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TRANSFORMER TECHNOLOGY^{MAG}

TRANSFORMER TECHNOLOGY ^{MAG}

Transformer Lifeblood: Oils & Fluids PART II

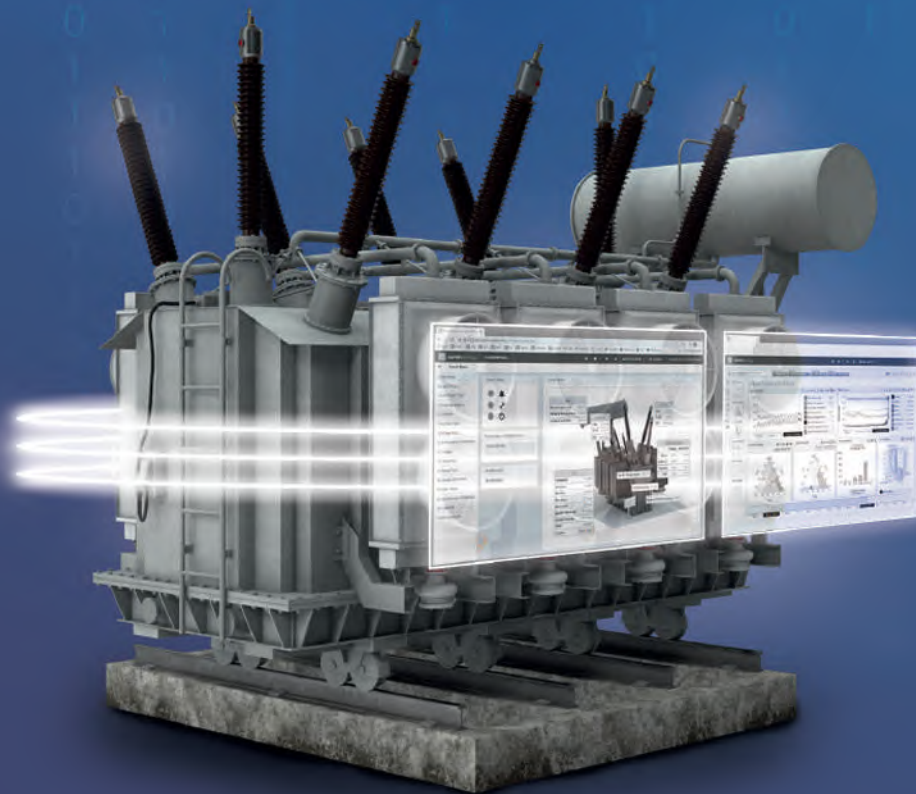
Interview with **Prabhat Jain** CEO-CTO of **Virginia Transformer Corp**
Insulating Liquids: The Lifeblood of Transformer Reliability
The Data Behind the Numbers: **IEEE C57.104™-2019 DGA Interpretation Guide**

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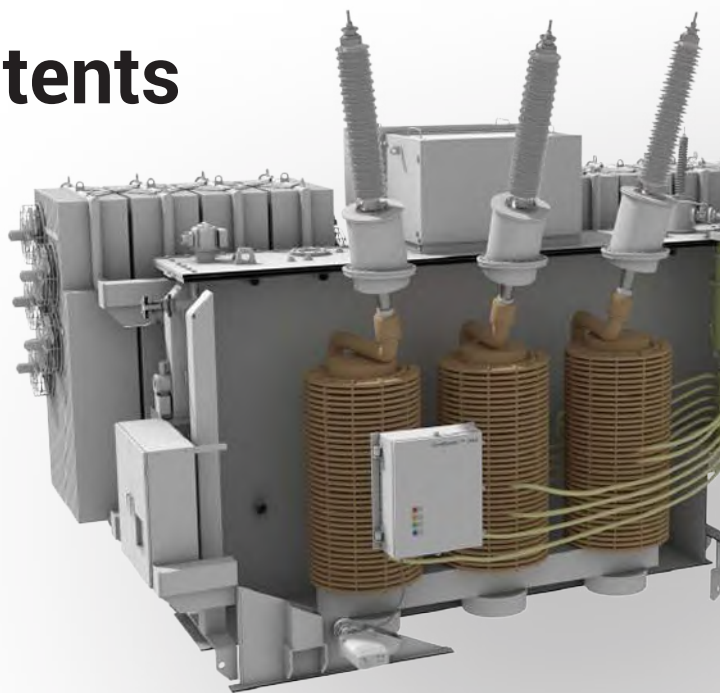
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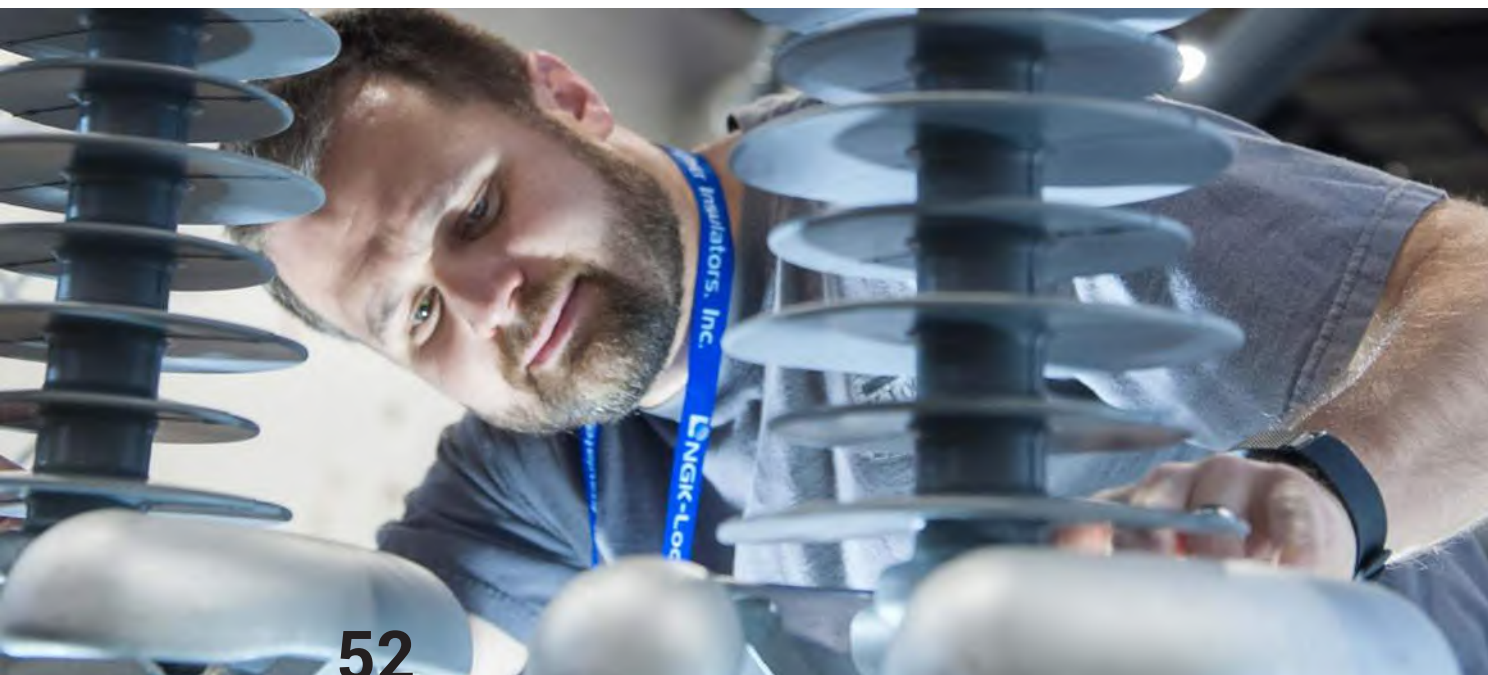
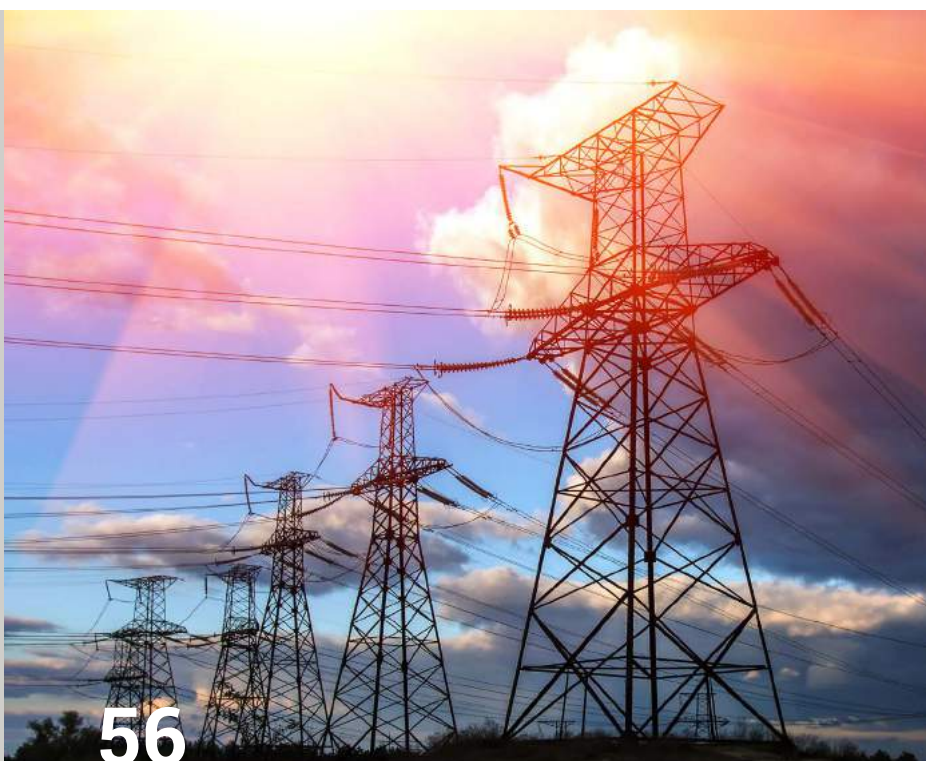
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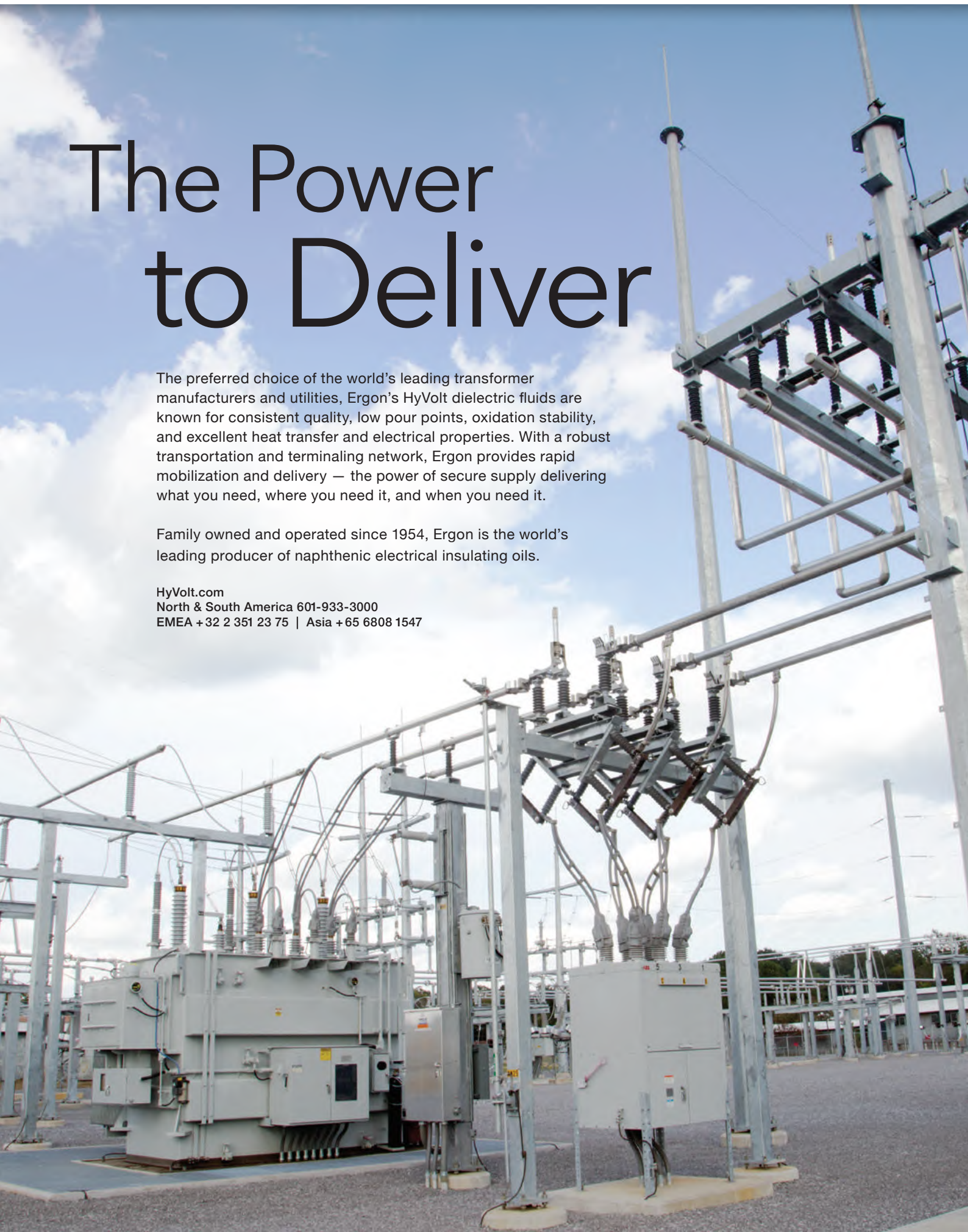
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Editors

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Editor in Chief

Alan M. Ross, CRL, CMRP

Associate Editor in Chief and Chair of the Technical Advisory Board

Corné Dames

Independent transformer consultant

Technical Advisory Board Member

Edward Casserly, PhD

Senior Scientist, Transformer oils

Maria Lamorey

Industrial OEM manufacturing

Contributing Editors

Diego Robalino, PhD, PMP

IEEE Senior Member

Alan Sbravati, ME, MBA

Transformer insulating materials

Marco Tozzi, PhD

Diagnostics and asset monitoring

Curtus Duff

Power transformer design

Traci Hopkins, IEEE Member

Transformer Condition Assessment

Jon Trout, PE

Electric utility

Graphic design

BE Konzept Communication Boutique

Photo Cover

Shutterstock

Sales & Marketing

Rachel Linke

rachel.linke@apc.media

Kevan Sears

kevan.sears@apc.media

Sales & Marketing Americas

Maria Salamanca

maria.salamanca@transformer-technology.com

Sales & Marketing Mexico

Fernando Campos

fernando.campos@transformer-technology.com

Sales & Marketing Brazil

Marcelo Braga

marcelo.braga@transformer-technology.com

Marketing Global

Marin Dugandzic

marin.dugandzic@apc.media



Editor in Chief

Alan M. Ross CRL, CMRP

Transformer maintenance
and reliability



Associate Editor in Chief
and Chair of the Technical
Advisory Board

Corné Dames

Independent transformer
consultant
Transformer oils

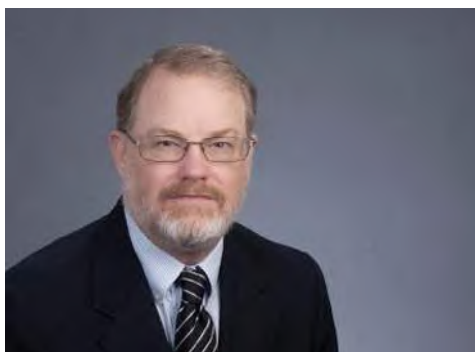


Contributing Editor

Diego Robalino PhD, PMP

IEEE Senior Member

Transformer condition
assessment and
diagnostics



Technical Advisory
Board Member

Edward Casserly, PhD

Senior Scientist,
Transformer oils



Technical Advisory
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Maria Lamorey

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Woodstock GA 30075, USA

transformer-technology.com



Contributing Editor
Alan Sbravati ME, MBA
Transformer insulating materials



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Marco Tozzi ME, MBA
Diagnostics and asset monitoring



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Power transformer design



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Dear Readers,

In Part 1 of the Oils & Fluids Issue we presented a variety of technical content about the different types of fluids, both mineral and vegetable, application information about how these fluids are being used, and comparative information on different types of fluids.

If we are to build more reliability into the electrical system, whether that be for the grid or for a data center or steel mill, then it stands to reason that the selection, testing and treatment of the fluid within the transformer is a critical decision.

At Transformer Technology we are committed to give you, our community, actionable information that can help you make key decisions for all stages of the life cycle of transformers: from design, to manufacturing, to installation, to testing and finally to maintaining and disposal.

With two issues focusing on Oils & Fluids we believe we are bringing insight that educates, informs, and inspires. Enjoy!



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then it stands to reason that the selection, testing and treatment of the fluid within the transformer is a critical decision.

