PYROLYSIS ADD ELECTRICAL ARCING INVESTIGATION OF FAULTS IN TRANSFORMER OIL

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Abstract
Pyrolysis and arcing experiments were performed on transformer oil. Pyrolysis temperature range was 200 – 700 °C. The results indicated that considerable decomposition of the oil occurs above 300 "C. At approximately 700 °C the oil is completely decomposed, with methane, ethane, and propane the major products. No evidence of acetylene was found at any temperature. The arcing experiments were performed in a novel 6-foot glass column; bubbles produced by electrical arcing partly dissolved in the oil as they traveled up the column into a 10 % nitrogen headspace. The production of fault gas products was greatly dependent upon the arc energy across the electrode gap.

Introduction

Pyrolysis and arcing experiments were performed on transformer oil. The decomposition of transformer oil as a result of heating was investigated over a temperature range from 200 to 700°C. The second set of experiments included an analysis of the gas bubble produced due to electrical arcing in columns 6 and 5 feet in length. The results of these two investigations are described in the following sections: **Pyrolysis Studies and Electrical Arcing Studies.**

<u>Pyrolysis Studies</u>

Pyrolysis studies on transformer oil were conducted at this laboratory several years ago. The oil was heated in stainless steel bulbs without a gas blanket. The pyrolysis results from 200 to 700 °C, shown in Pig. 1, differed from those of earlier investigations by Dornenberg[1] and Rogers.[2,3] The differences of interest were that no evidence of acetylene was found and the key ratios were reversed. Comparisons with their work, for example, show a ratio of less than 1 for C_2H_6/C_2H_4, as opposed to our results, which are considerably greater. Key ratios involving H_2 and the hydrocarbon gases C_3H_8, C_2H_6, C_2H_4, and CH_4 from our studies are presented in Table 1.

Table 1

Pyrolysis of Transformer Oil (Gas Ratios at 300 and 600˚C)

Species	**300 ˚C**	**600 ˚C**
C_3H_8/H_2	390	23
C_2H_6/H_2	100	16
C_2H_4/H_2	14	9
CH_4/H_2	12	13

The current pyrolysis investigation, which employed a nitrogen blanket, would be more compatible with actual condition in utility transformers. The results agree fairly well with the previous work at this laboratory.

Experimental

A temperature range of 200 – 700 °C was chosen to investigate decomposition and pyrolysis of transformer oil. Below 200°C minimal decomposition occurs, whereas at 700°C the oil undergoes complete pyrolysis. Stainless steel 150 cc bulbs were employed and placed in an electrical resistance furnace. The bulbs were filled with oil, with a nitrogen blanket. A heating period of three hours was considered sufficient to obtain large concentrations of decomposition gases. At the conclusion of the heating period the bulbs were cooled and analyses were performed by gas chromatography.

Results

Four temperatures in the 200 – 700 °C range were chosen for the tests. A time period of 3 hours was selected. Scotts standard gas was used for calibration purposes and contained 1000 ppm (±10%) of each of the nine gases of interest: H_2, CO, CO_2, O_2, N_2, CH_4, C_2H_4, C_2H_6, and C_2H_2. A Poropak N separation column was employed for analysis of CH_4, CO_2, C_2H_4 and C_2H_2. A molsieve 5A column was used for analysis of H_2, O_2, CH_4 and CO. A summary of the experimental results obtained at the four temperatures is presented in the following sections.

Tests Performed at 220 °C

The oil decomposition at 220 °C was investigated with a nitrogen blanket. In one test a small amount of O_2 was added to the nitrogen headspace to determine whether its presence hastens or increases the oil decomposition.

Three hours of heating was found adequate to sufficiently decompose the oil to produce species in an easily measurable ppm range.

Table 2 presents a compilation of the test results. The concentration values should be considered as arbitrary and as a basis for a 3-hour pyrolysis experiment. Values are presented for both the headspace analysis and the gas concentration in oil.

The addition of O_2 increased the oil decomposition considerably, which would be unrealistic for comparison with actual transformer oil decomposition.

The second part of Table 2 presents the gas ratios of interest and a comparison with the literature. The ratio of 12 for CH_4/H_2 is considerably higher than the results of Dornenberg [1] and Rogers [2,3]. Rogers reported ratios between 0.1 and 1.0, and Dornenberg reported greater than 1.0. The C_2H_4/C_2H_6 ratio of 0.39 from our studies is also different from the values of Rogers, 1 to 3, and Dornenberg, 2.5. However, it is closer to the IEC standard of 1.0.

