Aged Transformer Fire Risk Study - Life Safety Assessment

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How close is too close for people to be around service-aged transformers? How do you respond when asked this question by your client, the Owner and Operator of those transformers? This paper outlines the process undertaken to answer this question.

Background of the Challenge

The above question was asked in relation to the four generator step up units (GSU) for a major New Zealand power station. The oldest of the transformers have been in service since 1981. All four transformers are oil-immersed and located externally and adjacent to the generator hall of the power station. Within the transformer alley are unit and station transformers, to give a total of twelve transformers. The transformers are contained within one long, subdivided bund and are provided with automatic fire suppression (high velocity water spray). There are no fire separations between the transformers, however the GSU transformers are well separated by distance (approximately 60 metres).

Internal inspections have revealed that the insulation paper in some of the transformers was approaching end of life criteria. Details of the transformers are not included for commercial reasons. The internal condition of the transformers was found to be otherwise in good order. While the fact the paper insulation end of life criteria is pending is concerning it also needs to be acknowledged a number of external factors are required to occur for a transformer in this condition to fail. The end of life criteria is set because at this point it is unlikely that the transformer would survive a serious event external to its own terminals e.g. expected external fault currents.

Ageing of insulation systems reduces both the mechanical and dielectric withstand-strengths of the transformer. In an aged transformer failure, the conductor insulation is typically weakened to the point where it can no longer withstand the mechanical stresses during a fault current event. Turn-to-turn insulation then suffers a dielectric failure. Alternatively, a fault current event causes a loosening of winding clamping pressure, which in turn reduces the transformer's ability to withstand short circuit forces [1].

Replacements for the GSU transformers have long lead times and safety of the staff on site needed to be maintained while the transformers continued to operate. The asset owner sought advice on how best to achieve this goal. This safety risk was assessed quantitatively and recommendations made as to improvements which could be made to protect staff.

There are many design guidelines in existence outlining requirements for protection of transformers, such as NFPA850 [2]. An alternative approach was developed for this study, and used to evaluate the life safety risk posed by those transformers.

Identification of the Risks

Historical transformer failures include some spectacular explosions and fires [3], [4], [5]. Transformers by their very design have highly energised elements immersed within combustible oil. Causes of fires can vary greatly, but usually involve a short within the transformer, which creates an abnormal energy build-up within the transformer, rapidly increasing the pressure and temperature. This pressure and temperature build-up may lead to fire, explosion, or both.

The larger of these transformers contains around 79,000 litres of transformer oil (hyrdotreated light napehenic distillate, with flash point of 150°C). They have porcelain LV bushings located within steel bushing boxes (refer Figure 1).

