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# DGA Gases related to the Aging of Power Transformers for Asset Management

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**Abstract** – Life management technology is required as the failure risk of aged power transformers increases. Asset management technology is developed to evaluate the remaining life, establish the replacement strategies, and decide the optimal investment based on the reliability and economy of power transformers. The remaining life assessment uses data such as installation, operation, maintenance, refurbishment, and failure of power transformers. The optimal investment also uses data such as maintenance, outage, and social costs. To develop the asset management system for power transformers, determining the degradation parameters related to the aging of power transformers and evaluating the condition of power transformers using these parameters are important. In this study, since 1983, 110,000 Dissolved Gas Analysis (DGA) data have been analyzed to determine the degradation parameters related to the aging of power transformers. The alarm rates of combustible gases ($H_2$, $C_2H_2$, $C_2H_4$, $CH_4$, and $C_2H_6$), TCG, CO, and $CO_2$ were analyzed. The end of life and failure rate (bathtub curve) of power transformers were also calculated based on the failure data from 1981 to 2014. The DGA gases related to discharge, overheating, and insulation degradation were determined based on alarm and failure rates. $C_2H_2$, $C_2H_6$, and $CO_2$ were discharge, oxidation, and insulation degradation parameters related to the aging of power transformers.

**Keywords**: Alarm rate, Degradation parameter, DGA, Failure rate, Power transformer

## 1. Introduction

Dissolved Gas Analysis (DGA) is the most widely used diagnostic method to detect and evaluate power transformer defects [1-4]. Since 1983, Korea Electric Power Corporation (KEPCO) has annually analyzed DGA for all power transformers to prevent failure. The DGA diagnosis determines whether each DGA value or increase rate of gases exceeds the alarm concentration value. If the DGA value exceeds the alarm concentration value, then the DGA sampling interval is changed. If the DGA value is severe, then types of defects are evaluated, and the inside of the transformer is inspected. The alarm concentration values and the DGA sampling intervals of the international standards or countries are different. The international standards of DGA are IEC 60599 and IEEE C57.104, and KEPCO has its own alarm concentration value.

International Electrotechnical Commission (IEC) published the DGA standard in 1978. However, the first edition has limitations such as the absence of the alarm concentration values in certain cases, and it was based mainly on the experiences gained from the operation of power transformers. The alarm concentration values of the IEC standard were revised in 1999 based on the DGA data collected from 15,000 power transformers from 15 power companies, and again in 2015 based on the DGA data collected from 20,000 power transformers from 25 power companies [2]. In IEC 60599, 90% concentration value of the total cumulative number of DGA is determined as normal value, and the upper 10% is determined as the alarm concentration value. Changing the DGA sampling interval when the DGA values and increase rate of gases exceed the alarm concentration value, and taking immediate action in case of heavy concentration value are recommended. The types of defects in IEC 60599 are classified into discharge [PD (partial discharge), D1 (discharges of low energy), D2 (discharges of high energy)] and thermal faults [T1 (< 300℃), T2 (300℃ ~ 700℃), T3 (> 700℃)] of oil or paper. IEC Code and Duval's Triangle are used as defect identification methods [2, 5].

Institute of Electrical and Electronics Engineers (IEEE) published the DGA standard in 1991, and revised it in 2008. A four-level criterion, "Condition 1 - Condition 4," has been developed to classify risks of transformers. If the DGA values exceed the alarm concentration value, then the DGA sampling interval is changed according to the Total Combustible Gas (TCG) increase rate. The types of defects in the Key gases method are classified into thermal in oil, thermal in cellulose, partial discharge and arcing. Key gases, Doernenburg ratios, and Roger ratios are used as

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defect identification methods [3].

