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RETROFILLING OF RAILROAD TRANSFORMERS

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FINAL REPORT

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16. Abstract

The objective of this program was to assess the effectiveness of retrofilling an askarel transformer supplied by the United States Department of Transportation with a 50 centistokes silicone fluid. The work tasks included an assessment of the electrical and thermal characteristics of the transformer before and after retrofilling as well as an indepth evaluation of the retrofill concept.

As a result of this work it has been shown that:

1) The retrofilled transformer did not show any ill effects from the limited electrical testing.
2) Thermal tests revealed that the retrofilled unit ran 9.7°C hotter.
3) All but 107 lbs. of the original 2113 lbs. of askarel were removed from the transformer after 288 hours of flushing with 90°C silicone.
4) To reach the program objective of 58 lbs. of retained askarel an additional 3 months of flushing would have been required.
5) The mathematical model developed by General Electric in earlier studies as a predictive tool for estimating times to reach predetermined levels of PCB has been validated as a result of this study.

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SUMMARY AND CONCLUSIONS

SUMMARY

The objective of this program was to assess the effectiveness of retrofilling an askarel transformer supplied by the United Stated Department of Transportation, with a 50 centistokes silicone fluid. The work tasks included an assessment of the electrical and thermal characteristics of the transformer before and after retrofilling as well as an in-depth evaluation of the retrofill concept.

As a result of this work it has been shown that:

1) The retrofilled transformer did not show any ill effects from the electrical tests that were made. The highest voltage imposed was 11,000 volts. Since this is only operating voltage no conclusions should be drawn relative to the unit's adequacy to withstand frequency overvoltage or impulse voltage.

2) Thermal tests on the retrofilled transformer revealed that the unit ran 9.7°C hotter than when filled with Inerteen. It would have been higher had the cooler been cleaned prior to the Inerteen test.

3) Of the approximately 2113 pounds of Inerteen initially in the transformer all but 107 pounds were removed by draining and subsequent flushing with silicone. The composition of the Inerteen as determined by gas chromatography was 65% polychlorinated biphenyl (PCB) and 35% trichlorobenzene (TCB).

4) The equivalent of 288 hours (12 days) of continuous flushings with silicone at 90°C was required to achieve the residual of 107 pounds of Inerteen.

5) A multiple regression technique was used to estimate the amounts of Inerteen retained within the various structures of the transformer after draining and prior to flushing. Seventy-seven pounds was retained and subsequently removed by flushing from the insulation system in the axial direction; 77 pounds was retained and subsequently removed in the radial direction from thicker sections (1/8"); 107 pounds which remained was probably trapped in the core and thick sections (greated than 1/8") of pressboard, wood, etc.

6) Based on the Inerteen removal rate at the 288 hour mark it would have required <u>at least three months</u> of additional flushing to reach the program objective of 58 pounds. A more realistic estimate might be as long as one year if one considers that the removal rate continues to drop as the percentage of Inerteen retained decreases.

7) Normalization techniques have been developed for interpreting the retrofill procedure and can be used for future retrofill studies.

8) The mathematical model developed by General Electric in earlier studies as a predictive tool for estimating times to reach predetermined levels of PCB by the drain and flush method with silicone has been validated as a result of this study.

9) A major problem identified under this program was the realization that relatively large amounts (15%) of Inerteen remain in the transformer after a hot drain.

10) One of the problems in reaching predetermined levels of PCB after a drain and flush procedure is lack of <u>exact</u> knowledge of the initial amount of PCB in the transformer.

11) The ratio of polychlorinated biphenyl (PCB) to trichlorobenzene (TCB) as they were removed from the insulation system into the silicone did not change with time. There was therefore no preferential leaching.

<u>CONCLUSIONS:</u>

1) The railroad transformer studied under this program when retrofilled with silicone reached higher temperatures under constant load conditions when compared to Inerteen. Thus the insulation life of some transformers may be reduced if the units are not operated at reduced level after retrofilling.

2) While the retrofilled transformer showed no ill effects from the modest electrical testing it must be remembered that the tests performed were specifically chosen to assure electrical integrity. No low frequency overvoltage or impulse testing was done. Electrical tests on models and components done outside this program by General Electric indicate that askarel transformers retrofilled with silicone would have reduced dielectric integrity. The reduction is due to the following factors:

   a) Substantially lower positive impulse strength, particularly in creep could cause problems in transformers where the design did not provide for this weakness.

   b) Increased electrical stress at the interface of the two phase liquid region if all the askarel isn't flushed out of the transformer.

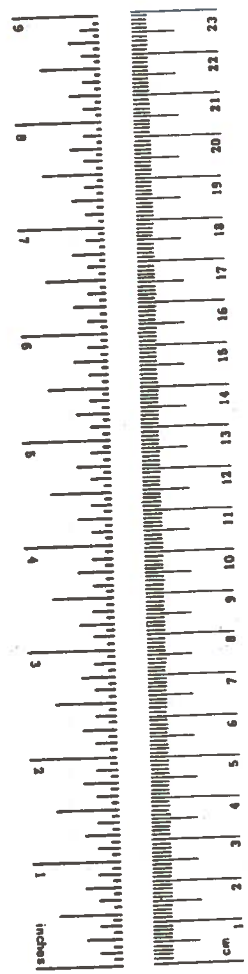
3) Work done under this program reinforces our generalized conclusion reached as a result of work done prior to this contract that:

> While transformers specifically designed around the characteristics of silicone fluid appear to be logical successors to askarel units, the two fluids are not one-to-one substitutes in existing transformers. Reliability and load capacity of an askarel transformer retrofilled with silicone may be decreased. An in-depth analysis of individual designs should be done prior to retrofilling.

METRIC CONVERSION FACTORS

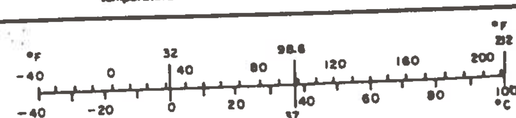
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

PCB's have been identified as toxic substances in the Toxic Substances Control Act and the sole producer of PCB based askarels has phased out of production. Several companies have announced the availability of transformers with silicone oil for applications that formerly required askarel insulation transformers. These new transformers are not simply askarel units with a substitute fluid. They are units designed around the unique properties of silicone oil.

A program to study the technical and economic aspects of the retrofill concept was conducted prior to this work by General Electric in 1976. The program involved both exploratory tests and analytical studies. Early in the program, it became apparent that there are many problems associated with the concept. An IEEE paper entitled "Problems Associated With Retrofilling of Askarel Transformers" presented at the 1977 Winter Power Meeting discusses these problems and the data that led to their identification.

The primary objective of this program was to assess the effectiveness of retrofilling an askarel transformer supplied by the United States Department of Transportation with a 50 centistokes silicone fluid. The work tasks included an assessment of the electrical and thermal characteristics of the transformer before and after retrofilling as well as in-depth evaluation of the retrofill concept.

2. PROGRAM OBJECTIVE AND TASKS

The primary objective of this program was to assess the viability of retrofilling an askarel railroad transformer with a 50 centistokes silicone fluid. Many concerns crystallized as a result of previous laboratory and analytical work done at General Electric prior to this contract. These concerns were enumerated in the previously identified IEEE paper. This program afforded the opportunity to obtain first hand experience with a "real" transformer rather than with laboratory models.

A thirty-year-old, 418 kVa Westinghouse railroad transformer, containing Inerteen[R]7336-8 as a dielectric fluid was supplied by the Department of Transportation for these studies. Analysis of this fluid via gas chromatography revealed its composition to be 65% polychlorinated biphenyl (PCB) and 35% trichlorobenzene (TCB).

R - Registered Trademark of Westinghouse.

Due to the age and service of the transformer, electrical and thermal tests made on the transformer had to be limited in severity to preserve the integrity of the unit for repeat testing after retrofilling with silicone. These limitations must be considered in forming conclusions of the results.

A brief description of each task and corresponding goals relative to each task follows:

Task 1

Under Task 1, a series of tests were conducted on the supplied transformer (a copy of nameplate characteristics can be found in the text) in the as-received condition. Two types of tests were performed, namely electrical and thermal tests. The electrical tests were:

1) Winding resistance measurements
2) Turn ratio
3) Percent impedance
4) Core loss
5) Exciting current

Thermally, a standard heat run test was made before and after retrofilling to determine the changes in temperature rises that occur as a result of the retrofill procedure. This gives an indication of load capacity of the transformer before and after the retrofill procedure.

Task 2

The objective of the task was to reduce the amount of PCB in the supplied transformer by the drain and flush method to 3% by weight based on the final amount of silicone required in the final fill. The target therefore was a residual content of approximately 58 pounds of Inerteen or 38 pounds of PCB.

Task 3

The objective of this task was to assess the effects of the retrofilling done in Task 2 on the thermal and electrical properties of the transformer.

3. RETROFILL PROCEDURES

A number of alternatives exist relative to reducing the amount of retained PCB's prior to final filling a transformer with silicone. Possible procedures include the following:

1) Drain and subsequent flushes with silicone.

2) Drain and pre-flush with a fluid other than silicone, flush with silicone and final fill with silicone.

3) Completely remove core and coil assembly and vapor phase (kerosene, mineral spirits, etc.), flush with silicone and then final fill with silicone.

Our decision to choose (1) hinged on the fact that all other approaches involve the use of a third material which might adversely affect the transformer. The use of high solvency fluids like 100% trichlorobenzene posed a potential hazard to the unknown insulation system of the transformer. The use of low boiling or intermediate boiling hydrocarbons posed the threat of poor flammability characteristics after final fill with silicone. It is known for instance that 1-2% by weight of kerosene drastically reduces the flash point of silicone.

The selection of an area in which to perform the retrofill operation involved several considerations. The primary requirements were a source of 25 hertz power to operate the pump, low pressure steam for heating the unit, and a remote location away from any manufacturing area. The only location which met these conditions was the vestibule area of the Sound Laboratory and thus the retrofill was performed there.

Several safety precautions were taken to eliminate the possibility of contaminating the area with PCB's. Prior to moving the transformer into the area, the floor where the yard trailer supporting the transformer was to be placed was covered with several layers of polyethylene. After positioning the unit, the edges of the ployethylene were supported with 2x6 wooden studs. This created a dam, capable of containing any potential leaks or spills. Both the drain and fill lines were fitted with additional valves since the condition of the valves present on the transformer was unknown.

Heating of the unit was accomplished through the finned tube heat exchanger normally used to cool the transfer. The top and bottom openings on the air side of the heat exchanger were sealed with aluminum plates. The top aluminum plate was attached to a low pressure steam line (3 pounds) and the bottom plate to a steam condensate trap. All condensate was disposed of via incineration. The transformer was then covered with 3-1/2 inch fiberglass insulation to decrease the heat-up time and reduce thermal losses.

The transformer pump was then connected to the 25 hertz power and energized to assure proper operation. Temperature measurements were made utilizing four thermocouples. These thermocouples were connected to a multipoint temperature recorder programmed to print out temperatures hourly. Two of the thermocouples were positioned at the ends of the transformer and the remaining two were located at the inlet and outlet of the heat exchanger.

The transformer was then tilted by placing two hydraulic jacks under the yard trailer. This positioned the drain valve at the lowest point possible.

With all preparation complete, the pump was energized and steam applied to the heat exchanger. The temperature of the unit was raised to 95°C and held overnight. The following morning, the Inerteen was drained from the transformer into five gallon pails for transfer to storage containers and subsequent weighing. This was accomplished in about four hours during which time the thermocouple readings on the walls of the unit remained above 75°C. The drain valve was then closed for 24 hours. Upon reopening the valve, an additional 20 pounds of Inerteen were drained. This brought the total Inerteen removed from the transformer to 1764 pounds. The pump was then energized to assure that no Inerteen remained in the duct work of the cooling system. As no additional fluid was removed due to this procedure, the initial drain was considered complete.

The first flush using SF97-50 silicone fluid was begun by filling the unit by gravity feed. A total of 1090 pounds of the fluid were added. A vent pipe with a valve was attached to the unit where a 3/4-inch pipe plug had been removed near the top of the transformer. This valve was installed to prevent pressurizing the unit during the heat-up cycle. The pump was then energized and steam applied to the heat exchanger.

Some problems were encountered during the flushing operations. The first problem was related to the availability of 25 hertz power. The motor generator set supplying the power was also needed for performing tests on new transformers in another area. This forced intermittent shutdowns of the flushing operation when the power was unavailable.

Another problem developed that could be considered weather-related. During the flushing operation, an abnormally warm weather spell occurred. During this time, the low pressure steam for the entire plant was shut down which prevented heating of the transformer. When cooler weather returned and the steam pressure was restored, the steam condensate pump in the building malfunctioned. This allowed condensate to backfill the steam lines preventing the steam from reaching the transformer. At this time, the low pressure steam was disconnected from the transformer and the unit was connected through reducing valves to a high pressure steam line and no further trouble was experienced.

In the analysis of the data, adjustments have been made in the rate of removal of Inerteen to compensate for the effect of these problems. However, the original data collected which includes time and temperatures is presented for reference in Table 1.

TABLE 1

SILICONE RETROFILL FLUSHING DATA

Cumulative Time, Days	Sample Interval Time, Hrs.	Trans. Temp., °C	Trans. Pump	% Inerteen in Silicone Solution	Mass Inerteen in Sil., Lbs.	Residual* Inerteen in Insul., Lbs.
0	0	10	OFF	-	-	349
0.88	21	10	OFF	6.5	72.4	276.6
0.98	2.5	10	ON	7.4	82.7	266.3
1.48	12	10	ON	9.0	101.1	247.9
3.88	57	10	OFF	9.0	101.1	247.9
5.05	28	90	ON	14.5	166.1	182.0
5.05	0	10	OFF	0	0	182.0
5.88	20	80	ON	2.9	30.9	151.1
6.88	24	70	ON	3.7	39.5	142.5
14.18	175	10	OFF	4.2	44.9	137.1
17.22	73	70	ON	5.2	55.8	126.2
17.91	16.5	80	ON	5.5	59.1	122.9
18.89	23.5	90	ON	5.8	62.3	119.7
24.35	131	10	OFF	6.1	65.6	116.4
24.77	10	90	ON	6.2	66.7	115.3
25.04	6.5	90	ON	6.3	67.8	114.2
25.71	16	90	ON	6.4	68.9	113.1
26.05	8.2	90	ON	6.5	70.0	112.0
26.72	16	90	ON	6.6	71.1	110.9
27.30	14	90	ON	6.7	72.2	109.8
27.80	12	90	ON	6.8	73.3	108.7
28.80	24	90	ON	6.9	74.4	107.6
30.76	47	90	ON	7.0	75.5	106.5

*Based on assumed Inerteen fill of 168 gallons.