Table 2

Results of Transformer Oil Decomposition at 220 °C

	Headspace Analysis (ppm)		Oil Analysis (ppm)	
	N_2 Only	N_2+O_2	N_2 Only	N_2+O_2
C_2H_4	21	39	29	54
C_2H_6	33	73	75	165
CH_4	92	400	33	144
CO_2	1000	1240	1030	1277
H_2	61	117	2.7	5.3

Ratios in Oil

IEEE Report 2-6-97, Oil Only

	N_2 Only	N_2+O_2	IEC Standard	Rogers	Dornenberg
CH_4/H_2	12	27	not significant >0.1	<1.0	>1.0
C_2H_4/C_2H_6	0.39	0.32	<1	1 to 3	<2.5

Tests Performed at 380 °C

The second temperature chosen for the oil decomposition studies was 380 °C. Although the decomposition is minimal at 220 °C, this is not the case at 380 °C. Considerable concentrations of the hydrocarbons and hydrogen are produced at this temperature, including CH4, C2H4, C2H6 and H2 (as shown in Table 3). A value of 24,000 ppm for C2H6 indicates a high degree of oil decomposition. However, since this is only ~3 % of the total gas composition the oil has not completely pyrolysized in the 3-hour experiment. An examination of the key ratios shows that CH4/H2 increases with temperature rise while the C2H4/C2H6 ratio decreases with temperature rise. Rogers suggests that the C2H4/C2H6 ratio at 220 and 380 °C is in the range of 1 to 3. Dornenberg's ratio for C2H4/C2H2 was ~3 for thermal decomposition. The IEC standard for this ratio at 380 °C is 1 to 4. These values are much higher than the value of 0.12 from the present work for oil decomposition in the presence of a nitrogen blanket. The results of the pyrolysis studies without an N_2 blanket are depicted in Fig. 1, which shows a value of ~ 0.3 for this ratio.

The CH_4/H_2 ratios of Rogers, Dornenberg and IEC show values of >1.0, >1.0 and >1.0, respectively, at 380 °C. The ratio for CH_4/H_2 in our work is 16.4 at the same temperature. In our earlier work, without the nitrogen blanket, the ratio was ~13.

Table 3

Pyrolysis of Transformer Oil at 220 and 380°C

Species	220 °C (ppm)	380 °C (ppm)
CO_2	1030	845
C_2H_4	29	2952
C_2H_6	73	24117
CH_4	33	4967
H_2	2.7	303
CO	0	298

Ratios in Oil

			IEC	
Species	**220 °C**	**380 °C**	**220 °C**	**380 °C**
CH_4/H_2	12	16.4	Insignificant	>1
C_2H_4/C_2H_6	0.39	.12	<1	1 to 4

Tests Performed at 540 °C

Pyrolysis at 540 °C was extensive, with the transformer oil decomposing rapidly. The knowledge obtained from the experimental data is mainly the distribution of the concentration of the products. The gas chromatographic analyses are shown in Fig. 3, which depicts product distribution employing the Poropak column. The major decomposition species is propane at 50% of the total gas volume produced, followed by ethane at 34%. These are uncorrected values for standard gas comparisons. Table 4 lists the pyrolysis products as measured by the gas chromatograph. Figure 3 shows the distribution of the products, from H_2 to C_3H_8. It is readily apparent that the C_2H_6/C_2H_4 is approximately 17.

Table 4

Pyrolysis of Transformer Oil at 540 °C

Species	**Uncorrected Percentage**
H_2	0.8
N_2	2.6
CH_4	7.6
C_2H_4	2.0
C_2H_6	34.0
C_3H_8	51.8

Tests Performed at 655 °C

At 655 °C, the highest temperature of the pyrolysis tests, the oil was completely decomposed. However, the product concentration was slightly different from the results of the tests at 540 °C. Tables 4 and 5 show the differences in the hydrocarbon species.

Table 5
Pyrolysis of Transformer Oil at 655 °C

Species	Uncorrected Percentage
H_2	7.6
N_2	11.6
CH_4	34.2
C_2H_4	2.9
C_2H_6	27.3
C_3H_8	16.4

The propane concentration at 540° was over 50%, whereas at 655° the C_3H_8 concentration had fallen to 16%. The ethane concentration at 540 ° was 34% and approximately the same at 655° (27%). Methane has the largest gas concentration at 655°, 34%, with a large H_2 concentration of 8%. The molsieve values (Fig. 4) also show that methane has the largest concentration of all the species.

The ratios of the results of the oil pyrolysis without a gas blanket are in substantial agreement with the current data.

