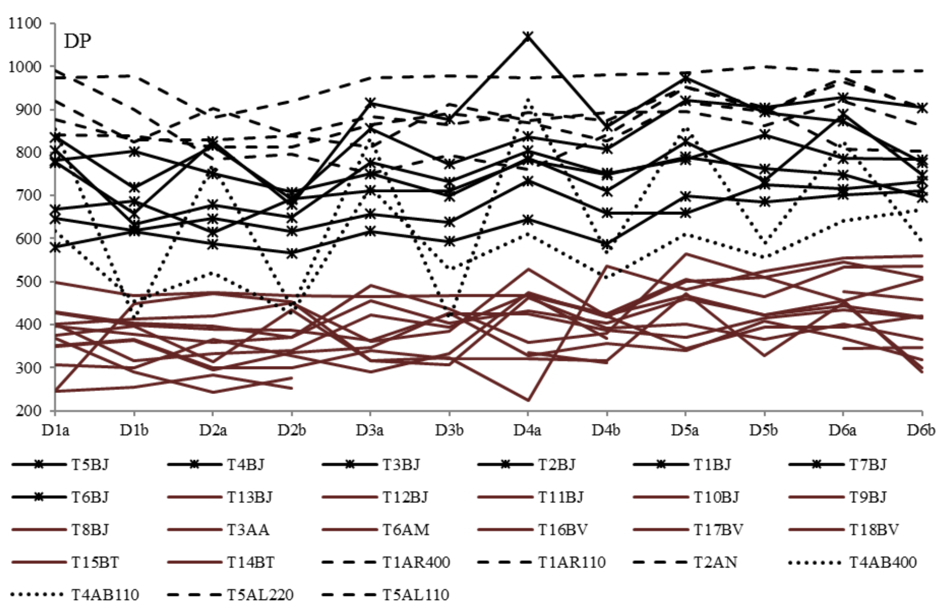


Figure 3. Comparison of DP results of aged paper insulation of up to now analysed devices. For types of curves differentiate for groups of transformers according to the producer (see Table 1).

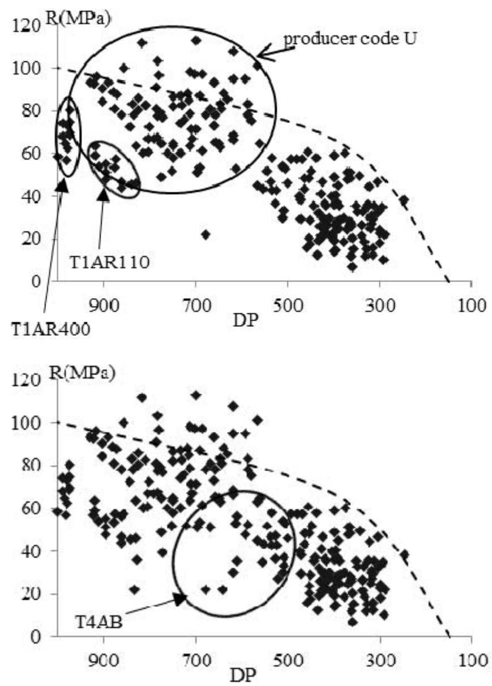


Figure 4. Reciprocal relationship between DP values and R values (MPa) in samples from conductors' paper wraps from winding of whole set of up till now analysed transformers, with which the measurement of tensile strength was performed. Dash curve theoretically shows expected correlation between R and DP for initial density of paper 1000 kg/m^3

aged insulation. In relationship with DP values it is interesting that samples with lowest tensile strength are some samples of inner wraps (coded name "a").

If we summarize reciprocal relationship of R and DP in whole set of analysed transformers, we can generalize the results on statement that in case of DP values (interval of values from 0 to 1000 is taken into consideration) the difference between minimal value in set of samples taken according to scheme in Figure 2 and maximal DP in this set is usually 150 to 200. In the case of autotransformers it is even less (50 - 100). When it is about values of R (interval of values from 0 to 100 is taken into consideration) then transformers are divided into two groups. Group of transformers with higher DP value (one producer) has difference between minimal values in set of samples taken according to scheme in Figure 2 and maximal R in this set is usually 20 to 40 and interval of R values correspond rather with ascertained rate of DP values. Group of transformers with different construction with more aged insulation has bigger difference between minimal and maximal R value in set of taken samples (30 to 50). R value is then in either whole set of samples of insulation or in some localities of winding lower than it would correspond to ascertained DP and it does not generally hold true that DP is in given localities also the lowest from the set of analysed samples.