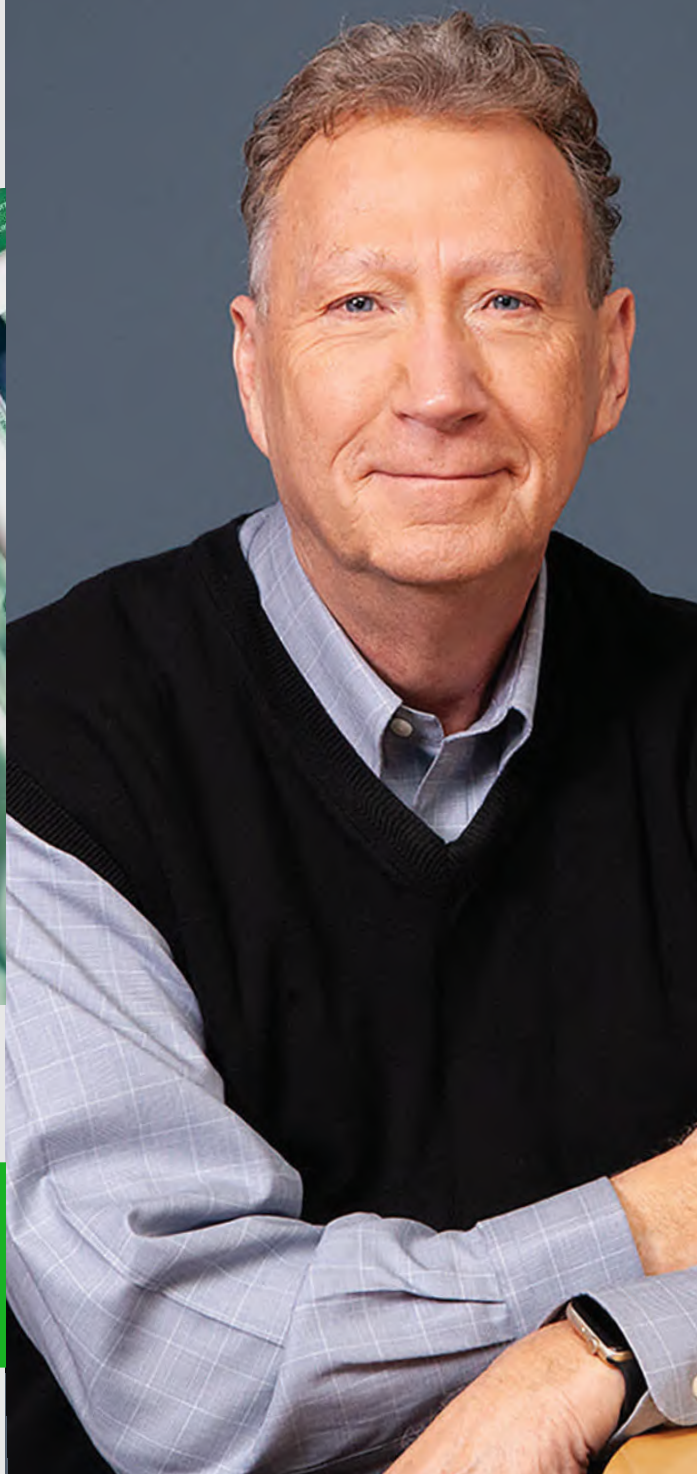
The February issue of Transformer Technology is themed, Transformers: The Heart of the Generation, Transmission and Distribution System. We will also preview the upcoming IEEE PES Conference and Exhibition coming in April in New Orleans. While we are already working on great content, it is still not too late to contribute to the February issue and add your voice to our Body of Knowledge, so please contact me at alan.ross@transformer-technology.com if you want to add your voice to the community.



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Alan M Ross



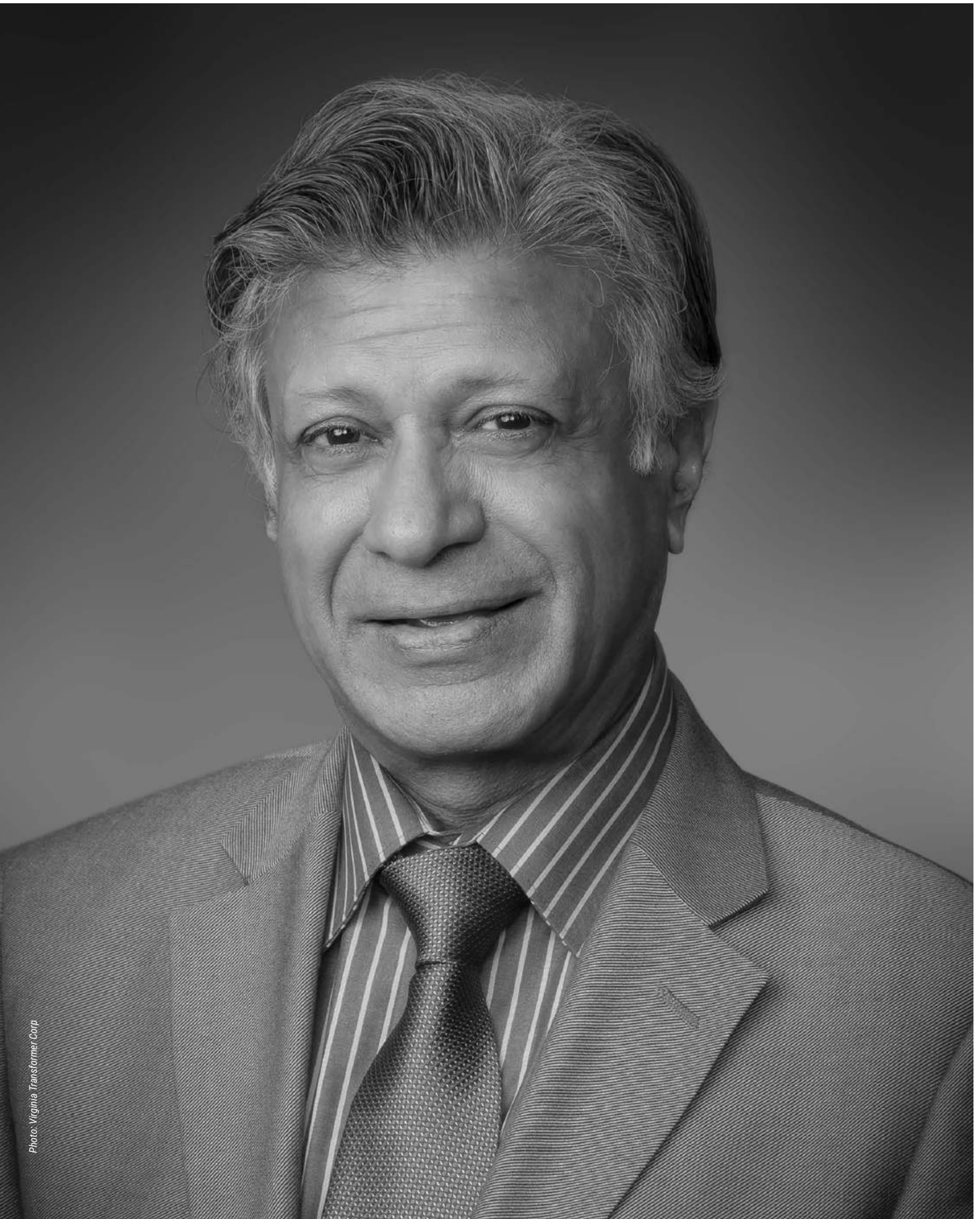
Prabhat Jain

CEO-CTO of Virginia
Transformer Corp

Interview with **Prabhat Jain**

“

I am a lifelong learner and I have always learned from people, and companies, that have been successful. When I see success, I think - Well, it can be done!



Transformer Technology talked to Prabhat Jain, CEO-CTO of Virginia Transformer Corp, a leader with a fascinating biography, a mechanical engineer with an MBA who originally worked in the company and had nothing to do with transformers but then turned a transformer guru as Virginia Transformer and Georgia Transformer (formerly Efacec), became arguably one of the very largest power transformer manufacturers in the world.



Alan Ross: Prabhat, welcome! This is an amazing accomplishment. How many years has it taken for you to do that?

Prabhat Jain: Thank you, Alan. It has taken 40 years now.

AR 40 years of anything with a committed vision can create growth. The vision of your company is to be “an internationally recognized manufacturer and supplier of high quality, specialized power transformers, associated equipment and services by fulfilling our commitments to the customer and our employees through continued growth and improvement.” This is a bold statement that says We are global and high quality. But as you were a mechanical engineer, from that time to now, a lot of people and companies have impacted you. So, your company is impacted by you, but who has impacted you?

PJ People have. I learn from people, from everybody. I am sure I am going to learn from you as well, with what you have accomplished and the things you are doing. That is what I do. Even when I listen to news, it's always educational for me. When I watch sports, it's educational for me. When people are successful, I say “Well, it can be done.” As long as we have the desire, that's the most important thing.

The next thing is to put together teams of people, to encourage them and excite them. We give them a vision and then, Voila, things happen! That has been my life story as I have continued to grow. Have companies impacted me? Yes. I watch companies that have been very successful that have existed for the last 100 years in our economy. And I say “Well, they must have a system or a process in place which sustains them”. And then I say, “I must have that, too,” because process is what makes the companies grow and continue to thrive and then provide the product and the services. Without the process, we could be just a bunch of renegades trying to do a lot of different things. But unless we have a process and an organization, we are not going to achieve the results.

So, to answer your question, it has been a wonderful journey for me to learn from people who have been successful, learn from the people who work in the company and then, of course, work with and then learn from the companies that have been successful in the past. And I see the leaders of these companies on the news, I listen to the interviews, and I say, “Yes, that makes sense”.

Process is what makes the companies grow and continue to thrive and provide products and services.

AR You mentioned three things: teams, leadership, and process. The most successful organizations in my history, have a real major commitment to teams and collaboration around teams. Collaborative teams have a real commitment to build up leadership. And then they have a commitment to process. So, it's not all about Superman. For the most part, people come to work, and they want to participate.

You now have Virginia Transformer, and you have Georgia Transformer (formerly Efavec). Tell me a little bit about how you create and standardize a corporate culture around collaborative teams.

PJ It just evolves. Let's put it this way. It is not something which one would go out and say, “I'm going to do this collaborative team culture and team building.” It's an evolution, at least in my case. As people came to work for me, I see their skills and then their natural instinct. And then you work around people to make their world, as opposed to me saying “This is the world and I want you to fit in it.” This is how I have done it. You see the people, you see what they can do, and you go “Wow, this is great! Let's do this and let's do this.” And as they continue to grow, then you can say “Hey, Joe, you want to hire a couple





of people for yourself, and then you can do more of what you like to do, and continue to grow?" At that point it kind of evolves into teams that then grow bigger and bigger. And, of course, as you build with the success of the people that are leading, then certainly they enjoy what they are doing. And that is the substance of success, really: Making people enjoy what they do; giving them the intellectual satisfaction. That's how I think Virginia Transformer has grown continuously. Because accomplishment is an acceleration. I think when you accomplish, you say, "Well, it can be done, and I will do more of that." And then we find other things to do as well.

AR Did you find a different culture when you brought in Georgia Transformer (formerly Efacec)? Did you have to change that culture, or was that also much more of just an organic move? Because I know they had a different culture than what you had at Virginia Transformers

PJ They did, Alan, you are right. Because it was run by expat, for the most part. That was the big difference. Then the expat left, which was in 2014 or thereabouts, just before we bought the company. I didn't realize that when we bought the company, what we will find. And that was a challenge. The culture was that the expat would tell people what to do and they did it. And then when the expat left, we found that, yes, there were processes, paperwork, systems, but nobody knew how to follow them. That was the big thing. The other thing I found was, that in Portugal, and for that matter, other European countries as well, the longevity of people in their job is much longer. And thus, there is far less need for monitoring and oversight processes. By far less. I visited several plants in Europe, and I found that there are very few inspectors and technicians. People just do the work themselves because they've been there for 20, 30 years. Here we don't have people with 25-year experience, so that was the challenge.

AR I am passionate about safety and engaged, committed leadership. The CEO must lead the whole safety effort. And we are moving to what we call behavioral safety. Any organization has to have a behavioral safety mindset.

Talk a little bit about how you have been able to implement that. How do you take your passion for safety and push that down through the organization, not mandating it, but creating it as a behavioral safety model?

PJ You know, we are safe at home, we are safe when we travel, so obviously, it is ingrained in us. That's number one. Number two is the sense of caring for people that drives me to be safe. Because I believe that people who come to work for Virginia Transformer, they want to go home safe. That is what drives me and I always talk about it. I say, "We must be safe". When I'm on the floor, if I see something, I call the supervisor, I call the people and say, "Hey, this is not safe". So, this is how I really practice safety. And it has been very successful.



Certainly, we can always be safer, there's no question about that. But the primary thing is to not just talk the talk but to walk the walk as well. That's what we have to do. Just saying things and then just going away, won't have an impact. The impact comes from continuously communicating and monitoring. Saying "Okay, what did you do last month or last week for safety? Yes, we had talks. I understand we had talks, but talks are one thing. What did you actually do? Did you see things?" Then they will say, "Yes, we saw things." And I will say, "That's great. That means now we've seen things, we can change them." And they would say "I didn't see anything. Everything was right". I will say, "No, no, that's not the real world".

So, I think this is what we must keep doing as leaders, especially in manufacturing areas, which have a lot more safety hazards, if you will. Our plant has a 0.6 of what we call the experience factor.

AR Your value statement says: "We pride ourselves on premium quality customer service and our expert engineering staff that works from 15,000 designs. We have an archive to assist us in designing the perfect transformer to meet your specific needs. We supply Transformers for utility, industrial transit, commercial alternative energy. Engineers making Transformers for engineers."

Could you talk about how you build quality into the systems? I know Virginia Transformer is committed to quality. But how do you build it today when we deal with specifications and often the customer's purchasing department will say, "We're going to get the cheapest cost."

Reliability begins at design. And today, design is often purchasing driven, which leaves a lot of room for quality problems. How do you battle that in the marketplace?

Quality is the essence of success and growth. It has three components: one is the design, another is the process, and the last one is oversight by engineers.

PJ That is the essence of success and growth. Quality has, I would say, just three components. One is the design, and the design is based upon experience and analytical tools to make sure that we are going to be successful; that the design will work for what it is intended to do. Number two is the process in the shop, how the product is put together. It's a custom-made product. There's very little opportunity to automate. What that means is that the training of the people, their knowledge of what they're doing, has to be adequate. But as I mentioned earlier, it is difficult because the longevity of shop people is very short here. So, we supplement that by engineers on the shop floor. So, it's the engineers designing, it's the engineers overseeing the product being built and then the product being handled. Product handling is critical.

Then we have another layer of engineers who have been around for 15 or 20 or 30 years. They have a set of experienced eyes and they can spot things faster than a younger engineer or a technical person who is going through a check sheet. Check sheets will only take you so far and will not deliver the quality and the reliability that exceeds the marketplace and that excites the customer who will then say, "This company gives me a more reliable product than others."

That's where we are. So, it's three components: One is the design, one is the process, and the last one is oversight by engineers. That's a part of quality.

Now, besides quality, what differentiates Virginia Transformer is also customer satisfaction. You mentioned specifications. It's a significant effort within our company all the way from the sales engineer to the field service technician, the last person. And then I profess, I train, I encourage all the people who are, as I call it, customer facing, to make sure that we understand and we respect and we service the customer. Engineers, technology, people. That's the mixture. But at the end of the day, a transformer is a highly involved design machinery, even though there are no moving parts. It has invisible forces which are causing the stresses. We develop the designs and

us to achieve our no-field-failure rate. I mean, it's a huge effort, and it is very satisfying when engineers learn that my product works well. It is the engineers who are the key to success and reliability and quality. As you said, everybody says, "We have quality", and it's a relative term.

I launched an initiative 'Pursuit of Perfection', and I wrote a series of six articles called 'Legacy of Excellence' to share with my employees what I have seen and achieved in the last 40 years.



analyze them on a continuous basis. Continuous basis means every time all the time. We then analyze the data, we analyze the results of the tests, the results from the field, et cetera. We do this to assess, to see why we had this situation. Through this analysis we have been able to bring these stresses to a uniform level. So, that there is far less variation of either dielectric or mechanical stresses, so there are no what we call high points. That has been one of the keys for

I launched an initiative three-four years ago, called Pursuit of Perfection. And I wrote a series of six articles called Legacy of Excellence to share with my employees what I have achieved in the last 40 years and to share what I have seen. How do we achieve excellence? People have to learn that. They have to learn what made Virginia Transformer successful, so they understand the company and what the measure of success is for us. There are many

small measures of success. Low sound is one, low partial discharge is another, very low failure rate, the field issues or lack thereof, performing on time and so on. Those are some of the measurements. However, as you said, there is no one lever which says, "This is the quality lever and if you twiddle it, it will go up." No. But it is easy, it is not difficult.

People coming to Virginia Transformer have to learn what made the company successful, so they understand the company and what the measure of success is for us.



you damage it. I mean, that's how simple it is. And these principles are not difficult to understand, but they must be practiced continuously because we have new people coming all the time. And that's also part of the challenge. So, the challenge is communication and upkeeping of the flow of handling and assembling and designing. We have lots of tools. As many tools as you can ever imagine for analysis. They are so wonderful that we can see all these color graphs, the red and the green and so forth. You can identify this is the hot spot or this is the high stress. Now, how do I make it uniform, so this will go away and everything will work at the same safety level?

There are many small measures of our success: low sound, low partial discharge, very low failure rate, lack of field issues, performing on time and so on.

AR You just hit onto two major hot topics for me. Engineer to engineer. You have engineers out at the customers' site that are engineering a system. So, they're buying transformers to engineer that system, and then by having more engineers involved at your site. That ought to be your new tagline: Engineers serving engineers.

Prabhat, thank you so much for talking to us.

PJ Thank you very much for taking an interest and allowing me to speak to the industry as to how we and every other transformer manufacturer should function, so we can service our country's grid with more reliable transformers. That's my goal.