Conclusions

The distribution and concentration levels for the fault gases are different in laboratory decomposition studies of transformer oil from those of fault gas analyses of oil from over-heated electrical transformers.

The laboratory tests employed a nitrogen blanket in stainless steel containers. Electrical transformers also contain oil with a nitrogen blanket, as well as a core with cellulose insulation, possibly providing a different environment during the overheating process. Therefore, the effects of cellulose decomposition on the fault gas concentration is unknown.

Our results of fault gas analyses from a large transformer agree with those of Rogers and Dornenberg in that the ratio of ethylene/ethane is reversed from those of the laboratory tests.

One other difference should be mentioned and that is that no acetylene in levels greater than 1 ppm is produced in the laboratory pyrolysis of the transformer oil whereas acetylene was reported in the analyses of Rogers and Dornenberg. This may indicate that while the oil was being overheated in the transformer some corona or low-level electrical discharges were taking place. Electrical discharges produce C_2H_4/C_2H_6 ratios greater than 1 whereas this ratio in pyrolysis is less than 1.

Finally, the results obtained in the current investigation of transformer oil pyrolysis for the ratios of CH_4/H_2 and C_2H_4/C_2H_6 may be an important aid to transformer engineers in determining the cause of electrical faults.

Electrical Arcing Studies

At the suggestion of Stan Lindgren of EPRI apparatus and experiments were designed to investigate the possible entrapment of fault gases in the bubbles produced from electrical discharges in transformer oil. Bubbles produced at the bottom of a 6-foot column due to electrical arcing across electrodes rose to a 10% headspace and were analyzed for fault gas concentrations.

Experimental

Two vertical columns were constructed, one 6 feet in length and the other 3 feet (see Fig.5). Each contained adjustable electrodes and oil sampling ports at 1-foot intervals. The columns were made of pyrex approximately 2 nun thick. The headspace gas was sampled directly by gas chromatographic analysis. Oil samples taken from the ports were analyzed by standard DGA methods.

The initial experiments employed electrode spacing of 1 mm. The voltage across the gap was 35 kV, with a current of 8 mA (280 watts) Experiments were performed at one hour, one-half hour, 15 minute and 2-minute intervals.

The relatively inert combustible gases, H_2 and CH_4, are only slightly soluble in the oil as compared to the hydrocarbon gases, C_2H_6, C_2H_4 C_2H_2. The partition of hydrogen in oil versus gas is 22.2 whereas the partition for acetylene between gas space and oil is nearly equal (0.97). The partition values are listed in Table 6.

Table 6

Partition of Fault Gases Between Oil and Gas Space

	Partition Ratio (ppm of gas in gas space/ppm of gas in oil)
O_2	7.9
N_2	13.6
CO_2	0.97
H_2	22.2
CH_4	2.78
C_2H_6	0.44
C_2H_4	0.73
C_2H_2	0.97

Results

The first bubble experiments were performed employing the 6-foot column. The length of arcing times were chosen arbitrarily at one hour, one-half hour, 15 minutes and 2 minutes. As soon as the arcing commenced the oil around the electrode begane to darken and at the conclusion of the hour the oil in the entire column was almost black. The gas sample was collected from the headspace in a 200 cc stainless steel bulb. The oil samples were taken at the port 1 foot from the bottom, or approximately 7 inches above the electrodes. Two other oil samples were collected from the ports at a distance of 3 feet and $5_{1/2}$ feet from the bottom.

The GC analyses showed considerable concentration of fault gases. For example, the analysis of the headspace at the conclusion of the one-hour experiment shows considerable quantities of H_2, CH_4 and C_2H_2 (see Fig. 6). This chromatogram can be compared with the one produced from the oil sample collected from the 5i-foot port (Fig.7). This chromatogram depicts the extracted gases from the oil sample. The results for the first set of four experiments are presented in Table 7.

Table 7

Summary of Bubble Experiments

	Gas concentration in Headspace (ppm)	Concentration in Oil at Three Levels		
		$5_{1/2}$ feet	3 feet	1 foot
One Hour				
H_2	10236	41	43	44
CH_4	3039	112	78	118
CO_2	207	98	187	311
C_2H_4	423	254	290	300
C_2H_2	11598	4536	4302	4325
One-Half Hour				
H_2	8007	33	34	38
CH_4	2091	61	57	50
CO_2	210	63	66	63
C_2H_4	303	59	59	59
C_2H_2	7497	1776	2204	1613
Fifteen Minutes				
H_2	5190	53	35	35
CH_4	930	46	47	36
CO_2	870	256	255	534
C_2H_4	42	75	92	70
C_2H_2	2103	1276	1329	1037
Two minutes				
H_2	3186	30	29	24
CH_4	171	16	14	3
CO_2	246	270	450	490
C_2H_4	12	48	9	10
C_2H_2	267	852	206	115