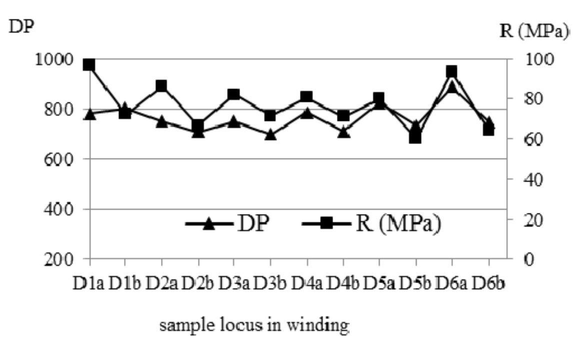


Figure 5. Comparison between DP and R (MPa) values in samples of conductors 'paper wraps from 400 kV winding from one of the transformers in correspondence with geometrical position of the sample in winding.

Table 3. Values of degradation products of paper insulation CO, CO_2 and oxygen levels for analyzed devices.

Code of a device	Parameters Code of a producer	DP	Values of gases in the final period of machine's running (ppm)		
			CO_2	CO	O_2
T1AR	400/121kV, bladder, U	924	500	82	1000
T1AR	400/121kV, bladder, U	824[2)]	500	82	1000
T2AN	400/121 kV, bladder, U	809	1940	353	2418
T1BJ	420/15,75 kV, bladder, U	728	5830	423	951
T2BJ	420/15,75 kV, bladder, U	578	7240	437	1694
T3BJ	420/15,75 kV, bladder, U	704	2720	151	2059
T4BJ	420/15,75 kV, bladder, U	706	5890	281	2639
T5BJ	420/15,75 kV, bladder, U	625	840	180	2600
T6BJ	420/15,75 kV, bladder, U	653	2700	270	5900
T7BJ	420/15,75 kV, bladder, U	656	4000	290	2300
T3AA[1)]	400/121 kV, bladder, C	299	5590	728	2333
T4AB	400/121 kV, bladder, L	423	3790	560	2661
T5AL[1)]	230/121 kV bladder, U	766	2000	776	8667
T5AL[1)]	230/121 kV bladder, U	843[2)]	2000	776	8667
T8BJ	420/15,75 kV, E	286	6540	1305	5892
T9BJ	420/15,75 kV, E	340	6150	915	17008
T10BJ	420/15,75 kV, E	312	6800	1500	9400
T11BJ	420/15,75 kV, E	296	4200	1100	14000
T12BJ	420/15,75 kV, E	364	6000	1200	12000
T13BJ	420/15,75 kV, E	330	5100	1100	14000
T14BT	420/15,75 kV, E	250	11000	1100	22000
T15BT	420/15,75 kV, E	270	6900	780	23000
T16BV	420/13,8 kV, E	369	4280	373	17574
T17BV	420/13,8 kV, E	374	6230	485	14732
T18BV	420/13,8 kV, E	314	2420	252	19971

DP is average of three lowest DP values from the set of 12 samples of winding

[1)] Running of this device was from the start accompanied by leakage in bladder.

[2)] DP value is the result of analysis of 110 kV winding. Other DP values in the table are from the analysis of paper insulations from the winding with highest voltage in a device.

Knowledge up to now show that great variance of values and increase or decrease of tensile strength alongside the winding, which does not correspond with trend of DP values, appear regularly and it show itself in both dominantly