During the first flushing operation, samples of fluid were drawn off periodically until a concentration of 14.5% by weight of Inerteen in silicone had been reached. This concentration represents a saturation temperature of 73°C. The unit was drained at this time since further heating and circulating would result in a high enough concentration to separate into two phases during cooldown while draining. A total of 1143 pounds of Inerteen and silicone were removed at this time.

The transformer was recharged with 1054 pounds of SF97-50 and the above process repeated until the concentration of Inerteen in silicone reached 7% by weight. At this time, the rate of diffusion of Inerteen from the insulation structure into the silicone fluid had decreased to about 0.03 pounds per hour. Figure 1 graphically illustrates the rapidly falling rate of diffusion of the Inerteen from the insulation. This shape of the curve, assuming 168 gallons initial fill, also implies that there may be Inerteen somewhere in the transformer which cannot be easily accessed by the silicone. Since the time required for removal of any appreciable amount of Inerteen at this rate is considerable, the transforme was again drained and a total of 1060 pounds of solution were removed.

Prior to the final fill of the transformer with SF97-50, two rinses of the unit with silicone fluid were made to reduce the amount of Inerteen in solution within the unit. In each case, about 200 pounds of fluid were added to the transformer, circulated by the transformer pump for fifteen minutes and drained. Samples of the fluid from these rinses were also analyzed for Inerteen content. The Inerteen present in the fluid from the second rinse was found to be negligible.

Reference to Table 2, an overall material balance of the retrofill operation, allows a clear view of the removal of Inerteen from the transfor during each step of the process. The residual Inerteen in the transformer at final fill shown in Table 2 is 108 pounds as compared with 106.5 pounds residual Inerteen in insulation in Table 1. The difference between the values is due to incomplete removal of the 7% Inerteen in silicone fluid during the rinsing operations. Since only about 20% of the available volume of the transformer was filled with silicone fluid during the rinses, not all of the 7% fluid could be removed.

In preparation for the final fill with SF97-50, a vacuum pump was attached to the vent pipe and the transformer was evacuated overnight. Al the hydraulic jacks were removed returning the unit to a level position. The following day, while filling the unit under vacuum, it was discovered that the pressure relief diaphragms on the transformer had ruptured due to the pressure exerted on them by the atmosphere during evacuation. An internal vacuum of 25 inches of mercury was being maintained by the spring loaded diaphragm covers even with the diaphragms ruptured. Alumin discs were installed as a replacement for the diaphragms and the retro-fill was continued. The fill was considered complete when the level of fluid visible in the sight gauge reached the higher (MAX) line on the gauge. This required 1093 pounds of SF97-50.

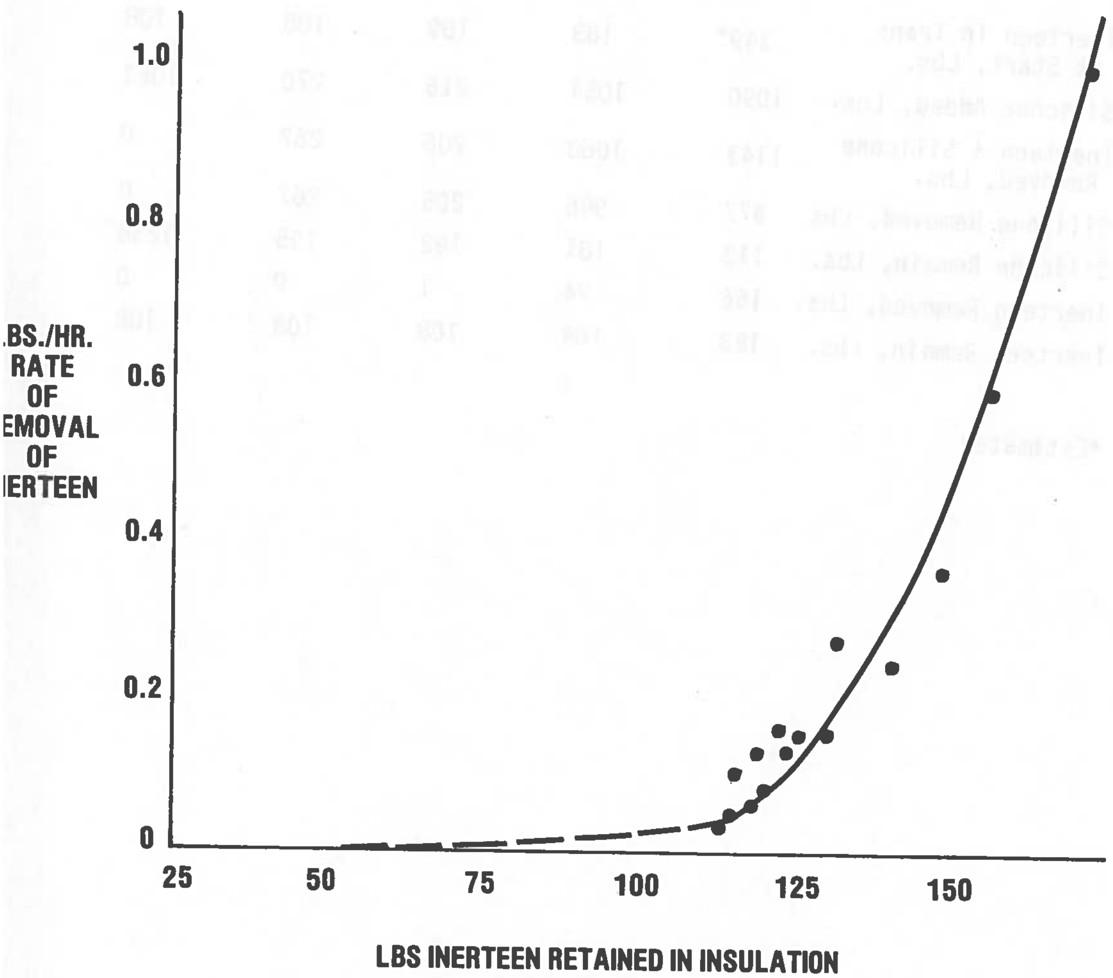

FIGURE 1. RATE OF REMOVAL OF INERTEEN VS. RETAINED INERTEEN (ASSUME 168 GAL. INERTEEN INITIALLY)

TABLE 2

SILICONE RETROFILL MATERIAL BALANCE

Variable	First Flush	Second Flush	First Rinse	Second Rinse	Final Fill
Inerteen in Trans. at Start, Lbs.	349*	183	109	108	108
Silicone Added, Lbs.	1090	1054	216	270	1063
Inerteen + Silicone Removed, Lbs.	1143	1060	206	267	0
Silicone Removed, Lbs.	977	986	205	267	0
Silicone Remain, Lbs.	113	181	192	195	1258
Inerteen Removed, Lbs.	166	74	1	0	0
Inerteen Remain, Lbs.	183	109	108	108	108

*Estimated

Silicone fluid was then drained from the transformer until the visible level in the sight gauge reached the lower (MIN) line. A total of thirty pounds or about four gallons of silicone were removed in the process. This procedure was followed to determine the possible range of Inerteen initially in the transformer and to allow for expansion during the heat run. If the specified 168 gallons of Inerteen is considered to fill the unit to halfway between the MAX and MIN lines of the sight gauge, a range of 166 to 170 gallons can be predicted as having been in the transformer at the beginning of the retrofill.

At the completion of the retrofill, a calculation of the total fluid in the transformer considering the silicone added and the expected residual Inerteen indicated an initial Inerteen volume of 168.4 gallons. This coincides with the original observation of fluid in the sight gauge at just above halfway between the MAX and MIN marks.

Figure 2 shows the transformer in the retrofill area after completion of the process.

3.1 Sampling Technique and Data Collection

Prior to beginning the retrofill procedure, standard solutions of Inerteen from the transformer and silicone fluid to be used for flushing and final fill were prepared. The specific gravity, viscosity and refractive index of these solutions were determined and calibration curves prepared. These curves, Figures 3,4, and 5, were used as standards to measure the concentration of Inerteen in silicone during the retrofill operation. By comparing the values determined by the three techniques, confidence in the data was greatly increased.

As these techniques were restricted by equipment to room temperature measurements an additional elevated temperature method of determining Inerteen content was required for situations where the silicone was saturated with Inerteen above room temperature. This was accomplished by preparing known mixtures of Inerteen and silicone which were heated with stirring to above the saturation temperature. Below the saturation temperature, the mixtures were cloudy. By recording the temperature at which the mixture clarified, a curve of percent Inerteen versus saturation temperature was developed. The same results are obtained from undersaturation, i.e. measuring the temperature at which solution of a given composition clouds on reducing the temperature. Figure 6 shows this relationship.

All sampling during the flushing operations was performed in an identical way. At each sampling, a quart of fluid was removed from the transformer through the drain valve and returned to the unit by means of the vent line prior to taking the sample. This prevented inaccuracies in the data due to poor circulation in the drain lines. All samples were

