# Transformer Fire Risk Mitigating Strategies

By

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# TRANSFORMER FIRE RISK MITIGATING STRATEGIES

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## Abstract

Transformers are crucial to power generation and distribution systems. Transformers can catastrophically fail, and explode and/or ignite. Because of the large quantity of fuel, resulting fires can emit significant amounts of heat and damage critical adjacent equipment and structures. The potential consequences include loss of energy supply, high repair costs, environmental contamination, and threat to life safety. Therefore, having an effective risk mitigation strategy for transformer fires is crucial in the use and operation of transformers. In many cases, providing an adequate fire barrier or radiation shield that is specifically designed can significantly reduce the consequences of the fire.

Transformer design in Australasia generally adopts the prescriptive design guides from Australian Standards or various other national or international design guides. Although these prescriptive design guides may provide some advice, they do not offer specific solutions for all transformers and their installation configurations, as they do not distinctively consider the environmental influences and the specific layouts and quantity of oil present or the constraints of both new and retrofit installations.

This paper compares the performance of fire barriers generically specified by the referenced design standards and comments on their efficiency by calculating shielded radiation from transformer fires. Three example transformers with different configurations are studied. A case study of an especially designed and constructed fire barrier is also presented, along with a discussion on transformer oil containment and management in the event of a catastrophic transformer failure, and generic fire risk mitigation strategies. This paper does not produce generic radiation solutions but illustrates through case studies how the referenced standards may be improved on in this respect.

## Introduction

Transformers in power generation plants change the voltage level from the generated electrical power to a level suitable for system load. They are critical in electrical power and energy systems. Large transformers commonly rely on mineral oil to assist with electrical insulation between windings, core and transformer tank and to remove the heat generated in the electrical losses [1]. The typical mineral oil used in large transformers has a flash point and fire point approximately of 110 to 170°C [2]. During an internal transformer fault, this temperature is almost certain to be exceeded, and temperatures many times in excess of the oil flash point can be present inside the transformer for many hours after the transformer has been de-energised by electrical protection. Even a de-energised transformer, if spilling oil, can explode within an hour of the initial internal fault. This time delay is determined by the rate of oil lowering and air surrounding the hot faulted materials.

Due to the presence of large amount of refined mineral oil with a high heat of combustion in the transformer, a transformer fire can be of tremendous size and incur significant damage to the adjacent equipment and structures, threaten lives and cause both tangible and intangible losses. For example, in 2000, a single transformer fire in Virginia destroyed two transformers and damaged the third, incurred a US$10 Million in damages [3]. In cases of fires involve generator step-up transformers where a spare is not available, it would be typical for the generator to be out of service for at least 18 months, for damage repair, and/or procurement of a replacement transformer, and it is often the lost generation revenue that dwarfs the high repair and replacement costs of the equipment.

Both reducing the likelihood of a fire and minimizing the consequences can decrease the business risk associated with transformer fires. While the former option is extremely important and receives considerable attention in modern asset management practices, the latter option should also be implemented to provide the additional level of safety. The focus of this paper is on minimizing the consequences and looks into relying on radiation shields to protect the buildings and equipment adjacent to the transformers.

## Failure Modes of Power Transformers

Understanding and reducing consequential loss of a transformer fire is highly important. Fortunately, transformer failures are relatively uncommon. Between 1997 and 2001, there were only 94 reported failures of transformers rated at 25MVA and above in the world [4], and not all of these failures led to transformer fires, according to this reference and probably significantly more as not all failures are recorded or reported. However, out of these incidents, a quarter of them were caused by insulation failure, and overloading, line surge and direct exposure to fire/explosion from external sources each causing 5% of the transformer failures. Most transformer faults do not lead to an explosion as many failure mechanisms are progressive. The damage of most faults are limited to the area of origin as the fault may cease to propagate due to the lack of fault energy or a protective device or function is triggered and starts to operate and removes the fault energy. High energy faults are uncommon and are associated to major insulation failure of a direct internal short to ground. It should be noted, however, that all of these failure mechanisms provided ignition sources that could lead to fires. Bushing failures in contrary, can be immediate and without warning, and are more common causes of transformer fires.

Due to the severe consequences, the risk of transformer fires is note worthy and risk mitigating strategies should be developed to reduce the likelihood and consequences of transformer fires. Understanding and analysing transformer fires and their radiation effects requires diverse skill and experience. There are many stakeholders in the electricity generation and transmission industry who do not understand the possibility of explosion or ignition in certain machinery, and therefore it is important to share the knowledge among various stakeholders to develop suitable fire safety strategies.