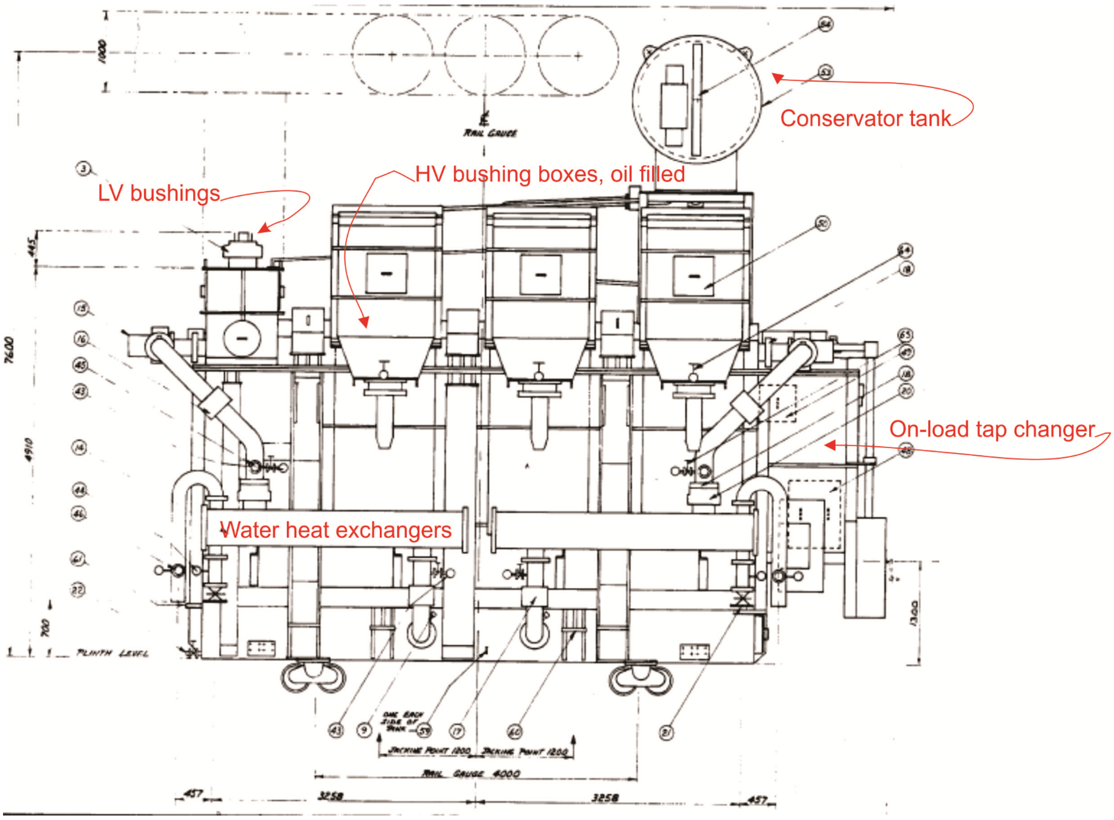

Figure 1 Transformer components, important in explosive failure considerations.

Three key risks that relate to personnel safety were identified in the event of a fire/explosion from one of these transformers. They were: 1) solid projectiles, 2) hot oil spray and 3) radiant heat. These risks are applicable to any power transformer: service aged or a new asset.

Possible solid projectiles identified included porcelain bushings and steel from the transformer shell or flanges. Of the projectiles, porcelain items were found to travel considerably greater distances than the steel items. Porcelain's brittle nature is considered to be responsible for this, with considerable energy being released suddenly in the failure of those items. Jansson [6] reports porcelain fragments being ejected several hundreds of metres following failures of transformers. Metal fragments following the failure of a similar GSU transformer were found to travel around 25m.

Solid projectiles provide two key life safety concerns: 1) any person struck by one of these projectiles is likely to be seriously injured, and 2) these items are likely to be hot, so could spread fire to other areas should they land on combustible materials.

Whilst other transformer fires have been known to eject porcelain fragments several hundred metres, for the transformers at the focus of the current study this scenario was considered to be less likely to occur due to the location of the porcelain components. In the installation of interest, porcelain external transformer bushings did not exist, and internal porcelain insulators were enclosed in the metal bushings boxes. Should the porcelain components explode, much of their energy will be absorbed by them having to penetrate the bushing boxes, reducing their likely travel distance. Metal fragment distribution was considered more likely and has been treated as the governing case for projectiles.

As a result of the pressure build up within the transformers prior to the case rupturing, there could be a large spray of hot oil ejected. Not all transformer failures result in rupturing of the transformer tank and subsequent fires. Hydro Quebec from Canada, collected failure statistics on their 735kV transmission system for 25 years, and recorded 175 transformer failures that resulted in 111 high energy arcs. These caused 44 tank ruptures, 18 of which resulted in fire [7]. From fires in transformers similar to those in this study, the oil spray was found to extend up to 28m.

Theoretical calculation of the potential for oil spray was also considered, given that rupture pressures within the transformer cases have been recorded and the material properties of the oil are well known. Undertaking these calculations requires assumption to be made about the orifice shape and size. For a circular orifice it was calculated that a jet of up to 54m could theoretically occur. The post-fire evidence is that these jets do not project this far, likely because the orifice is never circular and so the ejected oil is a spray rather than a jet. These theoretical calculations were discounted in the current risk assessment, but were useful in giving an understanding of the order of magnitude of the potential oil ejection.

Radiation from a transformer fire can vary with the failure scenario. For a fire which grows without explosion, the radiation would be less intense initially and would then build as the fire grew. The transformers we were assessing were enclosed within a bund, which could conceivably contain a burning pool of oil. The drencher heads were designed to focus on the transformer equipment and as such there were areas of the bund which are not protected by these heads. Drencher systems are only effective provided the pipework remains intact following a transformer explosion. Whilst there was evidence of this being a real concern Zalosh [8] observed they typically remain intact.

Radiation was calculated by spreadsheet, following the methodology outlined in Gordon *et al.* [9]. Limits on acceptable radiation levels were considered based on thresholds for occupants depending on whether they were walking past, stationary, or stationary and with a delayed ability to evacuate (such as those working up a ladder, or inside a neighbouring transformer). Occupant's ability to choose their direction of egress was also taken into account in these limits. These thresholds were taken from the SFPE Handbook [10] and are stated below.