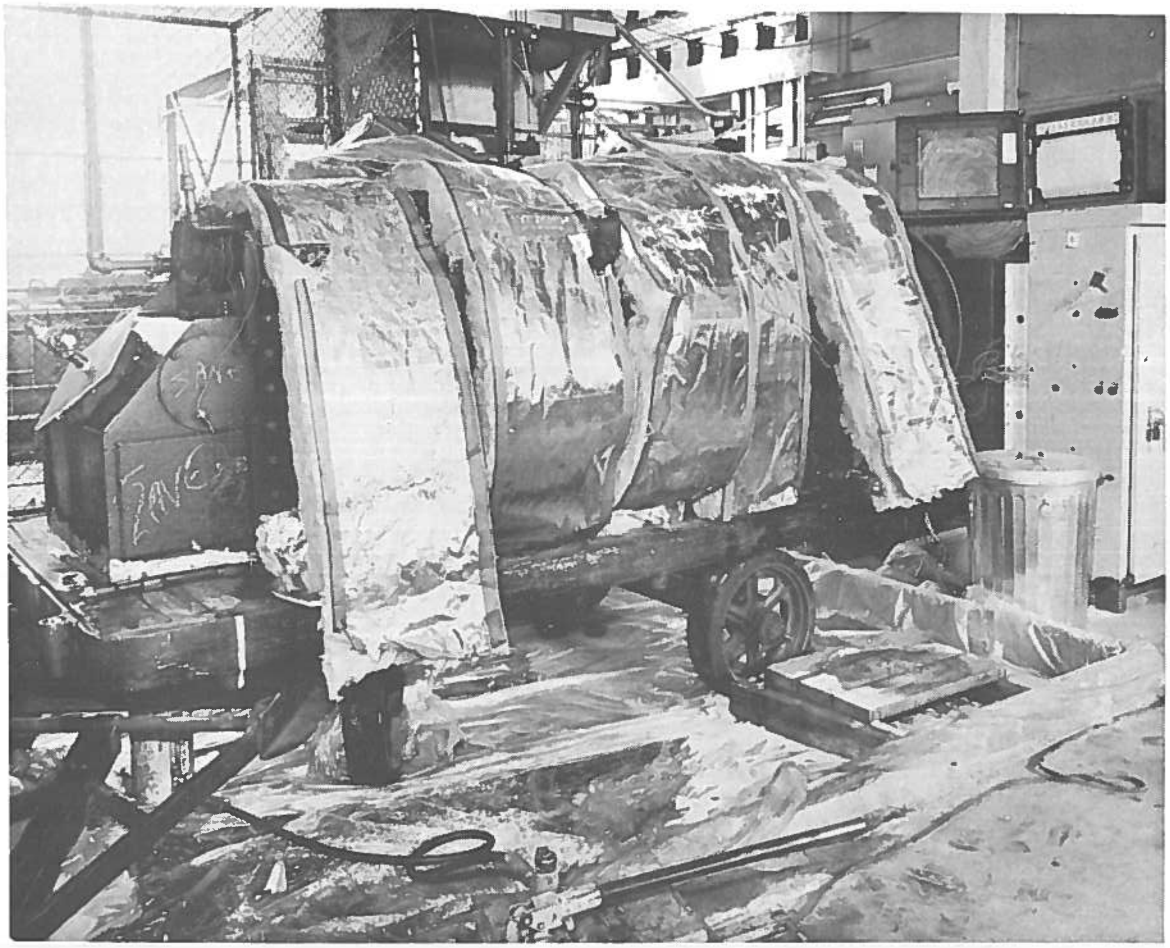

FIGURE 2. PHOTO-TRANSFORMER DURING RETROFILL

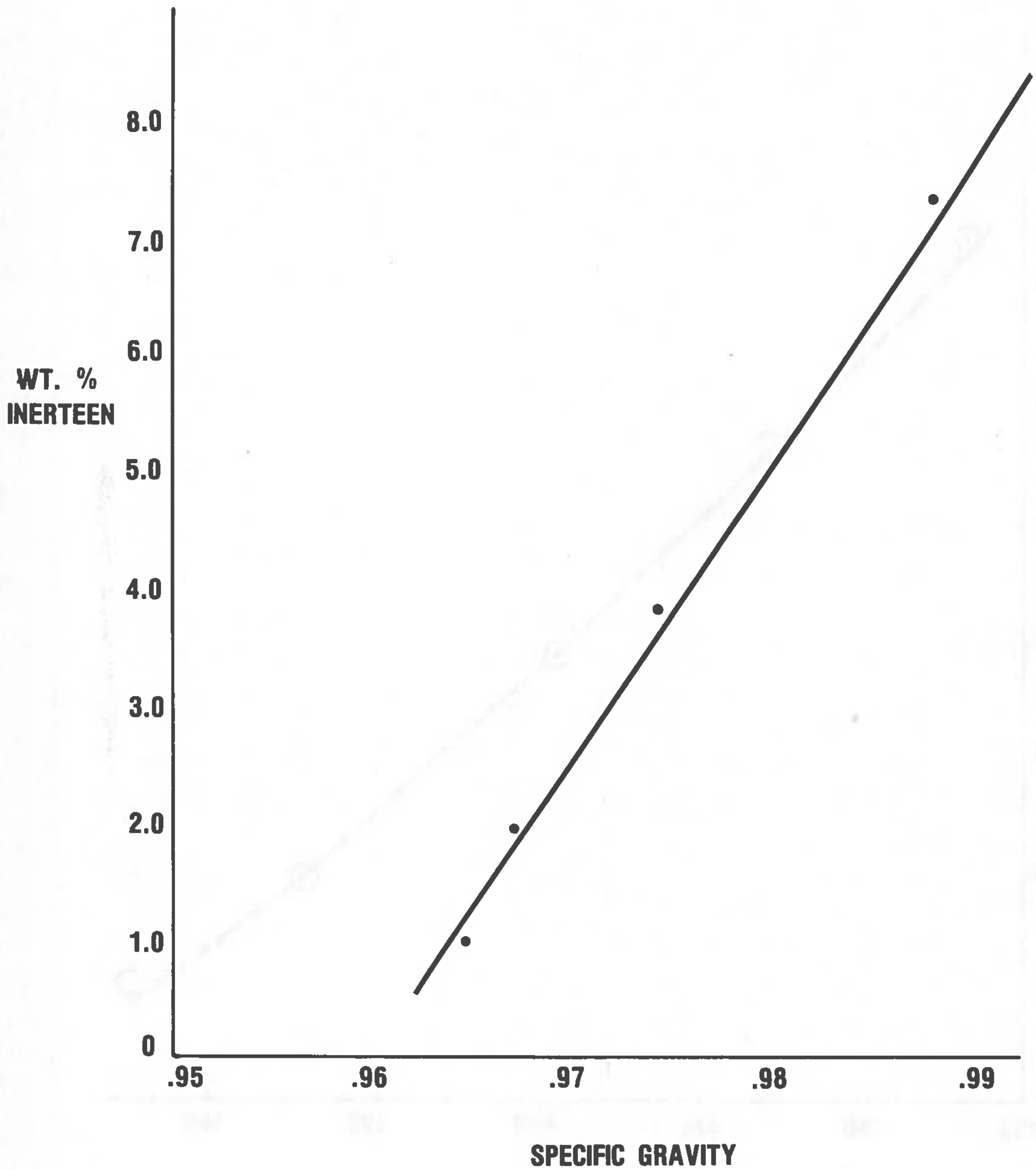

FIGURE 3. WT. % INERTEEN IN SILICONE VS. SPECIFIC GRAVITY

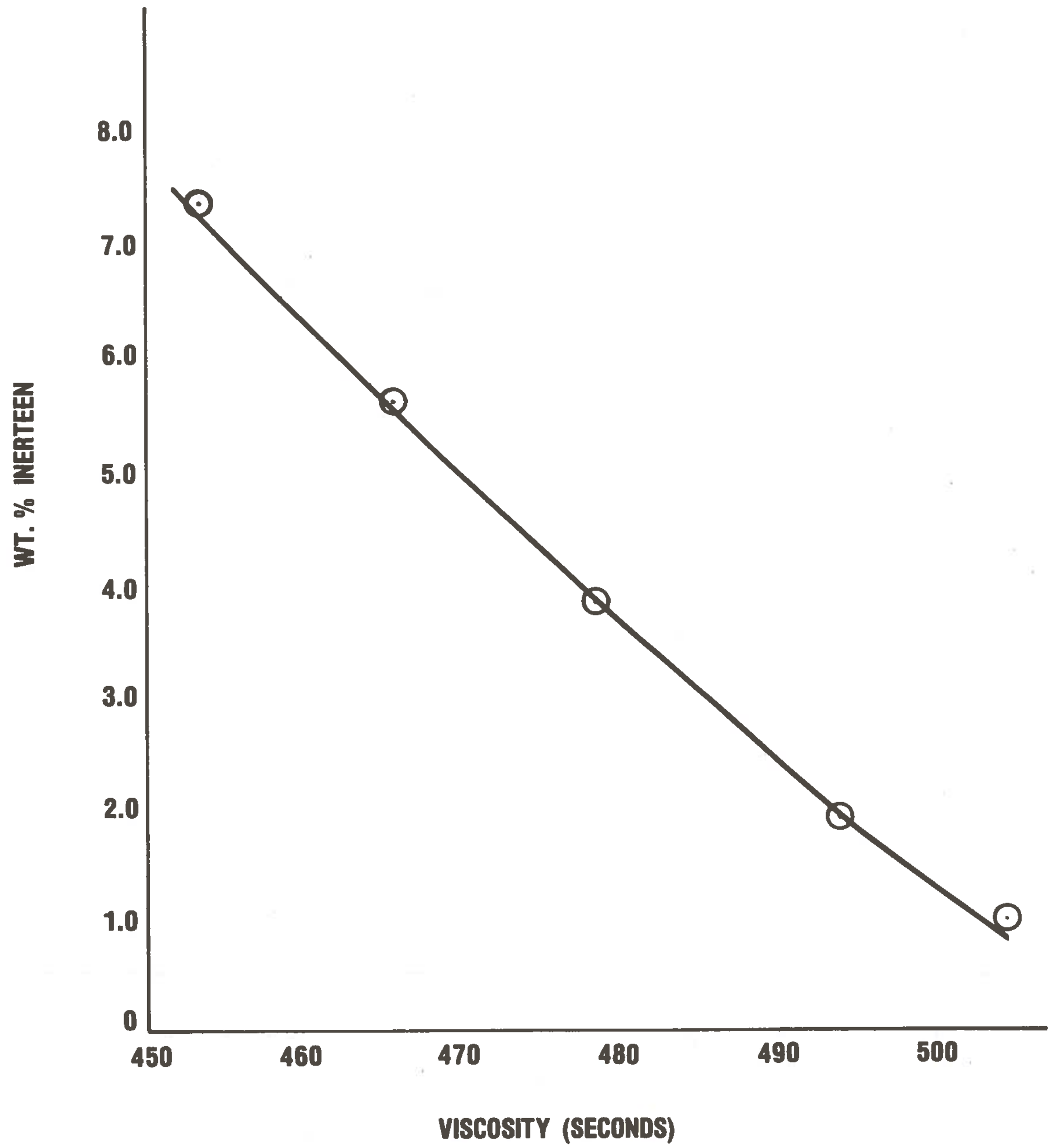

FIGURE 4. WT. % INERTEEN IN SILICONE VS. VISCOSITY

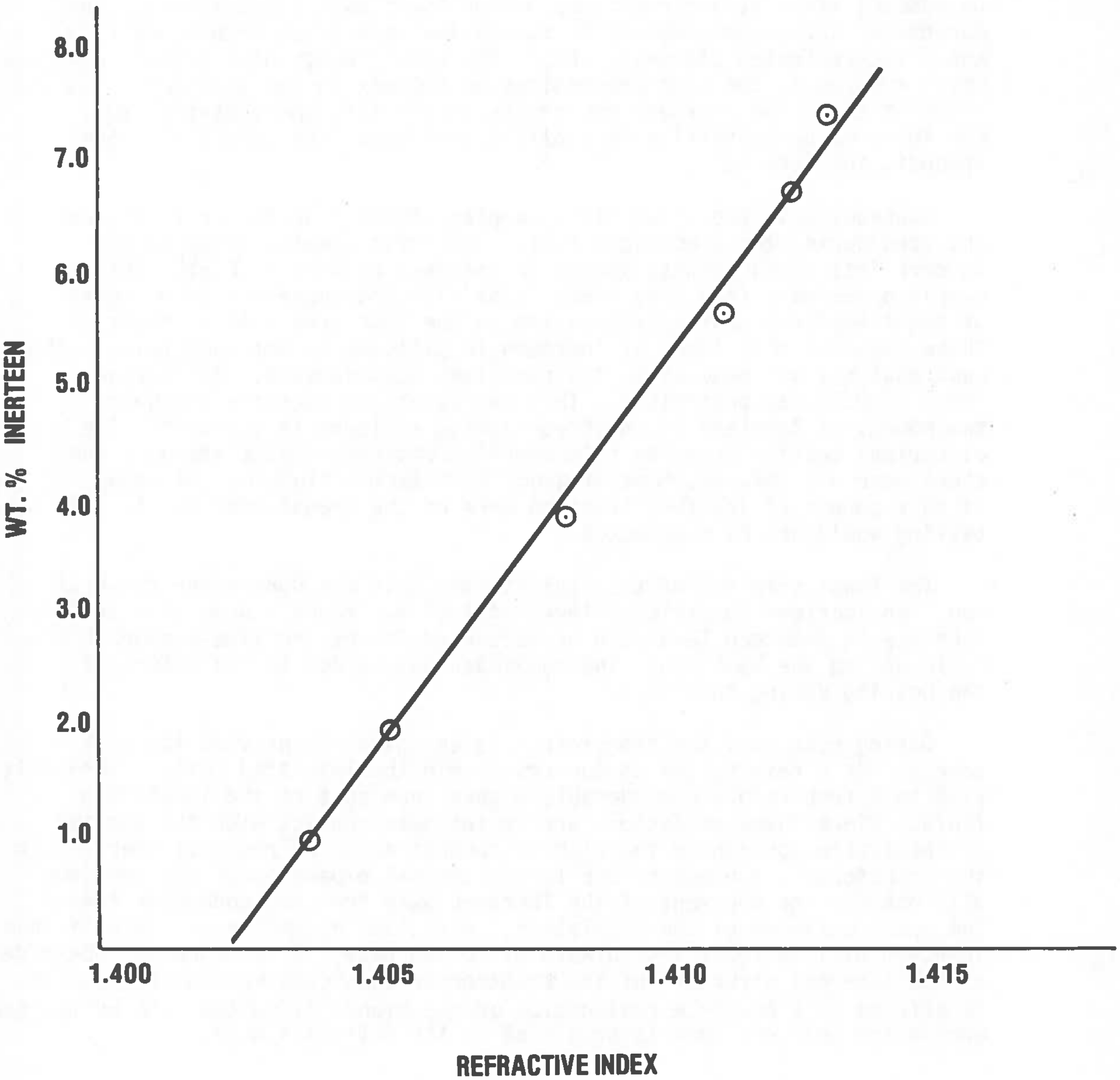

FIGURE 5. WT. % INERTEEN IN SILICONE VS. REFRACTIVE INDEX

analyzed as quickly as possible to maintain a running account of the diffusion rate of the Inerteen into silicone within the transformer. The results of these analyses are shown in the "% Inerteen in silicone solution" column of Table 1.

An additional analysis by gas chromatographic techniques was performed on samples taken at various times during the flushing operations. The purpose of these analyses was to assure that the trichlorobenzene (TCB) and polychlorinated biphenyls (PCB), the constituents of Inerteen, were being removed in the same proportions as present in the Inerteen. The ratio of these two Inerteen components in the silicone flushing fluid was found to be statistically constant throughout the retrofill. See Appendix for details.

Subsequent to the final fill, samples of the transformer fluid were analyzed during the electrical test. The first sample, taken prior to core loss measurements, showed an Inerteen content of 0.5%. This sampling was made five days after final fill and considerable movement of the transformer during relocation to the test area. As a result of these factors, this level of Inerteen in silicone is not surprising. The next analysis was made after the core loss measurements. An Inerteen level of 0.7% was determined. This represents an increase of about two pounds of Inerteen in the free flowing silicone in the unit. The electrical testing prior to this sampling was such that flexing of the steel core was induced, something not done during flushing. A removal of this amount of Inerteen from the core of the transformer due to this testing would not be unexpected.

The final sampling of the fluid in the unit was done after the heat run. An Inerteen in silicone level of 1.0% was found. A portion of this increase in Inerteen level can be accounted for by the time-temperature cycle during the heat run. The remainder may be due to the nature of the heating during this test.

During heat run, the transformer is energized to provide the heat source. As a result, the conductors within the insulated coils of the unit rise to a temperature considerably higher than that of the insulating fluid. Since these conductors are in intimate contact with the portion of insulation containing the highest concentration of residual Inerteen in the transformer, a pressure due to the thermal expansion of the Inerteen will enhance the movement of the Inerteen away from the conductor toward the outer survaces of the insulation. Also, the higher temperature of this Inerteen will increase its outward diffusion rate. In absence of knowledge of the internal structure of the transformer this combination of phenomena is offered as a possible explanation of the higher diffusion rate of Inerteen during the heat run than is predicted by the retrofill data.

3.2 Preliminary Data Analysis

For ease in interpreting the retrofill data, a number of assumptions and mathematical adjustments were made. The major factors that influenced the interpretation of the raw data were:

* Total assumed Inerteen mass in unit
* Raw data normalization techniques
* Transformer geometry, size and structure

Inerteen Mass - The ultimate objective in retrofilling an askarel containing transformer is to lower the PCB (polychlorinated biphenyl) content within the transformer to a prescribed low level. The program objective was a three percent residual PCB content based on the total mass of substitute silicone. To reach this objective, it is obviously important to be able to calculate accurately the final mass of Inerteen remaining within the unit after retrofill. The residual PCB content has to be determined, unfortunately, by difference, i.e. amount initially present minus the total amount removed from the unit. The experimental procedure provided us with an accurate estimate of the Inerteen mass removed from the transformer. However, the exact mass of initial Inerteen contained within the unit prior to retrofill was not available. To assess the significance of knowing the initial mass of Inerteen within the unit and the consequential effect it has on our estimate of the final residual PCB content, the following calculations are worth considering.

The nameplate volume of Inerteen was 168 gallons. A sample Inerteen mixture, prior to initial drain, was analyzed quantitatively by gas chromatography and found to contain approximately 65% PCB and 35% TCB. Based on the program objective of 3% retained PCB, a maximum of 58 pounds of Inerteen was our target. Because of the density difference between Inerteen and Silicone, a final fill with silicone would require approximately 1260 pounds. To arrive at a 3% concentration of PCB per contract, the program objective was 37.8 pounds of PCB of 58 pounds of Inerteen (65% PCB - 35% TCB). Since prior knowledge of the exact mass of Inerteen contained within the unit was not available, we assumed that the unit contained the nameplated 168 gallons. The level of Inerteen within the transformer could be observed on a fill gauge located on the transformer. It was noted initially that the liquid level within the transformer was approximately midway between the maximim and minimum level. By raising and lowering the liquid level within the fill gauge region it was noted that approximately 30 pounds of Inerteen occupied this space. Therefore, an error of approximately 2.5 gallons we atribute to our estimate of the initial liquid volume of 168 gallons of Inerteen within the unit. The specific gravity of Inerteen was measured to be 1.512 g/cc at 25°C. Assuming, therefore, that 168 gallons was originally within the unit at 25°C, then the total initial mass of Inerteen is calculated to be

$$1.512(62.4)(168)/7.5 = 2113 \text{ pounds.}$$

Normalization Techniques - During the retrofill operation, variations in process conditions made normalization of the retrofill data to a common data base a desirable feature. In order to take maximum advantage of the retrofill flushing data, the following set of operating conditions were sought:

* Maintain high fluid temperatures
* Maintain good fluid mixing to maximize the concentration gradient between the Inerteen in the insulation and the Inerteen in the flushant
* Avoid conditions of high Inerteen saturation within the silicone fluid.