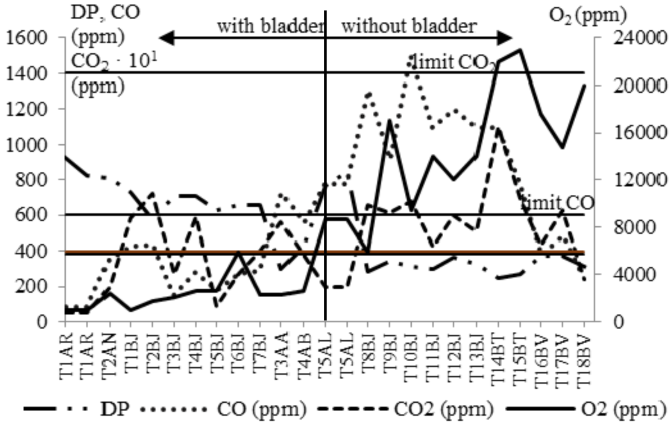


Figure 6. Content of degradation products of paper insulation CO a CO_2 and oxygen levels for all analysed devices. Interval of values "limit CO" respectively "limit CO_2" on vertical axis represents range of 90 % of typical values of gas concentration detected in power transformers according to IEC 60599. Transformers T3AA and T5AL had a problem with leakage of the bladder, T4AB was equipped with bladder no sooner than in 2004 (running since 1981).

represented groups of transformers with less and more aged paper insulation. The course according to Figure 5 is in the set of analysed devices practically an exception.

The values of degradation products of paper insulation CO a CO_2 and values of oxygen for all analysed devices are shown for comparison in the Table 3 and Figure 6. Selected levels of gases are values ascertained during some of the last DGA before liquidation or overhauling of a device. Concrete selection depended on the interval between sampling and switching off or intervention into oil filling and it was performed so that the values can represent the trend of DGA results for particular device. DP value is an average of three lowest DP values from the set of samples taken from winding.

3.2 INFLUENCE OF THERMAL DEFECT, NONFUNCTIONAL HERMETIZATION

Autotransformer T5AL is to a certain extent different from the trend that was up till now showed in overall evaluation of DP values alongside the winding by hermetized autotransformers from the same producer (see Figure 3) and that corresponded to some degree even with the state of paper insulations of power transformers from the same producer.

Above mentioned statement is evident in the Figure 7 and Figure 8 which compare some of the chosen transformers' representatives (see legend of graphs). Devices were chosen so that they represent characteristic "behaviour" of transformers from one producer assessed from the point of view of DP values of analysed winding. Narrowing of the set

Table 4. Typical Gas Concentration and Rates of Gas Increase

H (µl/l)	CH_4 (µl/l)	C_2H_6 (µl/l)	C_2H_4 (µl/l)	C_2H_2 (µl/l)
0 – 150 (µl/l)	30 – 130 (µl/l)	20 – 90 (µl/l)	60 – 280 (µl/l)	2 – 20 (µl/l)
35 – 132 (µl/l/year)	10 – 120 (µl/l/year)	5 – 90 (µl/l/year)	32 – 146 (µl/l/year)	0 – 4 (µl/l/year)

Ranges of 90% typical gas concentration according to IEC 60599 and ranges of 90 % typical rates of gas increase according to IEC 60599.

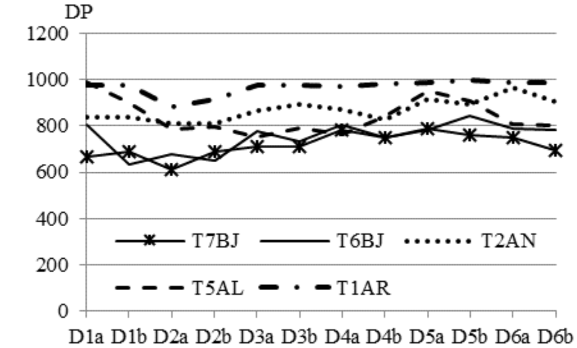


Figure 7. Dependence of DP values gained from winding samples from some of the analysed transformers from producer "U" on geometrical position of taken sample.

of transformers in comparison with Figure 3 highlighted the trend of values which can get lost when using values of all devices due to local divergences.

The device T5AL has paper insulation with high DP values which is typical for transformers from producer "U". In the case of this device more distinct inequality in aging of samples than it is usual in transformers of this producer showed up. Lowered DP values occur especially in 220kV winding in upper part of winding on the outer turn of the disk (D2a and D2b) and in the middle part of winding on the inner and outer turn (D3a, D3b, D4a).