The radiation thresholds provided us with three acceptable separation distances from the centre (geometric centre, in plan) of an operational transformer for life safety, which are activity dependant:

1. Beyond 16m, is safe to occupy provided rapid movement within 5 seconds can occur.
2. Beyond 29m, is safe to occupy provided occupants can evacuate within one minute.
3. Beyond 43m is safe for those who are unable to evacuate immediately (e.g. those up a ladder, or working inside a transformer).
4. As a broad comparison, it is noted that Factory Mutual [11] recommends 30.5m separation between a transformer and combustible construction.

In the operating transformer environment of interest, these separation distances meant that the maintenance staff would be unable to work on a GSU transformer while the neighbouring GSU was energised. However, to require two GSU transformers to be isolated in order to undertake maintenance requires a greater constraint on the operator in terms of scheduling.

Personnel Threatened by Transformer Fires

Adjacent to transformer alley on the study site was a major thoroughfare between the front entrance and the main control room for both pedestrians and vehicles. Additionally, above the transformers was a walkway providing an internal link between the office and control room. This walkway was glazed and overlooked the transformers. Beyond the control room the walkway was unenclosed and was used less often.

Public access was not allowed within the site and transformer alley was well separated from the edge of the site. On this basis, the public were not considered to be at risk from a fire in these transformers.

Maintenance staff were often required to be in close proximity to operating transformers to undertake maintenance and perform routine checks. These include thermal imaging to identify hot spots, as well as oil sampling and visual inspections. Irregular maintenance, such as internal inspections occurred at extended intervals and could include personnel entering the inside of the transformers (under access permit conditions).

Causes of Failures

Causes of transformer failures can vary. During consultation with the maintenance team on this project, it was suggested, following the analysis of the transformers, that any external faults may create sufficient load on the transformers to cause the paper insulation to fail. This would cause an internal short, leading to failure of the transformer and potentially fire and/or explosion.

It was identified early in this study that the causes of failure were difficult to identify and many would not able to be eliminated completely. On this basis, this study was focussed on mitigation measures.

Assessment of Threats

A review of the threats from radiation, oil spray and projectiles and their likelihood was undertaken on the basis of likelihood and consequence, using the following Tables (see Tables 1 and 2).

Specific risk items were scored for the possible affected parties; pedestrians on overhead walkway, maintenance staff on transformers, vehicles on roadway, staff in neighbouring buildings and staff walking between buildings. These scores were then compared to the acceptable risk levels provided by the Asset Owner. In this instance the risks of injury to staff (with no additional protection provided to the transformers) was assessed as being unacceptable.

Table 1 Probability Matrix for Assessing Events

2. Loss Likelihood/Probability Table

Probability Rating	Descriptor	Guide to Possible Likelihood			
		Definition	Experience	Estimated Frequency	
5	Almost Certain	The risk exposure will almost certainly be realised and is expected to occur in most circumstances.	Happens here fairly often.	Once or more in 1 year	100%
4	Likely	The risk exposure will probably occur in most circumstances.	Has happened here before.	Once in >1 – 2 years	50%
3	Possible	The risk exposure might occur at some time.	Has happened several times elsewhere.	Once in 2 – 5 years	20% to 50%
2	Unlikely	The risk exposure could occur at some time, however is not expected.	Heard of it happening before.	Once in 5 – 10 years	10% to 20%
1	Rare	The risk exposure may only occur or be realised in exceptional circumstances.	Never heard of it happening.	> once in 10 years	10%

Table 2 Scoring Table for Risk Events

Table Showing Link Between Likelihood x Consequence and 'Risk Scores'

Likelihood/ Probability	Low (1)	Moderate (2)	Significant (3)	Major (4)	Critical (5)
Almost Certain (5)	5	10	15	20	25
Likely (4)	4	8	12	16	20
Possible (3)	3	6	9	12	15
Unlikely (2)	2	4	6	8	10
Rare (1)	1	2	3	4	5

Consequences

These scoring methods were also used to assess the modified configuration, to determine whether the proposed measures were sufficient. Different options were proposed until the risk score was reduced to an acceptable value.

Mitigation Options

Existing mitigation measures included a dedicated high velocity water spray (HVWS) sprinkler system for each of the GSU and Unit transformers. Fire detection for this system utilised a network of pipework charged with compressed air, activated by sprinkler pilot heads and operating a deluge valve. This system would operate automatically on detection of a significant size fire in the transformers.

Each transformer had a dedicated detection and associated deluge initiation valve and operated as a "single knock" detection system. The high velocity sprays can be seen in operation in Figure 2.

Figure 2 HVWS Sprinkler system in operation on a transformer

Mitigation options to contain the effects of a fire or explosion were considered. These options also had to take into account the operational requirements for the stations, including visual checks, thermal imaging and oil sampling.