The difficult part is to communicate and to get the whole team together and saying, "We are going to build a better quality". That's the difficult part - Communication and getting people on board, getting people to get going and understanding the principle and then to work as a team. So, the engineer, the designer, the technical and the operator and then the trainer of the operator need to understand why the insulation is so critical. If you fold the insulation,

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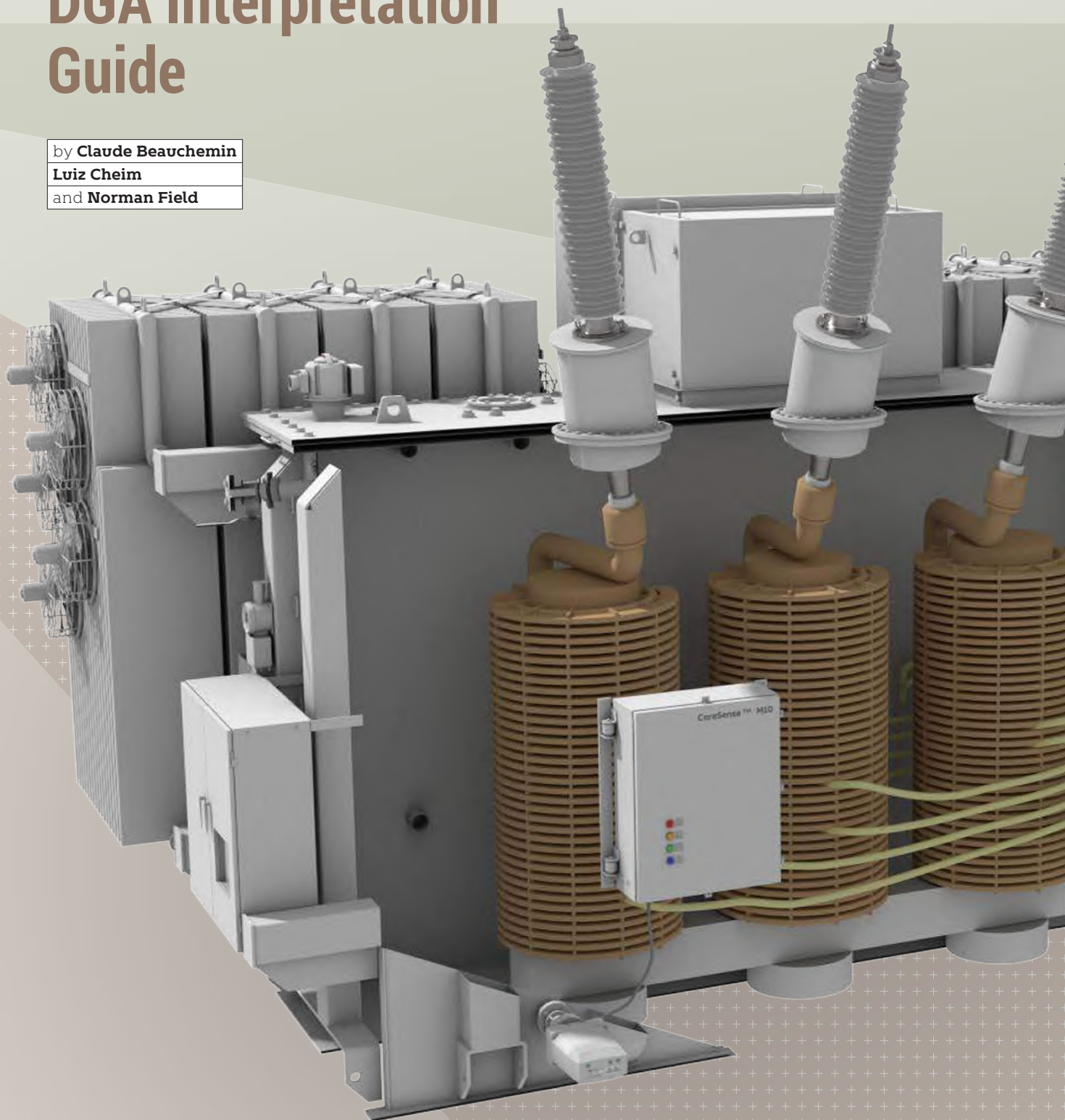


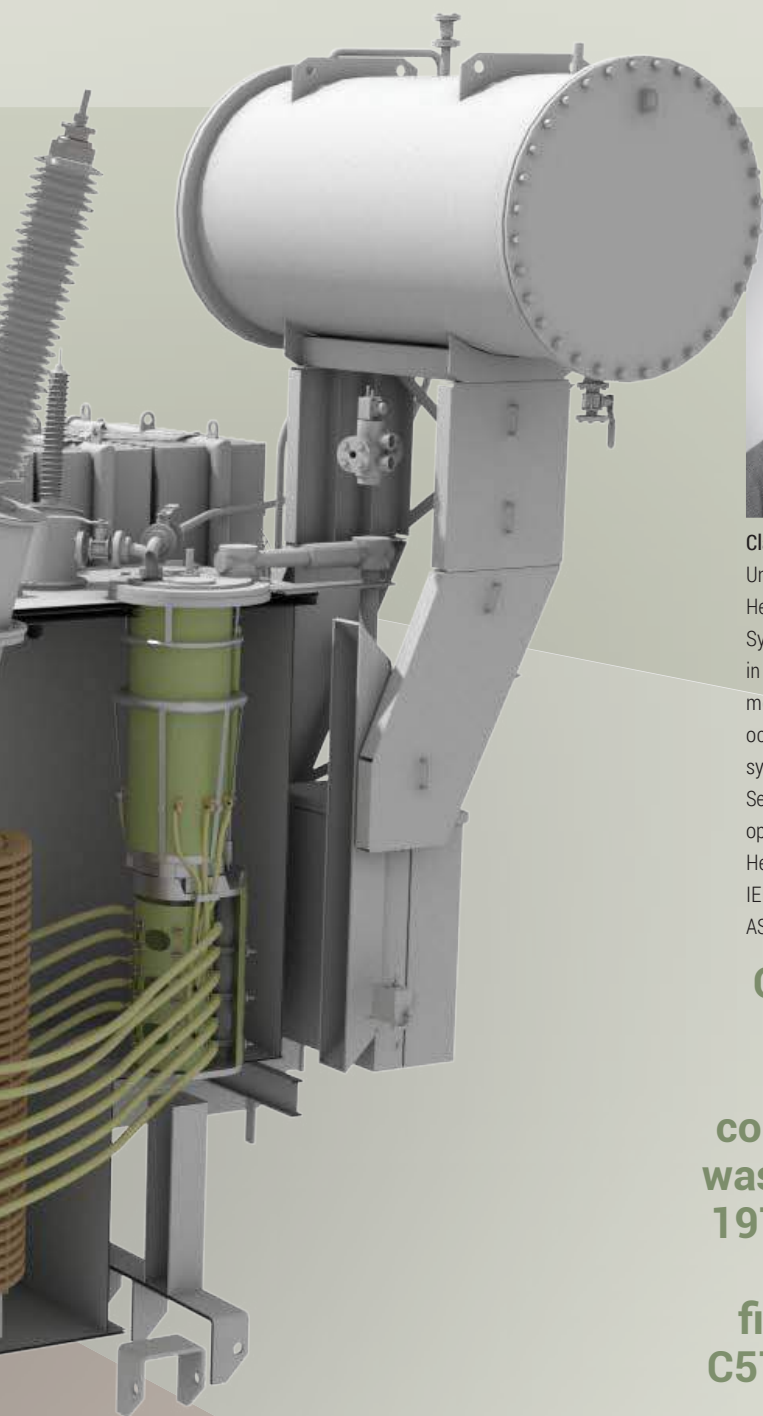
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The Data Behind the Numbers: IEEE C57.104™-2019 DGA Interpretation Guide

by **Claude Beauchemin**
Luiz Cheim
and **Norman Field**





Claude Beauchemin, OCQ, graduated from Université de Montréal in chemistry in 1976. He has been working for GE Canada (formerly Syprotec) for 30 years where he specialized in the development and application of on-line monitoring of power transformer physicochemical parameters (Hydran and Intellix systems). Claude joined TJ/H2b Analytical Services in 2011 as Director of Technical Development and Director of Quality Assurance. He is IEEE C57.104 WG Chair, member of the IEEE Transformer Committee, CIGRE, CSC, ASTM and the Ordre Des Chimistes du Québec.

One of the earliest set of norms for acceptable gas concentration levels was developed in the 1970s. These values were used in the first edition of IEEE C57.104™ published in 1978 and had remained virtually unchanged for four decades.



Dr. Luiz Cheim has been working with Hitachi-ABB Power Grids (Transformers) as a Sr. Principal R&D Engineer for a number of years, having over 30 years of experience in the power transformers industry. His major activities as part of a global R&D team are in the development of transformers condition assessment and performance models and algorithms, as well as the development of new sensors and state of the art monitoring technologies. Dr. Cheim is the proponent of the new Hitachi-ABB Transformer Inspection Robot. In August 2018 Luiz was granted the *Best Paper Award* by the Cigre organization in Paris, Study Committee A2/PS2 on the use of AI/Machine Learning techniques in support of transformer diagnostics. Dr. Cheim has filed for over 20 patents over the last 10 years alone. He has been a member of the IEEE and Cigre since the 1980s and has taken several prominent roles in both organizations. He was appointed as Technical Chairman of two Cigre SCA2 International Colloquia, in Moscow 2005 and Shanghai 2015, respectively.



Norman Field, P. Eng, has over 30 years of experience in the transformer industry. This includes 14 years in design and 16+ years providing a combination of electrical power apparatus asset management for end users clients, while continuing to perform in-factory and on-site transformer inspections and design reviews. Currently he is Supervising Engineer at Stantec. Norman is member of the IEEE Transformer Committee and IEEE C57.104 WG Vice Chair. He has enjoyed living and working in three countries and can occasionally be heard discussing DGA in Spanish.

Introduction

The analysis of gases dissolved in transformer insulating liquid (DGA) was introduced in the 1960s to detect early signs of incipient faults. One of the earliest set of norms for acceptable gas concentration levels was developed by the former CEGB in the 1970s based on DGA results from one geographic region [1]. These values were used in the first edition of IEEE C57.104™ published in 1978 [2] and had remained virtually unchanged for four decades.

In 2000, a complete review of the IEEE guide was initiated. A slightly updated version was released in 2008 [3] and the "new" guide, with new norm values, was published in 2019 [5] based on a vastly larger DGA data set than the first edition.

This paper describes the process followed by the revision working group to obtain the new set of norms.

Data Sourcing

The revision began with accumulating a large dataset of recent DGA results from sources using current oil sampling and

analysis methods. Contributors provided the data voluntarily, in good faith that it would be utilized for the sole purpose of revising the Guide. The raw dataset ("raw" meaning prior to any data processing) contained over 1,500,000 DGA reports from 18 contributors. Each report presented values of 9 dissolved gas concentrations: hydrogen, methane, ethane, ethylene, acetylene, carbon monoxide, carbon dioxide, oxygen, and nitrogen. Reports also contained information on equipment type, transformer type, number of phases, rating (MVA), voltage (kV), age, manufacturer, serial/ID number, oil preservation system, oil volume/weight, sampling date, analysis date, and the reason for the analysis (routine or investigation).

Data Cleansing

Initial Data Preparation

Once collected, the data "clean up" process began with the goal of discarding any data points deemed inapplicable, unreliable, or invalid, resulting in a processed, or "clean", high quality dataset.

Some data points were discarded for lack of essential information. Additional data was discarded if the DGA results did not belong to transformers, or were from transformers out of service, or from in-factory testing.

Second Level Filtering

Additional filtering was applied to eliminate duplicate results. Next, judicious corrections were made to some data point values with incorrect units for rating (kVA versus MVA) and voltage class (volts versus kV). Erroneous values could be corrected for some of the data by examining other accompanying variables such as oil volume and transformer type. While these corrections were cumbersome, this was necessary to not discard or misuse a disproportionate number of large or small transformers.

Data Anonymity and Security

The cleansed dataset was made anonymous by removing contributor names and replacing transformer serial/ID numbers with generic ID numbers. Furthermore, to address concerns from some of the data suppliers regarding its potential use outside of the guide revision, and in the absence of a formal Transformers Committee data repository, it was decided to permanently discard the data set after final processing and to limit the number of persons accessing and processing it to the three Officers of the Working Group.

It was also agreed that no single individual had the full data set in their possession at any time. Each Officer was responsible for only a subset of the data. The complete data set was assembled only once onto a single memory stick for the final analysis, handled in the presence of the three Officers and Working Group member witnesses.

After the analysis was completed and results were preserved independently of the raw data, the memory stick was reformatted and destroyed. While not optimal, this was a practical solution to address the data security concerns of the contributors.

General Characteristics of the Data Set

The data set population characteristics are as follow:

- Number of data contributors: **18**
- Total number of usable DGA reports: **1,391,436**
- Total number of transformers: **313,076**
- Total number of DGA reports with transformer age: **618,715**
- Total number of DGA reports with transformer rating: **738,188**



Figures 1 to 4 are graphical presentations of some characteristics of the data set: analysis year, transformer age, transformer rating, and number of days between successive DGA samples.

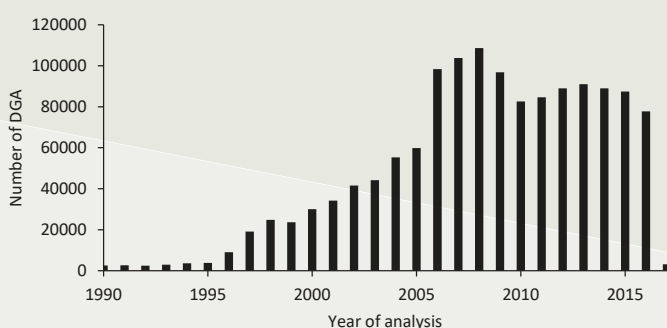


Figure 1. DGA report distribution as a function of the year of the analysis

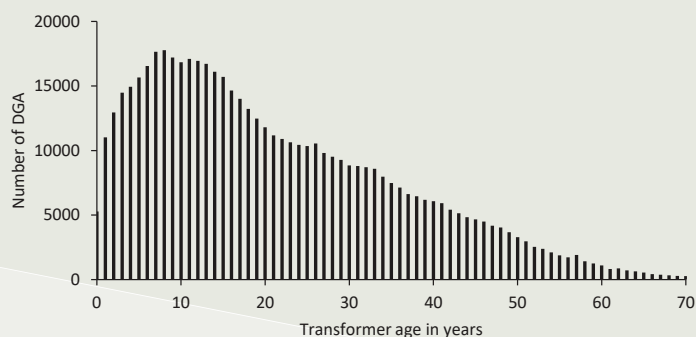


Figure 2. DGA report distribution as a function of transformer age at the time of sampling

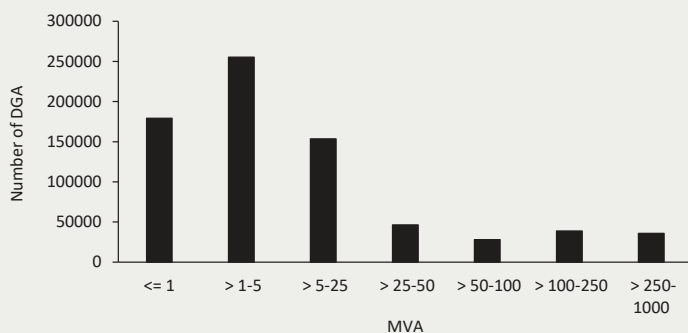


Figure 3. DGA report distribution as a function of transformer rating

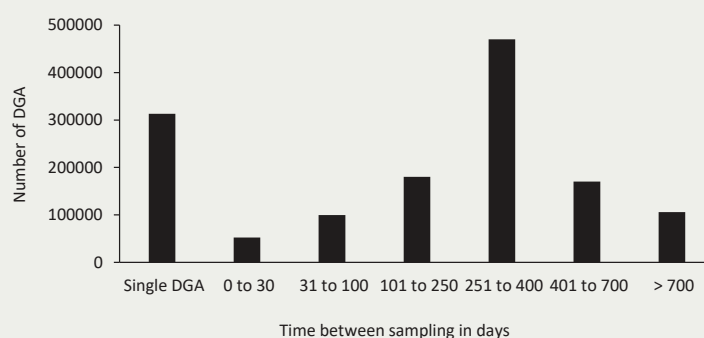


Figure 4. DGA report distribution as a function of time between samples

Table 1 provides the DGA report distribution as a function of the two principal factors used to segregate DGA: O_2/N_2 ratio and transformer age.

	O ₂ /N ₂ <0.2				O ₂ /N ₂ >0.2			
	Age in years							
	All	1 – 9	10 – 30	>30	All	1 – 9	10 – 30	>30
Number of DGA	876,314	84,215	179,829	113,264	495,561	59,320	86,983	72,039
% of DGA	63.0%	6.1%	12.9%	8.1%	35.6%	4.3%	6.3%	5.2%

Table 1. DGA report distribution as a function of O_2/N_2 ratio and transformer age

90 th Percentiles in ppm and delta in %									
Factor	DGA	H ₂	CH ₄	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂	CO	CO ₂	Average all gases
O ₂ Ratio <0.2	876314	83	87	91	54	0	901	9263	
O ₂ Ratio >0.2	495561	41	20	14	50	2	481	5011	95.4%
Max - Min/Average		67.7%	125.2%	146.7%	7.7%	200.0%	60.8%	59.6%	
Age 1 to 10 Years	147472	65	38	21	20	1	699	4076	
Age 10 to 30 Years	275286	58	67	59	47	1	896	7591	
AgeYear >30 years	189415	82	73	84	65	2	697	7851	67.2%
Max - Min/Average		35.1%	59.0%	115.2%	102.3%	75.0%	26.0%	58.0%	
Manufacturing Year >1987	331028	54	46	26	31	1	865	6171	
Manufacturing Year <1987	288202	84	81	90	65	2	705	7634	55.4%
Max - Min/Average		43.5%	55.1%	110.3%	70.8%	66.7%	20.4%	21.2%	
Maximum MVA <10	568682	69	64	56	59	1	884	9449	
Maximum MVA >10	356038	63	76	74	50	2	652	5689	31.0%
Max - Min/Average		9.1%	17.1%	27.7%	16.5%	66.7%	30.2%	49.7%	
HVkv <60	626153	66	65	56	58	1	864	9126	
HVkv >60	347877	69	79	83	52	2	643	5687	30.9%
Max - Min/Average		4.4%	19.4%	38.8%	10.9%	66.7%	29.3%	46.4%	
Oil Volume Galllons <2000	554687	72	67	58	58	0	912	9792	
Oil Volume Gallons >2000	218857	68	62	62	44	0	600	5527	20.6%
Max - Min/Average		5.7%	7.8%	6.7%	27.5%	0.0%	41.3%	55.7%	
Total Dissolved Gases <100000 ul/l	1043500	63	65	62	50	1	770	7300	
Total Dissolved Gases >100000 ul/l	328907	83	67	60	62	1	848	10328	14.2%
Max - Min/Average		27.4%	3.0%	3.3%	21.4%	0.0%	9.6%	34.4%	

Table 2. Influence of various factors on limit values

Extracting Usable Information

The primary interest of analyzing the dataset was to obtain the limits used to detect an abnormal condition. The distribution of gas levels was not Gaussian, but rather follow a highly skewed inverse distribution, therefore classic sigma analysis was not applicable. On the other hand, the data distribution for a calculated gas concentration differential between successive analyses (called "Delta" in the guide) and for trend (rate of change) was almost Gaussian with an average of zero. To address this difference of data distribution types, we used percentile values for the norms, as the percentile value will always, by definition, represent the 90th%-point (or 95th%-point) of the population, irrespective of the type of distribution. There is precedent in several industries to use the 90th and 95th percentiles values as limits for anomaly detection in data sets, and these were likewise chosen for DGA.