There are several studies in this field to investigate how to minimise the risk of transformer fires from different approaches. In terms of reducing the likelihood of a fire, Hansen et al. looked into reducing the flammability of the transformer oil vapour mixture prior to ignition to reduce the likelihood for ignition [5]. The Hydroelectric Research and Technical Services Group of Bureau of Reclamation of US Department of the Interior advised to replace mineral oils with ester-based insulating fluids that have higher flash and fire points, and use both active and passive fire protection systems on transformers in accordance with NFPA 851 [6].

Prescriptive design guides usually provide guidelines on minimizing the consequences of transformer fires through separation distances or fire barriers. Power generation companies in Australasia generally adopt the recommendations from design guidelines such as NFPA850 [7] and

NFPA851 [6] from the National Fire Protection Association of the United States, AS 2067 Standard of Substations and High Voltage Installations [8], or FM Global design recommendations [9].

Prescriptive design guides are relatively easy to follow and applicable for most situations and are expected to be conservative.  Nevertheless, the assumptions made behind the prescriptive design are mostly unknown, but many parameters that may affect the design are inherent from these assumptions.  Because each power generating plant is different and can be located in a remote area with an unusual surrounding environment, and can also have an odd configuration in relation to existing buildings and other plant, a generic prescriptive design may not always be the conservative design option.

***NFPA 850 and 851***

Regarding the fire separation between outdoor oil-insulated transformers and its adjacent structures, NFPA 850 [7] and NFPA 851 [6] require consideration on the type and quantity of oil in the transformer, the surface area and depth of the oil spill for determining the pool fire, type and amount of exposed equipment, type of construction of adjacent structures, and the provided fire suppression systems. However, it also provides a default generic calculation method for designing a transformer firewall size as shown in Figure 1 below, where X is the minimum line of slight separation distance without the firewall and is dependent on the transformer oil capacity.  This methodology assumes the most severe radiation flux is emitted from 0.31 m above the top of the transformer casing and oil conservator tank and ignores the effect of wind on the flame.

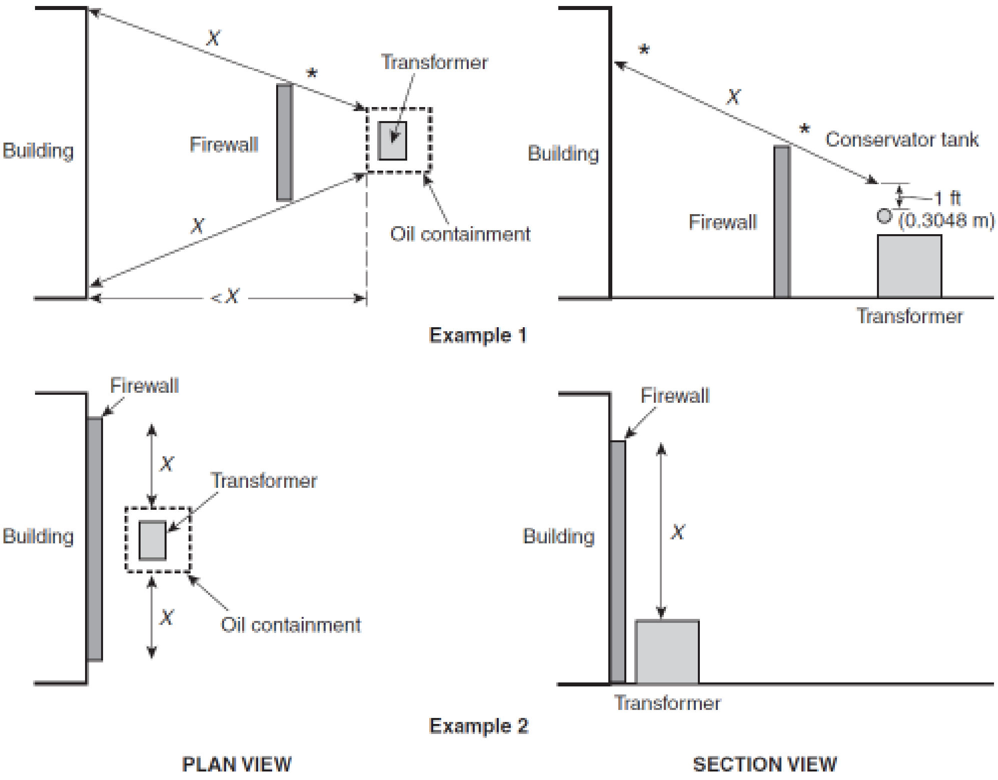


Figure 1
Illustration of Oil-Insulated Transformer Separation based on NFPA 850 [7]