Thermal radiation mitigation was considered using fire walls around the transformers. These would have been effective in preventing thermal radiation, projectiles and hot oil spray. However, constructing walls around the transformers would have prevented the opportunity for maintenance staff to access the transformers. They would also have prevented staff from undertaking visual, or thermal imaging checks without entering through the fire separations.

Radiation screens were considered as an alternative to the fire separations. Radiation screens, created from perforated metal sheets are typically used to protect against radiation and airborne fire brands in bushfire areas in Australia. These screens are typically created using fine stainless steel wire mesh, with apertures of less than 2mm in diameter and are tested to have a maximum radiant heat transmission of 40%. A typical example of this mesh is shown in Figure 3.

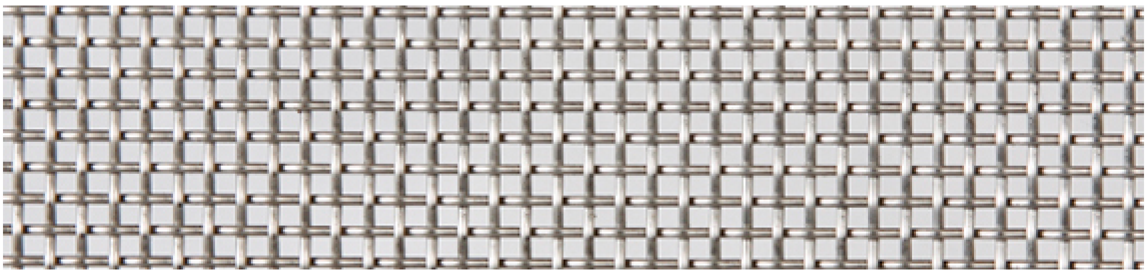

Figure 3 Close up of proposed radiation screen mesh. Wire diameter typically 0.3mm at 2mm centres

Radiation screens differ from fire separations in that they would mitigate thermal radiation (but not completely), and would allow heat conduction through the wall. Flames and smoke could also pass through the wall. Benefits of using radiation screens over fire walls include the reduced weight (which means less structure), and maintenance of visibility through the screens which allows for visual observations of the transformer to be undertaken.

Radiation screens constructed of mesh were considered suitable for reducing the impact of oil spray. While it was accepted that they were perforate and so would allow oil to pass through, the fine mesh would absorb much of the momentum of the spray, reducing its trajectory to extend barely beyond the mesh.

Personal protective equipment was also considered as a mitigation option. Heavy clothing offering thermal protection, such as structural fire-fighting equipment worn by Fire Service staff would protect against thermal radiation, but would only offer limited protection against projectiles and hot oil spray. This option was considered to be insufficient to allow for adequate protection for staff who were working in close proximity with the transformers while the transformers were live.

Replacement of the transformer oil with an ester-based product was considered. Doing so would increase the flash point of the oil, making internal fires less likely. This solution was ruled out on a technical basis. In order to replace the oil, the transformer would need to be removed from site to be re-tested for thermal and dielectric tests. The ability to readily perform these tests in New Zealand was considered, and this option was disregarded due to the necessity of extensive outage duration, high disassembly and re-assembly costs, and limited access to specialised test equipment. In addition, this option presented the risk of re-locating a service-aged transformer with insulation system near its reliable end of reliable life.

Actual Mitigation Options Taken

At the outset of this study, prior to the identification that these transformers were approaching their end of life criteria, the operator had put into place an exclusion zone of 20m around the transformers. Maintaining this was considered long term, but posed maintenance restrictions on both the transformers and the area in general which were considered unsustainable. The restrictions on access between buildings could have been worked around, with a permanent version of the temporary walkways a viable option.

Radiation screens were selected as being the most effective option for surrounding the transformers. The installation of the screens along the edge of the bund, including across the bund between transformers would allow for staff to be working on de-energised transformers while adjacent transformers were in-service. The proposed screens were intended to be constructed with a steel frame, with mesh screens, or punched steel panels inset. Gates were proposed in these screens to allow access into the transformer enclosures when they were de-energised.

Conclusion

This study involved reviewing the existing transformer configurations, access requirements for maintenance and circulation routes around the study site. Assessment of potential failure scenarios was undertaken and risks of failure were scored for each outcome. Mitigation methods were then proposed where risk scores were unacceptable and those potential failure scenarios were reassessed until risk scores were within the acceptable range.

This methodology was very flexible in its application. It did require clear understanding of the potential for failures and the likely consequences associated with those failures. In combining that understanding with a structured risk assessment approach, it was possible to quantify the risk, then propose and evaluate methodologies for reducing those risks.

At the conclusion of this study, the Asset Owner was provided with a number of recommendations which would allow the facility to continue to operate, whilst ensuring adequate risk reduction measures were present.

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