Table 3 lists the set of retrofill conditions found most favorable to the retrofill operation. Table 1 as noted earlier lists the raw retrofill data together with the process conditions that prevailed during the retrofill. With regard to actual service retrofill conditions, it is very unlikely that any extended flushing procedure would go on uninterrupted with respect to operating conditions. For example, if the flushing were to occur in situ while the transformer was still in service, the temperature of the flushant would vary depending on load. In a service shop, only 1 or 2 shifts per day may be available to maintain constant operating conditions. It is expected, therefore, that in practical systems, variations in the process conditions are likely to occur.

TABLE 3

RETROFILL DATA BASE CONDITIONS

Process Condition	Base Setting	Explanation
Temperature	90°C	Steam was used as a heat exchange medium.
Pumping	Normal	To create good fluid mixing action within the fluid phase, the circulation pump within the transformer was activated. Secondly, pumping served as a mechanism for heat transfer to the insulation.
Low degree of saturation	Less than 90% saturation	The mass transfer mechanism is largely controlled by the concentration gradient between the two phases.

The benefits derived from data base normalization should be emphasized. First, normalizing the data to a common data base enhances the physical interpretation of the data. Second, normalization establishes the actual time necessary to perform the retrofill task under a prescribed set of operating conditions. Finally, it makes comparison between the results of our experimental and mathematical model presented in our earlier studies possible.

Temperature Variation - During the retrofill operation, variations in flushant and transformer temperatures occurred. In order to adjust the retrofill times to a common data base temperature of 90°C, normalization equations relating the effect of temperature to flushing time needed to be developed. We described, in our earlier report, the effect of temperature on two important mass transfer properties: solubility and effective mass diffusivity.

Solubility is a very important property in relation to the flushing operation. The basic driving force for Inerteen removal from a transformer structure is the concentration difference that exists between the Inerteen rich phase and the silicone rich phase. The larger the concentration gradient between the two phases the greater is the driving force for concentration diffusion. A limit imposed on the concentration gradient is the effect of solubility on either of the two phase regions. Figure 7 is a plot of the solubility of Inerteen in silicone as a function of temperature. Note may be made that at 10°C the solubility limit for Inerteen in silicone is 9%. For a period of approximately 2.5 days during the first flush, the silicone flushant was saturated with Inerteen at 9%. Little if any additional mass transfer of Inerteen out of the insulation structure occurred during that period. Therefore, in adjusting the retrofill times we neglected time periods where silicone saturation had occurred.

In our earlier report, we noted a dependence of effective mass diffusivity on temperature. The exact relation was the following:

$$D = D_o \, 2^{\left(\frac{T-90}{30}\right)}. \qquad (1)$$

Where D is the effective mass diffusivity at temperature T, dependent on the mode of mass transfer, D_o is a constant for a given mode of mass transfer normalized to 90°C and T is the insulation temperature (°C).

To examine the effect of variation of the mass diffusivity on normalized time at 90°C, it is necessary to relate the mass diffusivity expression to the mass transfer rate expression. The closed form Fourier series expansion solution to Fick's second law of diffusion, relating the mass rate of Inerteen out of the insulation, is seen to be made up of a sum of individual contributions for each individual composite piece. However, examining the basic rate formula, a common expression is found to be contained within the complex mathematical solution. The common expression that relates diffusivity to flushing time is the following:

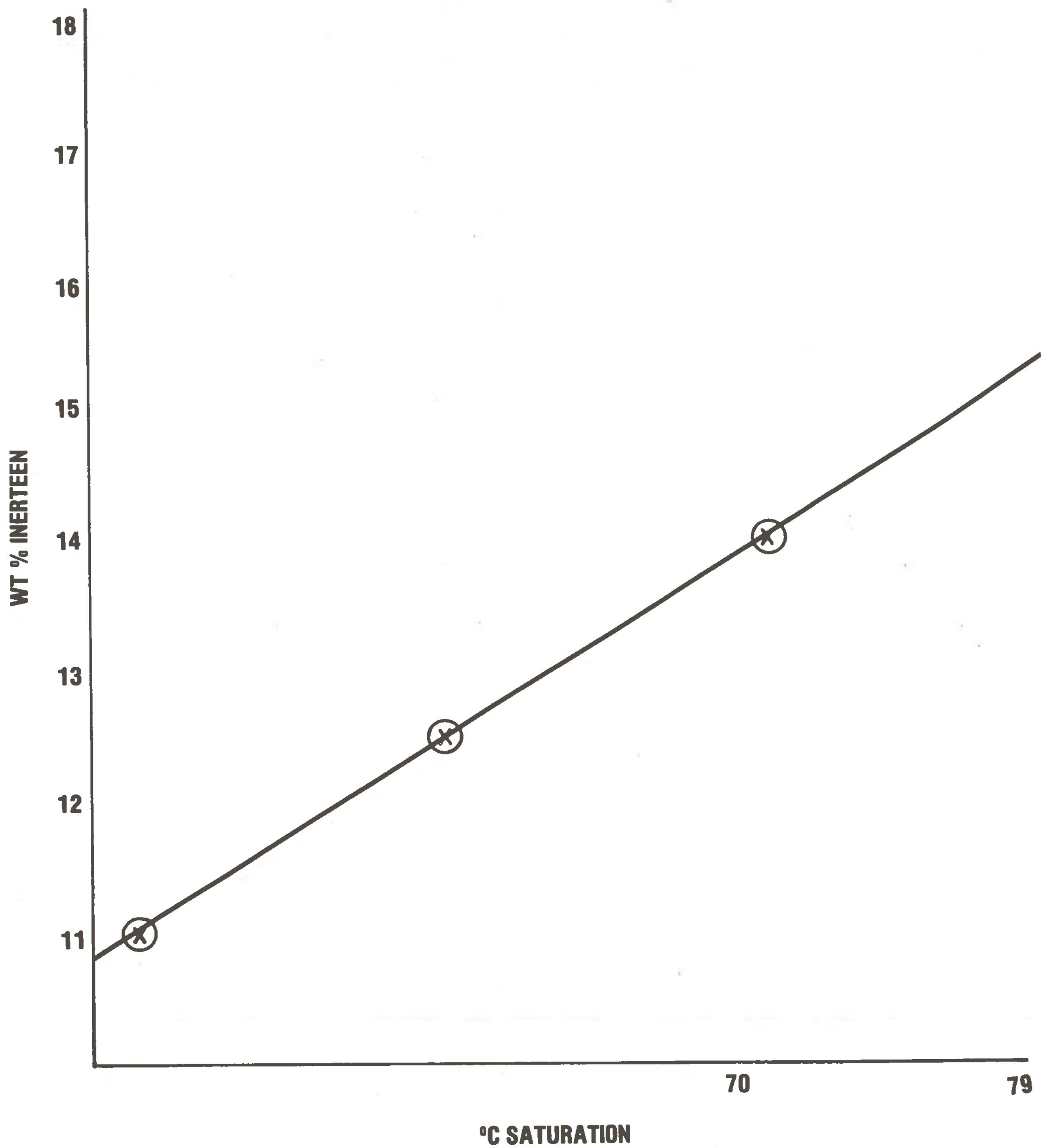

FIGURE 6. WT. % INERTEEN VS. SATURATION TEMPERATURE

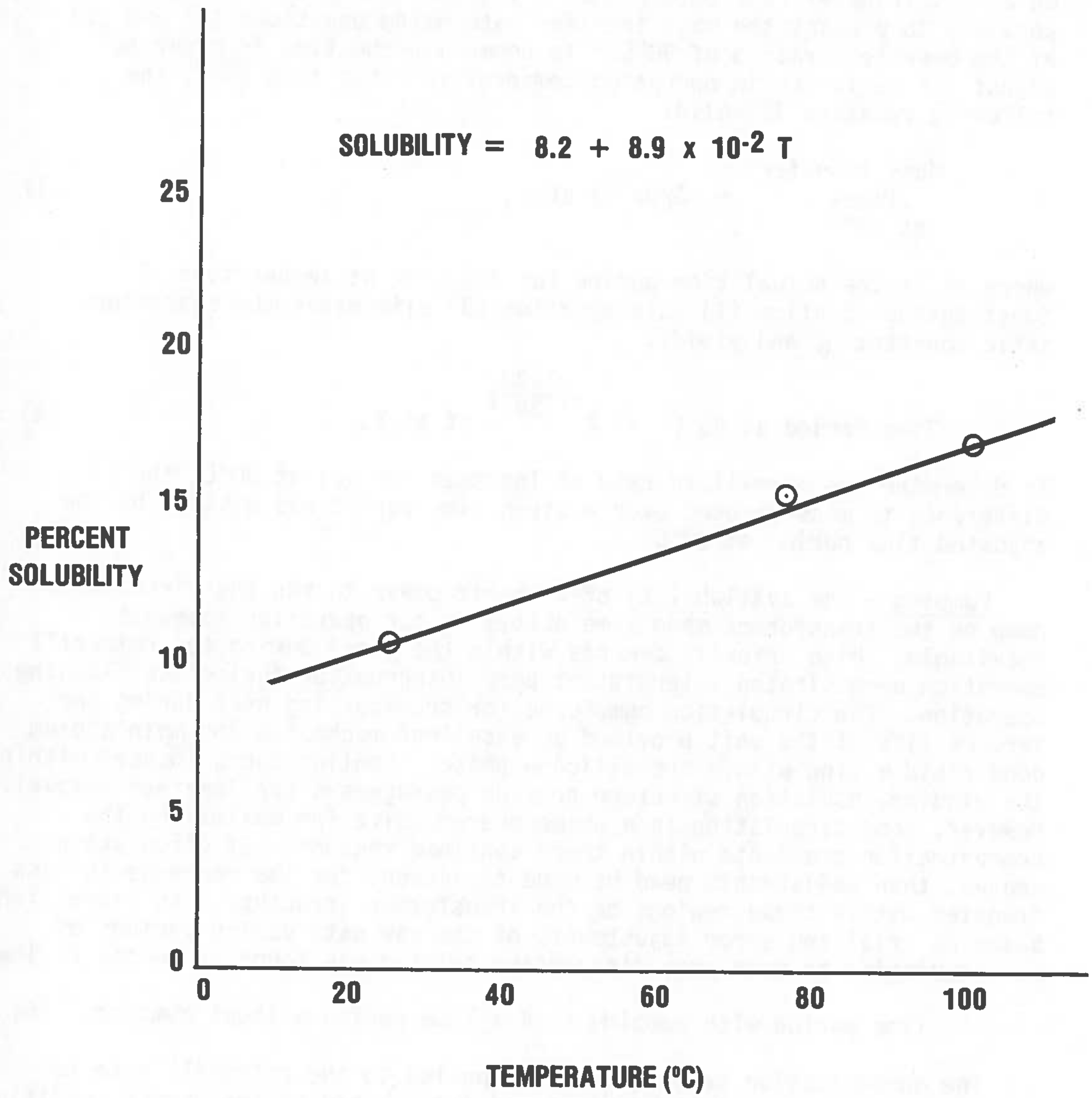

FIGURE 7. SOLUBILITY OF INERTEEN IN SILICONE VS TEMPERATURE

$$\begin{matrix}\text{Mass}\\ \text{Transfer}\\ \text{Rate}\end{matrix} = R_o \exp(-\lambda D\, t/L^2), \qquad (2)$$

where R_o is the mass transfer rate for an individual piece at the start of the flushing operation, λ is the eigen value dependent on the Fourier series expansion solution, L is the characteristic insulation thickness for diffusion, D is the effective diffusivity and t is time. Based on a mass transfer rate obtained at any given temperature T, it is possible to predict the mass transfer rate using equations (1) and (2) at the base temperature of 90°C. To normalize the time in order to adjust for variation in operating temperature other than 90°C, the following relation is valid:

$$\begin{matrix}\text{Mass transfer}\\ \text{Time}\\ \text{at } 90°\text{C}\end{matrix} = D/Do\ \Delta t \text{ at } T, \qquad (3)$$

where Δt is the actual time period for flushing at temperature, T. Substituting equation (1) into equation (3) eliminates the characteristic constant D_o and yields,

$$\text{Time Period at } 90°\text{C} = 2^{\left(\frac{T-90}{30}\right)}\ \Delta t \text{ at } T. \qquad (4)$$

To determine the normalized rate of Inerteen removal at 90°C, the difference in mass removed over a given time period was divided by the adjusted time period at 90°C.

Pumping - The availability of 25 hertz power to run the circulating pump on the transformer made time delays in our operation somewhat inevitable. High priority demands within the plant during the retrofill operation necessitated intermittent pump interruption during the flushing operation. The circulation pump used for transporting heat during the service life of the unit provided an excellent mechanism for maintaining good fluid mixing within the silicone phase. Cooling ducts located within the winding-insulation structure provide passageways for Inerteen removal. However, good circulation is a prime prerequisite for maximizing the concentration gradients within these confined regions. If circulation ceases, then adjustments need be made to account for the decrease in mass transfer within these regions of the transformer structure. An expression based on trial and error adjustments of the raw data during periods of no circulation to data when circulation existed was found to be the followin

$$\text{Time period with pumping} = .4 \times \text{Time period without pumping}. \qquad (5)$$

The normalization techniques were applied to the retrofill data to establish a set of normalized times and rates based on the preset conditions intended for the process.

Data Normalization - Table 4 lists the results of normalizing the raw retrofill data to the data base of 90°C, fluid pumping and low levels of silicone Inerteen saturation.

TABLE 4

NORMALIZED RETROFILL DATA
(90°C, PUMPING, UNDERSATURATION)

Normalized Time (days)	Inerteen Mass Removal Rate (lb/day)	Residual Inerteen Mass (lbs)
.03	1313	313
.06	623	271
.11	234	257
.74	56	215
1.65	47	167
2.29	13.7	147
2.84	11.7	140
4.03	5.7	132
5.25	6.1	125
6.01	3.3	121
6.68	9.6	118
7.07	2.5	116
7.42	4.1	115
7.89	1.6	114
8.36	3.7	113
8.83	1.8	112
9.46	1.9	110
10.00	2.2	109
10.75	1.1	108
12.23	0.6	107

Both the rate of Inerteen removal and the residual Inerteen mass within the transformer are plotted as functions of normalized time in Figures 8 and 9. The estimate of the initial mass of Inerteen within the transformer structure is seen to impact greatly upon our interpretation of the residual mass of Inerteen versus time. However, interpretation of the Inerteen removal rate is clearly not affected by our estimate of the initial mass of Inerteen. The process of differentiation clearly eliminates the need to know the initial data base. Comparison of both the analytical and experimental results of our earlier report to the retrofill Inerteen removal rate data should shed light on the validity of our earlier mathematical model. This comparison will be made further on this report.