KEPCO published the DGA standard in 1985, and revised it thrice in 1999, 2002, and 2008 based on the statistical analysis of accumulated data, the DGA characteristics from abnormal transformers, and the internal inspection results of power transformers. Alarm concentration values are classified into four levels, namely, Normal, Caution I, Caution II, Abnormal, and Danger. $C_3H_8$ was added to DGA, and the alarm concentration value of $C_2H_2$ decreased in the 2002 revision. Caution I and Caution II were divided, and CO and $CO_2$ management methods were changed in the 2008 revision [1]. The DGA sampling intervals were changed to six months in Caution I, three months in Caution II, and one month in Abnormal. The inside of the transformer is immediately inspected when the DGA values exceed Caution II or Abnormal concentration values thrice continuously and when TCG exceeds 1,000 ppm or the DGA values exceed Danger concentration value. However, the inside of the transformer is not inspected in case CO or $CO_2$ is Caution I. If CO exceeds 1,200 ppm and $CO_2$ exceeds 7,000 ppm, then the inside of the transformer is inspected. The types of defects in KECO are classified into seven types as partial discharge in oil, arc in oil, overheating in oil (low/medium/high temperature), overheating of paper and degradation of insulation or oil. Key gases, gas patterns, and gas composition ratios are used as defect identification methods.

The types of faults used in IEC, IEEE, and KEPCO are classified into discharge ($H_2$, $C_2H_2$), thermal ($C_2H_4$, $CH_4$, $C_2H_6$), and insulation degradation (CO, $CO_2$).

Life management technology is required as the failure risk of aged power transformers increases. Asset management technology is developed to evaluate the remaining life, establish the replacement strategies, and decide the optimal investment based on reliability and economy of power transformers. The remaining life assessment uses data such as installation, operation, maintenance, refurbishment, and failure of power transformers. The optimal investment also uses data such as maintenance, outage, and social costs. Safely operating aged power transformers is important because many transformers installed in the economic growth period exceed 30 years of operation. Thus, the development of diagnosis methods and life determination technologies related to the aging of power transformers is necessary.

Power transformers should not be operated until the end of life because their failure has a significant effect on the power system. Therefore, power transformers must be replaced before failure occurs when the risk of transformers increases. However, it would be difficult to determine the end of life, the remaining life, and the replacement strategy for power transformers. To develop the asset management system for power transformers, determining the degradation parameters related to the aging and evaluating the condition are important.

In this study, since 1983, 110,000 DGA data have been analyzed to determine the degradation parameters related to the aging of power transformers. The alarm rates of combustible gases ($H_2$, $C_2H_2$, $C_2H_4$, $CH_4$, and $C_2H_6$), TCG, CO, and $CO_2$ were analyzed. The end of life and failure rate (bathtub curve) of power transformers were also calculated based on the failure data from 1981 to 2014. The DGA gases related to discharge, overheating, and insulation degradation were determined based on alarm and failure rates.

## 2. Dissolved Gas Analysis in KEPCO

Fig. 1 shows the cumulative number of power transformers of KEPCO in operation and DGA sampling. KEPCO has installed foreign-made power transformers before 1970, but has installed domestic-made power transformers since 1970. Such as 154 kV three phase 45/60 MVA since 1970, 345 kV single phase 167 MVA since 1978, and 765 kV single phase 667 MVA since 1998.