Data Analysis

Preliminary Analysis

The three authors, independently of each other, performed several preliminary data evaluations of their data subsets of data, using both spreadsheets and R scripts, to determine how the complete data set should be analyzed and what parameters should be investigated. The analysis needed to be unbiased and applied consistently to all DGA reports from the clean data set.

In transformers, gas levels and generation rates are influenced by several factors. Therefore, it was initially attempted to establish various norms as a function of many such factors to discern between normal and abnormal DGA. To decide which factors to use in the final analysis, a table was created of the gas concentration 90th and 95th percentile values as a function of a split in 2 categories (low VS high) for each factor considered. The percent difference was computed between the two values for each gas and the results were ranked as a function of the average differential. The factors evaluated were the O_2/N_2 ratio (less or more than 0.2), age (an exception with three split points: 1-10, 10-30 and >30 years), year of manufacturing (before or after 1987), rating (less or more than 10 MVA), voltage class (less or more than 60 kV), oil volume (less or more than 2000 gallons) and total amount of dissolved gases (less or more than 100,000 ppm).

It was deemed that more than two factors would render the 90th and 95th percentile limit tables too complex for practical use. Therefore, the two most influential factors were selected for the limit tables: O_2/N_2 ratio and transformer age. Manufacturing year was strongly correlated to age, so it was not used as a separate factor. Segregating the data further by MVA, kV, oil volume, and total gas content did not significantly influence the limit values and those factors were not used (see Table 2).

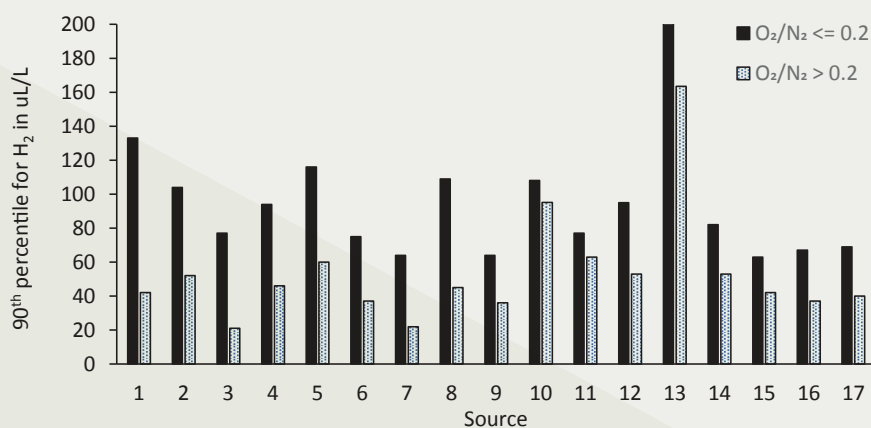
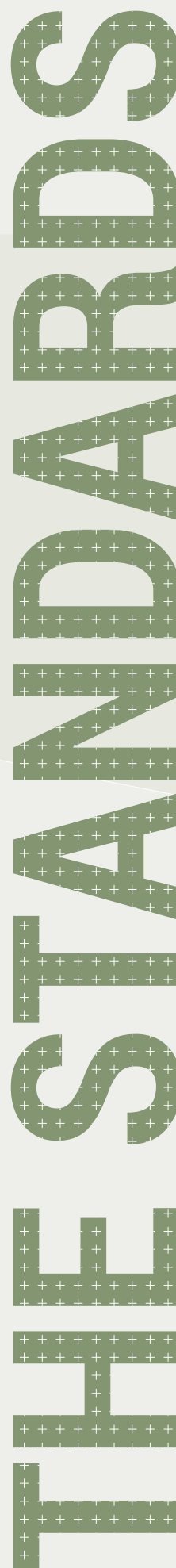


Figure 5. Example of the variations of percentile values observed between the sources (90th percentile for H₂)



		O_2/N_2 Ratio ≤ 0.2				O_2/N_2 Ratio > 0.2			
		Transformer Age in Years				Transformer Age in Years			
		Unknown	1 – 9	10 – 30	>30	Unknown	1 – 9	10 – 30	>30
Gas	Hydrogen (H_2)	80	75	75	100	40	40	40	40
	Methane (CH_4)	90	45	90	110	20	20	20	20
	Ethane (C_2H_6)	90	30	90	150	15	15	15	15
	Ethylene (C_2H_4)	50	20	50	90	50	25	60	60
	Acetylene (C_2H_2)	1	1	1	1	2	2	2	2
	Carbon monoxide (CO)	900	900	900	900	500	500	500	500
	Carbon dioxide (CO_2)	9000	5000	10000	10000	5000	3500	5500	5500

NOTE: During the data analysis, it was determined that voltage class, MVA, and volume of mineral oil in the unit did not contribute in significant way to the determination of values provided in Table 1.

Figure 6. Example of the final result: Table 1 of the new IEEE C57.104TM-2019 "Guide for the Interpretation of Gases Generated in Mineral Oil-Immersed Transformers"

For guide revisions, it should be expected to spend at least as much time in data collection and cleaning as in data processing.

Final Analysis

Final data analysis was performed with R software [4] scripts developed specifically for this task by the first author. In total, those scripts contained approximately 3000 lines of code and comments in native R (V3.3.2). To facilitate witness oversight of the final analysis, the "Read" and "Save" functions of the code, were specifically designed to read and write data to specific file locations in such a manner that the witnesses could verify that the original data was not copied to anywhere else other than onto a single memory stick. The final data analysis session, including several iterations and adjustments, was completed in two days.

Prior to data merging, each cleaned data subset (18 in total) was analyzed to verify the integrity of the data and to compute general statistics of interest to gauge variance among the 18 different data contributions. Given the large amount of data, one could be tempted into a false sense of analytical precision by theoretically obtaining extremely "precise" results (calculating 90th percentile limits to the nearest ppm, for example) and falsely assume that the result is perfectly representative of the industry condition. This is far

from the real-life situation, where it is well known that typical (i.e.: 90th percentile) gas concentrations can vary widely from one transformer network to another. So, for each of the 18 data subsets, percentile limits were computed for each gas. Comparing the calculated limits between the 18 subsets confirmed their large variability, as illustrated in Figure 5 example. This also led to the necessity of limiting the number of significant digits used in the various tables of the guide, to not present a false sense of precision.

With the merged data, the next step was to process it to extract the desired information. This included generating percentiles for all possible combinations of factors, including those unlikely to result in usable data. This was done for two reasons: a) For each factor, the optimal breaking point was not known in advance so it was necessary to perform analyses with several different partition sets, and b) As the data would be destroyed after the final analysis, this was the only opportunity to collect as much analytical information as possible, and decide later what output would be used, discarded, or kept for future work.

Furthermore, some of the factor split points depended on the values



obtained by the analysis itself. To be able to adjust those criteria during the process, the various factor break points were separated from the analysis script and stored in the form of loadable tables. As the analysis was progressing, it was possible to adjust those points based on intermediate results, update the files and repeat the process in an iterative way without having to change the script proper (which risks introducing new undetected errors). As an example of such iteration, delta and rate computation (Tables 3 and 4 of the new guide) were to be computed only from data below the selected 90th percentiles for level values, which was not known until the first part of the analysis was completed.

For each transformer, the gas level increase or decrease (delta) was computed from each pair of successive DGA (approximately 1 million pairs). Using the same data for each transformer, a series of successive overlapping sequences of 3 to 6 points were created and evaluated by a linear best fit (slope), providing approximately one million sequences. The 95th percentile values of these deltas and slopes were used to create tables 3 and 4 of the guide. To perform this operation on a standard PC in a single day (due to the necessity to perform the analysis in the presence of several persons) a large amount of preparatory work was needed to simplify and optimize the script. The analysis generated several files, containing all the information needed to generate the final tables now shown in the guide. Those files were saved and are all that remain of the data analysis.

To account for the large variations between sources (see Figure 5), the 90th and 95th Percentile values for dissolved gas concentrations, deltas and rates norms were rounded as follows:

1 to 10:	No change
10 to 50:	5
50 to 100:	10
100 to 250:	25
250 to 500:	50
500 to 1000:	100
1000 to 2500:	250
2500 to 5000:	500
Above 5000:	1000

Furthermore, the values from different age groups were combined in one when they differed by less than 35%. Figure 6 illustrates the final Table 1 [5] of the guide.

Lesson Learned

For work requiring the collection of large amounts of data from volunteer sources, especially if this data could be commercially sensitive, it is imperative that a legal framework (NDA, waiver, Terms & Conditions of Use, etc.), secure data storage facilities, and accessibility protocols are in place before collecting any data. A standardized form is needed for the collection of the data, noting that a singular date format is especially important. It should be expected to spend at least as much time in data collection and cleaning as in data processing.

References

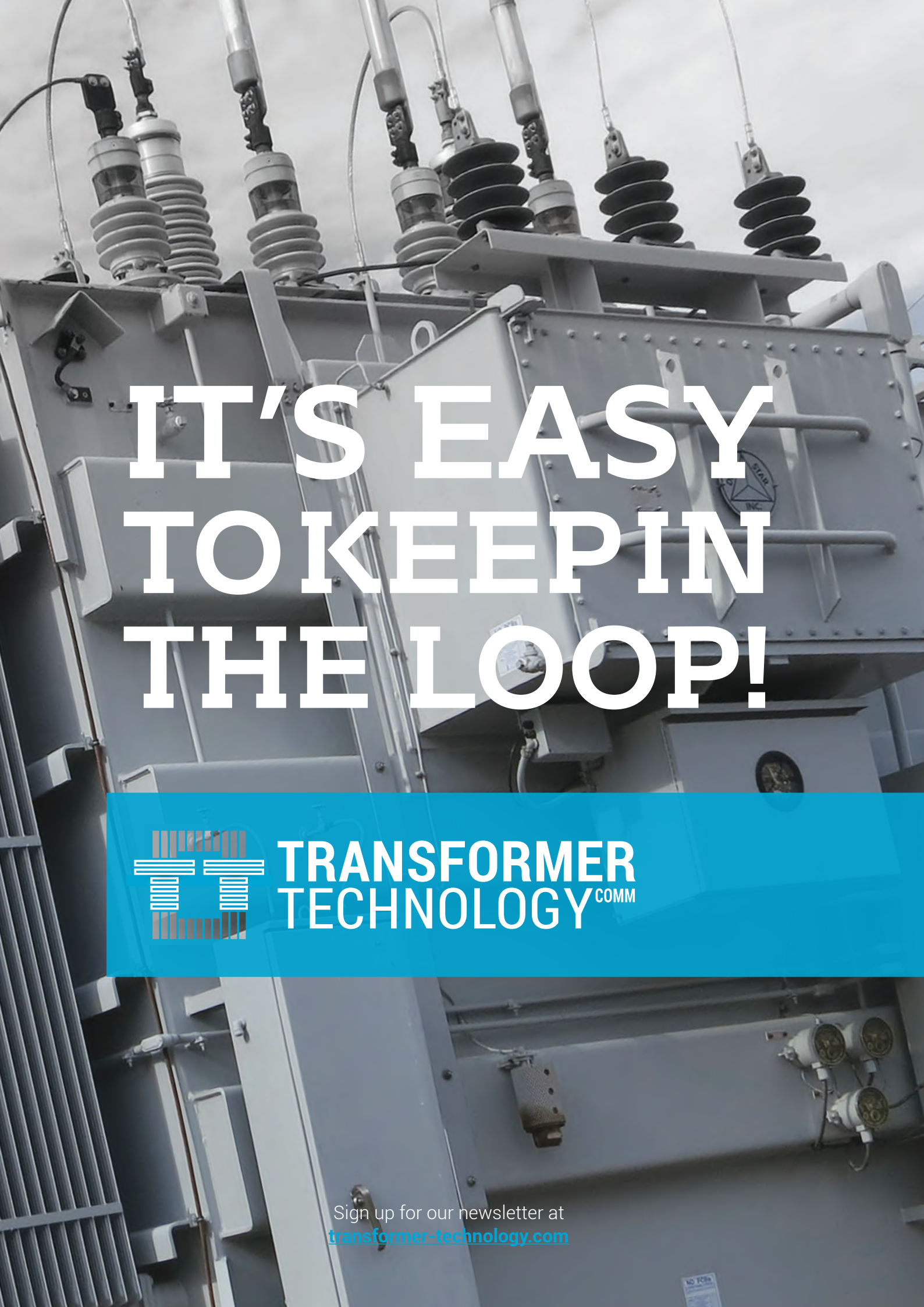
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Acknowledgements

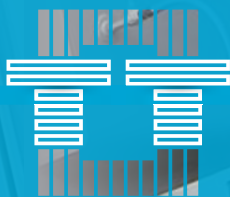
The authors wish to take this opportunity to thank all participating IEEE C57.104™ Working Group members, data contributors (utilities and laboratories), and their employers, for their confidence and support throughout this lengthy and challenging revision process. Without them, this work would not have been possible.

A Note

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Insulating Liquids: The Lifeblood of Transformer Reliability

by Jason Dennison

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You may know that your transformer is filled with a liquid known as an insulating or dielectric liquid, but do you know why?

The very first transformers did not have an insulating liquid in them. Air acted as the dielectric medium inside early transformers and this became a problem as energy needs expanded, given the early designs of transformers. In early transformers, energy losses generated a significant amount of heat in the core and coils and the air wasn't effective at drawing away the heat. As a result, early

transformers' size was limited – otherwise the heat was simply too much, and the transformer would fail due to overheating.

Elihu Thomson patented the use of mineral oil as an insulating liquid in 1893 as a way to manage the heat and improve the operation of transformers, and within about five years this advancement was commercially available. The early intent was focused on dissipating heat while also dielectrically protecting the energized parts of the transformer, and mineral oil proved to be a very good medium for this.

If the transformer is the heart of the electric power system, the insulating liquid is the blood, and it can tell you an incredible amount of information about the transformer's condition.



Jason Dennison is the Director of Diagnostic and Analytical Services at SDMyers, LLC. Dennison leads the world's largest transformer liquid testing laboratory with a team focused on safe operation while generating high volume data analysis and diagnostics. He obtained a bachelor's degree in Chemical Engineering from the University of Akron with Polymer Specialization and is a Lean/Six Sigma Black Belt with project management experience spanning industries such as rubber processing, metal machining, petrochemicals, compliance, software development, laboratory chemical hygiene and processes, and data analytics and diagnostics. He is a member of IEEE and ASTM and presents nationally as an authority on transformer fluid analysis.

The Functions of Insulating Liquids

Fast forward several decades, and mineral oil became the de-facto insulating liquid in large transformers. For smaller applications, transformers that use air as the dielectric also became popular for many applications, commonly referred to as "dry type" transformers. Into the 1940s, vacuum-filling as a process opened further advancement in transformers' application and size. As larger, liquid

filled transformers grew in use, four primary functions of the insulating liquid became well-known:

1. Dielectric Strength
2. Heat Transfer
3. Protection of Solid Insulation
4. Diagnostics

These four functions are widely recognized and the liquid inside these transformers is crucial to the normal operation of transformers from generation to distribution.

These functions point to why these liquids are so crucial:

Dielectric Strength – The liquid insulates energized components inside the transformer, helping to ensure routine operation of the transformer. While the liquid is an insulator, there is another insulation medium in transformers – called the solid insulation. Solid insulation is comprised of paper and board that serve to insulate the winding. Interestingly, it is the combination of the solid and liquid insulation that is so profound due to a synergy between the two that yield a dielectric strength improvement of 20 – 25% greater than expected. The combination is greater than the sum of its parts!

Heat Transfer – Transformers, depending on size and load, can generate a significant amount of heat. The liquid helps dissipate that heat and enables transformer designers to use natural and generated convection to keep the transformer within operating parameters for temperature and load. Liquid properties such as viscosity, heat capacity, relative density, and the thermal expansion coefficient are all key properties affecting the liquid's performance in heat transfer.

Protection of Solid Insulation – Transformers contain solid insulation comprised of paper and board that lend strength to the transformer in normal operating conditions. This paper is susceptible to damaging effects of oxidation, and the liquid acts as a barrier between the solid insulation and "bad actors" that lead to oxidation such as oxygen, heat, and moisture.

Diagnostics – The liquid inside the transformer is analogous to the blood in our body, and just as a blood sample can tell the doctor about our health, the liquid can be tested to help evaluate the condition of the transformer. This was not part of the original intent of adding insulating liquid to transformers, yet it has become an incredibly useful aspect to help ensure the reliable operation of a transformer.

The very first transformers did not have an insulating liquid in them. The use of mineral oil as an insulating liquid was patented in 1893 and within about five years, this advancement was commercially available.

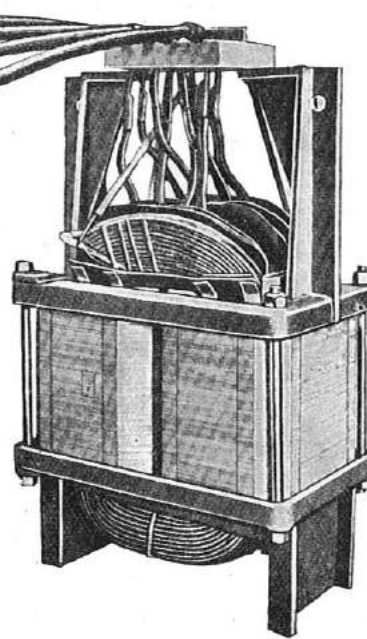
Liquid Types

In early transformers, the insulating liquid of choice was mineral oil, due to its dielectric strength and ability to handle heat generated in the transformer.