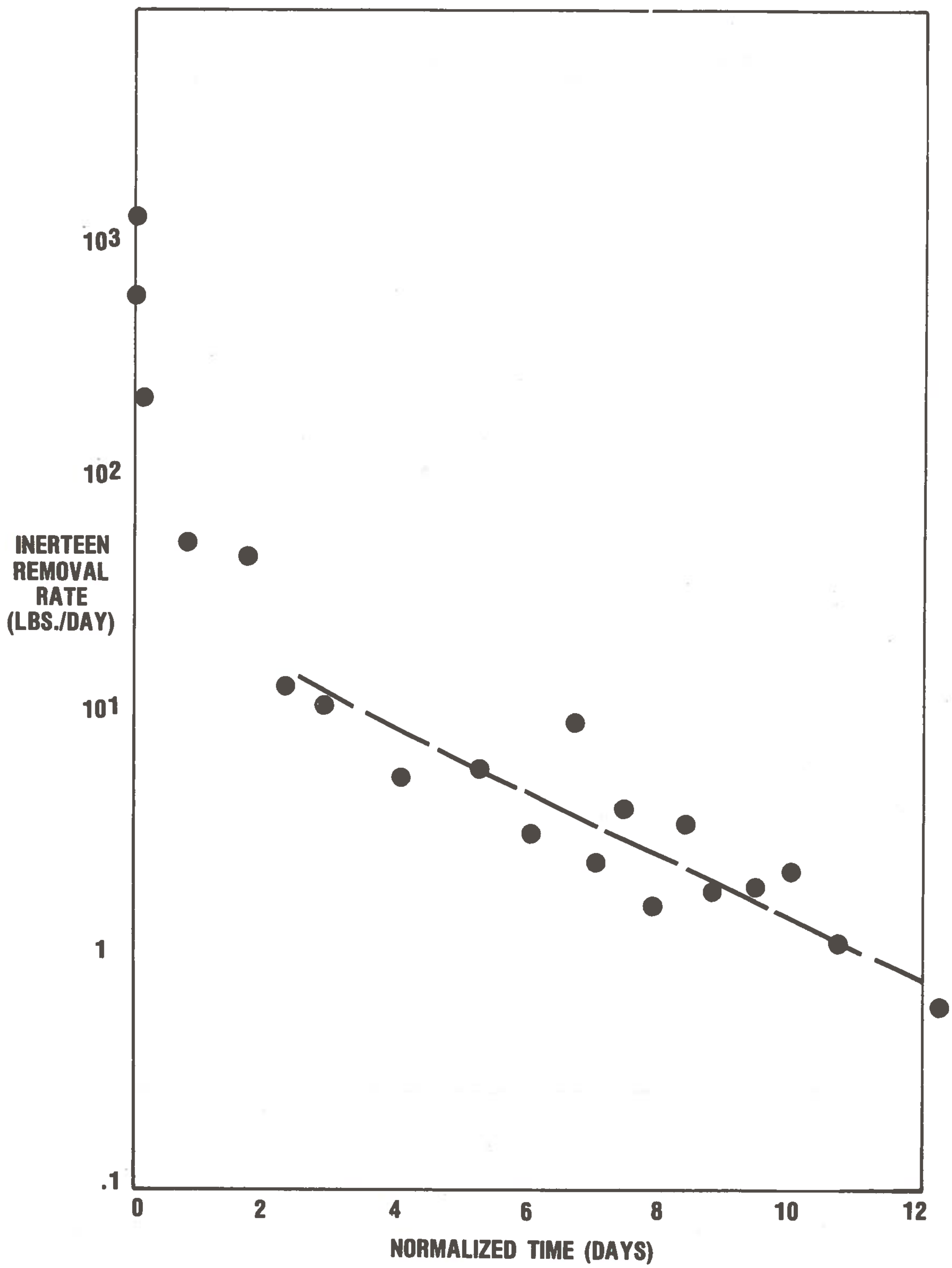

FIGURE 8. INERTEEN REMOVAL RATE VS FLUSHING TIME

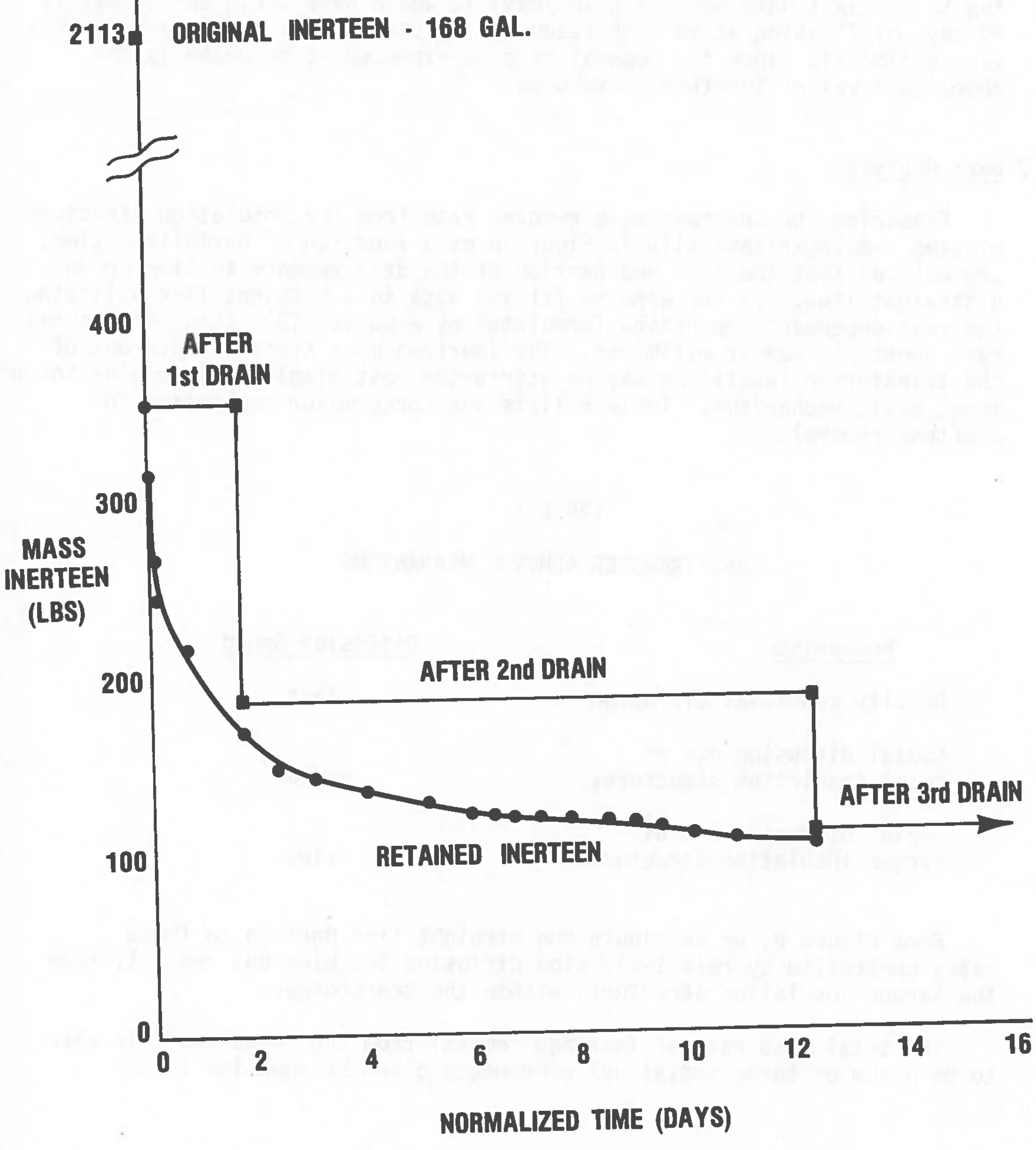

FIGURE 9. INERTEEN RESIDUAL MASS VS TIME

It is obvious from inspection of Table 4 that the rate of Inerteen removal decreases as a function of time. An optimistic estimation may be made, however, of the time required to reduce the Inerteen level to the program objective of 58 pounds. Assuming a rate of removal corresponding to our last data point (.6 lbs/day) it would have taken approximately 90 days of flushing at 90°C to reach the 58 pound level. This estimate is very optimistic since the removal rate is expected to decrease as the absolute level of Inerteen is reduced.

3.3 Data Analysis

Examining the Inerteen mass removal rate from the insulation structure plotted semilogarithmically in Figure 8 as a function of normalized time, one notices that the tail end portion of the data appears to line up on a straight line. If one were to fit the data to a straight line utilizing the rate dependent expression formulated by equation (2), then diffusional rate constants may be estimated. The Inerteen mass transfer rate out of the transformer insulation may be attributed most simply as a combination of three basic mechanisms. Table 5 lists the three major mechanisms for Inerteen removal.

TABLE 5

MASS TRANSFER REMOVAL MECHANISMS

Mechanism	Diffusion Speed
Gravity and axial diffusion	fast
Radial diffusion out of small insulation structures	medium
Radial diffusion out of larger insulation structures	slow

From Figure 8, we attribute the straight line portion to those rates controlled by relatively slow diffusion leaching out radially from the larger insulation structures within the transformer.

The total mass rate of Inerteen removal from the transformer is seen to be a sum of three individual components given by equation (2).

$$\text{Inerteen Mass Removal Rate} = \sum_{i=1}^{3} R_i \, e^{-\frac{\lambda_i D_i t}{L_i^2}} \, . \qquad (6)$$

If one were to plot log of equation 6 as a function of the normalized retrofill time, t, it is generally noticed that for large times the curve is approximated by a straight line. The reason for the straight line portion is that for large times exponential involving large rate constants decay to zero leaving only the slowest exponential as a remainder. By fitting a straight line to the last few data points by the standard least square technique, the rate constants and the initial rates may be calculated. One can then obtain values of the rate expression

$$R_1 e^{-K_1 t}, \text{ where } K_1 = \frac{\lambda_1 D_1}{L_1^2} .$$

If the above expression were subtracted from the rate data a set of residual rate data would develop.

$$\text{Residual Rate} = \text{Rate} - R_1 e^{-K_1 t} . \qquad (7)$$

By taking the next few data points for the log of the residual rate and repeating the "peeling off" procedure, the next slowest exponential parameter, K_2, may be estimated. In essence, this procedure was followed as is noted graphically in Figure 10 to determine the mass transfer rate constants, K_1's. From the Fourier series expansion, the eigen value λ may be seen to depend on an index i by the following relation:

$$\lambda_i = (2i-1)^2 \ \frac{\pi^2}{4} . \qquad (8)$$

However, for diffusional estimates the lengthy summation may be simplified to one term involving the first expression in the summation. The slope of the log of the rate data is directly related to the effective diffusivity by the following relation:

$$K_i = \frac{\pi^2}{4} \ \frac{D_i}{L_i^2} . \qquad (9)$$

Table 6 lists the rate constants determined from the "peeling off" procedure when applied to the normalized rate data.

TABLE 6

MASS TRANSFER RATE CONSTANTS VERSUS MECHANISM

K_i (days^{-1})	Significance
.307	Large sections - radial diffusion
.965	Small sections - radial diffusion
24.40	Gravity and axial diffusion

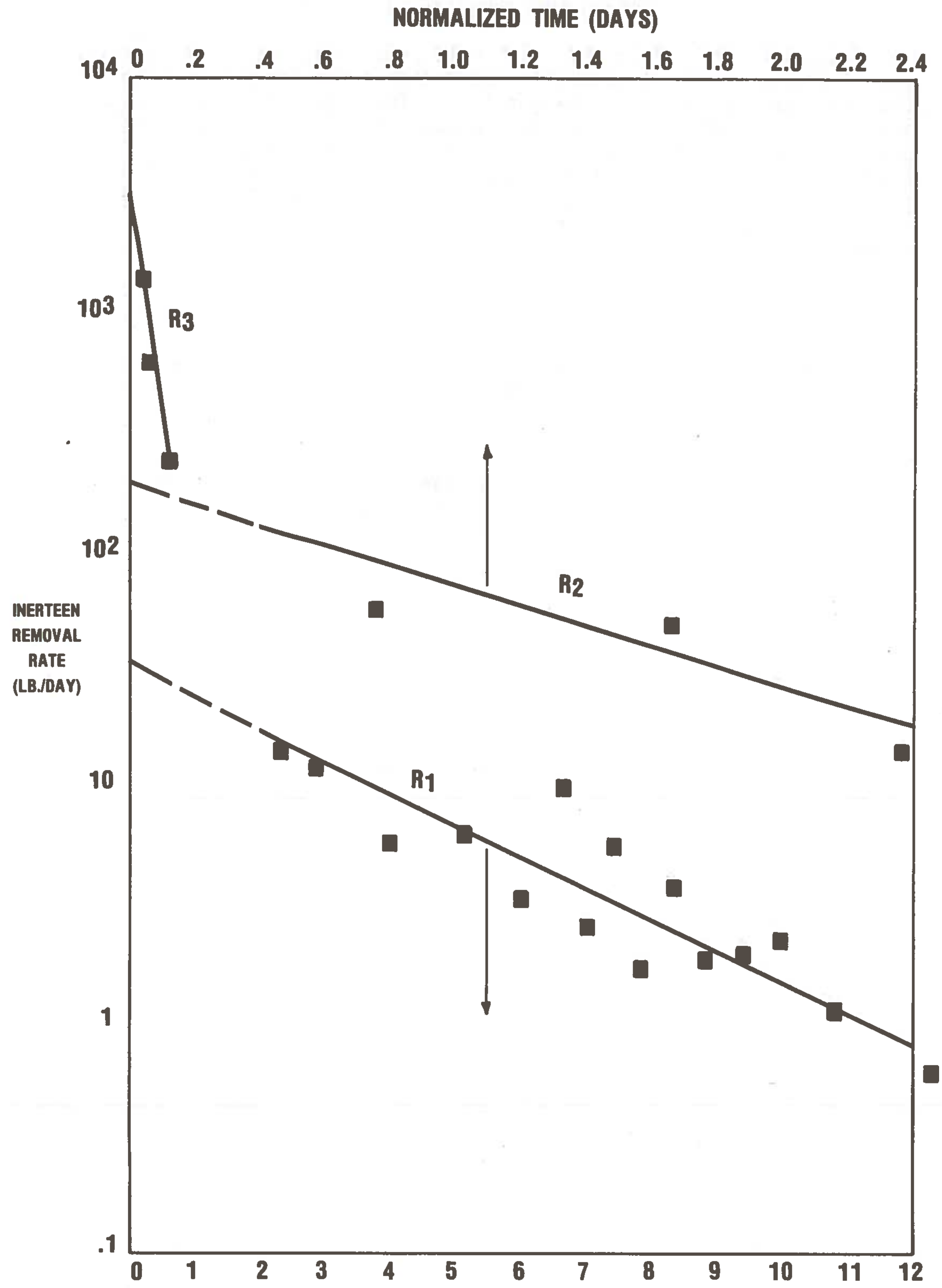

FIGURE 10. INERTEEN REMOVAL RATES VS NORMALIZED TIME

Additional information relative to the transformer unit's structure is needed to complete the estimates of the effective diffusivities. The data that is needed is the thicknesses of the insulation comprising the unit. Prior knowledge of the insulation thicknesses unfortunately was not available. The assumption that we made, in order to estimate the effective diffusivities, was that the insulation thicknesses were similar to those of our present Metroliner transformer. The rated fluid capacity of our present Metroliner transformers is approximately 165 gallons. The insulation thicknesses of these units average between 1/8" for large sections to 1/16" for small sections of insulation.

