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Why Forensic Analysis is a Critical Step in Motor Repair - Case Study - Part 2

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Forensic Analysis of a Silicone Oil Filled Mobile Transformer

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Abstract- **When a number of new silicone oil filled mobile transformers failed, an evaluation of one of the remaining transformers was commissioned. The forensic analysis involved the tear-down and evaluation of the working transformer and components. In this paper we will discuss the steps involved in developing this type of forensic analysis, a few of the findings, and recommendations. Problems identified a range from design issues through to insulation coordination issues that did not cause the initial failures, but were identified as high risk future issues.**

I. INTRODUCTON

Modern television programs can cause a misunderstanding as to the actual work involved in forensic analysis. They rely upon human interviews in order to develop scenarios then apply science, resulting in significant wasted time. In true forensic analysis techniques, the investigator must start out without a conclusion in mind, investigate the actual failure, then work backwards in order to determine what root-cause(s) initiated the fault. In true Root-Cause-Failure-Analysis (RCFA) human intelligence and interviews are considered the least accurate information when developing conclusions and recommendations.

Before starting an RCFA, the level of analysis must be determined. There are a great many flavors to this type of process from a simple 5-Why program, where a simple fault allows an average of five 'why' questions to get to the solution, to far more advanced practices. The key to any forensic analysis effort, however, is to preserve the evidence as quickly as possible. It is also important to ensure that any investigation is performed without finger-pointing. In addition, it is equally important to understand that any failure can have multiple causes which may include:

- Misapplication of the component or system;
- Improper operation;
- Improper or ineffective maintenance;
- Age; and/or,
- Corrective action/repair failures.

The root causes, themselves, will usually fall into one of the following:

- Inadequate or no:
  - Training
  - Procedure(s)
  - Specification(s)
  - Acceptance criteria
  - Vendor review
  - Design review
  - Maintenance practice(s)
- Equipment age (worn out)
- Random reliability failure

In the case of the study shown in this paper, several silicone oil filled, sealed, 12.5/25kV mobile transformers failed catastrophically within three years of operation. Oil analysis identified the possibility that more were in various stages of potential failure and communication between the equipment owner and vendor had become confrontational. It was determined that a more advanced form of RCFA would be required.

II. RCFA PROCESS

A properly performed RCFA analysis requires detailed logical steps and following the evidence. It requires significant discipline in not pursuing tracks that are either emotionally driven or do not follow the logical, Socratic method.

The steps involve preserving the data and evidence, organizing the analysis and selecting a team, analyzing data, communicating findings and recommendations, with follow-through and tracking of recommendation results. Understand that it is possible that recommendations and conclusions formed by the team will not be followed if outside sources, events or politics prevent the appropriate measures. However, properly documented RCFA allows application of these measures once the situation changes.

The first step in the process involves preserving data:

- People: Who was involved?
- Parts: What components were damaged?
- Paper and Electronic: Records, information, history, data, logs, tests, emails, etc.
- Position: Where and what conditions?
- Paradigms: What conditions? Lowest bid? Personnel changes? Political climate? Other environmental conditions.

The primary investigator/facilitator (facilitator) should usually be knowledgeable about the equipment but uninvolved with the failure being investigated. The second step is the development of the investigation team, to be selected by the facilitator, and must consist of all stakeholders in the RCFA. This can include, depending on the situation, buyers, lawyers, operators, maintenance, repair, vendors, managers, etc.

During the investigation, itself, the following steps are followed:

- State the failure event: this is the question to be answered. It must be a statement of fact and not draw any conclusions. For instance, in the case of the mobile transformers: "three transformers have catastrophically failed primary coils during operation."
- Determine the failure modes that could be the direct cause, such as winding shorts, insulation failure, partial discharge, contamination, etc.
- Develop hypothesis around each failure mode.
- Perform tests and investigations to prove/disprove each hypothesis. As soon as a hypothesis is disproved, stop following that path.
- Continue developing failure modes and hypothesis. Multiple branches of investigation are likely and multiple conclusions are likely (it takes an average of seven to eleven events to lead to a failure [1]).
- Determine underlying causes:
    - Physical
    - Human
    - Latent
- How can the problem be prevented in the future: there may be multiple options, some may be discarded for any number of reasons. All such reasoning should be recorded.
- Report findings and obtain decisions with responsibilities assigned and timelines set.
- Track in order to determine impact of corrective actions/inactions over time.