Although it is too early to draw definitive conclusions the results do show some trends: fault gas solubility in oil takes place almost from the start of the arcing; the concentration of fault gases in the headspace is greater than the solubility of the gases in oil; the hydrocarbons, C_2H_2 and C_2H_4 are quite soluble in the oil; and the fault gas concentrations are not linear with the time elapsed. For example, as can be seen from Table 7, the H_2 concentration in the headspace for the half-hour experiment is 80% of the one-hour experiment and the two-minute value is 30% of the one-hour value. Similar trends were found for the oil analyses. The first experiment with the 3-foot column produced some startling results. The electrode spacing was slightly greater than for the tests with the 6-foot column. This gap required 40 kV and 10mA.

Table 8

Comparison Between 30-Minute

Experiments of 6-Foot Column and 3-Foot Column.

Arc Energy Was Different for the Two Experiments

6’	Column	35 kV	8 Ma	280	Watts
3’	Column	40 kV	10 Ma	400	Watts

Uncorrected Concentration Values

	6’ Column (ppm)	**3’ Column (ppm)**
H_2	2805	44802
CH_4	734	33839
CO_2	106	578
C_2H_4	94	6129
C_2H_2	2614	171068
	Ratio	
H_2/CH_4	3.82	1.32
H_2/C_2H_2	1.08	0.26

(400 watts) to produce a stable arc. This compared to 35 kv and 8 mA (280 watts) for the 6-foot column tests. The fault gases concentration were over 10 times those for the previous tests (see Table 8). Approximately 25% (0.10 g) of the headspace gas contained fault gases.

The preliminary experiments indicate that the production of fault gases is greatly dependent upon the arc energy. This will have to be explored further with the future experiments.

References

1. E. Dornenberg and W. Strittmatter, "Monitoring Oil-COOled Transformers by Gas Analysis." Brown Boveri Review, Vol. 5, Mo. *74,* pp 238-247.
2. R. R. Rogers, "U.K. Experience in the Interpretation of Incipient Faults in Power Transformers by Dissolved Gas-in-Oil Chromatographic Analysis (A Progress Report)." Minutes of the Forty-second Annual International Conference of Doble Clients, 1975, Sec. 10-201, Doble Engineering Company, Watertown, MA.
3. R. R. Rogers, "Concepts Used in the Development of the IEEE and IEC Codes for the Interpretation of Incipient Faults in Power Transformers by Dissolved Gas-in-oil Analysis.' Presented at the IEEE 1978 Winter Power Meeting.