***AS 2067***

As illustrated in Figure 2, AS 2067 [8] requires the minimum height of the inter-transformer fire/blast wall to be of the height of the taller transformer (including conservator tank) plus 0.3m. The required minimum fire/blast wall width is the greater of the maximum length of the transformers, or the width of the widest transformers plus 0.6 m. Furthermore, a guideline for the separation distance between the outdoor transformers without an enclosure to the combustible neighbouring building surface is provided. If the neighbouring building has a surface located closer than the minimum separation distance, that surface is required to be fire rated to a minimum of 120 minutes, or having a minimum of 120 minutes rated firewall between the building and the transformer.

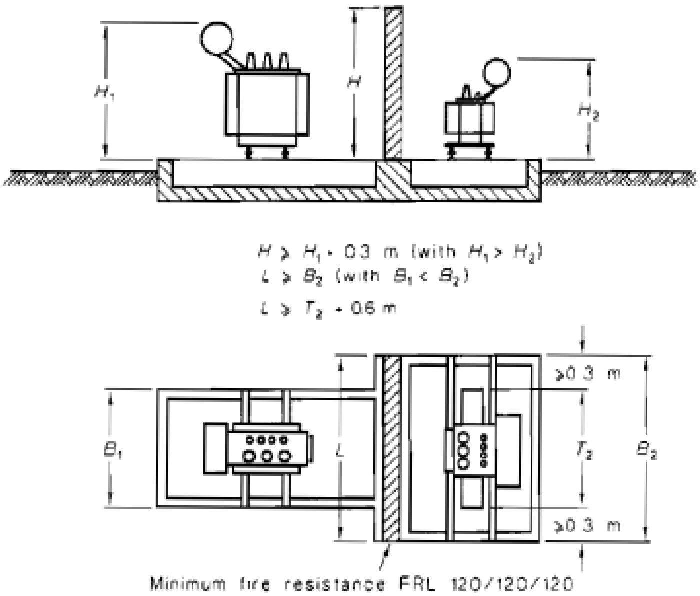
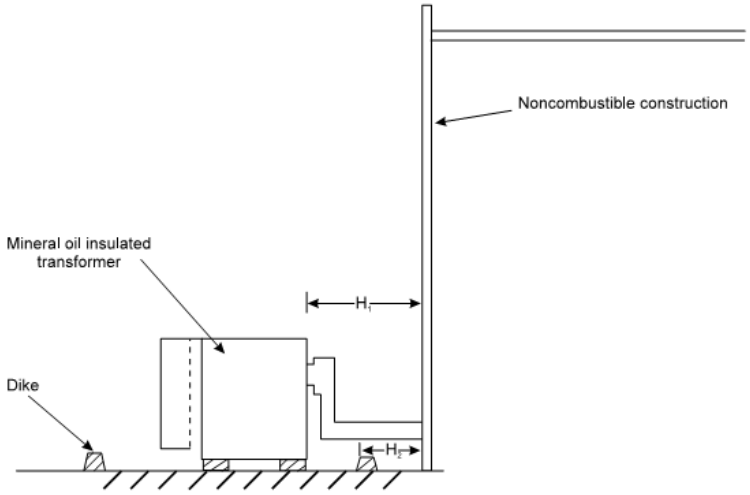


Figure 2

Illustration of Oil-Insulated Transformer Separation based on AS 2067 [8]

***FM Global***

The requirements of FM Global data sheet 5-4 [9] are similar to NFPA 851 and AS 2067 regarding fire separations between transformers as shown in Figure 3. FM Global generally requires a two-hour concrete block or reinforced concrete construction between the transformers that extends 0.3 m vertically and 0.6 m horizontally beyond transformer components which could be pressurised as the result of an electrical fault. The barriers are also required to be capable of withstanding not less than 25% of full design wind loads at the maximum fire exposed material temperature. The recommended fire separation distance is approximately twice that of the distance required by NFPA 850. However, the flame height and the wind tilting effect made in the assumptions are still unclear.