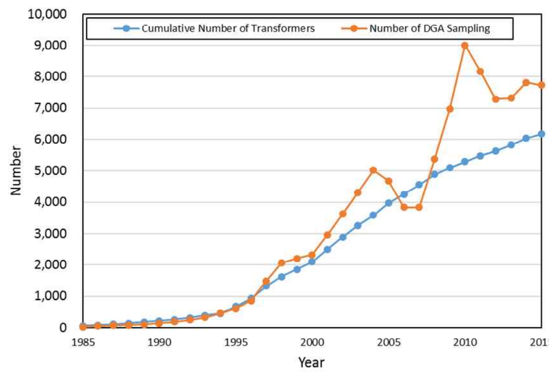



**Fig. 1.** Cumulative number of power transformers and DGA sampling

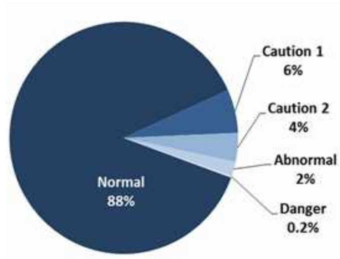



**Fig. 2.** Distribution of DGA results

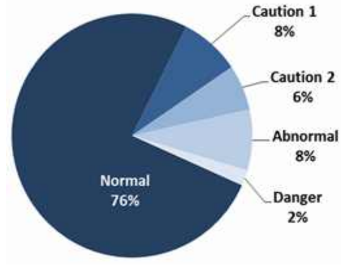



**Fig. 3.** Distribution of transformer with DGA results

Furthermore, 154 kV single phase 15/20 MVA transformers have been installed since 1995 because the transportation weight on a bridge was limited to 40 tons in 1994. Power transformers with the Gas Oil Seal Tank (GOST) type oil preservation system were installed until 1995, but the conservator type has been installed since 1995. The ratio of 154, 345, and 765 kV transformers are 87%, 11%, and 2%, respectively. The ratio of single and three phase transformers are 91% and 9%, respectively.

A total of 6,168 power transformers operated in KEPCO in 2016. The annual average DGA sampling number for the last 5 years is about 7,600, because DGA is annually analyzed for all transformers, and the DGA sampling intervals are changed when the DGA values exceed the alarm concentration value. As shown in Fig. 1, the number of DGA sampling proportionally increases with the number of power transformers.

Fig. 2 shows the distribution of 110,000 DGA results with Normal value of 88% and Alarm value of 12% (Caution I of 6%, Caution II of 4%, Abnormal of 2%, and Danger of 0.2%). Fig. 3 shows the distribution of transformers with Normal value of 76% and Alarm value of 24% (Caution I of 8%, Caution II of 6%, Abnormal of 8%, and Danger of 2%). IEC 60599 defines the upper 10% concentration value of the total cumulative number of DGA as the alarm concentration value. Thus, 90% of transformers are defined as normal state. However, 24% of power transformers in KEPCO are in the alarm state despite the alarm concentration value of KEPCO is higher than that of IEC [1, 2]. This result increases DGA sampling and maintenance costs. Thus, investigating whether the alarm concentration value of KEPCO is appropriate is necessary

Fig. 4 shows the DGA alarm rate related to the age of power transformers. The DGA alarm rate increases with the age of transformers, and reaches 20% at 23 years, 30% at 25 years, and 40% at 40 years. In particular, Caution II or Abnormal alarms increase after transformers are operated for 30 years. Thus, power transformers begin to deteriorate after 30 years of operation.

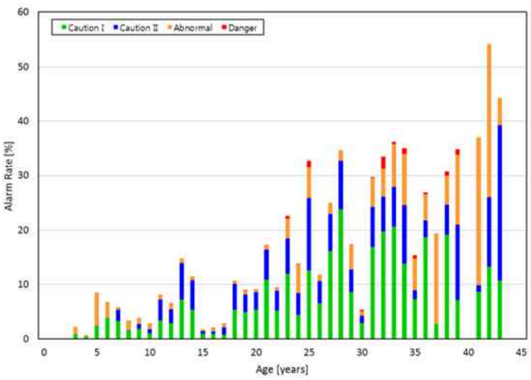



**Fig. 4.** DGA alarm rate related to the age of power transformers

## 3. Failure Rate of Power Transformers in KEPCO

Fig. 5 shows the characteristic life (63.2%) of the Weibull distribution from the failure data to calculate the end of life of power transformers. Generally, in high voltage engineering, if the failure data do not show a normal distribution, then the characteristic life of the Weibull distribution is recognized as the end of life. In this study, 642 failure data of power transformers were collected from 1981 to 2014. The characteristic life of power transformers from the failure data is 55 years, as shown in Fig. 5. Power transformers should not be operated until a failure occurs because of the degradation of insulation. Therefore, transformers must be replaced if the risk of failure increases. If failure occurs because the transformer is not replaced at the proper time, then a much larger outage cost than the price of a power transformer could be incurred. Transformers replacement depends on national regulations, transformer management policies, business conditions, and maintenance budgets. The technical replacement of transformers can be determined by the failure rate (bathtub curve).