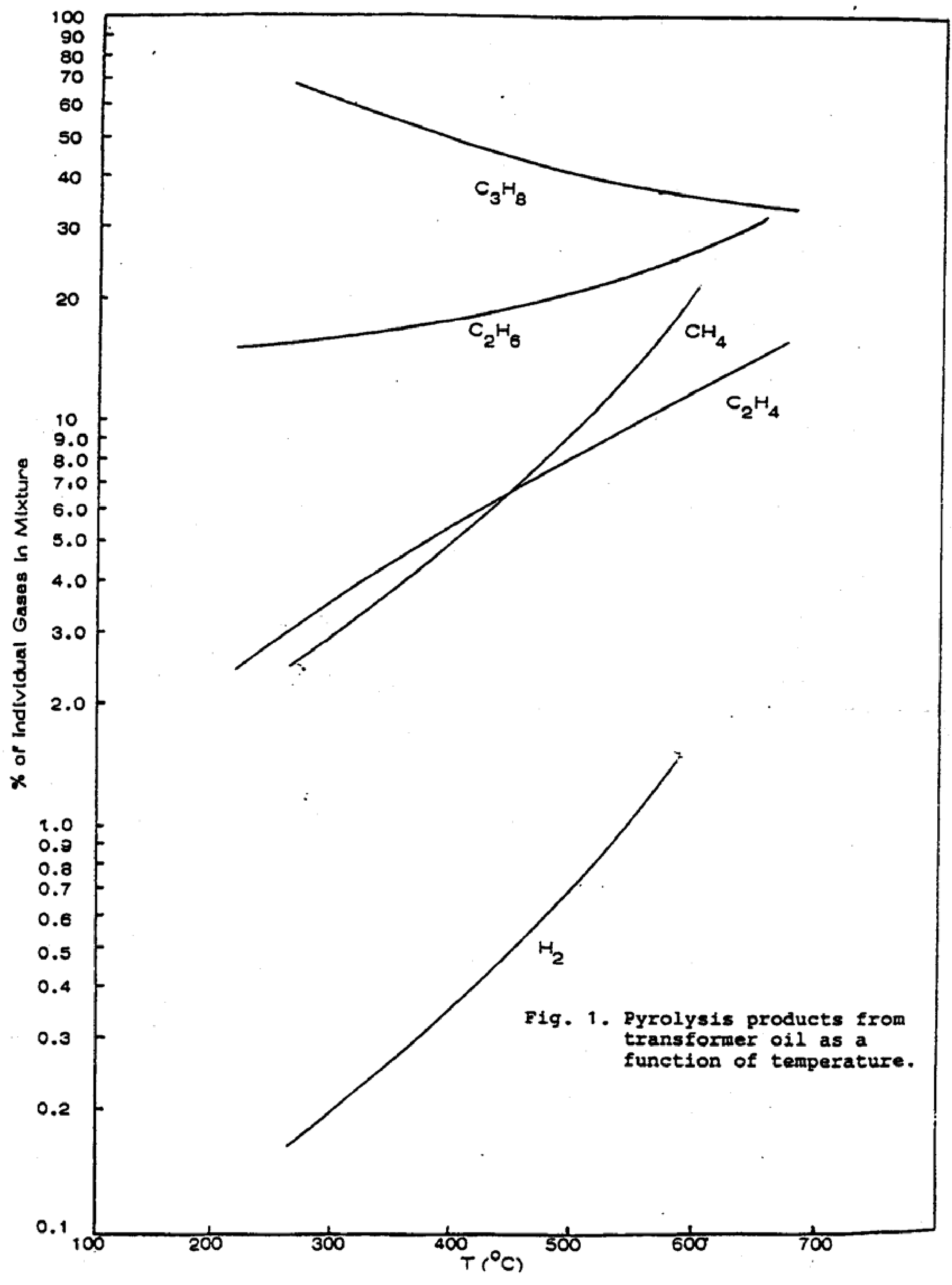
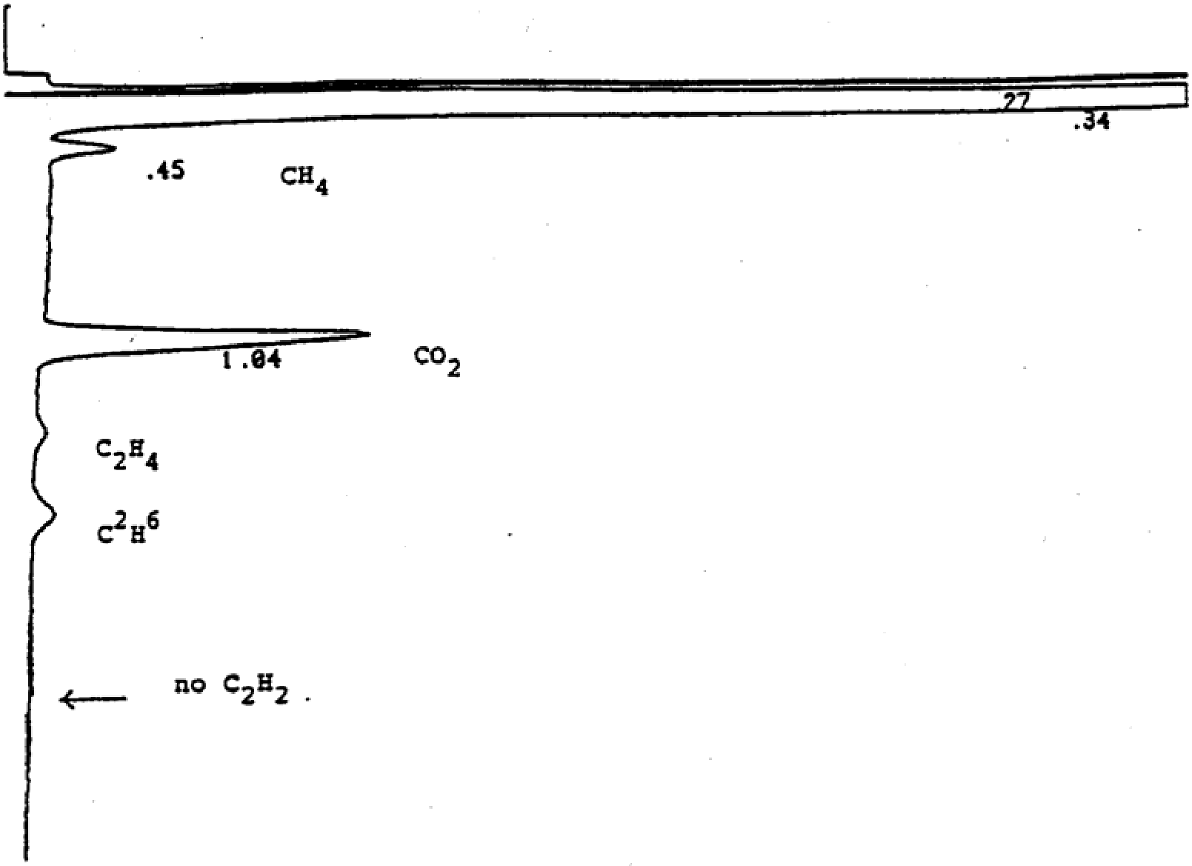