It was so common that to this day, the insulating liquid inside transformers is generically referred to as the "oil" inside the transformer, even though other liquids have been used for years as well. For a time, pure PCBs were used as an insulating liquid but due to environmental and health concerns, PCBs are now a rarity in transformers. Let's look at the common insulating liquids used in liquid-filled transformers:

Mineral Oils

Today, many transformers are still filled with naphthenic or paraffinic mineral oil, often called "transformer oil". This is a derivative of petroleum oil that is well-established as a



dielectric liquid, which has strong performance in terms of cooling and is known to have high dielectric strength. Due to its long history of use in this application, mineral oil characteristics are well-understood as they relate to performing diagnostics on the liquid. Mineral oils also perform well in applications difficult for other liquids such as load tap changers where arcing occurs in the insulating liquid, or in free-breathing

applications where exposure to oxygen causes polymerization of some liquids. Mineral insulating liquids generally have a price advantage compared to other liquids. Mineral oils are also readily processable and can be restored to near-new condition by hot oil cleaning processes.

Silicone Liquids

Silicone liquids are a synthetic oil that can be used as a dielectric liquid. Silicone has high dielectric strength, high flash and fire points, and is chemically inert. These characteristics have led to the use of silicone oil in indoor applications where flammability is a significant

These four functions are widely recognized and the liquid inside these transformers is crucial to the normal operation of transformers from generation to distribution.

concern. Silicone also has a slow oxidation rate in the presence of oxygen at elevated temperatures (>175°C); when oxidation does occur over time, it results in polymerization of the liquid, which is measurable by the viscosity of the liquid, but does not form harmful acids or sludges. Use of silicone oils in transformers has been decreasing over recent years, as arguably better performing and definitively more environmentally friendly liquids (natural and synthetic esters) have become available at lower prices.

Natural Esters

Natural esters are a type of environmentally friendly dielectric liquid that is readily biodegradable, derived from agricultural crops such as corn, rapeseed, soybean, and sunflower. While this is an advantage in itself related to spill containment and material handling, these liquids have some performance advantages compared to mineral oil as well. They typically have high flash and fire points, making them great for indoor applications where flammability is a concern. Esters also have a high capacity for moisture saturation, leading to claims that refilling an oil-filled transformer with a natural ester can aid in dehydrating the solid insulation. These esters polymerize when exposed to oxygen, typically have higher viscosity than mineral oils, and are not as readily processable for restoration to near-new condition. Natural esters are compatible with mineral oils, making retrofills feasible when service is needed. There are also synthetic ester liquids available with similar characteristics but improved low-temperature performance and formulated to prevent oxidation if exposed to air, as in free-breathing applications.

In early transformers, the insulating liquid of choice was mineral oil, due to its dielectric strength and ability to handle heat generated in the transformer. It was so common that to this day, the insulating liquid inside transformers is generically referred to as the "oil" inside the transformer, even though other liquids have been used for years as well.

The Heart of Power System Reliability

If the transformer is the heart of the electric power system, the insulating liquid is the blood, and it can tell you an incredible amount of information about the transformer's condition. Liquid sampling and testing is cost-effective and highly informative, and the liquids also play a key role in other diagnostics such as infrared (IR) thermography and continuous monitoring devices.

Typical Tests

The most common tests are indicators of general aging and contamination, moisture incursion, and incipient faults. It is imperative that the sample pulled is representative, and methods exist to help define the sampling process such as ASTM D923. Once you have a good sample, there are many tests available. Typical tests are:

- **Liquid Screen** – A group of tests that looks for signs of premature aging of the dielectric liquid. A liquid screen can also point to contamination from internal issues such as coking or sludge, or external issues such as contamination from other liquids.
- **Karl Fischer** – This test measures the amount of moisture in the dielectric liquid, and the liquid

temperature can be used to calculate the percent saturation of water. This is an important test because elevated moisture results in accelerated aging of the solid insulation and if high enough can even result in the failure of the transformer. Moisture in dielectric liquids can also lead to oxidation and formation of acids that degrade the solid insulation.

- **Dissolved Gas Analysis (DGA)** – DGA detects the presence of key gases that can identify incipient faults from low- to high-energy events and can point towards issues with the solid insulation.
- **Power Factor** – This test can indicate liquid breakdown, contamination, and in some cases, moisture.
- **Inhibitor** – Transformer oil typically includes an inhibitor to help prevent oxidation, which can lead to premature aging of the liquid; this test quantifies the amount of inhibitor in the liquid.
- **Furan Analysis** – A byproduct of paper degradation is the formation of certain compounds, called furans, which can be quantified and correlated to the state of aging of the solid insulation in the transformer.
- **Metals in Oil** – This test can determine very low quantities of dissolved metals such as aluminum, copper, and iron.

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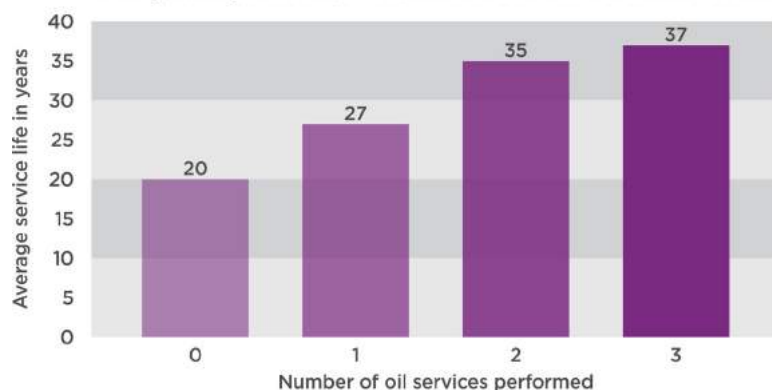
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Infrared Scanning / Thermography

Liquid-filled transformers also provide an opportunity to use infrared scanning to look for signs of thermal issues in your transformer. Infrared scanning, or thermography, can identify anomalies such as overloading, unbalanced loads, low liquid levels, issues with the cooling system, hot spots, loose connections, and faulty gauges. While thermography can be used on any electrical asset for thermal profiling, the insulating liquid helps highlight issues such as hot spots, liquid level, or other cooling issues due to the heat transfer properties of the liquid.

The data shows that insulating oil maintenance results in about six years of additional service life each time it is performed!



Average Service Life Related to Number of Oil Services Performed*An SDMyers study based on 1,534 decommissioned oil-filled transformers > 500 kVA***Liquid Monitoring**

Another benefit of the insulating liquid is that technology advances in the past several years have created the opportunity to monitor some health characteristics in addition to laboratory testing. Monitoring devices are readily available that can monitor moisture levels and dissolved gas (DGA) levels, which have long been only available by laboratory testing.

These devices often offer additional data collection as well, such as liquid temperature or even load on the transformer to aid in diagnostics. The ability to closely watch trends in these important insulating liquid related values is a significant step in ensuring the reliable life of a liquid-filled transformer.

Ensuring the Reliable Life of your Transformer

The insulating liquid in your transformer is at an intersection where its use is ubiquitous and the potential to learn about the health of the transformer is enormous. It is crucial to the reliability of your transformer, so it should be a priority to keep in excellent condition and correct any deficiencies quickly. The data shows that insulating oil maintenance (oil reclamation, moisture reduction, or re-inhibit) results in about six years of additional service life each time it is performed! Keeping the transformer in good condition via routine and responsive maintenance and maintaining the insulating liquid are sure-fire ways to help ensure the reliability of your electrical power system and extend the useful life of your critical power assets.



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Materials Compatibility: Lessons Learned from the Transformer Oils Study

by David Holland

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A study was conducted to assess the compatibility between each of four leading transformer oil products and each of eight common transformer component materials. The sample of four transformer oil products tested included two primarily naphthenic oils and two isoparaffinic-based transformer oils. Results of the test were twofold. First, both isoparaffinic-based transformer oils demonstrated compatibility across a wider set of transformer component materials than either of the tested naphthenic oils. Second, two commonly used materials in transformer components, neoprene and nitrile, demonstrated poor compatibility across all four of the tested transformer oils. This article describes the test methodology and discusses the study results that may be of interest to manufacturers and operators of transformers.

The quality of the gasket material plays a key role in achieving compatibility with mineral oil.



David S. Holland is currently Global Fluids Customer Applications Development Technical Professional at ExxonMobil Chemical Company. Employed by the company since 2010, he has previously held positions in chemicals manufacturing, supply chain and technology. David received his B.Sc. degree in Chemical Engineering from the University of Florida. David can be contacted with questions at david.s.holland@exxonmobil.com.

Compatibility testing between the transformer oil and other solid insulation materials in the transformer is essential for the understanding of long-term performance of transformer oil design.

Introduction and Scope

Transformers include many types of insulation materials in addition to the oil, each material critical to the system performance. Solid insulation materials like rubber seals/gaskets or elastomers are frequently examined for compatibility. Separate from these, resin, laminate, silicon, paper and others may also be included. Materials compatibility testing is essential for the understanding of long-term performance of transformer oil design. One well known issue in transformer operation is oil leakage from gaskets. In fact, seal gaskets have the potential to become a critical root cause of failure in transformers. CIGRE's working group conducted a survey and found that 13% of power transformer failures were due to leakage [1]. According to a Renewable and Sustainable Energy Review [2], damaged seals and oil leakages account for 32% of outages. Another study on failures in power system transformers concluded that the most common cause of failure in 20–400 MVA transformers was general ageing and insulation deterioration [3]. Therefore, understanding compatibility is necessary to ensure safe operation. The less influence the oil has on the gasket materials, the less deformation and deterioration of the gasket will occur. Not only is the choice of a high-quality transformer oil important in this equation, ensuring the use of high-quality materials is also necessary for safe and long lasting transformer design. It is known that rubber gaskets can leach particles into the oil due to the solvency nature of the oil. Not only will this degrade the quality of the gasket, but it can also reduce the electrical insulating properties of the oil and impact the overall insulation performance of the system. It is evident from the study outlined here that the quality of the gasket material plays a key role in achieving compatibility with mineral oil.

Significance and Use

The compatibility between the transformer oil and other solid insulation materials in the transformer is important for long term reliability. The magnitude of changes in the electrical, physical, and chemical

properties of the oil after immersion of the solid materials are important for determining the presence and extent of contamination and therefore the suitability of the oil and materials in that system. The test method utilized may also help confirm the quality of the solid materials since both high quality and commercial grade options are available for use in transformers. In the case of power transformers where longevity and long-term performance are important, it is important to use high quality grades, especially for any elastomeric components.

Standard and Experiment

The standard method ASTM D3455 *Compatibility of Construction Material with Electrical Insulating Oil of Petroleum Origin* was used. The method is quite involved in terms of preparation, execution, and it requires accurate measurement of the oil properties in the analysis. In the method, each oil sample receives an oven-treated test specimen (solid components) immersed in it and together each sample is treated in an oven at 100°C for a duration of 164 hours. After this period, the sample is removed, allowed to cool, and the test specimen is removed. The oil is then tested for select physical, electrical, and chemical properties to detect and quantify the resulting contamination that may come from immersion at high temperature.

Sample material

Neoprene

Nitrile

Nylon

Copper with resin

Copper

Paper

Silicon steel

Painted laminate

At this point, the oil and solid material can be evaluated for suitability in the transformer design. Table 1 lists the test specimens chosen for the test.

The method itself provides guidance for (1) the types of materials typically analyzed, (2) a specified solid quantity to oil volume ratio,

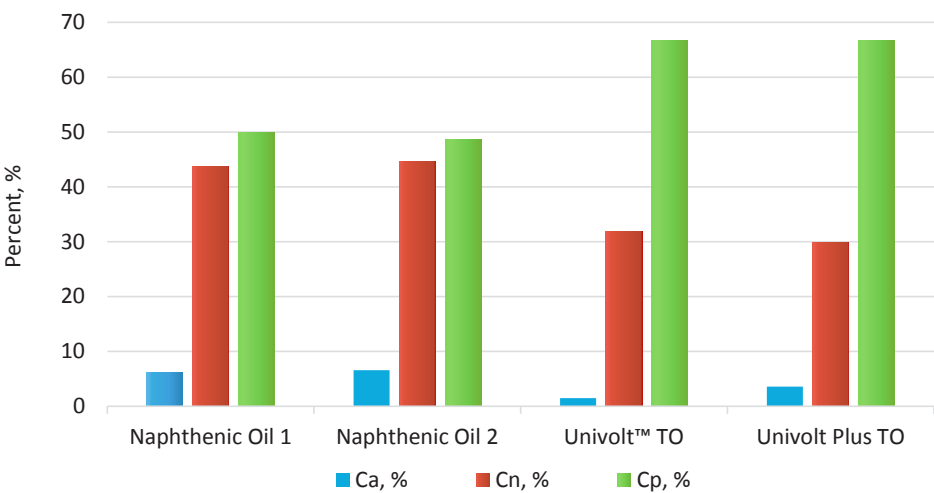
Table 1. Solid test specimens for compatibility testing

and (3) the analytical methods recommended to assess oil quality after the immersion period. Though specifications for the oil tests are recommended, they do not define the compatibility of a system per se because values for these limits were derived from typical values of most mineral oils available on the market at the time the method was finalized. For this reason, it is often helpful to do comparative testing, e.g. testing multiple oil products or testing alongside a known baseline.

The Transformer Oils Being Compared

Figure 1 shows the composition of the four distinct transformer oil products chosen for this study. Two typical transformer oils containing high naphthenic carbon content were compared with two oils (Univolt™ and Univolt Plus transformer oil) containing higher isoparaffin content and lower naphthenic carbon content. While containing both naphthenes and isoparaffins, these two oils will be referred to as “isoparaffinic oils”.

The magnitude of changes in the electrical, physical, and chemical properties of the oil after immersion of the solid materials are important for determining the presence and extent of contamination and therefore the suitability of the oil and materials in that system.



Results

The 2021 analysis by Doble Engineering shows high variation in the compatibility results for neoprene, nitrile, nylon and less variation for copper, paper, and laminate. In fact, all oils are determined to be compatible with laminate, copper, silicon steel and paper. Therefore, the focus of the discussion is on the more susceptible materials: neoprene, nitrile, nylon and copper with resin. Table 2 shows the final compatibility determination for each oil.

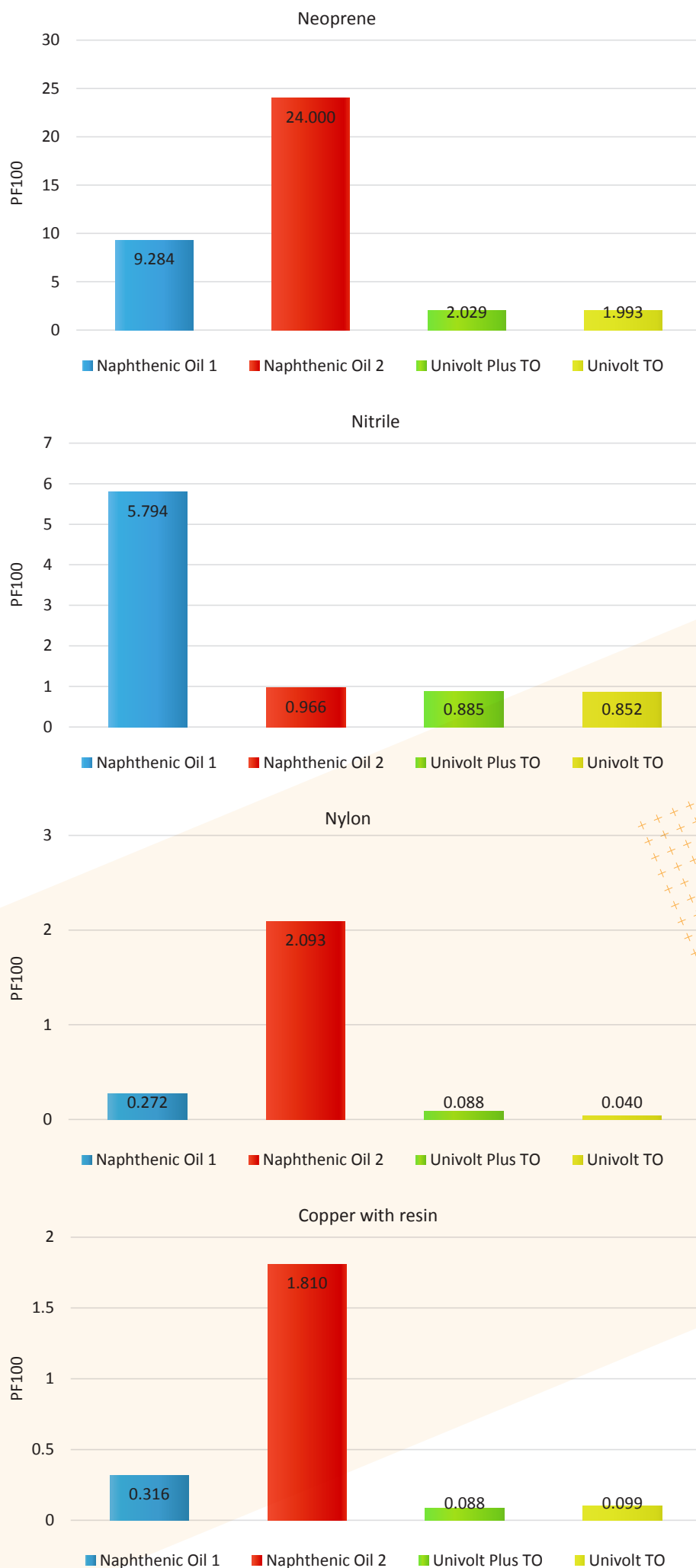


Sample material	Naphthenic Oil 1	Naphthenic Oil 2	Univolt TO	Univolt Plus TO
Neoprene	NC	NC	NC	NC
Nitrile	NC	NC	NC	NC
Nylon	NC	NC	C	C
Copper with resin	NC	NC	C	C
Copper	C	C	C	C
Paper	C	C	C	C
Silicon steel	C	C	C	C
Painted laminate	C	C	C	C

