Proactive Fire Safety for Transformers

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Quantifying Risk of Transformer Failures
Proactive versus Reactive Risk Mitigation Approach

Prevent or react? Which would you rather be in a position to do when it comes to catastrophic (sustained) fires that develop as a result of transformer failures?

If you're like most people, prevention is the preferable choice.

Today's substation designers and asset managers are ***proactively*** using field proven technology to prevent catastrophic incidents. In particular, they are specifying and substituting less-flammable fluids (Envirotemp™ FR3™ fluid) in lieu of traditional mineral oil dielectric coolant.

Conventional guidance offered by IEEE 979, NFPA 850, or NFPA 851 which rely on *reactive* systems (spatial separation, deluge water spray systems, or fire walls) to mitigate the spread of the eventual fire that can develop during a mineral oil filled transformer failure. By taking a preventative approach by filling transformers with less-flammable fluids such as Envirotemp™ FR3™ fluid, utilities can eliminate coping with long-term exposure to risk.

Less-flammable dielectric fluids, typically identified as those fluids having a fire point above 300 ºC (572 ºF), reduce the likelihood of a pool fire and fire propagation. Since Envirotemp FR3 was introduced, there has not been a reported failure resulting in a pool fire for a transformer that was filled with Envirotemp FR3.

Transformer Failure Modes

In order to understand how less-flammable fluids reduce risk, one must understand transformer failure modes and the physical and chemical nature of the materials used in manufacturing transformers.

The benefits of this proactive approach are obvious as communities grow and people live in closer proximity to older, installed substation transformers.

Many transformers fail because their insulation system is no longer able to withstand stresses created during naturally occurring events (such as lightning, switching impulse, overloading, Ferro resonance, secondary short circuit, line fault, etc.)

An event such as those outlined above causes the insulation system to experience localized stress; the insulation system is unable to withstand that stress, and a breach occurs (typically somewhere in the paper). From this breach, a (low or high resistance) arc generates, and continues until it is extinguished (either the source is removed or the distance becomes so large that the dielectric fluid quenches it).

Much depends on how long the arc survives. During the life of the arc, much of the energy associated with the arc (approximately 95%) is consuming/destroying the materials surrounding the arc. The remaining energy is heating the surrounding materials.

For the dielectric fluid, this means the arc is tearing apart the molecules, generating combustible gases (acetylene for example) at a substantial rate. As long as the arc survives, pressure continues to quickly build inside the transformer tank.

The rapid buildup of pressure and the ability of the tank and components to withstand the physical challenges being placed upon them determine the potential impact of the catastrophic failure. If the arc is extinguished quickly, and the tank and components withstand the pressure such that no venting occurs, the transformer simply stops operating. If however, the arc is sustained, the pressure builds to a point where the tank or components cannot withstand the stress. The weakest part of the tank will be compromised (i.e. a bushing is dislodged, or a weld gives way, etc.) and volatile gases will escape. Mixed with air and an ignition source, the gases will explode, causing substantial damage.

When this occurs, heat released from the initial burning of combustible gases may vaporize and burn a dielectric fluid that is close to its flash point. If the heat of combustion continues to vaporize the fluid, a sustained fire on top of the liquid will result.

It is at this point that the characteristics of the dielectric fluid become paramount.

The predominant dielectric coolant is mineral oil. Mineral oil, while exhibiting reliable dielectric properties, typically does not provide an adequate margin of fire safety during transformer failure. Mineral oil, with a fire point of approximately 155 ºC, requires significantly less heat to bridge normal operating temperatures outlined in IEEE C57.91 to its fire point as compared with less-flammable fluids like Envirotemp™ FR3™ fluid.