Fig. 1. Pyrolysis products from transformer oil as a function of temperature.

CHANNEL A INJECT 04/13/98 16:13:09 STORED TO BIN # 3



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04/13/98 16:13:09 CH= "A" PS= 1.

FILE 1. METHOD 0. RUN 3 INDEX 3 BIN 3 INPUT 100

PEAK#	AREA%	RT	AREA	BC
1	8.201	0.27	4834	02
2	87.623	0.34	51651	02
3	0.989	0.45	583	03
4	3.188	1.04	1879	01
TOTAL	100.		58947	

Fig. 2. Integrated analysis of decomposition of transformer oil at 220°C.

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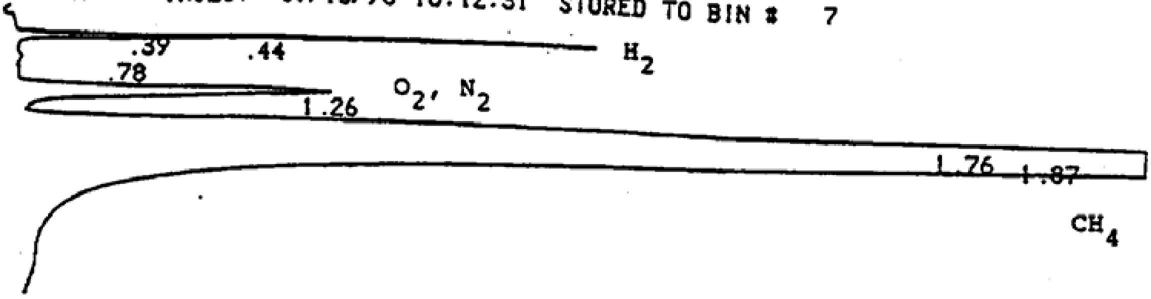


DATA SAVED TO BIN # 7

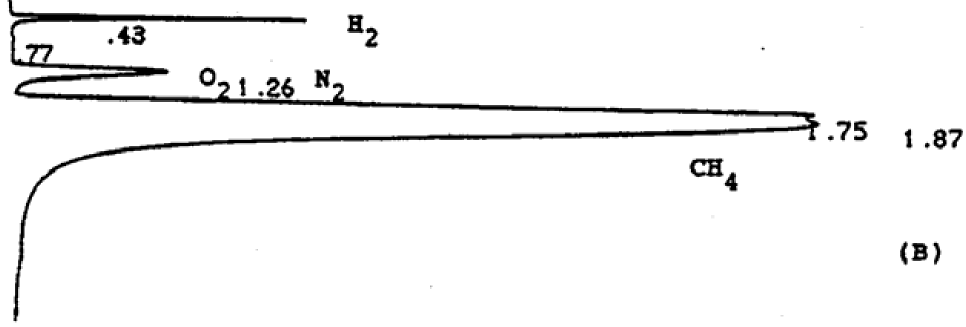
FILE 1. METHOD 0. RUN 7 INDEX 7 BIN 7

PEAK#	AREA%	RT	AREA BC
1	0.156	0.39	2331 02
2	2.92	0.44	43704 03
3	0.022	0.78	329 01
4	4.963	1.26	74282 02
5	18.477	1.76	276554 02
6	73.463	1.87	1099586 03
TOTAL	100.		1496786

(A)

AT [0.5, 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048, 4096] (16.) = 32

CHANNEL A INJECT 07/15/98 16:17:44 STORED TO BIN # 8



(B)

DATA SAVED TO BIN # 8

07/15/98 16:17:44 CH= "A" PS= 1.