Comparison between diffusivity estimates based on equation (9) and our previously determined values shed confidence not only on our experimental data but also on the predictions made by the mathematical model. Table 7 lists the comparison between the two methods for estimating the effective mass diffusivity of Inerteen out of the transformer insulation into the silicone flushing solvent.

TABLE 7

COMPARISON BETWEEN ESTIMATED DIFFUSIVITIES FROM PREVIOUS WORK AND THOSE CALCULATED FROM PRESENT RETROFILL DATA

K_1(days - 1)	L_i(inch)	Mechanism	D_i (90°C) Retrofill	D_i (90°C) Previous
.307	.125	large - radial	8×10^{-5}	3×10^{-5}
.965	.0625	small - radial	6.4×10^{-5}	3×10^{-5}
24.36	.125	axial - gravity	6.4×10^{-3}	3×10^{-3}-3×10^{-2}

From Table 7, excellent agreement is seen between the diffusivity coefficients estimated experimentally from laboratory model studies summarized from our previous studies and those measured from the present retrofill data. To appreciate the significance one must consider the assumptions used in both techniques for estimating these coefficients. To briefly list the assumptions made, they were: analytical solution simplification, unknown insulation thicknesses, temperature dependence, solubility effects, normalization techniques, unknown composite structure within unit and finally the uncertainty of the fluid flow pattern within the transformer.

From the rate constants obtained by the "peeling off" method, the rate expression given by equation (6) may be integrated to obtain the mass contributions of Inerteen by the various rate mechanisms. From Table 4, 349 pounds of Inerteen remained within the unit after the initial drain.

However, some of the residual Inerteen was loose within the structure and should not be included with the mass of imbedded Inerteen. A plot of the percent Inerteen measured in the silicone during the initial flush, Figure 10, indicated by extrapolation to zero time that approximately 3.5 percent of the total mass of added silicone was Inerteen lying loose within the transformer before fill. Since 1090 pounds of silicone was added to the transformer during the first flush, approximately 38 pounds of Inerteen was loose within the unit after the initial drain. Therefore, it is assumed that only a total of 311 pounds of Inerteen was initially imbedded or entrapped within the composite structure of the transformer prior to the initial flush.

If we integrate the Inerteen rate equation (6), the total mass may be seen to be expressed as a function of time by

$$\text{Mass of Inerteen Removed from Composite} = M_o + \sum_{i=1}^{3} M_i \exp(-K_i \times t), \qquad (10)$$

where M_i is the mass contribution of Inerteen by mechanism i, M_o is the final residual mass of Inerteen that cannot be removed from the transformer by the above described mechanisms of mass removal.

A multiple linear regression technique was used to estimate the mass contributions by each of the mechanisms of mass removal. Table 8 lists the results of the fitting procedure.

TABLE 8

INERTEEN MASS REMOVAL CONTRIBUTIONS

M_i (pounds)	Mass Fraction	Mechanism
107	.34	core, wood, questionable?
77	.25	gravity, axial
77	.25	radial, small pieces
50	.16	radial, small pieces

A multiple correlation coefficient of .9987 was realized from the fit. A value this close to unity indicates that the three step mechanism adequately describes the retrofill phenomena. The residual mass of 107 pounds of Inerteen remaining within the unit after retrofill is the least trustworthy parameter in the analysis. The reason for this as stated before comes from method of differences for assessing the mass of Inerteen remaining within the unit. However, a few additional remarks may be made. First, no knowledge of the mass of Inerteen that is bound up within the core laminates has been made. Furthermore, diffusion

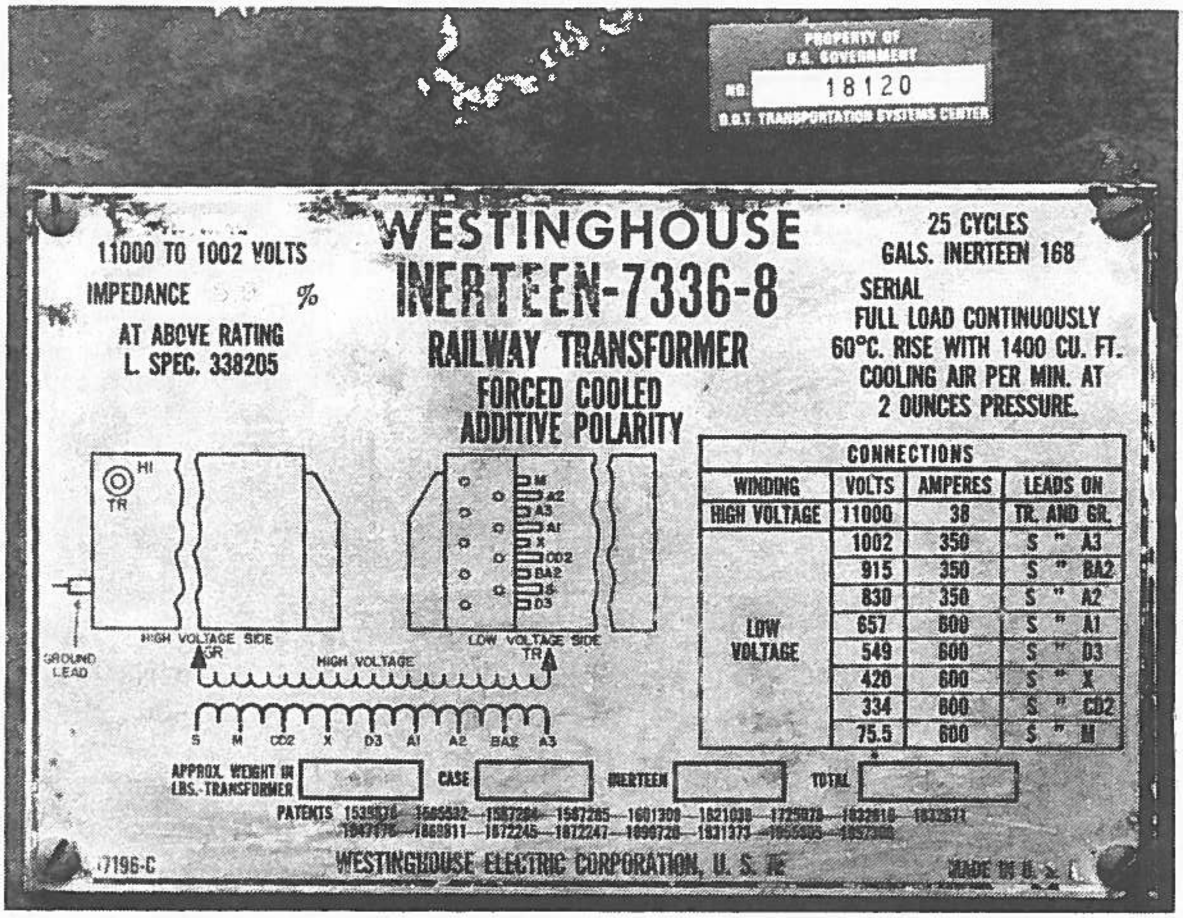

FIGURE 11. PHOTO-NAMEPLATE OF TRANSFORMER

coefficients out of dense structures such as maple have not been measured. These diffusional times may be extremely long. Finally, the structure of the transformer is ill defined and therefore, estimation of areas for possible Inerteen entrapment could not be made.

If we compare the mass of Inerteen removed by gravity and axial effects to the total mass of Inerteen removed from the start of the first flush, we find that gravity and axial effects account for 38% of the Inerteen removed. This removal mass is in close agreement with our finding of 30% removal by gravity within the first 24 hours of our model studies.

4. ELECTRICAL AND THERMAL TESTING OF TRANSFORMER BEFORE AND AFTER RETROFILLING

4.1 Background and Objective

Normally the intent of a factory test program is to impose tests which qualify a transformer for years of useful service. Usually the first unit of a given design gets design tests as well as routine tests.

Design tests include impulse tests which impose lightning type voltages in excess of what the unit should see in service and thermal tests which cause the unit to carry currents which will heat up the conductor and liquid to temperatures as great as it would experience in service. If the temperatures attained in the heat run exceed those known to be safe for the insulation employed the unit has failed the test.

Routine tests are made on the first unit and also on every other unit. These tests and their purpose are shown below.

Test	Purpose
Resistance Measurement	To be sure the correct conductor has been used in each winding and to check the continuity of each winding.
Ratio	To insure that each winding has the correct number of turns.
Percent Impedance	To insure that proper dimensions are maintained throughout the coil so that voltage regulation and short circuit strength can be predicted.
Core Loss and Exciting Current	To insure that the core steel is of the correct material, properly manufactured and that the unit can hold full operating voltage.

Test	Purpose
Hi-Pot Test	To insure that windings are insulated from each other and from ground.
Induced Test	Checks lead in terminal for several times normal to ground and checks for several times normal voltage turn to turn.

The Westinghouse unit (see Fig. 11 for copy of nameplate) which was tested was over thirty years old and had been removed from service prior to its selection for this project. The tests agreed to were therefore of limited severity from a dielectric standpoint so as to preserve the unit for the thermal comparison with Inerteen and then with silicone. Our objective of preserving the unit for the thermal comparison was accomplished whereas a more severe type of test program could very well have caused a dielectric failure in a unit of this vintage.

4.2 Test Program

The tests decided upon for the project together with specific ANSI Standard reference were as follows:

Test	ANSI Std. Reference
Transformer Voltage Ratio	C57.12.90 Section 5
25 HZ No Load Core Loss	C57.12.90 Section 4.3
25 HZ Exciting Current	C57.12.90 Section 4.4
Room Temperature Resistance	C57.12.90 Section 2
Impedance	C57.12.90 Section 4.5.1
Temperature Rise Tests	C57.12.90 Section 6

The purpose of these tests is the same as is tabulated under "Background and Objective". The Hi-Pot test and the induced test were deleted because they stress the insulation at several times what it would be stressed at operating voltage and we did not want the unit to fail.

An estimate of the resistance of the entire high voltage winding, the entire low voltage winding and the 657 volt tap of the low voltage winding was available to us from some old Westinghouse heat run data on similar transformers. By checking the nameplate (copy attached) of the unit we determined what terminals we should connect to in making these readings and wrote appropriate instructions to the shop.

The ratio on the 11,000 to 1002 connection calculates by dividing 1002 into 11,000 to obtain 10.978. The ratio on the 11,000 to 657 connection calculates 16.743. In the test the ratio is measured by a data scan ratio bridge. In this system we impose a known voltage on the high side and read ratio directly.

The percent impedance which we test for is best clarified by the formula below:

$$\%IZ = \frac{IZ}{V} \times 100 \text{ where}$$

I = rated current
Z = impedance of the transformer being tested
V = rated voltage.

Usually the voltage does not change and the ohmic impedance at one frequency never changes. Therefore, if the current doubles so does the % IZ. As a convenience we usually multiply ratios of volt amperes to find how the percent impedance changes. Thus in our particular case:

N.P.* %IZ at 418 KVA = 5.9%

Our measurement was made on 11,000-1002 Volt Connection

N.P.* Low Voltage Current on this connection - 350 amperes

New KVA = 1002 x 350/1000 = 350.7

$$\text{New calculated \% IZ} = \frac{350.7}{418} \times 5.9 = \underline{4.95\%}\ .$$

Any transformer has internal losses which are not available to the load. A small portion of these losses are generated in the core and are called no load losses. The major portion of the internal losses are load losses which means they are present inside the transformer when it is loaded. For the heat run comparison we decided to simulate only the load losses. This means that both heat runs were made with a short from S to A1, and enough voltage on the primary to cause 35.8 amperes to flow. Under this condition the rated current of 600 amperes flows in the low voltage winding.

In the first part of the heat run the temperature of the liquid is monitored via thermocouples until it stabilizes. In this way the rise of the liquid over ambient temperature is obtained. Next, each winding carries rated current until stabilization. The unit is then shut down and the resistance of the winding measured as soon as possible and then every subsequent minute until ten readings are obtained. A curve back to time zero is then plotted. From this curve the resistance at time zero is obtained and, in turn, the temperature at time zero. The temperature at time zero is, of course, the estimated winding temperature just prior to shutdown.

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*N.P. = nameplate.

The attached photo (Fig. 12) shows the heat run set up for this particular test. The photo shows the transformer and the blower which was provided to cool the unit. The air supply called for on the nameplate was 1400 CFM. The blower available for this heat run could not be adjusted below 2000 CFM and for the record that is what was supplied for this test.

4.3 Test Results

The test results are tabulated in Tables 9 and 10 of this report.

Reference to Table 9 reveals differences in core loss and exciting current between the Inerteen filled and silicone filled readings. Also Table 12 indicates that the 25 Hz percent impedance had to be calculated from 60 Hz data in the silicone filled case. This was accomplished as follows:

$$60\ \text{Hz}\ \%\ IZ = 10.09 \qquad 60\ \text{Hz Watts} = 8680 = I^2R$$

$$\%\ IR = \frac{IR}{V} \times 100 = \frac{I^2R}{V.I} \times 100 = \frac{I^2R}{KVA \times 10}$$

$$\%\ IR = \frac{8680}{351 \times 10} = 2.47$$

$$\%\ I\ x\ @60\ \text{Hz} = \sqrt{10.09^2 - 2.47^2} = 9.78$$

$$\%\ I\ x\ @25\ \text{Hz} = \frac{9.78 \times 25}{60} = 4.08$$

$$\%\ IZ\ @\ 25\ \text{Hz} = \sqrt{4.08^2 + 2.47^2} = 4.77.$$

Where I = Rated Current
R = Transformer Winding Resistance
Z = Transformer Impedance
X = Transformer Reactance
351 = KVA of Measurement Connection.

4.4 Conclusions Relative to Electrical and Thermal Testing

As previously stated this transformer was over thirty years old and had been removed from service prior to this project. The tests agreed to were of limited severity from a dielectric standpoint so as to preserve the unit for the thermal comparison of the unit with Inerteen and then with silicone.