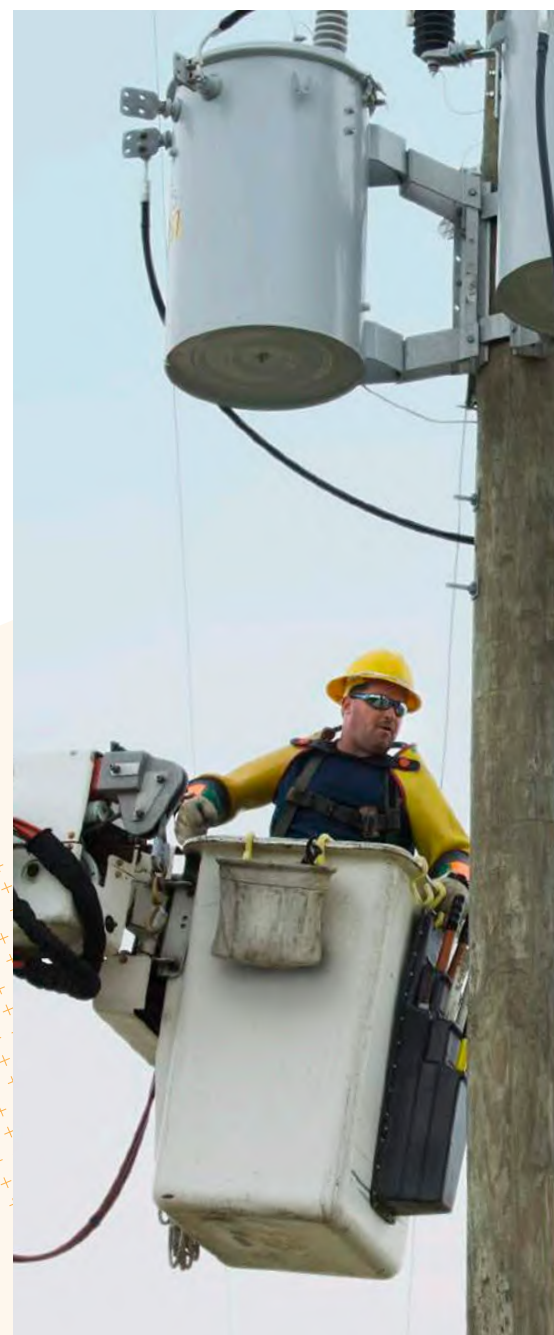
Table 2. Compatibility results of ASTM D3455.
NC = not compatible, C = compatible

Figure 1. Percentage of aromatic carbon content (Ca), naphthenic carbon content (Cn), and isoparaffinic content (Cp), based on ASTM D2140. Naphthenic Oils 1, 2: Doble TOPS Survey 111. Univolt, Univolt Plus TO: Doble TOPS Survey 112



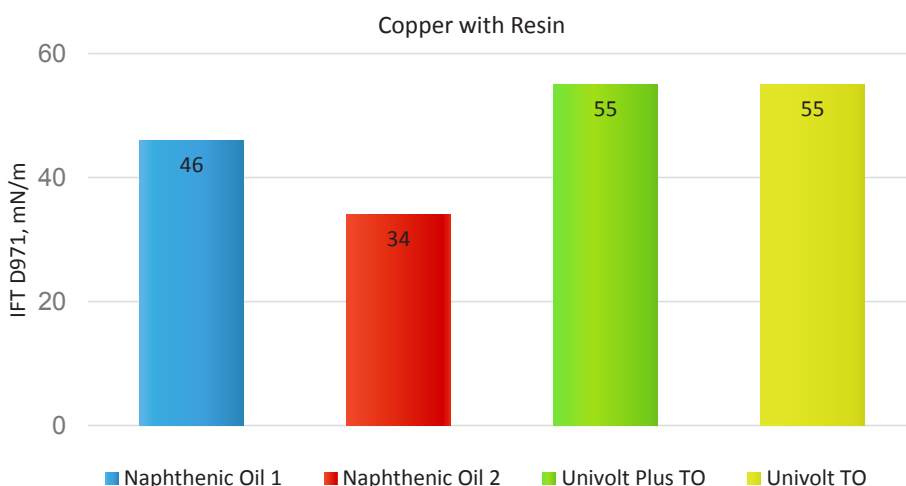
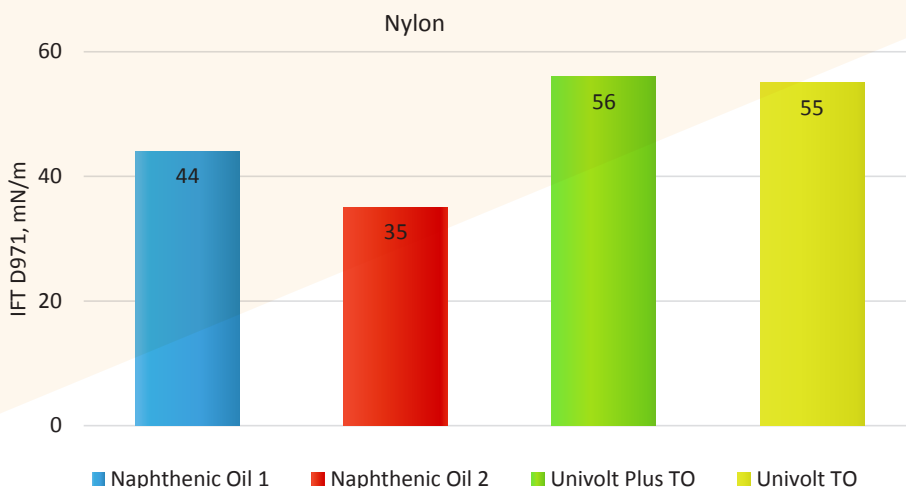
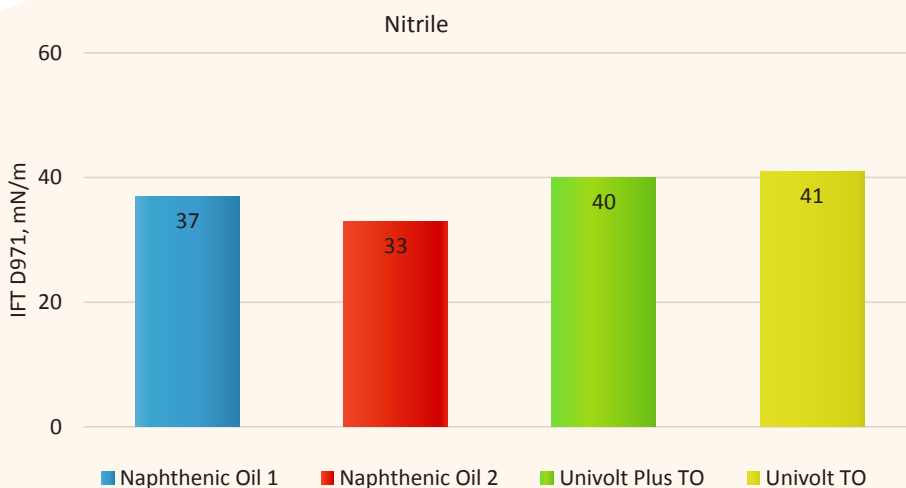
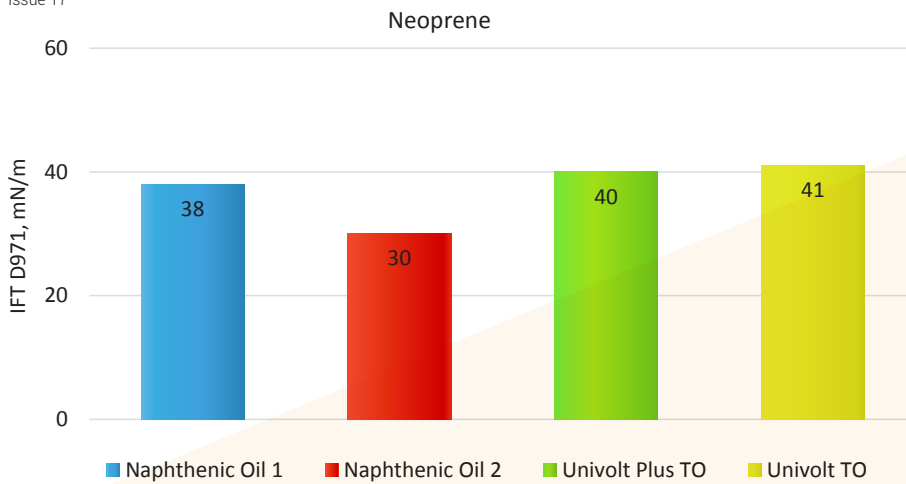


Figures 2-5. Power Factor at 100°C (PF100) of the oil after immersion

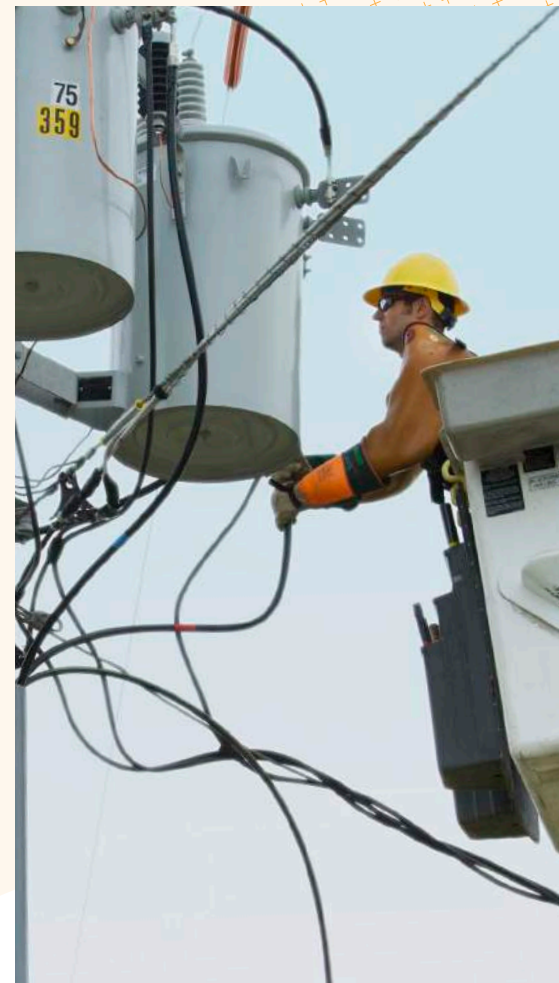


Figures 2-9 show the test results of the oil properties compared for a single material. Figures 2-5 focus on the measured Power Factor at 100°C (PF100) of the oil after immersion. Figures 6-9 show the measured Interfacial Tension (IFT) after immersion.

The isoparaffinic oils exhibited a lower PF100 for all materials and maintained a higher IFT, especially for the most susceptible elastomer materials like neoprene and nitrile. For Figures 2-9 above, the isoparaffinic grades have better demonstrated performance.



Figures 6-9. The measured Interfacial Tension (IFT) after immersion



OEMs and utilities that are concerned about the longevity of their transformers should consider using an isoparaaffinic-based transformer oil to maximize material compatibility.

The study informed that both grades of neoprene and nitrile were actually incompatible with all the oils. This result was not unexpected considering neoprene is known to show poor compatibility with mineral oils. While this study shows it is not advisable to use neoprene or nitrile in transformer construction, higher quality of grades of these types of materials should be available which may show better compatibility with mineral oil than the commercial grades have. For example, nitrile with a high concentration of acrylonitrile would be a better choice.





Acknowledgements

This work was financially supported by Exxon Mobil Corporation.

Discussion

Good material compatibility between transformer oils and gasket materials is an important property of oils which can help reduce the risk of seal failure and leaks. This report offers a direct comparison of several oils' compatibility performance with different gasket materials. Maintaining a low PF100 is desired as it indicates less dissolved impurities due to the oil having less influence on the elastomer. The main cause for the difference in the gathered results is the fact that isoparaffinic oils have less aromatic and naphthenic carbon content than the naphthenic based oils. Aromatics and naphthenes are two carbon constituent types that are related to solvency strength and tend to have low aniline points. Conversely, isoparaffinic oils have high aniline points. Therefore, improved materials compatibility is owed in part to having a lower solvency strength of the oil.

The results for compatibility of mineral oil with common gasket materials like neoprene and nitrile is not surprising as neoprene and nitrile generally do not perform well interacting with mineral oils. While ultimately not compatible, the data do show the materials actually had less of an interaction with the isoparaffinic products than with the naphthenic products. After heat treating, the isoparaffinic products showed the lowest Power Factor response and maintained a higher Interfacial tension. As said previously, this would for the most part be due to the base oil composition. The isoparaffinic products, having lower naphthenic content, have directionally lower solvency. In addition, naphthenic carbon content is known to have embedded aromatic constituents which will directly contribute to solvency. (ASTM D2140 is a measurement of total aromatic content, whether the aromatics are pure compounds or constituents of naphthenes, i.e. embedded aromatics.)

Conclusion

There is a lot of focus on the elastomer type components because of their difficult compatibility with mineral oil products. Neoprene continues to be the most affected material when exposed to mineral oil. Based on ASTM D2140 compositional analysis, isoparaffinic-based transformer oils have very low aromatic carbon content, and naphthenic-based transformer oils can present a range of aromatic carbon content, typically 5-20%. From a compositional and solvency perspective, naphthenic-based mineral oils tend to interact with elastomer components more than do isoparaffinic-based mineral oils, as shown in the PF100 and IFT data. OEMs and utilities that are concerned about the longevity of their transformers should consider using an isoparaffinic-based transformer oil, such as Univolt TO, to maximize material compatibility. In addition to oil suitability, this study also provided insight into the quality of materials. Mainly the materials other than neoprene and nitrile should be considered for elastomeric transformer components, as these two materials demonstrate poor compatibility across the range of tested transformer oils. When considering nitrile, preference should be for the higher quality grades for use in transformer construction. Transformer manufacturers and utility companies may like to consider this information in materials selection or qualification processes.

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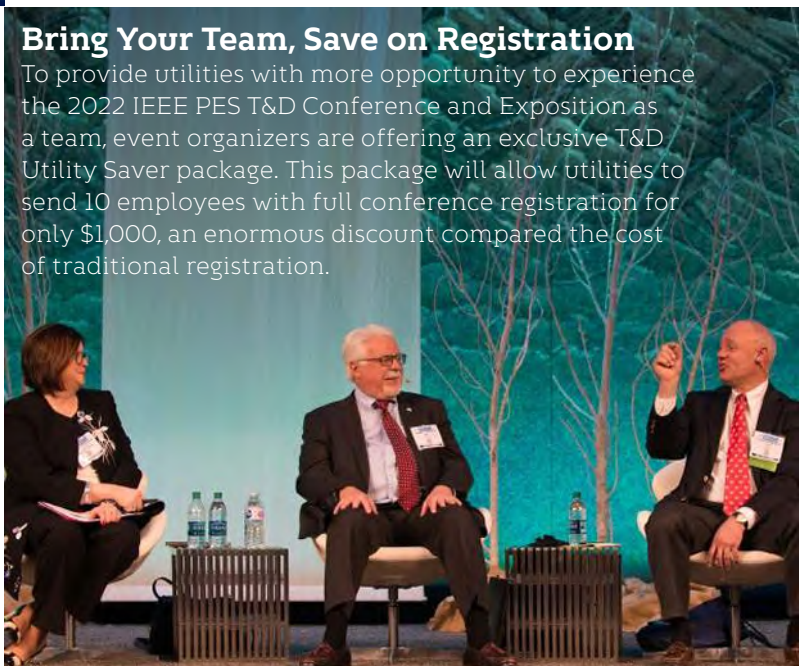
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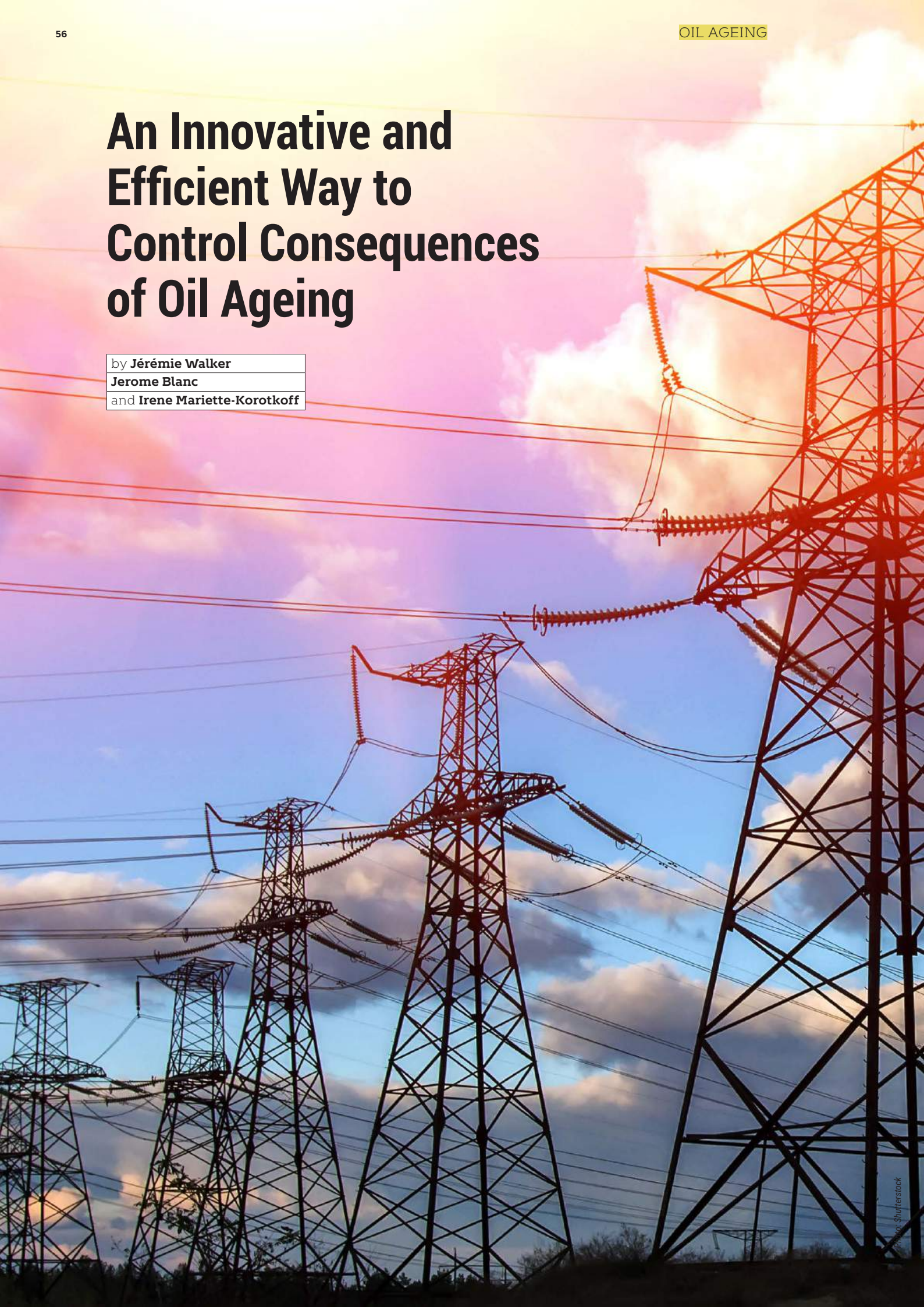
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An Innovative and Efficient Way to Control Consequences of Oil Ageing

by **Jérémie Walker**

Jerome Blanc

and **Irene Mariette-Korotkoff**



Gas accumulation in mineral oil can make partial discharges persistent and lead to transformer explosion, increasing the risk of fire. A gas-evolving mineral oil can become gas absorbing by adding a few percent of methylpolyarylmethane derivatives, a highly efficient additive that can limit the impact of mineral oil decomposition for transformers affected by corona partial discharge.