Fig. 6 shows the failure rate of power transformers related to the aging of power transformers. Power transformers start to deteriorate after 23 years of operation, and the failure rate reaches 5% (B5) in 32 years. Thus, setting the replacement life of power transformers to 32 years is desirable. The failure rate of Fig. 6 is attributed to

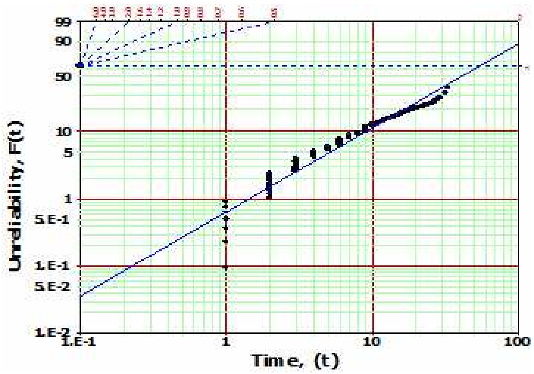



**Fig. 5.** Weibull distribution of power transformers

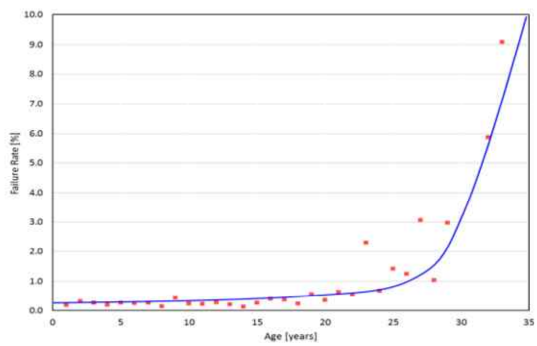



**Fig. 6.** Failure rate of power transformers

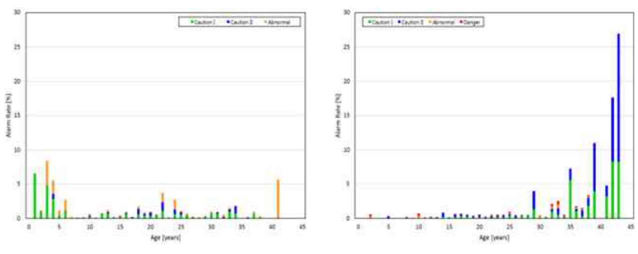
the effect of the GOST type oil conservation system. The failure rate of the conservator type oil conservation system after 1995 is expected to be slower than that in Fig. 6. The failure rate in Fig. 6 corresponds to the DGA alarm rate related to the age of power transformers in Fig. 4.

## 4. Alarm Rates of DGA due to the Aging of Power Transformer

### 4.1 Gases related to discharge degradation

Fig. 7(a) shows the alarm rate of $H_2$ in relation to the age of power transformers. The alarm rate of $H_2$ is high until the first 5 years of operation, however, it gradually decreases and becomes marginally low relation to the aging of power transformers. $H_2$ is known an effective gas to detect partial discharge because it is produced in large quantities by partial discharge, and $C_2H_2$ is produced by arc discharge in excess of thousands of pC. However, it is known to be produced by overheating in oil and core. In particular, it is produced in power transformers that have never been operated or without the defects at the beginning of operation. These phenomena are caused by the reaction of oil with oxygen, moisture, iron and galvanized steel, and the free water with coating material on iron or stainless steel with dissolved oxygen in oil [3,4]. Thus, detecting defects in the internal inspection by $H_2$ is difficult. Furthermore, few cases have indicated transformer failure because of a sudden increase in $H_2$ only. For these reasons and as shown in Fig. 7(a), $H_2$ is unrelated to failure rate, thus, it is inappropriate to use it as an index in relation to the aging of power transformers.