H1 = Transformer less than 500 gal. and where ground slopes away from building dike not needed. Horizontal distance is measured from transformer to building.
H2 = Where ground is flat or slopes to building dike should be provided. Horizontal distance is measured from dike to building.

Figure 3
Illustration of Oil-Insulated Transformer Separation based on FM Global [9]

Without investigating the phenomenon of explosion which is associated with violent fire with very short duration, the heat generated from a sustaining transformer fire and the likely flame height can be calculated using fundamental fire engineering equations. Subsequently, the receiving heat flux at the adjacent buildings or equipment can be derived, and the firewall can be designed accordingly to the level acceptable to the adjacent structures.

## Assessment Methodology

The mechanisms of how transformer fires initiate may involve arcing faults resulting in the ejection of oil aerosols, yielding mostly ethane, ethylene, methane, acetylene, and small quantities of hydrogen. These ejections potentially are accompanied by the explosion of the transformer main tank and result in fire. Moreover, failures of the connection bolted sections and edges can result in dislodgement of the transformer lid and hatch covers.

Case studies have indicated that the ruptures of transformers are mostly along the welded or bolted seams of the transformer main tank or tears along a corner seam of the main tank. The result of this rupture mechanism is that the transformer oil typically does not ignite in one explosion, and instead the fire can have significant time duration due to the abundant fuel source. It should also be noted that within the transformer there is a significant amount of oil impregnated solid insulation that is also a significant fuel source. Whilst these rupture and fire mechanisms seem more common in older transformers, these can still happen in new transformers, especially in the case of high voltage bushing failure, such as the example transformer 1 studied below.

A typical transformer installation consists of a bund for containing the oil at the base, often without or with little drainage capacity to remove oil. Therefore, when a transformer fire occurs, the bund can provide a pool fire around the transformer with rich fuel. Furthermore, the transformer vessel may not fully rupture and provide a continuous and on-going fuel source for the fire. Thus the transformer itself is a source of fuel at the point of rupture.

The calculations used in this study take account of these scenarios by assuming a pool fire at the base which has a cross-sectional area equal to the bund area, and another pool fire which has a cross sectional area equal to the top plate area of the transformer. The calculation methodologies are well established for pool fires [10, 11]. Using the methods established by Tien et al. [12], the radiation effect on to surrounding structures and equipment can be calculated, with or without considering the tilting of the flame caused by the wind.

From the designer's prospective, this exercise is to provide a heat flux outcome to be compared against the acceptable level of received heat flux at the neighbouring structures or plant. In many situations, the neighbouring structures are not very sensitive to the heat flux, and so a higher received radiation heat flux might be acceptable. However, some equipment requires a more restricted acceptable level of received heat flux, such as condensers or generators, to avoid deformation of the equipment, piloted ignition or even auto-ignition depending on the materials of cladding and construction. The acceptable level of received heat flux at the neighbouring structures or plant also depends on the relevant asset owners and stakeholders, and consideration should include the importance and reinstatement cost of these structures or plant, the redundancies and the risk of operation discontinuity. It could be for example that a number of transformers are lined up along a platform and if one fails with a fire it is important for the other transformers to remain in operation, in order to maintain business continuity. If the heat flux from a tilting flame front is excessive; the adjacent transformer top oil protection may operate and remove it from service.

**Example Transformers**

This section presents some examples of designing flame barriers for outdoor transformers. Three transformers are assessed in accordance to the requirements of NFPA 850, FM Global and fundamental fire engineering equations.