It generally holds true for transformers "U" that samples of paper insulation from the whole set have relatively high DP values (see foregoing text) and that the regularly repeated place with moderately worse state of insulation is on the

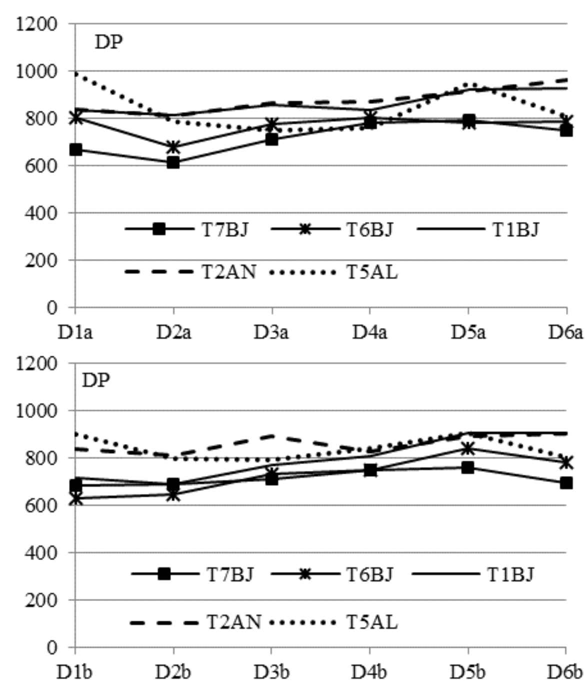


Figure 8. Dependence of DP values of inner wraps of paper insulation and outer wraps of paper insulation (meaning in direction from the core of conductor) gained from samples of winding of some of the analysed devices on the geometrical position of the taken sample.

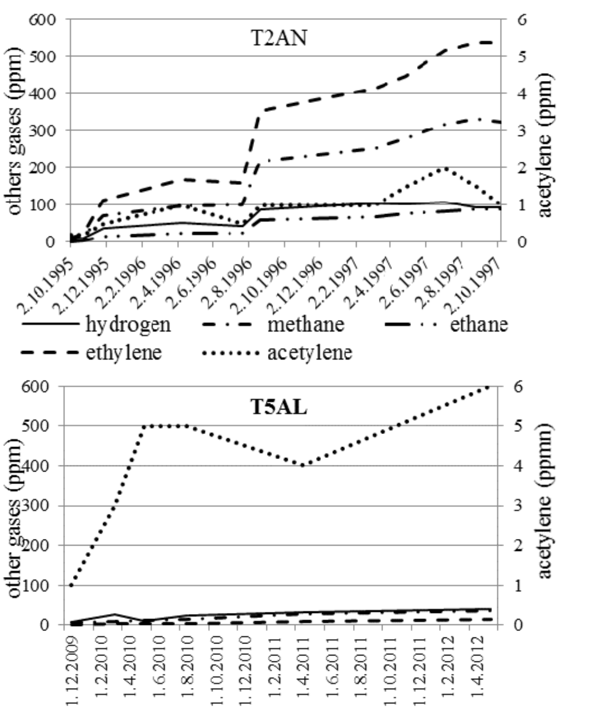


Figure 9. Comparison of development of dissociation products for transformers T2AN (fault T3 according to IEC 60599 detected) and T5AL (DGA indicates fault D2 according to IEC 60599).

outer turn of upper disk (D2a and D2b). If other inequalities of aging show themselves in insulation then it is worse state of paper wraps in the contact with oil (samples coded "b") which occurs more frequently in the lower part of winding. In the case of transformer T5AL this scheme is partially valid for results of DP in 110kV winding where the worse state of outer wraps in contact with oil applies alongside whole winding.

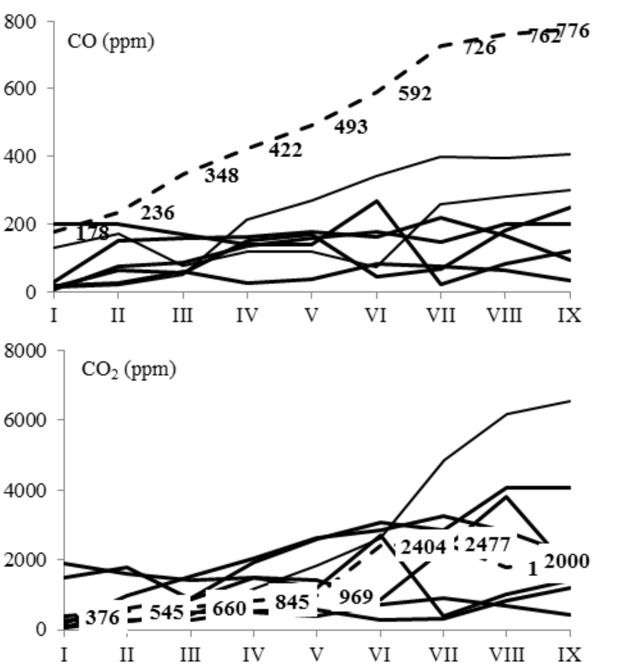


Figure 10. Amount of CO and CO_2 in up till now analysed transformers from group "U" for selected periods of running (longer operating period without interventions into oil filling in the last third of device's life).