The unit did not show any definite ill effects from the tests that were made. The highest voltage imposed was 11,000 volts. Since this is only operating voltage no conclusions should be drawn relative to the unit's adequacy for low overvoltage tests or impulse voltage tests.

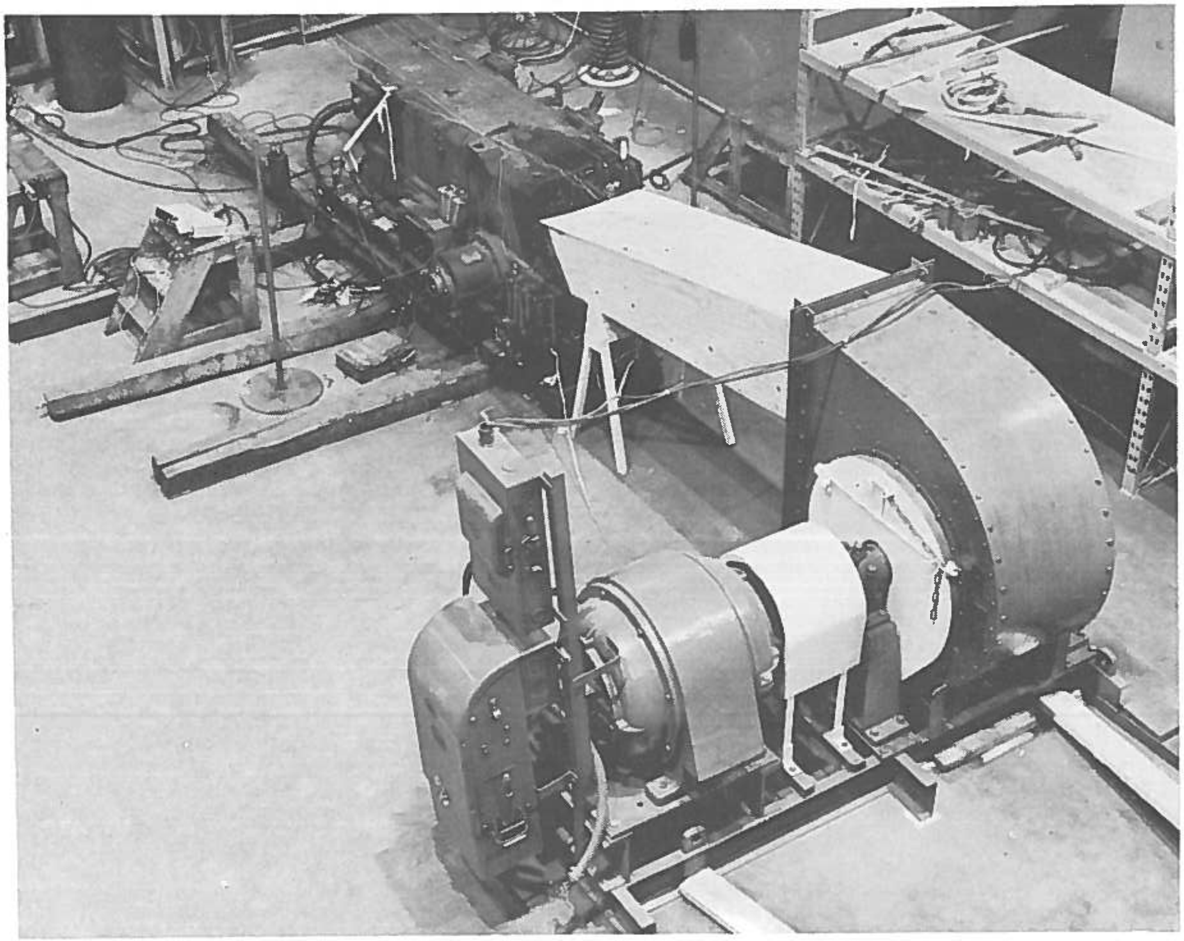

FIGURE 12. PHOTO-TRANSFORMER DURING HEAT RUN

TABLE 9

ELECTRICAL TEST DATA ON WESTINGHOUSE RAILROAD TRANSFORMER S/N 4082271

Test or Test Element	Calculated Value If Available	Test Value Filled With Inerteen	Test Value Filled With Silicone
1. Transformer Voltage Ratio Test			
a. 11,000-1002 Connection	10.978	10.956	10.954
b. 11,000-657 Connection	16.743	16.707	16.703
2. 25 Hz No Load Core Loss Test in Watts			
11,000-1002 Connection		1615	1831
3. 25 Hz Exciting Current 11,000-1002 Connection Expressed as a Percentage of Rated Current of 350 Amperes		4.36	5.91
4. Room Temperature Resistance - Ohms	Temp = 25°C	Temp = 23.1°C	Temp = 21°C
a. High Voltage Winding	4.0	4.108	4.068
b. Low Voltage 1002 V Connection	.030	.02855	.02933
c. Low Voltage 657 V Connection	.014	.01482	.01442
5. Percent Impedance, 25 Hz - 11,000 to 1002 Volt Connection, 350.7 KVA	4.95	4.73	Measured at 60 Hz 10.09 With 8680 Watts Load Loss. Change to 25 Hz = 4.77

The silicone retrofilled unit ran hotter than when filled with Inerteen, while a temperature differential of 9.7°C was observed. Reference to Table 10 reveals differences in the liquid correction, the high voltage winding rise and the low voltage winding rise when comparing the Inerteen filled and the silicone data.

4.5 Discussion of Results

The change in core loss and exciting current shown in Table 9 would not normally be expected. Things that explain this kind of change are:

1. A shorted turn in the transformer which call for more than normal current and loss but would not be serious enough to cause complete failure. The slight decrease in ratio shown in Table 9 makes this a remote possibility.

2. Due to age of transformer the core joints may have suffered in movement leading to higher exciting current and loss.

3. Movement of the transformer may have caused a second core ground. Two core grounds create a loop for circulating current and additional loss.

The change in the liquid temperature correction is probably due to a thermocouple malfunction. We would tend to believe that the 2.4° shown for silicone is the correct one. We could not, however, verify this contention since it was impractical to repeat the Inerteen run once the unit was filled with silicone.

We would not tend to attribute the changes in winding rise shown in Table 10 to any unusual characteristic of silicone. The more likely cause for the deviation is related to the very short thermal time constant which the windings in transformers of this size tend to have. This means that the first reading of resistance has to be taken very fast in order to achieve accuracy in extrapolating to time zero. This is very difficult to accomplish in most cases because safety rules require power to be disconnected before personnel can closely approach the unit. From our experience we would tend toward believing the 17.5°C rise of the high voltage winding over liquid and the 15.5°C rise of the low voltage winding over the liquid.

5. SUMMARY OF RESULTS

The objective of this program was to assess the effectiveness of retrofilling an askarel transformer supplied by the United States Department of Transportation, with a 50 centistokes silicone fluid. The work tasks included an assessment of the electrical and thermal characteristics of the transformer before and after retrofilling as well as an in-depth evaluation of the retrofill concept.

TABLE 10

THERMAL TEST DATA ON WESTINGHOUSE RAILROAD TRANSFORMER S/N 4082271

Test or Test Element	Calculated Value If Available	Test Value Filled With Inerteem	Test Value Filled With Silicone
Heat Run Data - Short S to Al. Runs made at 60 Hz. Current in high voltage held at 35.8 amps to get 600 amps in low voltage. Liquid into cooler defined as top liquid. Liquid out of cooler defined as bottom liquid. During run pump operating at 323 volts 25 Hz, single phase.			
a. Ambient Air Temperature		31.0°C	30.5°C
b. Top Liquid Rise Over Ambient, °C		40.6	52.5
c. Correction = $\frac{\text{Top Liquid-Bottom Liquid}}{2}$		0.2	2.4
d. Effective Liquid Temperature, °C		71.4	80.6
e. Effective Liquid Rise Over Ambient, °C		40.4	50.1
f. High Voltage Winding Rise Over Liquid, °C		17.5	12.7
g. High Voltage Winding Rise Over Ambient, °C		57.9	62.8
h. Low Voltage Winding Rise Over Liquid, °C		5.8	15.5
i. Low Voltage Winding Rise Over Ambient, °C		46.2	65.6

As a result of this work it has been shown that:

1) The retrofilled transformer did not show any ill effects from the electrical tests that were made. The highest voltage imposed was 11,000 volts. Since this is only operating voltage no conclusions should be drawn relative to the unit's adequacy to withstand low frequency overvoltage or impulse voltage.

2) Thermal tests on the retrofilled transformer revealed that the unit ran 9.7°C hotter than when filled with Inerteen. It would have been higher had the cooler been cleaned prior to the Inerteen test.

3) Of the approximately 2113 lbs. of Inerteen initially in the transformer all but 107 lbs. were removed by draining and subsequent flushing with silicone. The composition of the Inerteen as determined by gas chromatography was 65% polychlorinated biphenyl (PCB) and 35% trichlorobenzene(TCB).

4) The equivalent of 288 hours (12 days) of continuous flushings with silicone at 90°C was required to achieve the residual of 107 lbs. of Inerteen.

5) A multiple regression technique was used to estimate the amounts of Inerteen retained within the various structures of the transformer after draining and prior to flushing. Seventy-seven lbs. was retained and subsequently removed by flushing from the insulation system in the axial direction; 77 lbs. was retained and subsequently removed in the radial direction from relatively thin sections (.062") of the insulation structure; 50 lbs. was retained and subsequently removed in the radial direction from thicker sections (1/8"); 107 lbs. which remained was probably trapped in the core and thick sections (greater than 1/8") of pressboard, wood, etc.

6) Based on the Inerteen removal rate at the 288 hour mark it would have required <u>at least three months</u> of additional flushing to reach the program objective of 58 lbs. A more realistic estimate might be as long as one year if one considers that the removal rate continues to drop as the percent Inerteen retained decreases.

7) Normalization techniques have been developed for interpreting the retrofill procedure and can be used for future retrofill studies.

8) The mathematical model developed by General Electric in earlier studies as a predictive tool for estimating times to reach predetermined levels of PCB by the drain and flush method with silicone has been validated as a result of this study.

9) A major problem identified under this program was the realization that relatively large amounts (15%) of Inerteen remain in the transformer after a hot drain.

10) One of the problems in reaching predetermined levels of PCB after a drain and flush procedure is lack of <u>exact</u> knowledge of the initial amount of PCB in the transformer.

11) The ratio of polychlorinated biphenyl (PCB) to trichlorobenzene (TCB) as they were removed from the insulation system into the silicone did not change with time. There was therefore no preferential leaching.

6. CONCLUSIONS

1) The raliroad transformer studied under this program when retrofilled with silicone reached higher temperatures under constant load conditions when compared to Inerteen. Thus the insulation life of some transformers may be reduced if the units are not operated at reduced level after retrofilling.

2) While the retrofilled transformer showed no ill effects from the modest electrical testing it must be remembered that the tests performed were specifically chosen to assure electrical integrity. No low frequency overvoltage or impulse testing was done. Electrical tests on models and components done outside this program by General Electric indicate that askarel transformers retrofilled with silicone would have reduced dielectric integrity. The reduction is due to the following factors.

   a) Substantially lower positive impulse strength, particularly in creep, could cause problems in transformers where the designs did not provide for this weakness.

   b) Increased electrical stress at the interface of the two phase liquid region if all the askarel isn't flushed out of the transformer.

3) Work done under this program reinforces our generalized conclusion reached as a result of work done prior to this contract that:

   While transformers specifically designed around the characteristics of silicone fluid appear to be logical successors to askarel units, the two fluids are not one-to-one substitutes in existing transformers. Reliability and load capacity of an askarel transformer retrofilled with silicone may be decreased. An in-depth analysis of individual designs would be done prior to retrofilling.

7. RECOMMENDATIONS

As a result of work to date, a number of follow-up programs or investigations suggest themselves in order to more fully assess the concept of retrofilling with silicone. These programs must address the safety and reliability of the retrofilled transformer. The environmental impact of retrofilling is also of concern but outside the scope of this work.

Safety

Silicone fluid is presently being offered as a replacement for the heretofore conventional askarel fluid in new railroad transformers. The flammability characteristics of the 50 centistokes silicone is close to askarel and essentially equivalent from a safety point of view. It should be remembered however that silicone fluid is a polymeric material and the selection of a 50 centistokes material is a trade-off between flammability and heat transfer characteristics. By way of example the use of a higher viscosity (and thus higher molecular weight) silicone would result in improved flammability characteristics and worsened heat transfer characteristics. Fortunately transformers designed for use with silicone exhibit no increase or decrease in viscosity or molecular weight over the life expectancy of the transformer. This is essential if the flammability and heat transfer characteristics are to remain constant.

Problem Definition

It is of concern that the retrofilling process resulting in a mixture of polydimethylsiloxane and residual askarel in transformers may provide a source of potential acid catalysis leading to marked increases or decreases in the molecular weight and viscosity of the silicone fluid. An increase in viscosity could result in poorer heat transfer characteristics and higher temperatures. Should the molecular weight increase to the point of gel formation a catastrophic failure might result. A reduced molecular weight might result in progressively worsening flammability characteristics and eventually to a point where it no longer fits the National Electric Code standard for "High Firepoint, Liquid Transformers".

There are two possible routes for acid catalysis to occur in retrofill transformers. First, arcing of mixtures of silicone and chlorocarbon does produce some hydrogen chloride. The relation of the concentration of chlorocarbon to arc energy and the arc duration to the amount of hydrogen chloride produced is not known. Nor is it known whether the conditions in transformers --presence of paper, water from paper degradation and temperature--will result in the hydrogen chloride formed catalyzed equilibration or reversion.

Second, many askarel compositions contained tetraphenyl tin. Over the years this may have reacted with arc former hydrogen chloride to form various phenyl tin chlorides--organic derivatives of $HSnCl_4OH$. While it is not definitely known that if these Lewis Acids are present in a transformer along with paper, water, etc., they would cause a reversion and degradation of the liquids, the possibility does exist.

The possibility appears to exist that blends of silicone with small amounts of chlorocarbon (especially old askarel containing tin compounds) in transformers could result in serious chemical degradation of the silicone. Depending on the condition, degradation could lead to equilibration with loss of end groups to produce gel, or to reversion to low molecular weight fragments which would increase the fluid flammability.

With the above facts in mind it is recommemded that the following work be done:

Tasks

1) Determine the effect of HCl, H_2O and Sn on the viscosity of 50 cs silicone fluid as a function of time and temperature.

2) Develop mathematical model for predicting viscosity changes of silicone for any given condition of time and temperature in presence of HCl, H_2O and Sn.