Fig. 7(b) shows the alarm rate of $C_2H_2$ in relation to the age of power transformers. The alarm rate of $C_2H_2$ increased rapidly after 30 years of operation, and in particular, Caution II increased rapidly after 40 years. $C_2H_2$ is known as an effective gas to detect arc discharge because it is produced in large quantities by discharge in excess of thousands of pC. Paper of transformers deteriorates by the heat from the normal load except during random failures. Paper of the hot spot parts by the winding temperature most severely deteriorates, and arc discharges occur between the turns or the layers of the winding [6]. Defects in paper initially start with partial discharge of low energy and develop into arc discharge of high energy. Therefore, $C_2H_2$ is produced by arc discharge because of the degradation of paper. As shown in Fig. 8, $C_2H_2$ is highly related to the failure rate and the aging of transformers. Thus, using $C_2H_2$ as an index of arc discharge in relation to the aging of transformers is appropriate.



(a) $H_2$ (b) $C_2H_2$

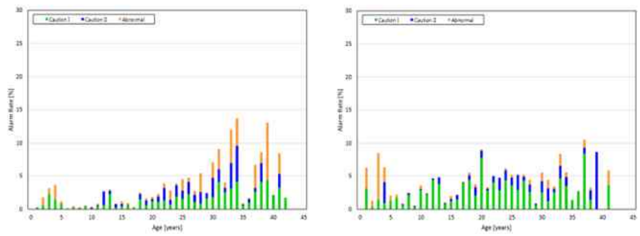
**Fig. 7.** Alarm rate of $H_2$ & $C_2H_2$ due to the aging of transformers

### 4.2 Gases related to overheating degradation

Fig. 8(a) shows the alarm rate of $C_2H_4$ in relation to the age of power transformers. The alarm rate of $C_2H_4$ slightly increased after 30 years of operation, but it is marginally related to the aging of transformers. $C_2H_4$ is known to be a characteristic gas produced through local overheating such as the circulation current of core and short circuited core layers and loose contacts. However, these defects are unrelated to the aging of transformers. As shown in Fig. 8(a), $C_2H_4$ is unrelated to failure rate, and using it as an index of the aging of transformers is inappropriate

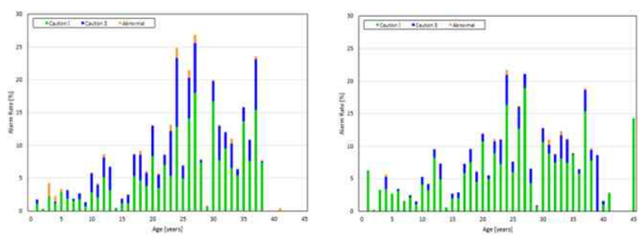
Fig. 8(b) shows the alarm rate of $CH_4$ in relation to the age of power transformers. The alarm rate of $CH_4$ is constant regardless of the aging of transformers. $CH_4$ is known to be a characteristic gas produced by low temperature overheating such as the circulation current of core and the degradation of oil. As shown in Fig. 8(b), $CH_4$ does not increase with the aging of transformers; instead, it occurs randomly. Thus, using $C_2H_4$ as an index of the aging of transformers is inappropriate.

Fig. 9(a) shows the alarm rate of $C_2H_6$ in relation to the age of power transformers. The alarm rate of $C_2H_6$ rapidly



(a) $C_2H_4$ (b) $CH_4$

**Fig. 8.** Alarm rate of $C_2H_4$ & $CH_4$ due to the aging of transformers



(a) $C_2H_6$ (b) TCG

**Fig. 9.** Alarm rate of $C_2H_6$ & TCG due to the aging of transformers

increased after 20 years of operation, and it is highly related to the aging of transformers, whereas that of $C_2H_2$ in Fig. 7(b) rapidly increased after 30 years of operation. Saturated hydrocarbons such as $C_2H_6$ are known to be produced at relatively low temperatures and oil oxidation

Fig. 10 shows the transformers with the GOST type oil preservation system in KEPCO. The GOST type oil preservation systems have been installed since 1978, and their operation stopped in 1995 because the conservator type oil preservation system was developed. Moisture and oxygen can penetrate into oil in transformers with the GOST type oil preservation system because the air is in contact with the oil via the breather in the operation or ambient temperature.