***Example Transformer 1***

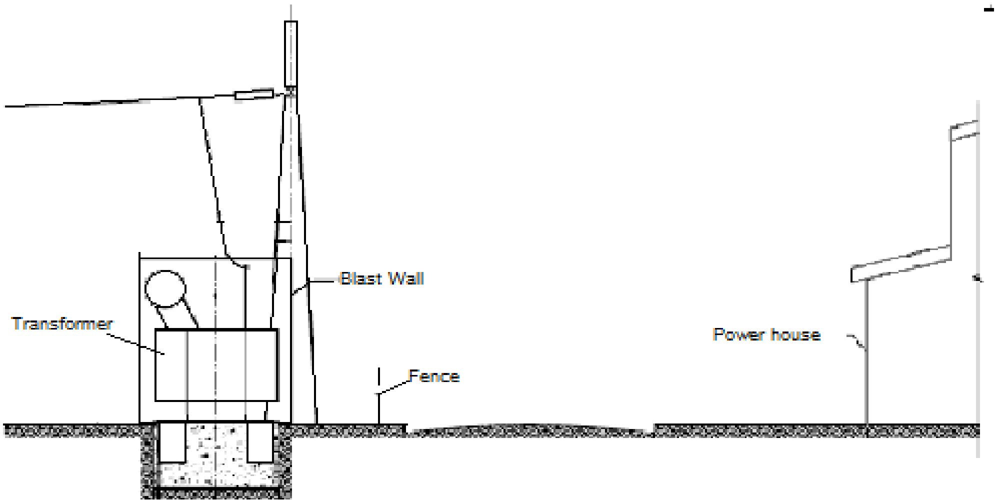


Figure 4
Schematic Drawing of the Layout of Example Transformer 1

Example transformer 1 is a 14-year old 100 MVA generator step-up transformer in the Philippines which caught fire in 2008. Table 1 shows the key parameters of the transformer and Figure 3 shows the general layout. The cause of failure was that one of the high-voltages bushings failed, providing the initial source of fuel to feed the fire. It is also suspected that the exploding porcelain hit the Buchholz relay and consequently discharged the entire oil volume of the conservator tank onto the fire. The fire was under control within 30 minutes with more than 9,000 litres of oil consumed, but the fire severity shattered all transformer bushings, melted the aluminium casting, and complete destruction of external ancillary equipment. Internally the failed bushing exploded inside the tank sending debris throughout the active part of the windings. However, because of the presence of the fire wall and adequate separation distance to the neighbouring transformer, as well as the oil bund successfully containing the oil; the adjacent transformer was not damaged.

Table 1
Key Parameters of Example Transformer 1

| | |
|---|---|
| Transformer Type | 100 MVA, 13.8/230 kV generator step up |
| Dimensions | 5.3 m high, 6.1 m long, 2.45 m wide |
| Bund size | 9.5 m long, 4.5 m wide |
| Contained oil | 35,000 litres, mineral oil, heat of combustion 46MJ/kg, flash point 140$^{o}$C |
| Separation distance to the adjacent building (power house) | 26 m |
| Separation distance to the adjacent building | 23 m away, 6 m high structure |
| Wind condition | Calm, assumed no wind |

***Example Transformers 2 and 3***

Example transformers 2 and 3 are typical realistic transformers. Table 2 shows the key parameters of the transformers.

Table 2
Key Parameters of Example Transformers 2 and 3

| | **Example Transformer 2** | **Example Transformer 3** |
|---|---|---|
| Transformer Type | 95 MVA, 33-110 kV | 230 MVA, 11-220 kV |
| Dimensions | 4.0 m high, 7.0 m long, 5.9 m wide | 4.8 m high, 7.4 m long, 4.6 m wide |
| Bund size | Assumed 1.5 m clear width all around the transformer, i.e. 10.0 m long and 8.9 m wide. | Assumed 1.5 m clear width all around the transformer, i.e. 10.4 m long and 7.6 m wide |
| Contained oil | 35000 litres of mineral oil, assumed heat of combustion is 46 MJ/kg [11], and a flash point 140$^{o}$C [2] | 65000 litres of mineral oil, assumed heat of combustion is 46 MJ/kg [11], and a flash point 140$^{o}$C [2] |
| Separation distance to the adjacent building | 15 m away, 10 m long by 10 m wide and 8 m high structure. | |
| Wind condition | Moderate/near gale, 30 knots, 56 km/hour | |

**Calculations and Discussions**

In the calculations, the fire is assumed to burn freely in the bund and from the top of the transformer plate. This is considered the worst of the free burn conditions and the resultant radiation calculation is undertaken.

Three fire scenarios are considered based on the general transformer layout:

- Scenario 1 - the rupture of the transformer tank during an explosion causing a pool fire at the bund level.
- Scenario 2 - Failure of the transformer tank joint caused by a transformer explosion causing pool fires both at the bund and approximately 30% of the top surface of the transformer vessel area.
- Scenario 3 – Complete failure of the tank joint and a pool fire at the bund and at 100% of the top surface of the transformer vessel area – this is less likely to happen than the other two scenarios.

Tables 3 to 5 show the fire size from all three example transformers under the three scenarios, calculated using the method mentioned in the discussion on calculation methodology.