Jérémie Walker holds PhD degree in Mass Spectrometry from Swansea University (Wales, UK).



Jerome Blanc is a Chemical Engineer from Chimie ParisTech (France).

Working at Arkema Research Centre located in Pierre-Benite, France.



Irene Mariette-Korotkoff is a Senior Scientist specialized in dielectric applications.

Working at Arkema Research Centre located in Pierre-Benite, France.

Arkema team has more than 30 years of experience in the development and analyses of dielectric and insulating fluids for high voltage capacitors and transformers. Beyond some valuable technical publications made at international events in these fields, they are members of CIGRE and of International Electrotechnical Commissions (IEC) to contribute to the maintenance of standards.

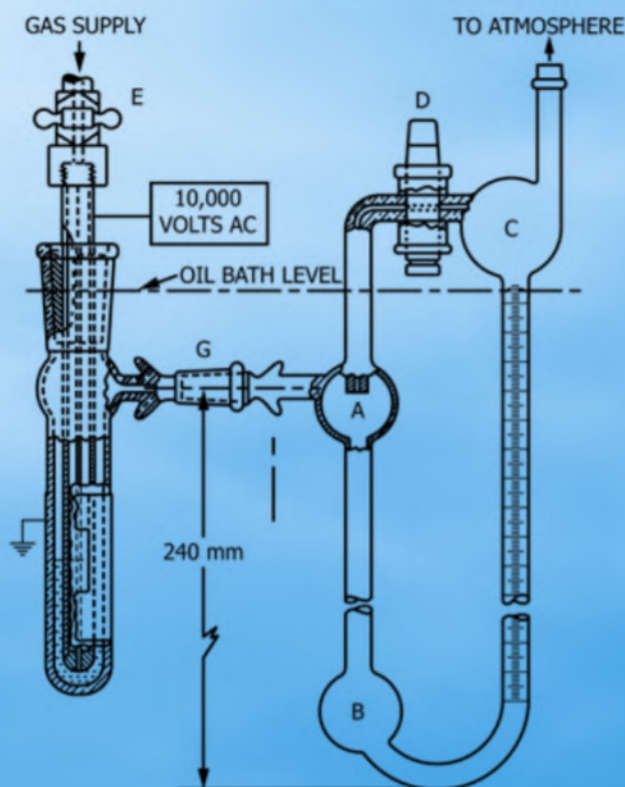


Figure 1. Schematic diagram of gassing-cell and gas-burette assembly (from IEC 60628 [1])

Background

The oil used in transformers has several main functions as it acts as electrical insulation, cooling medium and information carrier. Besides, there are some additional properties expected from transformer oil, such as compatibility with cellulose insulation, fire safety consideration and environmental requirements. Mineral oils have been widely used in transformers for more than a hundred years. However, most mineral oils are now highly refined to meet health and environment requirements as well as more stringent requirements for corrosive sulphur. Highly refined oils usually contain less aromatic and other unsaturated compounds due to the hydrogenation process. Consequently, the gassing tendency of the mineral oils becomes more positive. This phenomenon and a way to deal with it will be described more precisely in this article.

About Gassing Tendency

The gassing tendency refers to the behavior of an insulating liquid when gases have been produced due to low energy electrical stresses.

When the gassing tendency is negative, the gases are absorbed by the oil. When the gassing tendency is positive, more gases are produced than the absorption capacity of the oil.

This concept could be characterized in the following way:

- When the gassing tendency is negative, the gases are absorbed by the oil.
- When the gassing tendency is positive, more gases are produced than the absorption capacity of the oil.

The gassing tendency of transformer insulating fluids under partial discharge conditions has become an increasingly important issue because the presence of gas increases the potential for failure. To ensure a harmonized definition and a reliable measuring method, the gassing tendency of insulating fluids is fully described in IEC standard 60628-A [1].

After being dried and saturated with hydrogen gas, the insulating liquid and the hydrogen pocket above the liquid are subjected in the specific cell to a radial electrical stress under following experimental conditions:

- Voltage: 10 kV
- Frequency: 50 Hz
- Temperature: 80°C
- Test duration: 120 min

During the test, the liquid level in the burette is closely monitored, and the gassing tendency is calculated from the difference between the initial level and the level after 120 min.

A Practical Solution to Solve Positive Gassing

As mentioned above, due to health and environmental issues, mineral oils are almost exempt of aromatic and mainly poly aromatic hydrocarbons (PAH). It is known that the presence of aromatic hydrocarbons has a strong effect on

the negative gassing tendency of the oil. The aromatic species act as hydrogen scavenger if the mineral oil is decomposed due to a partial discharge default of the transformer.

An easy way to cope with this consists in using methylpolyarylmethane derivatives (carrying aromatic rings) as a

complement to mineral oils, in a range of 4 to 8 weight-% in average (and depending on the type and origin of the mineral oil). It will restore the negative gassing performance of the mineral oil.

Methylpolyarylmethane derivatives are available products as they have been extensively used as heat transfer fluids, at service temperatures up to 330°C, thanks to their excellent thermal stability. This use confirms the high stability of this type of molecules. In addition, since methylpolyarylmethane derivatives are synthetic liquids, they have a well-defined composition. Methylpolyarylmethane derivatives are not of the same structure of polyaromatic hydrocarbons, they are

For medium and low voltage transformers, the preferred solution consists in a mineral oil treatment with external tools in order to eliminate maximum of dissolved hydrogen, water traces and other impurities. This treatment is costly and requires a transformer shutdown during a period from one to several days, depending

	Transformer	Power (kVA)	In/Out (kV)	Methylpolyaryl methane derivatives (weight-%)	Gassing tendency mineral oil (µl/min)	Gassing tendency mineral oil with additive (µl/min)
With prior treatment	Case 1	1600	15/0,4	5.6	12.5	-11
	Case 2	500	63/10	6.3	10	-19
	Case 3	2600	34/0,7	8.5	5	-29
Without prior treatment	Case 4	2600	34/0,7	8.5	0	-56
	Case 5	2600	34/0,7	8.5	5	-48
	Case 6	2600	34/0,7	8.5	8	-25

Table 1. Overview of the results for the group of transformers

of transformer size and quantity of oil to treat.

Practical Example

To demonstrate the benefits of the addition of methylpolyarylmethane derivatives in mineral oil of transformers affected by corona partial discharge several studies have been launched over the last years.

First, a series of two transformers underwent a preliminary treatment of the mineral oil in order to remove a maximum of dissolved hydrogen before adding the methylpolyarylmethane additives into the mineral oil.

A second series of four transformers associated with a group of wind turbines were treated by direct addition of the methylpolyarylmethane in the mineral oil already present to the transformer. The oil from these transformers has been monitored and evaluated over several years.

Table 1 summarizes the result obtained on the different transformers.

The amount of methylpolyarylmethane derivatives added was defined by analysis of mineral oil gassing tendency. The target is to reach a gassing tendency in the range of -10 to -20 µl/min measured for the mineral oil. This target value is

important to have enough negative gassing tendency in the liquid medium to absorb the hydrogen formed due to the corona partial discharge phenomenon.

The oil analyses are done by an external laboratory specialized in transformers oil analysis.

Thanks to their high aromaticity, methylpolyarylmethane derivatives exhibit a strong gas-absorbing ability.

The gassing tendency is measured according to the IEC 60628-A [1], see Table 2.

The trend is similar for all the transformers that received an addition of methylpolyarylmethane oil.

This clearly confirms that the gassing tendency of the transformer oil went from a positive status to a negative status that enables to absorb the hydrogen formed due to the corona partial discharges transformers default.

This comes from the fact that thanks to their high aromaticity, methylpolyarylmethane derivatives exhibit a strong gas-absorbing ability.

For example, according to IEC 60867-1993 standard, it is said to be as low as 130 µl/min for pure methylpolyarylmethane oils [2].

In the case of oil pretreatment (Cases 1 and 2 in Table 2), the hydrogen increase noticed after few days is normal. During the oil treatment, it is not possible to treat all the oil present in transformer since the oil present in the paper, wood and cardboard is not completely removed. After restarting the transformer this remaining fraction of oil is mixed with the cleaned oil and after few days of operation an equilibrium is reached.

Beyond the positive effect observed for the gassing tendency, it is important to know that the addition of methylpolyarylmethane derivatives does not interfere with other methods to monitor transformer defects. As an example, let's consider thermal defects and the role of dissolved gas analysis (DGA).

Dissolved gas analysis (DGA) is among the most powerful tools for detecting faults in electrical equipment in service. For that reason, DGA analytical techniques and interpretation methods are continuously being investigated and improved. Indeed, to follow the technical trend regarding the increasing use of non-mineral oils (such

as natural and synthetic esters and silicone oils), DGA analytical techniques for non-mineral oils were developed. Among the parameters that needed to be adjusted, time is a critical one. For the extraction of gases dissolved in oil, the viscosity of the oil is a key parameter that needs to be considered to allow sufficient time to reach the equilibrium. The more viscous the oil, the longer the equilibrium time. These parameters are described in the dedicated standard IEC 60567 [3].

Regarding the results, DGA interpretation methods for mineral oils are based on many cases of transformers in service where gas

formation could be attributed to a specific type of fault. Gas formation patterns are basically the same in mineral and non-mineral oils (the same types of gases are formed for a given type of fault), but with some quantitative differences in the ratios of gases formed. That is particularly important to make sure that in the case of the addition of methylpolyarylmethane derivatives in mineral oils, electrical or thermal defects are not hidden.

A 15x15 grid of plus signs (+) arranged in 15 rows and 15 columns, totaling 225 plus signs.

	Hydrogen amount in transformers (mg/l)					
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Before oil treatment	1055	19460	37185	33976	43217	34243
Oil after treatment	66	20				
Few days after additive treatment	250	1836				
6 months	70	1570				
1 year	20	1137	24746	23271	17169	32769
2 years	12		14281	16355	10883	24907
3 years	10	270	-	-	-	-

Table 2. Dissolved hydrogen evolution for the group of transformers currently in operation



Comments and Conclusions

The production of gas is the result of the electro-chemical degradation of the fluid into smaller molecules such as hydrogen. In the case of gas-evolving fluid (mineral oil), the gas can accumulate and make partial discharges persistent. The accumulation of the gas could lead to explosion of the transformer and significantly increase the risk of fire to take place. A gas-evolving mineral oil can become gas absorbing by adding a few percent of methylpolyarylmethane derivatives.

The benefits of the methylpolyaryl-methane derivatives is their efficiency even if the mineral oil contains some high quantity of dissolved hydrogen. The high efficiency of this additive to limit the

impact of mineral oil decomposition for transformers affected by corona partial discharge phenomenon is important for transformer owners.

The addition of methylpolyarylmethane derivatives does not interfere with monitoring of other defects such as thermal defects.

In addition, the treatment cost will be strongly reduced as it is demonstrated in this article that preliminary oil treatment before additive adding in the transformer is not mandatory.

In the meantime, other electrical parameters such as breakdown voltage will remain comparable and the addition of this aromatic fraction

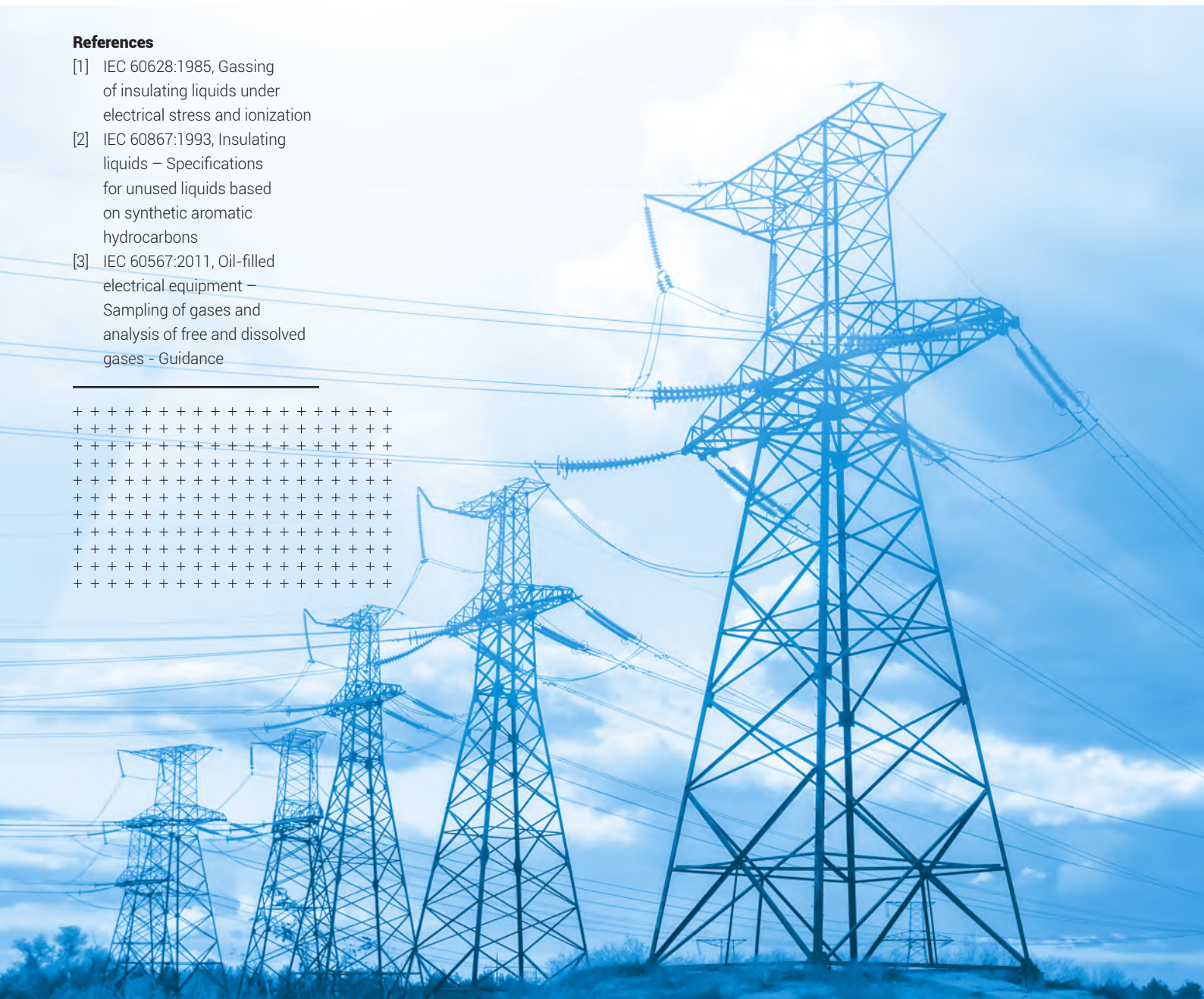
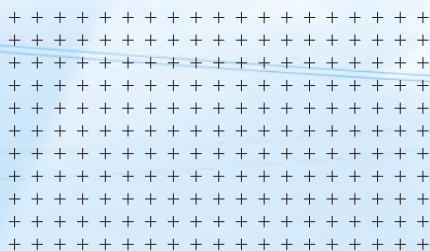
will not bring an issue for oil breakdown strength. Moreover, it was proven that the addition of methylpolyarylmethane derivatives does not interfere with the monitoring of other transformer defects such as thermal defects.

Based on these
interesting results

applied to the case of mineral oils in transformers, it would be worth conducting a similar evaluation for transformers filled with vegetable oils and suffering from partial discharge issues.

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Decay Particles and Regeneration of Ester Dielectric Liquids A Challenge!

by **U. Mohan Rao**
I. Fofana
and **P. Picher**



Issouf Fofana, Fellow of the IET, holds a bachelor's degree in electro-mechanical engineering, and a master's and doctoral degrees obtained from École Centrale de Lyon, France. He was a postdoctoral researcher in Lyon in 1997 and was at the Schering Institute of High Voltage Engineering Techniques at the University of Hanover, Germany from 1998 to 2000. He was a Fellow of the Alexander von Humboldt Stiftung from November 1997 to August 1999. He joined Université du Québec à Chicoutimi, Canada as an Associate Researcher in 2000, and he is now a professor there. Dr. Fofana has held the Canada Research Chair, tier 2, of insulating liquids and mixed dielectrics for electrotechnology (ISOLIME) from 2005 to 2015. He is the Research Chair on the Aging of Power Network Infrastructure (ViAHT), director of the MODELE laboratory and the International Research Centre on Atmospheric Icing and Power Network Engineering (CenGivre) at UQAC. He is a member of the ASTM D27 Committee. He is the 2021 IEEE Jidan Chen Award. Since 2018, he is chairing the IEEE Technical Committee on Liquid Dielectrics. He has authored/co-authored over 300 scientific publications, three book chapters, one textbook, edited four books and holds three patents.