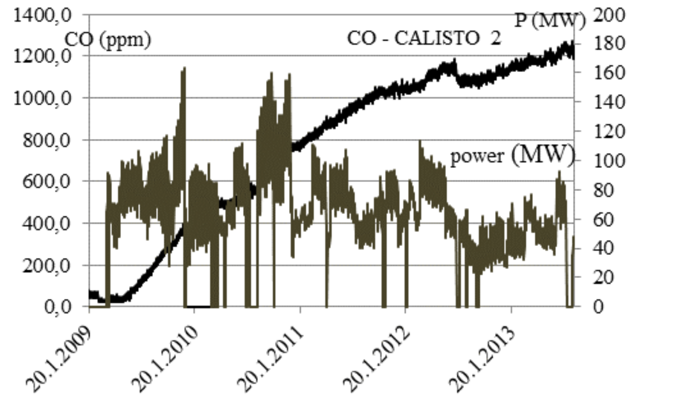


Figure 11. Development of CO in transformer T5AL according to data from online monitoring CALISTO2 from 2009 to 2014.

Winding 220 kV is from the point of view of DP values is altogether in worse state than the 110 kV winding, usually it is the other way around. Higher rate of aging occurs also in the inner and outer turn of middle disk (D3a, D3b, D4a) and in the upper half of winding (turn number 2, 3 and 4) there are more aged paper wraps on conductor (samples coded "a"). Transformer had according to DGA results and a record of operating history problems with hermetization and cooling and the suspicion of fault D2 according to IEC 60599 (discharge of high energy) was diagnosed by laboratory in 2002 and 2010. In the graphs in the Figure 9 it is apparent that the values of concentrations of gases and the rate of increase were more likely low (apart from acetylene) but the ratios of concentrations can indicate this fault.

In Figure 9 the distinctive difference in the rate of increase of dissociation gases in both transformers is evident. Displayed time interval represent approximately two years of running in both cases. The increase of gases in transformer T2AN is rather steep and the rate of increase of gases is higher than the interval of values of usual rates of increase observed in the majority of running devices as it is stated in standard IEC 60599. This concerns especially methane and ethylene on the contrary the concentration of acetylene is very low (see secondary vertical axis in graph Figure 9). In transformer T5AL the increase rate of majority of dissociation gases is low in comparison with usual values but the exception is the increase of acetylene unlike the T2AN. Nevertheless it is evident from the part of this Table 4 that these values are not critical.

Device T5AL was simultaneously characterized by relatively high content of gases and also by high value of CO which despite repeated degassing of oil exceeded upper limit for typical concentration of this type of degradation product which is given by IEC 60599 as 600 ppm. From graphs that compare concentration values of gases CO and CO_2 ascertained from DGA during the running the unique position of the device T5AL among transformers of group "U" is evident. The device has unusual high CO values although the content of CO_2 ranges in span typical for other devices (Figure 10 and Figure 11).

4 ANALYSIS OF FURANS

Literature states several models for reciprocal relationship between values of furans content and DP values, these models differ in conditions of aging that are used for gaining source data in the process of derivation of correlation. Models are mostly based on results of in laboratory implemented accelerated aging and they cannot take into account many parameters (temperature of oil, content of water in paper, the oxygen content, the acidity of oil, the construction of transformer, type of used paper, the decrease in not-hermetized devices) that affect the content of furans dissolved in oil, see for example the study [12]

Values showed in Table 5 and used in correlation curve Figure 12 are calculated from relationship that is mentioned in study [13], proceeding from operating data and laboratory measurements. The equation for the relationship between DP value and the level of content of 2-furaldehyde, where 2FAL is the value in mg/l and it has the form:

$$DP = \frac{\log(2FAL) - 1{,}51}{-0{,}0035} \tag{4}$$

It is necessary to take into consideration the migration of furans between paper insulation and oil during the evaluation of aging level of paper insulation on the basis of furan content. Especially the influence of temperature participates in migration, when the share of 2FAL in oil increases with growing temperature at the expense of paper insulation. Bigger content of furanic substances stays however always in paper insulation. In the range of temperatures from 55 to 100°C the content of 2FAL dissolved in oil after reaching the state of equilibrium is approximately 15% of total content of produced 2FAL [14].