Table 3
Emitted Heat Flux of Scenario 1 – Pool Fire at the Bund

| | **Transformer 1** | **Transformer 2** | **Transformer 3** |
|---|---|---|---|
| Pool fire area ($m^2$) | 26 | 47.7 | 45 |
| Heat release rate (MW) | 32.4 | 59.9 | 56.5 |
| Duration of fire without oil drainage (hours) | 7.3 | 4.0 | 7.8 |
| Flame height under windless condition (above the base of transformer) (m) | 7.6 | 8.3 | 8.5 |
| Emissive Power ($kW/m^2$) | 70.4 | 53.4 | 56.0 |

Table 4
Emitted Heat Flux of Scenario 2 – Pool Fire at the Bund and 30% of the Top Lid Area of the Transformer

| | **Transformer 1** | **Transformer 2** | **Transformer 3** |
|---|---|---|---|
| Pool fire area ($m^2$) | 43.9 | 60.1 | 55.2 |
| Heat release rate (MW) | 38.1 | 75.4 | 69.3 |
| Duration of fire without oil drainage (hours) | 4.3 | 3.2 | 6.4 |
| Flame height under windless condition (above the base of transformer) (m) | bund fire: 7.6<br>transformer fire: 10.3 | bund fire: 8.3<br>transformer fire: 11.1 | bund fire: 8.5<br>transformer fire: 11.5 |
| Emissive Power ($kW/m^2$) | bund fire: 70.4<br>transformer fire: 110 | bund fire: 53.4<br>transformer fire: 94.5 | bund fire: 56.0<br>transformer fire: 97.9 |

Table 5

Emitted Heat Flux of Scenario 3 – Pool Fire at the Bund and 100% of the Top Lid Area of the Transformer

| | **Transformer 1** | **Transformer 2** | **Transformer 3** |
|---|---|---|---|
| Pool fire area ($m^2$) | 57 (bund: 26; top lid: 15) | 89 (bund: 47.7; top lid: 41.3) | 79 (bund: 45; top lid: 34) |
| Heat release rate (MW) | 50.4 | 111.7 | 99.2 |
| Duration of fire without oil drainage (hours) | 3.3 | 2.1 | 4.5 |
| Flame height under windless condition (above the base of transformer) (m) | bund fire: 7.6<br>transformer fire: 12.7 | bund fire: 8.3<br>transformer fire: 14.6 | bund fire: 8.5<br>transformer fire: 14.7 |
| Emissive Power ($kW/m^2$) | bund fire: 70.4<br>transformer fire: 91.0 | bund fire: 53.4<br>transformer fire: 70.3 | bund fire: 56.0<br>transformer fire: 74.5 |

Based on the results in Tables 3 to 5, it is apparent that Scenario 1 is not as severe as Scenarios 2 and 3. Between Scenarios 2 and 3, as shown in Tables 4 and 5, although in Scenario 3 the emissivity power of the transformer fire is less, the pool fire area on top of the transformer is larger, and therefore the area for emitting energy to the neighbouring structure, which is based on the diameter of the pool fire and the flame height, is also larger.

Knowing the emitting heat flux from the transformer fire, subsequently the received radiation heat flux at the interested neighbouring structure can be calculated. The required height of firewall is based on the firewall being constructed at the edge of the bund. A nominated heat flux limit of 4 $kW/m^2$ is assumed in the calculation, which generally would raise the temperature of a steel plate to approximated 400°C over a two hour period. The following tables show the calculation results of Scenarios 2 and 3 in comparison with the minimum required firewall dimensions from NFPA 850 and FM Global.

Table 6

Received Heat Flux from Studied Example Transformers under Scenario 2 -– Pool Fire at the Bund and 30% of the Top Lid Area of the Transformer

| | **Transformer 1** | **Transformer 2** | **Transformer 3** |
|---|---|---|---|
| Received Radiation Heat Flux without Firewall ($kW/m^2$) | 5.6 | 16.2 | 16.5 |
| Fire barrier based on NFPA 850 (m) | none required | | |
| Received Flux with NFPA 850 fire barrier ($kW/m^2$) | 5.6 | 16.2 | 16.5 |
| Fire barrier based on FM Global | none | Neighbouring building is to be protected at full height (8 m) | |
| Fire barrier based on AS 2067 | none required | | |
| Required height of firewall for reducing received flux to $4kW/m^2$ (m) | 2.9 | 6.2 | 6.4 |