Fig. 11 shows the alarm number in DGA of transformers over 20 years of operation as oil preservation systems. Most alarms in DGA occurred in transformers with the GOST type oil preservation system compared with those with the conservator type.

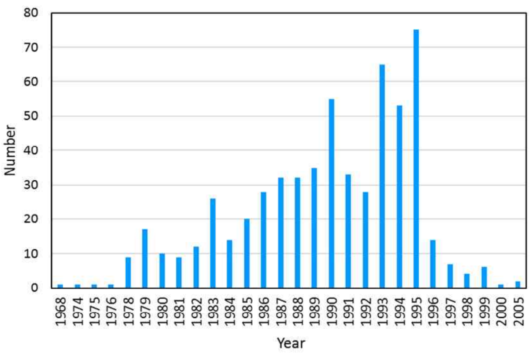



**Fig. 10.** Transformers with the GOST type oil preservation system

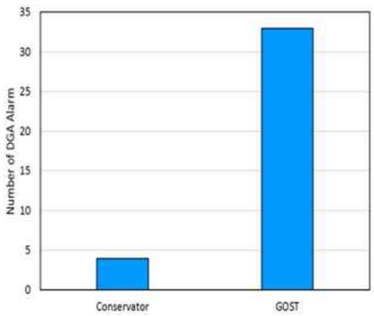



**Fig. 11.** DGA alarm as oil conservation systems

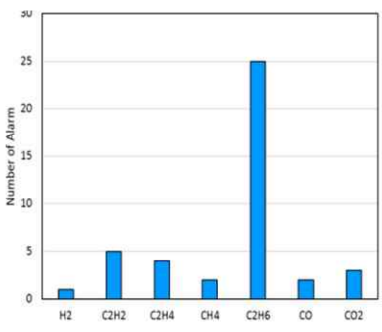



**Fig. 12.** DGA alarm gases of transformers with the GOST type oil preservation system

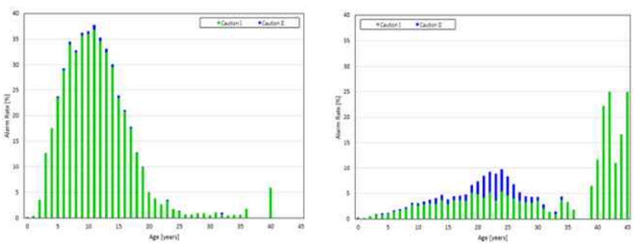
As shown in Fig. 12, the gas occurred alarm in DGA is 60% in $C_2H_6$ in transformers with the GOST type oil preservation systems. In addition, the cause of failure of transformers with GOST type oil preservation system was analyzed by moisture and air due to gasket degradation. Oil or paper can absorb oxygen or moisture when in contact with air, and these are known as degradation catalysts that can significantly shorten the life of paper. Paper promotes degradation by reaction with moisture. Oxygen in oil or paper also causes oxidation. Therefore, the failures in transformers with the GOST type oil preservation system are mainly caused by moisture and oxygen degradation. As shown in Fig. 11, $C_2H_6$ is highly related to the aging of transformers, and thus, using as an index of oxidation related to the aging of transformers is appropriate.

Fig. 9(b) shows the alarm rate of TCG related to the age of power transformers. The alarm rate of TCG highly increased after 20 years of operation. The alarm rate of TCG is analyzed similarly to that of $C_2H_6$ because of the effect of the amount of $C_2H_6$. TCG does not need to be used as an index of the aging of transformers because TCG is overlapped with $C_2H_6$.