This was the process that was followed for the narrative that is to be the subject of the remainder of this paper. The following narrative will not discuss the process directly but will discuss specific findings and their conclusions. The complete original study progressed over 90 days with laboratory time being the primary delay. The on-site investigation was performed in less than five days.

III. Conditions and Evidence

Information had been presented to the facilitator that three mobile transformers had failed in less than three years of operation. Upon initial review, it was determined that evidence of the cause of failure had become tainted due to teardowns, repairs, and disagreements between the owner and vendor. Third party investigators had been brought in to evaluate field operation, electrical conditions, interview operators, and had exhausted significant resources with no results. Additional studies and directions were provided with no logical basis for expenses and tests. The only solid facts included test data, location of failure within the transformers in the form of digital photos, the nameplates, the oil, drawings, and oil analysis. Information such as materials used was not available due to the breakdown in communication that had resulted.

It was recommended by the facilitator to identify another transformer that was in poor condition, based upon oil analysis results, and have a third party contractor involved in a tear-down investigation. The facilitator also made overtures to a number of laboratories that had silicone transformer oil experience. Based upon an industry lack of experience and challenges by the vendor, it was determined that two laboratories would be selected.

In Table 1, the test limits as obtained from IEEE Std. C57.146-2005 [2] are provided:

TABLE 1
Dissolved Gas Concentration Threshold Levels (ppm)

	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	TDCG
Threshold Level (ppm)	200	100	1	30	30	3,000	30,000	3,361

It should be noted that the transformers in question are sealed and the lack of venting was noted and expected to result in higher values. It was also determined that samples were to be taken of the transformer under investigation after it had been sitting idle and at room temperature. The results were found in Table 2.

TABLE 2
Oil Analysis Results from Transformer Under Investigation (ppm)

	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	TDCG
Sample 2 (ppm)	21	125	0.9	18	7.9	185	1200	358
Sample 1 (ppm)	22	117	1.0	19	8.8	173	1620	341

Both laboratories reported the test results as severe arcing in the transformer while the results were well below those values that had caused the transformer to be removed from service in the first place (Table 3). According to the standard [2]: partial discharge results in primarily hydrogen and methane with small amounts of carbon monoxide, acetylene and ethane; electrical arcing results in hydrogen, methane, carbon monoxide and low levels of acetylene with a larger amount of hydrogen to acetylene.

TABLE 3
Dissolved Gas Concentration In Operation (ppm)

	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	TDCG
Threshold Level (ppm)	316	4604	10	112	65	747	3769	5854

A filter exam was performed on each sample and identified 0% carbon, 30% fibers, and 70% particulate. The visual appearance was given as the oil being 'clear and bright with fine particles.' It was determined that conditions merited the disassembly and inspection of the transformer, requiring that the lid be ground off.

IV. Disassembled Inspection

As noted in Figure 1, a grey deposit existed throughout the transformer. Several possibilities were considered and a sample was sent for laboratory review.