Table 5. Furans and DP value of transformers.

	T16BV	T17BV	T18BV	T19BV	T20BV	T21BV
2FAL (ppb), 11/2010	310	300	130	40	230	510
2FAL (ppb), 09/2011	330	300	100	30	240	480
2FAL (ppb), 06/2012	340	320	120	40	260	520
2FAL (ppb), 02/2013	devices of 1st block in liquidation			60	360	690
DP from the paper sampling, 09/2009	543	480	563	754	705	385
calculation of DP from 2FAL, 11/2010	577	581	685	831	614	515
DP from paper sampling (12 samples) during liquidation, 09/2012 average (lowest/highest) value	412 (359/460)	403 (363/434)	353 (295/409)	devices are still running		
calculation of DP from 2FAL, 06/2012	565	573	695	831	599	513
calculation of DP from 2FAL, 02/2013	devices of 1st block in liquidation			745	558	493

	T15BT	T14BT	T22BT	T23BT
2FAL (ppb), 11/2011	3130	510	3610	260
2FAL (ppb), 09/2012	3540	690	-	-
2FAL (ppb), 11/2012	-	-	3910	360
DP from paper sampling (12 samples) during liquidation, 11/2012 average (lowest/highest) value	296 (245/346)	368 (243/477)	devices are still running	
calculation of DP from 2FAL, 09 a 11/2012	275	477	262	558

	T2AN	T3AA	T6AM	T5AL
2FAL (ppb), 09/2001	25			
2FAL (ppb), 09/2002	27			
2FAL (ppb), 11/2003	30		369 (09/2003)	
2FAL (ppb), 11/2004	36		290 (07/2004)	
2FAL (ppb), 07/2005	39			
2FAL (ppb), 07/2006	42		350 (05/2006)	
2FAL (ppb), 09/2007	54			
2FAL (ppb), 09/2008	56			
2FAL (ppb), 08/2009	60			
2FAL (ppb), 05/2010	70	6 (07/2012)	140 (08/2011)	5 (02/2014)
DP from paper sampling, 10/2004	860			
calculation of DP from 2FAL, 10/2004	844			
DP from paper sampling (12 samples) during liquidation, taking date of paper, average (lowest/highest) value	05/2011 870 (804/972)	08/2012 347 (299/471)	04/2012 465 (423/505)	03/2014 840 (751/990) winding 220 kV 893 (824/974) winding 110 kV
calculation of DP from 2FAL, taking date of oil	761 (05/2010)	1066 (07/2012)	562 (05/2006)	1088 (02/2014)

Furans and DP value of transformers meant for disposal or of overhauled transformers, in which the analysis of DP of taken samples of paper was performed at the same time as the determination of 2FAL concentration, and the DP value calculated from 2FAL concentration according to Chendong's relationship.

Note: in the second half of year 2006 there was a decrease of furans in devices T6AM (one-phased units, intervention into oil filling was not stated in the documentation, change in laboratory methodology?)

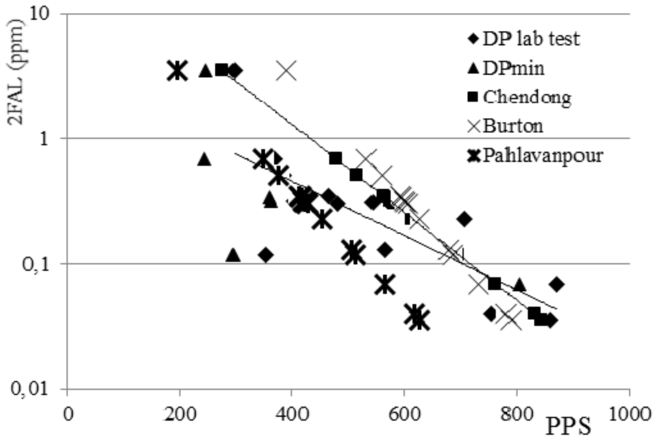


Figure 12. Correlation between 2FAL content and DP value of transformers meant to disposal or of overhauled transformers, in which the analysis of DP of taken samples of paper was performed at the same time as the determination of 2FAL concentration, and the DP value calculated from 2FAL concentration according to Chendong's relationship, Burton's relationship and Pahlavanpour's relationship [14].