3) Determine viscosity changes in silicone that occur in model structures (which have been retrofill treated - askarel and silicone) under specific thermal and corona conditions.

4) Repeat 3 with a specific transformer design.

5) Relate changes in silicone viscosity to changes in flammability and/or heat transfer characteristics in 1 through 4.

6) Develop model to predict flammability characteristics of silicone in retrofilled unit as a function of service, life and conditions.

Reliability

One of the major shortcomings of silicone relative to conventional askarel fluid is its weakness in positive impulse strength, especially in creep. In those transformers where creep distances are not adjusted to account for this discrepancy, the reliability suffers.

It is recommended that no transformer be retrofilled with silicone without a thorough knowledge of design margins, insulation system and creep distances. It is further recommended that the manufacturer be consulted prior to retrofilling to identify potential creep problems on a case by case situation. Additional laboratory creepage measurements might be necessary so that the manufacturer can be supplied with a data base relative to positive impulse creep in silicone fluid.

8. APPENDIX A

DETERMINATION OF RATIOS OF PCB/TCB DURING FLUSHING

OBJECT OF INVESTIGATION:

To characterize the askarel (Inerteen 7336-8) from a railroad transformer and to determine the change, if any, in the composition during the silicone oil flushing.

METHOD OF INVESTIGATION:

Appropriate dilutions of the Inerteen along with unknown mixtures of aroclors (PCB) and trichlorobenzene (TCB) were injected into an electron capture gas chromatograph and compared visually. Quantitative determination of the PCB/TCB concentrations was also performed by comparisons against known standards.

RESULTS:

The Inerteen is most similar to a mixture of Aroclor 1254 and trichlorobenzene (See Figures A-1 and A-2).

	% PCB	% TCB	PCB/TCB Ratio
Inerteen Composition	64.9	35.1	1.85
Final sample first flush			1.78
98 hrs. of the second flush			1.88
168 hrs. of the second flush			1.95
214 hrs. of the second flush			1.86
264 hrs. of the second flush			1.87.

CONCLUSIONS:

In comparing Figures A-1, A-2, and A-3, it is obvious that the Inerteen is a mixture of Aroclor 1254 and trichlorobenzene.

The above quantitative results indicate essentially no change in the Inerteen PCB/TCB ratio during the flushings.

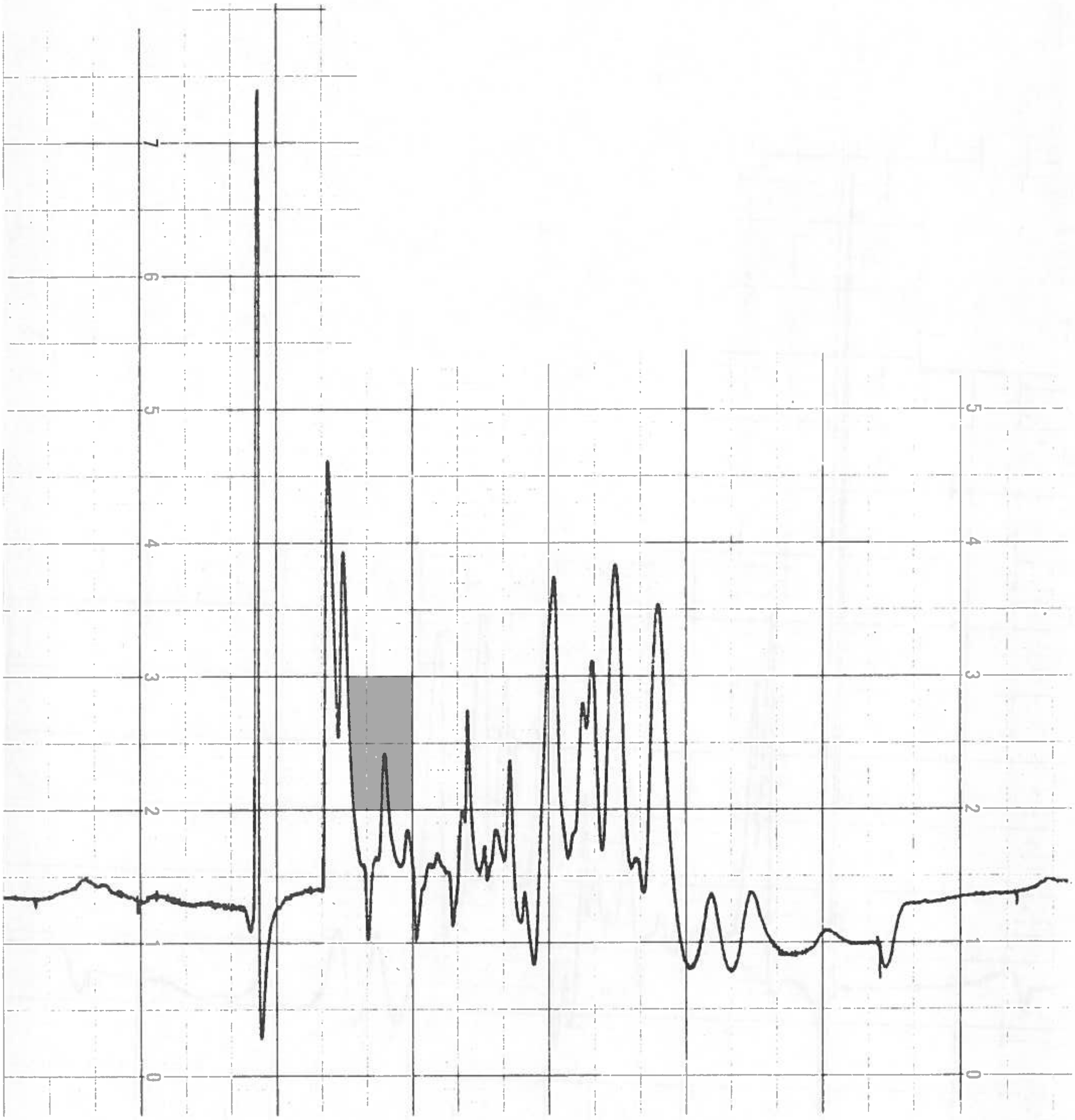

FIGURE A-1. CHROMATOGRAM OF: 50% AROCLOR 1254
50% TRICHLOROBENZENE

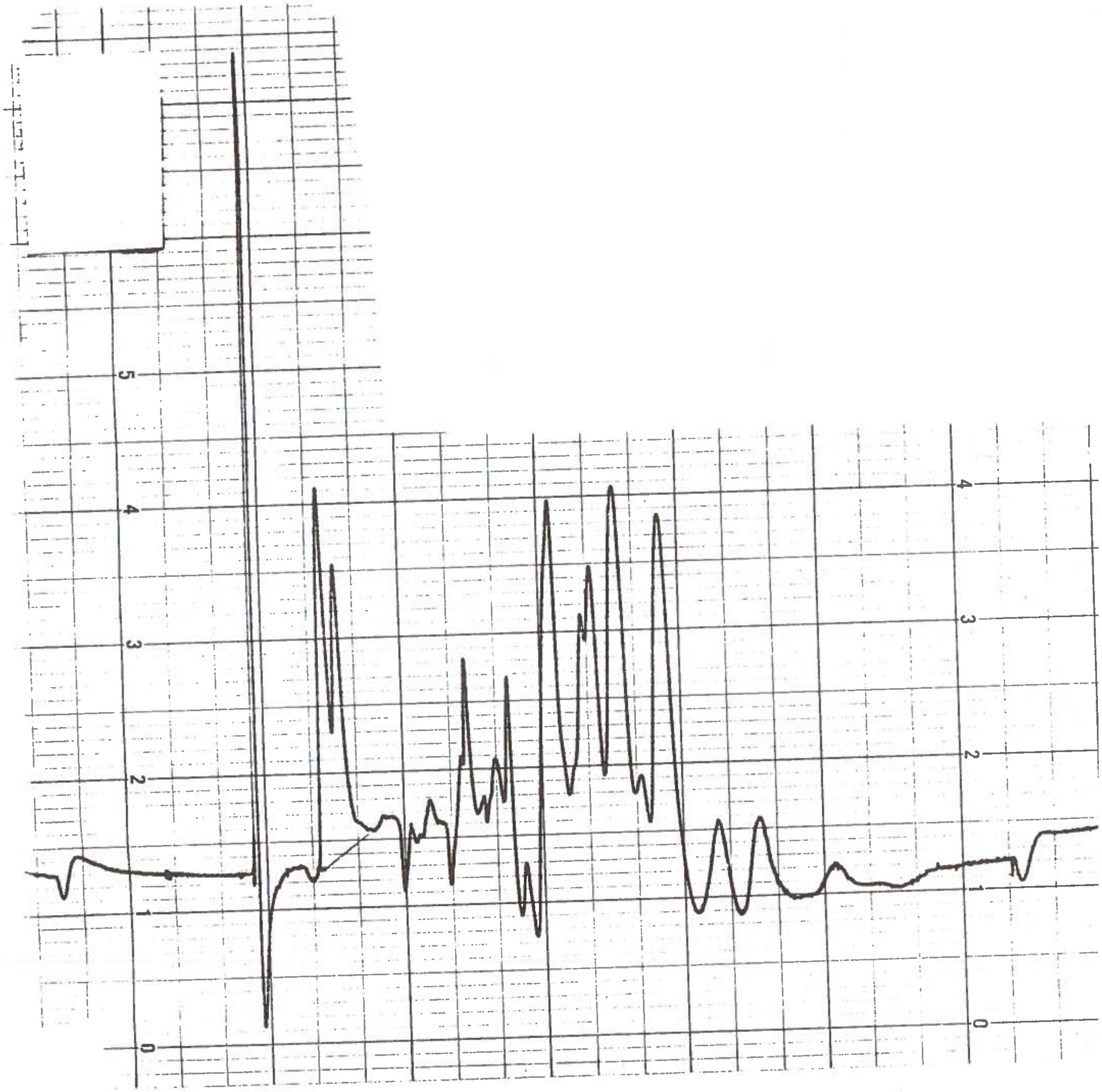

FIGURE A-2. CHROMATOGRAM OF ASKAREL FROM WESTINGHOUSE UNIT BEING TESTED

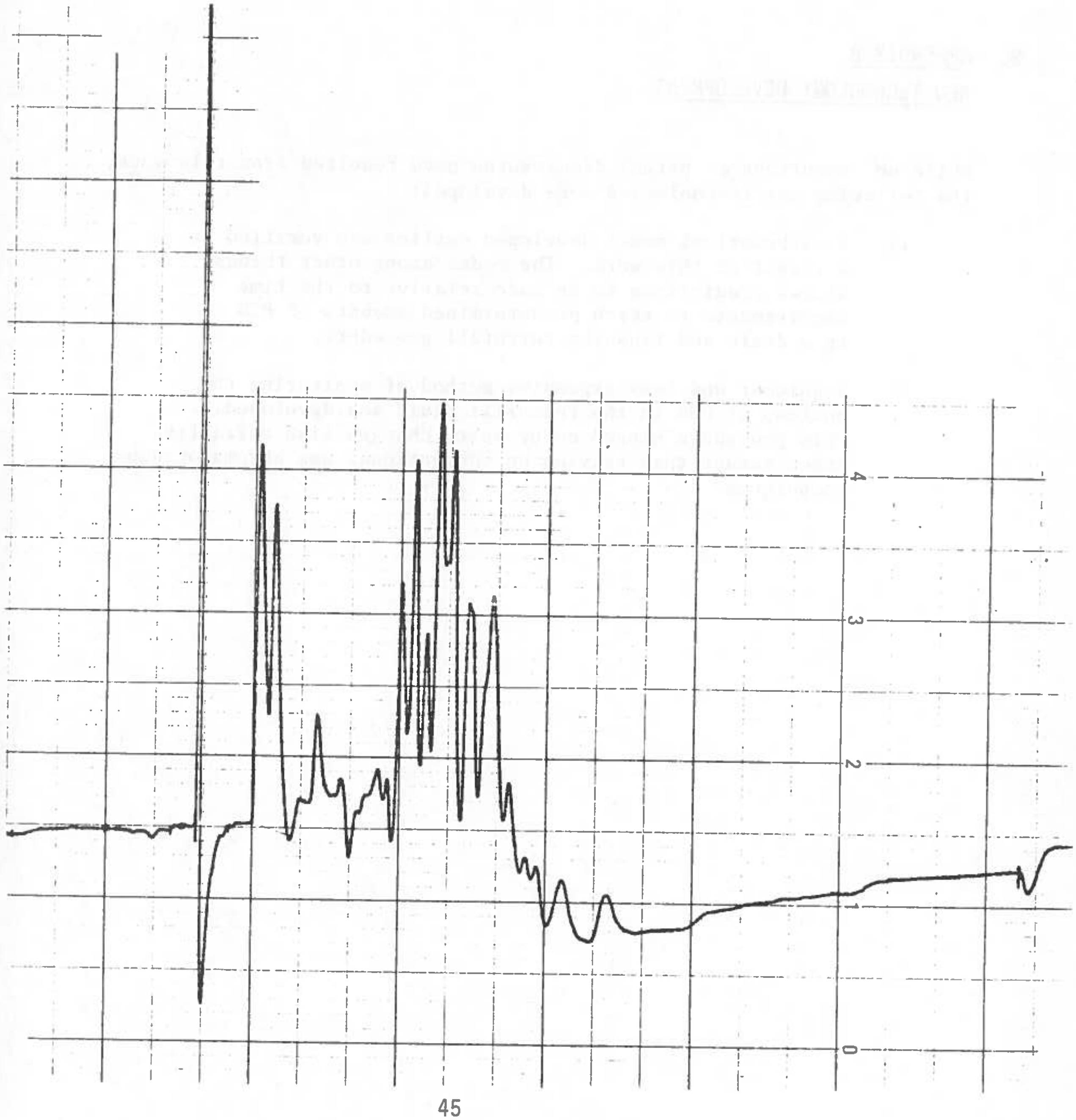

FIGURE A-3. CHROMATOGRAM OF: 70% AROCLOR 1242
30% TRICHLOROBENZENE

9. APPENDIX B

NEW TECHNOLOGY DEVELOPMENT

While no inventions or patent disclosures have resulted from this work, the following new technologies were developed:

1) A mathematical model developed earlier was verified as a result of this work. The model among other things allows predictions to be made relative to the time requirements to reach predetermined amounts of PCB in a drain and flushing retrofill procedure.

2) A quicker and less expensive method of monitoring the buildup of PCB in the retrofill fluid was developed. This procedure hinged on property changes like refractive index rather than relying on conventional gas chromatography techniques.

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