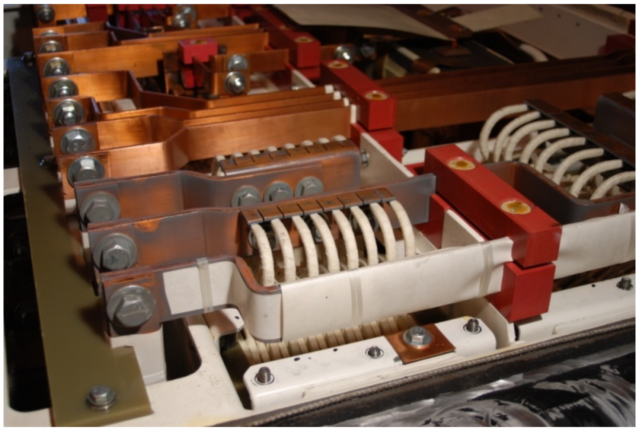

Fig 1: Grey Matter on Bus Bars

The material was identified as mainly made up of silicone, aluminum, copper, iron, zinc, magnesium, calcium, sodium and titanium (Table 4). The material was attracted to the bus bars with the metal being made up primarily of the same material as the bolts/threaded rods throughout the transformer. The generation of the material was estimated as having been the result of movement between the threaded rods and suspension springs located with the component buckets (Fig 2).

A majority of the grey material was on a specific electrical filter that should not have been carrying significant current. This allowed the facilitator to identify potential capacitor filter calibration issues, which were reported.

TABLE 4
Makeup of Grey Material (ppm)

Al	Cr	Cu	Fe	Pb	B	Tn
85	3	25	48	2	2	20
Mg	**Ca**	**Si**	**Na**	**Ti**	**Li**	
10	29	>2926	9	46	2	

Fig 2: Fretted Bolts and Buckets

It was noted that there was no guide or material between the threaded rods and there were visible signs of fretting.

One coil was removed from the transformer in order to evaluate the primary. Once the outer insulating paper was removed, it was noted that the varnish impregnated paper around each bare copper wire was tacky. It was also noted by the facilitator that the enamel on the secondary conductors was sloughing off. It was discussed and determined that the sample coil should be unwound by hand.

Fig 3: Burn Spots Between Primary Conductors

As identified in Figure 3, there were ‘burn spots’ throughout the primary between conductors in the center layers, with the copper conductors visibly pitted directly underneath. There were other areas where the grey matter could be found attached to the tacky insulation paper. It was determined that the ‘arcing’ noted in the oil samples may have resulted from these indicators. It was also noted that the pictures in the first transformer failures showed the faults occurred in roughly the same area as the ‘burned’ spots in the sample primary. The tackiness was attributed to possible incompatibility of the conductor varnish with either the silicone oil or the dissolved gasses.

The investigation of the conductors in the secondary identified that at all points the enamel could be removed from the copper conductors with a fingernail. It was assumed that this might also be due to incompatibility with either the silicone oil or the dissolved gasses. While none of the failures had occurred in the secondary, by this point, it was noted that the conditions indicated a high potential of failure in the future. The degradation of the secondary conductor enamel was such that the selected research laboratory was unable to determine its chemical makeup.

Further investigation indicated that the transformer had been reduced in size as the silicone oil allowed for a higher operating temperature while the use of silicone oil in this application was specified by the owner for the purpose of fire safety. Higher temperature materials were used, but no records of an insulation coordination study using the selected insulation materials and silicone oil could, or would, be produced.

V. Conclusion

The overall study, utilizing RCFA techniques, cost less than $100k USD total while pre and post studies performed utilizing other types of processes resulted in costs far exceeding that. The full time of the study, less than three months, was also far less than the more than year prior and several years following the study. To date, the conclusions of the RCFA have not been successfully disputed.

The conclusions indicated that:

- Periodic tuning of the filter capacitors would be required versus the one-time set up tuning presently performed;
- Several options for mitigating the existing conductive material were presented, but not pursued, due to additional investigations;
- An insulation coordination study must be specified in the original purchase of future transformers;
- The existing insulation system must be replaced upon failure of each transformer, if not before;
- Acceptance criteria for dissolved gasses and particulate must be agreed to by both the vendor and owner; and,
- The bucket suspension system must be modified to eliminate metal from permeating the oil due to fretting.

The root causes were determined to be a poor purchasing specification and poor practices in design for manufacture.

References

[1] Robert J Latino and Kenneth C Latino, *Root Cause Analysis: Improving Performance for Bottom-Line Results Second Edition*, Boca Raton, FL: CRC Press LLC, 2002.

[2] IEEE, *IEEE Guide for the Interpretation of Gases Generated in Silicone-Immersed Transformers*, IEEE Std C57.146-2005.