FILE 1. METHOD 0. RUN 8 INDEX 8 BIN 8

PEAK#	AREA%	RT	AREA BC
1	2.896	0.43	43849 01
2	0.023	0.77	345 01
3	4.877	1.26	73845 02
4	19.001	1.75	287676 02
5	73.202	1.87	1108282 03

Fig. 4. Pyrolysis of transformer at 655°C. Attenuation for (A) is 16 and 32 for (B).

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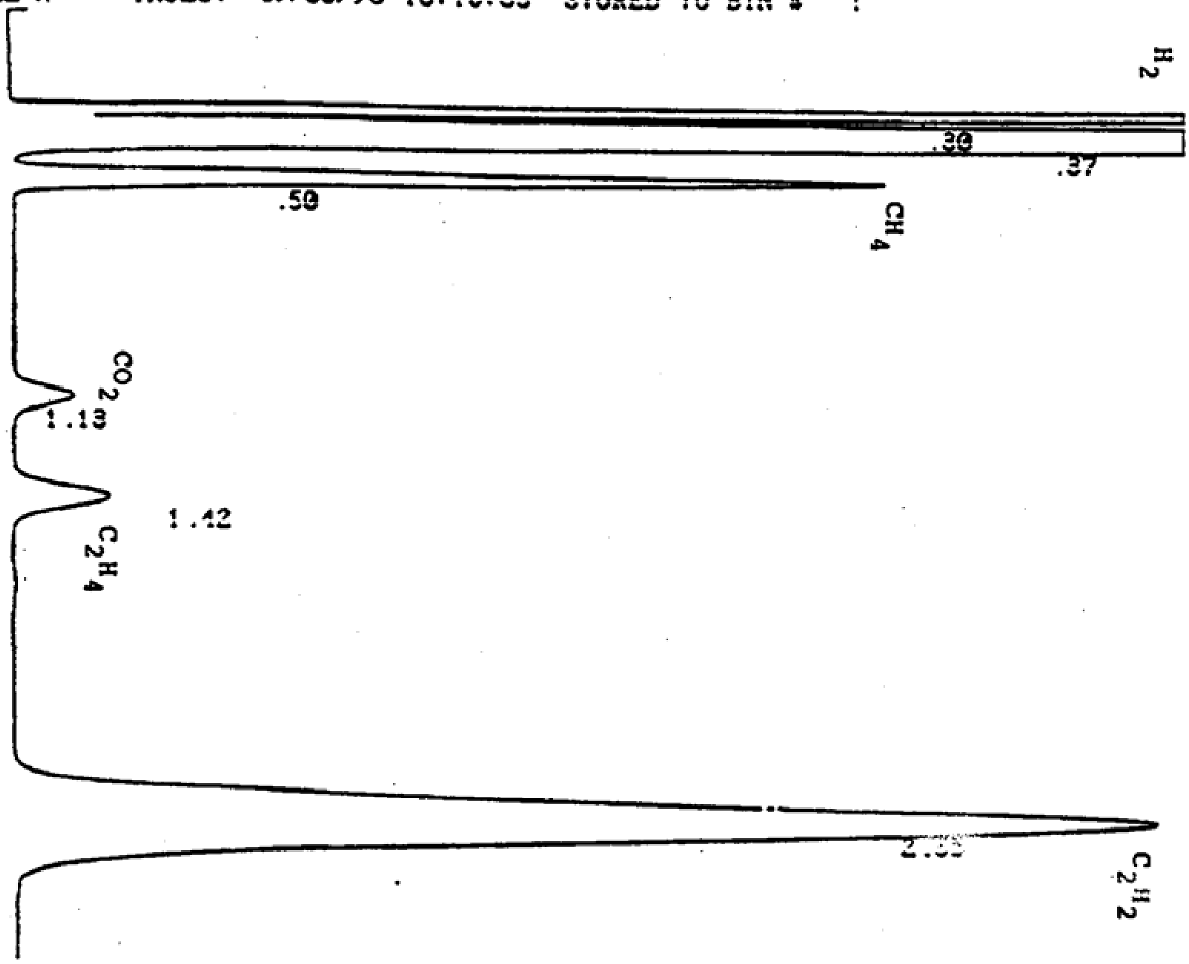

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09/30/98 13:10:35   CH- "A" PS- 1.

FILE 1.   METHOD 0.   RUN 1   INDEX 1   BIN 1

PEAK#	AREA%	RT	AREA	BC
1	22.49	0.3	15618	02
2	52.402	0.37	36390	02
3	4.261	0.5	2959	03
4	0.491	1.13	341	01
5	0.956	1.42	664	01
6	19.4	2.35	13472	01
TOTAL	100.		69444	

Fig. 6. Fault gas concentration in headspace from arcing in 6-foot column.