4.1 CORRELATION OF 2FAL CONTENT IN OIL AND DP OF ANALYSED DEVICES

Table 5 summarizes known values of furans in liquidated transformers in which the analysis of DP of taken samples of paper was performed at the same time as the determination of 2FAL concentration (either these two values were both determined simultaneously during the liquidation of a device or in some phase of running, when the DP was determined from the sample taken during necessary revision intervention into inner space of a device). In this case we have both DP value and 2FAL concentration at disposal, both values determined by laboratory. Based on these data it is possible at least in the small set of data to verify the correlation relationships by calculation of DP and by comparison with the chemically determined value. If the date of DP determination and 2FAL concentration determination is not the same and if there is acceptable time difference then the nearest figure of 2FAL concentration in time is chosen for calculation of DP.

DP values gained by laboratory analysis of samples of paper insulation wraps and used in the Figure 12 are either average value from 12 samples alongside the winding (see method of sampling in chapter 2.2 during liquidation of device) or one value gained by sampling during reparation of transformer. The series DP_{min} are the lowest values of DP from the set of 12 samples (they are available only for samples taken during liquidation where all 12 samples are present). The levels of 2FAL content (ppm), which are the same or are at least very close in date of oil sampling as the taking of paper samples and these two samplings are not separated by intervention into oil filling, are matched with them. For DP values calculated from 2FAL in Table 5 the Chendong's model was used [13], see equitation (4).

In the correlation curve it is evident that the Chendong's model has much worse correlation for minimal real DP value determined by analysis of samples from winding then it does for the average value of all 12 samples. Further it is necessary to release that the content of furans in oil is the effect of degradation of all cellulosed components present. Even if we ignore furans produced by constructional trafoboard or wooden elements, there are still other windings in the container. Their contribution to furans production will depend on the weight of paper insulation of individual windings and that is the information which we do not usually have at disposal for older running devices. If we despite above mentioned reservations adjusted the correlation of 2FAL and DP values determined by laboratory analysis, it would correspond to the relationship:

$$DP = \frac{\log(2FAL) - 0{,}5223}{-0{,}00217} \tag{5}$$

5 CONCLUSION

From up to now acquired results it is evident, that the information database generation by the postmortem analyses of the insulating system of transformers meant for disposal or of overhauled transformers has immediate utilization in operating practice.

At the same time, just as the next analyses continue, the observations appear in evaluation process of particular cases that are possible to generalize and to use for definition of the next trends in this research sphere.

Relational coefficient determined based on the results of post-mortem analysis (see 2.1) is generally valuable for particular group of transformers. The typical attributes of aging are identical for the most of the transformers in the group, see for example the development of DP values alongside the winding. The group of transformers with similar level and character of aging is defined rather by manufacturer and construction than by the way of running which has far less influence. The correlation of DP and tensile strength corresponds with typical transformers groups but there are some distinct differences in the level of paper aging according to DP and tensile strength for some of the transformers in the group. The results of DGA and non-standard events during the running of the transformer are information essential for aging level evaluation. The results of some case studies show that the running problems (ineffective cooling, leaking, higher gases development) manifest themselves in the level of relational coefficient. Generalization of results of correlation between DP and 2FAL performed in this study is limited by the small number of input data and by non-systematic observation of furan values. We continue to expand the database.

Considering the fact that the detail data record of running history is always the part of every study of individual transformers (service, nonstandard intervention, failures, DGA, rate of gases development, state of oil filling, device temperature, etc.) then the database and the conclusion resulting from it are continuously updated.

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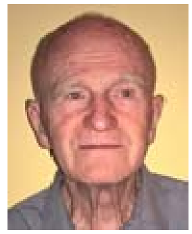

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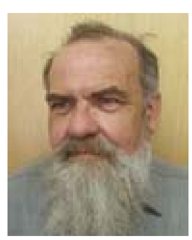

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