Thermodynamics of fluids
Analysis of typical transformer failure modes shows that arcing under oil is the industry's most problematic failure mode. The arc is very hot and contains a lot of energy. Here is one unrealistic but noteworthy analysis of the effect of arc energy on Envirotemp FR3 fluid:

Assumptions:

- A transformer has 30,000 L (≈ 8000 gal) of Envirotemp FR3 fluid.
- The oil temperature is 90°C
- 100% of the arc energy goes into heating the fluid (realistically, less than 5% of the arc energy goes into heating the fluid, the remaining 95% is producing combustible gases as outlined above)

If 100% of the arc energy heated the fluid, the amount of heat required to elevate the temperature of 30,000 L of Envirotemp FR3 fluid just 1K to 91°C is 58 MJ. <u>58 MJ is the equivalent of a 100MW fault lasting 29 cycles.</u> In order to sustain combustion, Envirotemp FR3 fluid temperature would need to be elevated to over 300°C.

To make this analysis realistic requires recalculating the fault energy based on less than 5% of the arc energy heating the fluid, i.e., the results calculated above must be multiplied by 20. That is, the amount of heat actually required to elevate the temperature of 30,000 L of Envirotemp FR3 fluid just 1K to 91°C is 1,160 MJ (the equivalent of a 100 MW fault lasting 580 cycles or about 10 seconds).

Quantifying Risks
Consumer demand continues to force increased loading of aged transformers. Seasonal loading effects (summer loading for A/C, storm severity, etc.) increase the risk of transformer failure.

As our cities continue to grow, urban sprawl is entangling older substation transformers. With new substations likely to be located closer to the population than in the past (as space will continue to be at a premium), and the use of underground substations becoming more prevalent, the population is exposed to an increasing potential for harm.

Given the average age of existing transformer fleets, failures are occurring more frequently, and industry experts expect the rate of failures to continue to climb. The probability of catastrophic failure increases exponentially with the use of mineral oil as the traditional dielectric fluid.

Financial Considerations
The historical technology and the traditional approaches leave firms exposed to the eventful failure and resulting costs associated with repairing or replacing the fire damaged infrastructure. Worse, in order to have a favorable return on investment (ROI is a typical financial go/no go decision criteria), first investment cost must be minimized; forcing consideration of true owning costs over the life of the equipment to be minimized (or ignored completely). For example, normal accounting costs associated with reactive approaches may include:

- Site selection and preparation
- Substation design
- Purchase and installation of transformer (and spare)
- Purchase and installation of fire suppression equipment (deluge system or fire wall)
- Infrastructure installation (cable, protective relay systems, cable towers, etc.)
- Insurance premiums

Other (long term) costs that may not normally be accounted for include:

- Maintenance cost of fire mitigation systems
- Rehabilitation of fire suppression system and site conditions (replacement of damaged infrastructure; bus/cable, bracing, pipes, towers, etc.)
- Emergency replacement costs of transformers
    - if used, unknown quality of transformer
    - if used, unknown insulation life expectancy
- Lost revenue for longer than required down time
- Site remediation of oil vented during initial failure mode

When total ownership costs are considered, the small premium for less-flammable fluids is easily justifiable. Risk mitigating professionals understand and advocate the use of less-flammable fluids in transformers because it reduces their long term exposure to damage and future insurance claims.

FM Global® recognizes there is a significant opportunity to mitigate catastrophic risk and advocates the use of less-flammable fluids in transformers, as indicated in their Loss Prevention Data Sheets (for example, less-flammable fluids are even suitable substitutes for costly deluge systems or increased spatial separation distances, resulting in a significantly reduced initial investment, as well as long term maintenance costs).

Additionally, the US National Electric Code (NEC 450.23) recognizes that the probability of a transformer fire occurring when filled with less-flammable fluid is much lower than when filled with mineral oil that it permits indoor applications of less-flammable filled transformers without requiring traditional fire vaults.

CONCLUSIONS

History is focused on reacting to substation-related events. Our industry is realizing that there is affordable technology available which helps minimize the long term risk associated with catastrophic transformer failures.

The analysis above indicates that Envirotemp™ FR3™ fluid provides increased margin of safety combined with the flawless historical track record of less-flammable fluids making *proactively* specifying (or retrofilling) substation transformers with Envirotemp FR3 fluid the best solution for mitigating risk associated with transformer failures.