### 4.3 Gases related to insulation degradation

Fig. 13(a) shows the alarm rate of CO in relation to the age of power transformers. The alarm rate CO is high until 20 years of operation, but decreased regardless of the aging of transformers. Most CO alarms showed the Caution I. CO is known to be mainly produced by overheating of paper, but it is also produced by oxidation of oil. In addition, CO is marginally low relation to the internal defects of transformers because CO depends on the ambient temperature or the load. However, the cause of CO producing a high concentration value up to 20 years of operation has not yet been clarified. As shown in Fig. 13(a), CO is unrelated to failure rate, and thus, it is inappropriate to use it as an index of the aging of transformers.

Fig. 13(b) shows the alarm rate of $CO_2$ in relation to the



(a) CO (b) $CO_2$

**Fig. 13.** Alarm rate of CO & $CO_2$ due to the aging of transformers

**Table 1.** DP in paper from three aged and four failed transformers

| Age | DP | Condition | Remark |
|---|---|---|---|
| 26 | 695 | good | disposal |
| 17 | 647 | good | disposal |
| 22 | 672 | good | disposal |
| 21 | 678 | good | internal fault |
| 25 | 632 | good | internal fault |
| 23 | 641 | good | internal fault |
| 26 | 512 | normal | internal fault |

age of power transformers. The alarm rate of $CO_2$ rapidly increased after 40 years of operation. $CO_2$ is known to be produced by low temperature overheating of paper and oxidation of oil. Furthermore, $CO_2$ is produced more rapidly by the moisture and oxygen in transformers with the GOST type oil preservation system. The moisture content in paper is increased by degradation and air contact during operation, thereby promoting the hydrolysis of paper. In addition, paper is deteriorated by oxygen, thereby degrading the rate of paper to be 2-3 times higher. In other words, $CO_2$ can be caused by the long-term degradation of transformers because of oxygen and moisture in oil and paper.

The degree of degradation of paper can be generally measured by the Degree of Polymerization. Cellulose is a polymer compound composed of glucose molecules, and the mechanical strength of paper is determined by the number of connections of the glucose molecule chains. The number of connected molecules is called Degree of Polymerization. Degree of Polymerization indicates the degree of decomposition of paper, and it is directly related to the tensile strength of paper. Thus, it is used as an index of the life of paper. Paper of a new transformer has Degree of Polymerization of about 1,000, and the deteriorated paper is known as about 200 [7, 8].

Table 1 shows the results of DP in papers from three aged and four failed transformers. The transformers were operated from 20 - 26 years. As shown in Table 1, the DP results for seven disposed transformers were all “good”. In other words, the paper of the transformers for 26 years did not show significant degradation. Therefore, paper will deteriorate rapidly after about 40 years of operation, as seen in the alarm rate of $CO_2$ in Fig. 13(b). Therefore, $CO_2$ is highly related to failure rate, and thus, using it as an index of insulation degradation in relation to the aging of transformers is appropriate. In general, the life of transformers is calculated by the Arrhenius equation of IEEE C57.140 [9]. However, the Arrhenius equation is related to the degradation rate of paper. IEEE C57.104 states that the life of paper is not the life of transformers.

In summary, paper rapidly deteriorates after 40 years of operation and reaches a characteristic life (63.2%) in 55 years. However, setting the replacement life of 32 years based on the failure rate is desirable because power transformers should not be operated until the end of life.

## 5. Conclusion

In this study, 110,000 DGA data since 1983 were analyzed to determine the degradation parameters related to the aging of power transformers. The alarm rates of combustible gases ($H_2$, $C_2H_2$, $C_2H_4$, $CH_4$, and $C_2H_6$), TCG, CO, and CO2 were analyzed. The end of life and failure rates (bathtub curve) of power transformers were also calculated based on failure data from 1981 to 2014. The DGA gases related to discharge, overheating, and insulation degradation were determined based on alarm and failure rates. $C_2H_2$, $C_2H_6$, and $CO_2$ indicated discharge, oxidation, and insulation degradation parameters related to the aging of power transformers, respectively. Paper rapidly deteriorates after 40 years of operation, and reaches a characteristic life (63.2%) in 55 years. However, setting the replacement life of 32 years based on the failure rate is desirable because power transformers should not be operated until the end of life.

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