Fig. 5. Gas Bubble Column

5	1.824	1.42	1075 02
6	5.031	1.82	2965 02
7	16.5	2.34	9723 03
TOTAL	100.		58929

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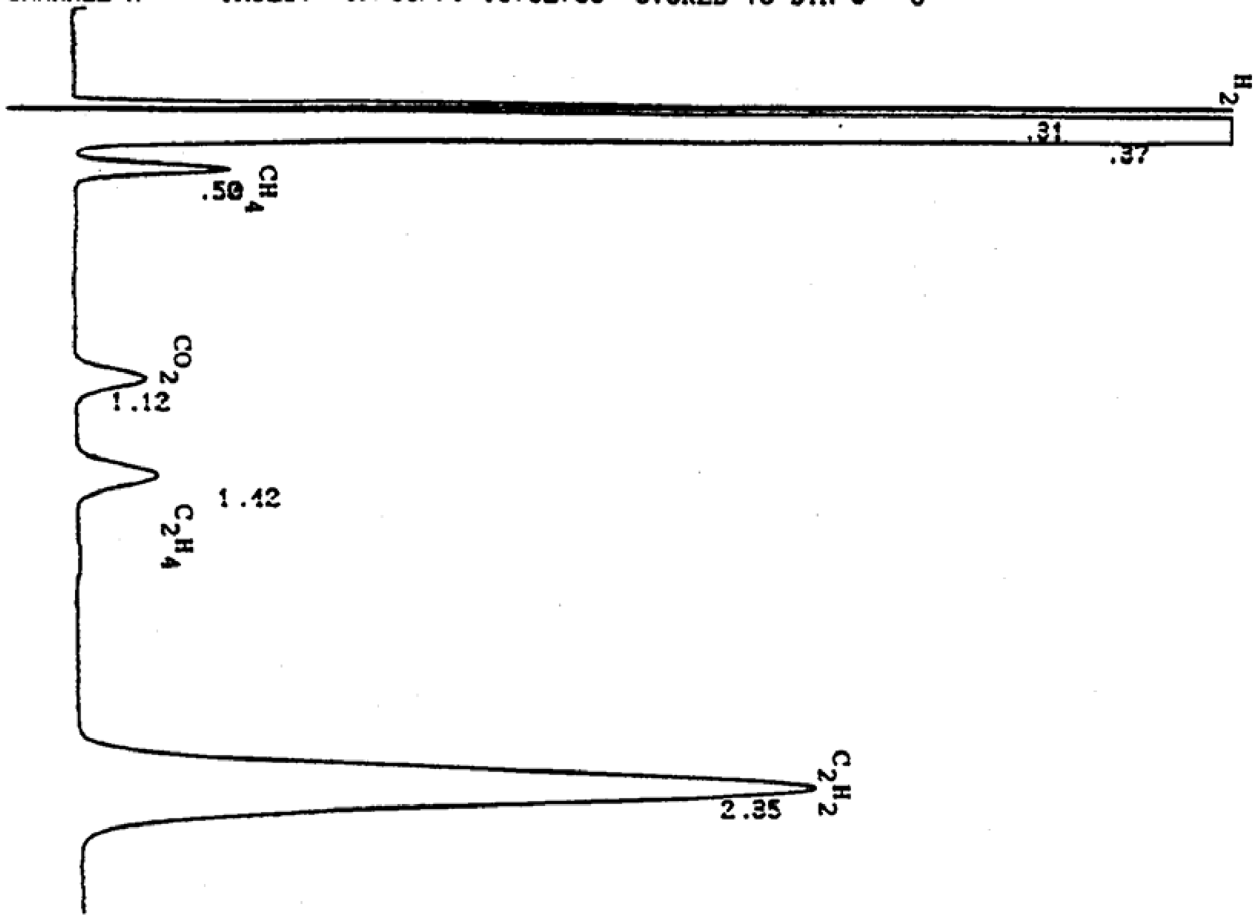

DATA SAVED TO BIN # 6

09/30/98 13:32:38 CH- "A" PS- 1.

FILE 1. METHOD 0. RUN 6 INDEX 6 BIN 6

PEAK#	AREA%	RT	AREA BC
1	5.679	0.31	3152 02
2	74.587	0.37	41399 02
3	1.791	0.5	994 03
4	0.787	1.12	437 01
5	1.063	1.42	590 01
6	16.093	2.35	8932 01
TOTAL	100.		55504

Fig. 7. Fault gas concentration from arcing in 6-foot column in oil at 5½-foot level.