U. Mohan Rao, Senior Member, IEEE, holds a bachelor's degree in electrical and electronics engineering, and a master's and doctoral degrees obtained from the National Institute of Technology, Hamirpur, India. At present, he is a lecturer in the Department of Applied Sciences at Université du Québec à Chicoutimi (UQAC) in Canada. He is also a postdoctoral researcher at UQAC with the Research Chair on the Aging of Power Network Infrastructure (ViAHT). Dr. Mohan is a Senior Member of IEEE and Member of the IEEE DEIS. He is also the Secretary for the IEEE Technical Committee on Liquid Dielectrics. His main research interests include aging phenomena of high-voltage insulation, condition monitoring of electrical apparatus, alternative dielectric materials, transformer insulation in cold countries, and AIML applications.



Patrick Picher, Senior Member, IEEE, received the B.Eng. degree in electrical engineering from the Université de Sherbrooke, Sherbrooke, Québec, Canada, in 1993, and the Ph.D. degree from the École Polytechnique de Montréal, Montréal, Québec, in 1997. He is currently a Researcher and a Project Manager with the Hydro-Québec's Research Institute, IREQ. His research interests include transformer modeling, diagnosis, and monitoring.

Ester dielectric fluids are no longer restricted to laboratory investigations and serve several transformers connected to the electric power network. Along with other technical aspects, it is also essential to understand the regeneration aspects of these alternative insulating liquids. Fuller's earth is a popular and widely accepted adsorbent for regenerating mineral oils. The feasibility of using Fuller's earth for ester dielectric liquids is reported in this article.

Introduction

Transformers are considered to be the most critical and expensive equipment in the power system network. In these important machines, the insulation system is composed of oil and paper. Mineral oils, derived from petroleum (non-biodegradable resources), are typically used in the power transformer industry. However, since the past few decades, ester dielectric liquids are being popular [1]. Due to the global warming, "sustainable development" has become a very important concept for the scientific community. The focus is now on harvesting renewable resources instead of depleting fossil fuels, and the use of more environmentally friendly materials. Ester fluids (biodegradable resources), which exhibit excellent thermal performance, enhanced fire safety and increased environmental protection, are foreseen as the workhorse for the decades to come.

It is no wonder that the most recent Paris climate accord (Paris Agreement) signed by 195 countries, dealing with the mitigation and adaptation of greenhouse gas

emissions and the divestment from fossil fuels, has spurred the exponential development of renewable energy-based technologies. This consequently calls for the need, demand and importance of ester liquids for use in transformer insulation systems. It is established that ester liquids favor longer service life of the solid insulation system while delivering high workability of the transformer [1].

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The global transformer technology involves billions of gallons of insulating liquid filled in the transformer tanks. It is known that mineral insulating oil degradation is reversible by appropriate treatment methods (regeneration, reconditioning, and re-refining). It is desirable that the degradation of ester liquids is also reversible. However, the information on the choice of liquid treatment is challenging and has not yet been entirely explored by the researchers. In addition to the choice of treatment, information on treatment method, treatment type and materials that are to be adopted, etc. is tremendous and stands challenging for the transformer owners. Although different approaches exist, Fuller's earth treatment is a traditional practice of rejuvenating mineral insulating oils. Therefore, it is interesting to understand the feasibility of Fuller's earth as an adsorbent for ester liquids. Regeneration is about removing the decay products (soluble and colloidal), so the type of decay particles needs to be known as this allows choosing the best regeneration method and adsorbent for ester liquids. This article discusses the

results on some experimental studies performed on the degradation and treatment of ester liquids. Some information on the factors to be considered for the regeneration of transformer liquids is also reported.

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Regeneration of Transformer Liquids

Treatment of transformer liquids is a process carried out to rejuvenate the insulating liquid. Increase in aging is reflected by darker oil color that indicates polar contaminant (Table 1). The advantages include extended life of the insulating liquid, enhanced solid insulation performance,

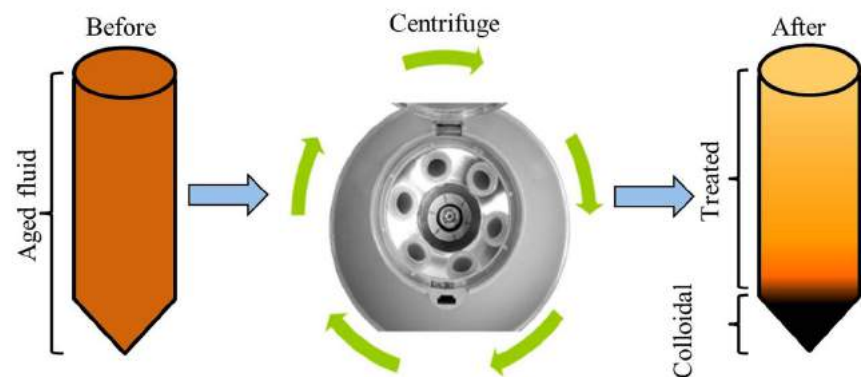
and improved workability of the insulation system [2]. It is to be recalled that the treatment of the in-service liquid includes regeneration (or reclamation) and reconditioning. Treatment of the liquid is performed with an aim to removing soluble and colloidal decay particles (regeneration), dissolved gasses and water (reconditioning). Regeneration is done when the decay concentration (acids, sludge, polar compounds, furans, and other oil/paper oxidation products) is high, while the liquid is expected to be in acceptable condition [2]. Reconditioning is performed when all the liquid parameters are within limits with having excess dissolved gasses or water. Regeneration involves one or a combination of several steps including, adsorbents, mechanical agitations, filtration and scavengers [2, 3]. Recondition involves dehydration, degassing, and vacuum systems. However, reconditioning is also performed along with regeneration. Also, the choice of treatment techniques depends on various factors including, the condition (ageing) of the oil-paper, the color of the liquid and other economic aspects.

Good	Acceptable	Marginal	Bad	Very Bad	Extremely Bad	Disastrous
Effect on transformer						
Proving these functions: 1. Efficient cooling 2. Preserving insulation	Polar compounds (sludges) in solution (oil's oxidation byproducts) causes the drop in IFT and rise in Total Acid Number.	Fatty acids coat the windings. Sludges in solution ready for initial fall out. Sludges in insulation voids highly probable.	In almost 100% of the transformers in this range, sludges are deposited on the core and coils. Sludge is first deposited in fin areas.	Deposited sludges continue to oxidize and harden. Insulation shrinkage is taking place. Premature failure a good possibility.	Sludges insulate cooling fans, block vents causing higher operating temperatures and hot spots.	Vast quantities of sludges may require other means than desludging procedures.

Table 1. Effect of oil quality on transformer

The reclamation aspects of mineral insulating liquids used in liquid-filled electrical apparatus are reported in the IEEE standard C57.637 [2]. Presently, there is no established standard for the reclamation of ester liquids. However, very few authors reported the regeneration of esters with various adsorbents [3, 4]. The details of the adsorbents are not well discussed in the existing literature. However, high treatment temperatures influence the oxidation stability of natural ester liquids and exhibit a notable impact on the weight of the available antioxidants in the bulk of the liquid. To the best of the authors' knowledge, this treatment temperature is not yet investigated by researchers or reported in the existing literature. The chemical composition of ester liquids is completely different from that of mineral oils. The aging processes in mineral oil and ester liquids are therefore completely different. Thus, there is a need to understand the nature of the decay particles before investigating the choice of treatment and other avenues of regeneration. This report presents the type of decay particles in ester liquids and the feasibility of Fuller's earth for the regeneration of ester liquids.

Figure 1. Schematic of centrifuge treatment



Observations

Nature of Decay Particles

To know the type of aging byproducts in ester liquid vis-à-vis mineral insulating oils, accelerated thermal aging of mineral oil (MO), natural ester (NE), and synthetic ester (SE) was performed. The thermal aging was performed at 115°C, 150°C, and 175°C for two weeks each, thus totaling to six weeks of age in the presence of the kraft paper (cellulose) and catalyst. The aged liquids were subjected to mechanical agitation using a typical centrifuge as per ASTM D 1698. The illustration of the centrifuge treatment of aged

liquid is shown in Figure 1. Due to the centrifuge force exerted on the colloidal decay particles, they moved to the tip of the centrifuge tube, thus allowing the separation between the colloidal and soluble particles in the liquids.

It was found that at lower aging conditions (115°C), mineral oil did not witness any colloidal particles. However, at 150°C and 175°C colloidal particles were noticed. In the case of ester liquids, the colloidal particles were not evident through the aging cycle. The view of the centrifuge tubes demonstrating the separation of colloidal particles is presented in Figure 2.

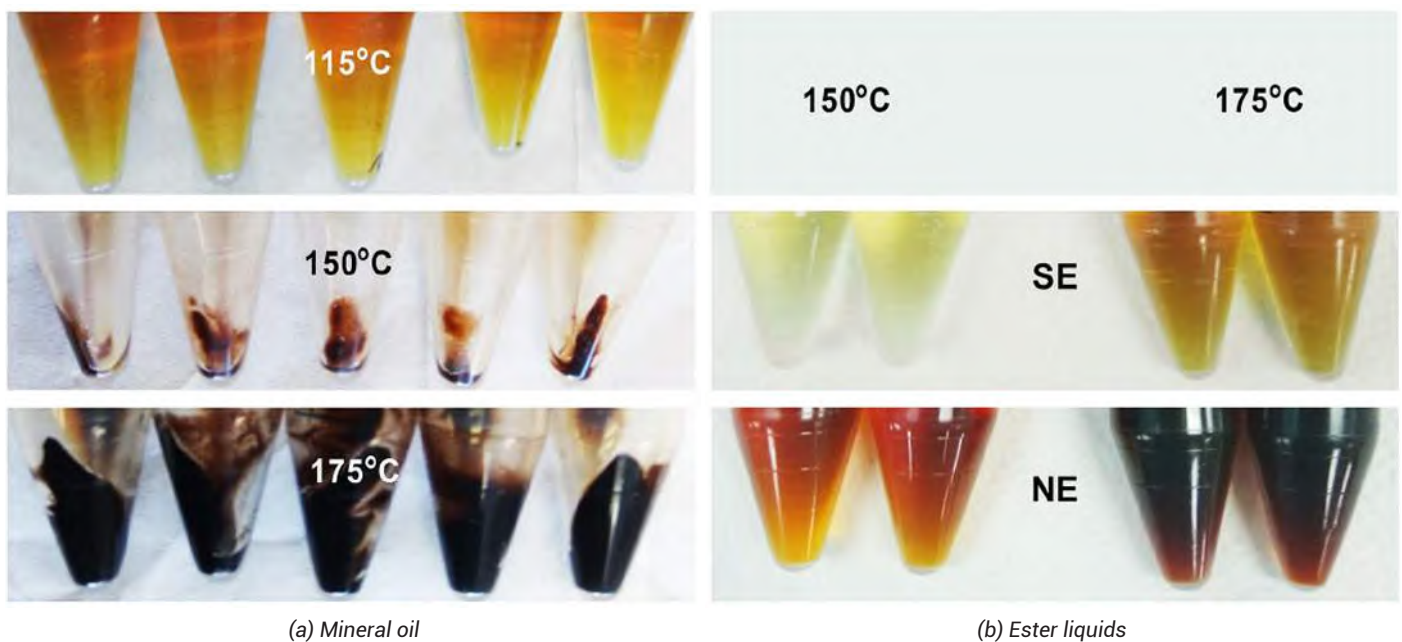


Figure 2. View of centrifuge tubes after treatment of mineral oil and ester liquids at different aging conditions

It was found that esters generate less sludge or colloids while having a high scope for the generation of soluble decay particles. However, it is challenging to comment that ester dissolves sludge or does not generate any sludge with degradation.

Thus, one may understand that the treatment of esters may be mostly focused on the removal of soluble particles along with water and dissolved gasses. The detailed analysis of the results is reported by the author's group in [6].

The changes in the concentration of dissolved decay contents in esters have not witnessed any significant change with the Fuller's earth reclamation.

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Figure 3. View of the laboratory setup for Fuller's earth reclamation

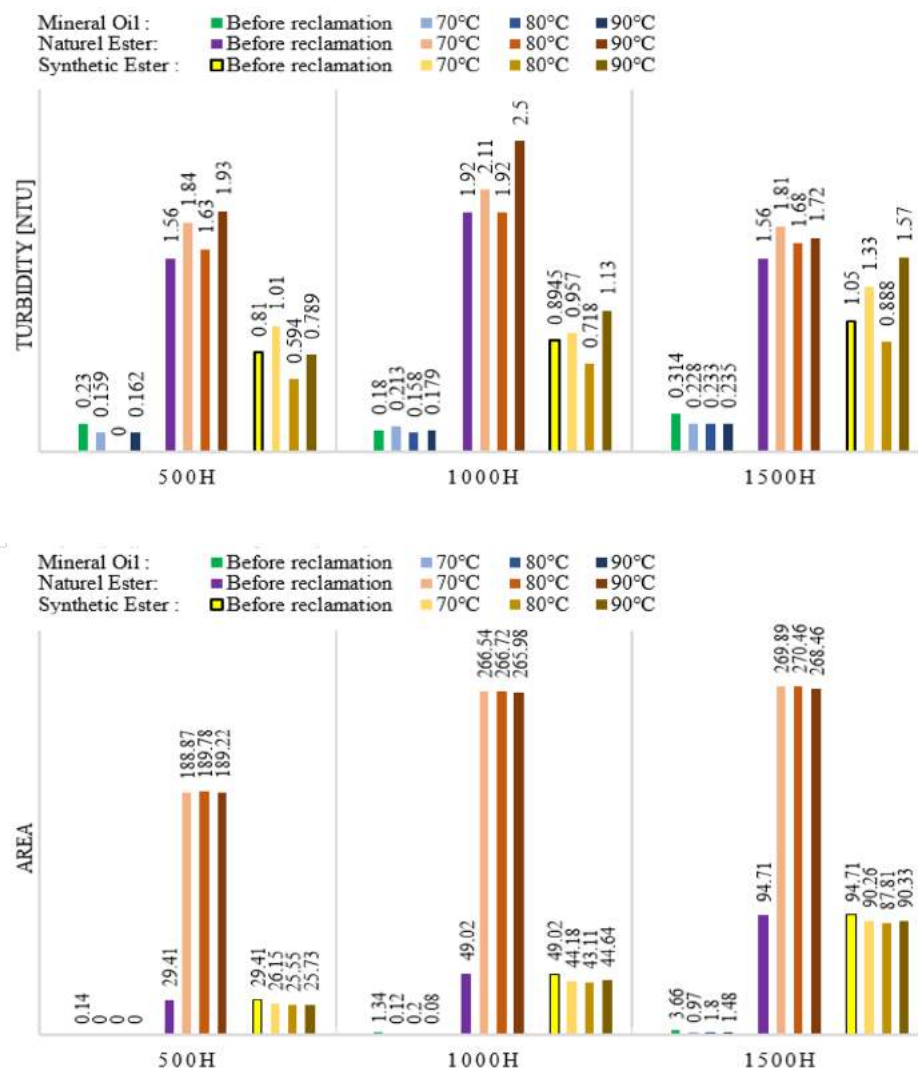
Regeneration of Ester Liquids Using Fuller's Earth

Mineral oil (MO), natural ester (NE), and synthetic ester (SE) were aged as per ASTM D1934 under open beaker conditions in the presence of cellulose and catalyst. Thermal aging was performed at 115°C with an aging history at 500, 1000, and 1500 hours. To perform Fuller's earth treatment as per ASTM D 7150, a laboratory-scale apparatus was fabricated, as shown in Figure 3. The authors have reported the complete details of the setup including the control unit in [4] and [7].

The treatment temperature is a vital parameter for the insulating liquid regeneration process. It is a major parameter that could decide the efficiency of the sorbent and the effectiveness of the treatment process. The sorption process (adsorption or absorption) is attributable to the sorbent's surface properties. The surface properties of any sorbent are temperature-dependent and vary based on the type of the decay products in the feed liquid. Thus, the aged liquids are reclaimed (using Fuller's earth) at a treatment temperature of 70°C, 80°C, and 90°C. Before colloids appear in a liquid, the first sign is the drop in the interfacial tension (IFT) followed by an increase of the total acid number (TAN) and dissolved decay products (DDP) [8]. Dissolved Decay Products (DDP) and turbidity, which change with a larger rate than the IFT values, were investigated as alternative index for insulating oil degradation assessment. Since the TAN or IFT, which are used to reflect the oxidation performance of mineral oils [2], may not be suitable for esters, the reclaimed fluid is collected and tested for turbidity and UV spectroscopy to understand the level of reclamation and feasibility of Fuller's earth for ester liquids. The changes in the turbidity and dissolved decay products for aged and treated (at different temperatures) liquids are presented in Figure 4.

It is seen that the turbidity values are increasing with aging. However,

Figure 4. Changes in the liquid properties before and after reclamation at different temperatures [7]



the turbidity is not reduced with reclamation, especially for the ester-based liquids. It is noticed that the increase of turbidity is slightly less at 80°C of treatment temperature as compared to 70°C and 90°C.

The changes in the concentration of dissolved decay contents in esters have not witnessed any significant change with the Fuller's earth reclamation.

Also, the selected range of treatment temperatures has the least influence on the reclamation of ester liquids. However, the reclamation of esters with Fuller's earth is found unsatisfactory for the present experimental conditions. The detailed analysis of this study has been reported by the author's group in [5]. Also, regeneration for natural esters in particular is challenging.

Conclusion

This report presents the results of the type of the decay particles and the feasibility of Fuller's earth treatment for ester liquids. It is found that the soluble decay content mostly governs the degradation in ester liquids and the suitability of Fuller's earth for ester liquids is questionable. The regeneration avenues and possibilities of the regeneration of esters are still a challenge that needs to be explored.

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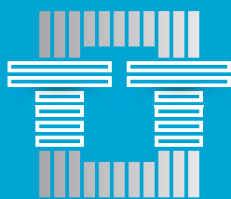
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