The high received radiation heat flux from Transformers 2 and 3 are caused by the wind effect (tilting the flame to approximately 60 degrees), and also the relatively short separation distance (15 m). Based on the New Zealand Building Code acceptance criteria, with an acceptable radiation level of 17kW/m$^2$ the level of received radiation heat flux from all three example transformers do not raise concern, assuming that only 30% of the transformer top plate ruptures.. Based on the calculation above, design based on NFPA 850 and AS 2067 is sufficient, and design based on FM Global may seem conservative. According to Building Code Australia with the acceptable radiation level of 12.5 kW/m$^2$, Transformers 2 and 3 would require a fire wall to the neighbouring properties to reduce the radiation level even though AS 2067 does not require one. These acceptance criteria do not apply to more sensitive equipment such as condensers. Based on the calculation, the required height of the firewall at the edge of the bund for Transformers 2 and 3 is higher than 6 m to reduce the heat flux to 4 kW/m$^2$.

Table 7
Received Heat Flux from Studied Example Transformers under Scenario 2 -– Pool Fire at the Bund and 30% of the Top Lid Area of the Transformer

| | **Transformer 1** | **Transformer 2** | **Transformer 3** |
|---|---|---|---|
| Received Radiation Heat Flux without Firewall (kW/m2) | 7.2 | 27.1 | 26.9 |
| Fire barrier based on NFPA 850 (m) | none required | | |
| Received Flux with NFPA 850 fire barrier (kW/m$^2$) | 7.2 | 27.1 | 26.9 |
| Fire barrier based on FM Global | none | Neighbouring building being protected at full height (8 m) | |
| Fire barrier based on AS 2067 | none required | | |
| Required height of firewall for reducing received flux to 4kW/m$^2$ (m) | 5.0 | 9.4 | 9.4 |

If the asset owner or stakeholders wish to investigate a more conservative scenario, the case where the entire transformer top lid has been ruptured may need to be assessed. The results shown in Table 7 indicate that the received radiation heat flux caused by a fire from Transformer 2 or 3 are alarmingly high. This is because of the high flame height acting together with the wind tilting the flame closer to the neighbouring building. The wind effect is not a variable addressed in the standards. This is why based on NFPA 850 and AS 2067, the transformers 2 and 3 would not require a flame barrier between them and the neighbouring equipment or buildings. However, with such a high heat flux, combustible building materials could ignite. To reduce the receiving heat flux to 4kW/m$^2$, the required height of the firewall at the edge of the bund for Transformers 2 and 3 is increased to 9.4 m, which is a significant wall.

Obviously, in both Scenarios 2 and 3, by following the design guide of FM Global recommendation and construction of the neighbouring building with fire resistant material to the full height can also protect the content and reduce the receiving heat flux inside to less than 4kW/m$^2$. However, such construction is not always an option, especially in existing facilities or power plants containing transformers, and specific calculation may be required as Tables 6 and 7 demonstrated that neither NFPA 850 or AS 2067 are always suitable or conservative. Nevertheless, at the end it depends on the asset owners or stakeholders to decide the level of risk that is acceptable, which may include the wind condition, the rupture type, and failure of active fire safety precautions.

It should be noted that in NFPA 850, AS 2067 and FM Global specify for two hours fire rated structure as the fire barrier. The two hours fire rating means the structure can sustain the ASTM E119 or ISO 834 standard fire for two hours, which has no real correlation with the burning duration of the transformer fire as described in AS 2067. Therefore, for a violently burning fire, it is possible the flame barrier may fail much earlier than two hours. Besides, the transformer may burn longer than two hours with a fire temperature much higher than 2 hours of standard fire, the risk associated with providing only a two hours fire rated wall should be clarified with all the asset owner or stakeholders in the risk assessment and subsequent design process. Whilst not the subject of this paper it is possible to analyse the requirements, and advise on the wall construction considering transformer fire temperatures to provide the specified fire wall duration required.

The study did not examine the effect of transformer water based deluge or other suppression systems as often these systems are not always installed around by all transformers, and by inspection it is clear that initial explosions may render these systems inoperative.

It should be noted that NFPA also emphasises the benefits of using fire-extinguishing gravels, in the bund underneath the transformer, suspended as a “sandwich” layer above a catchment basin and drained via flame traps to oil containment, as highly effective additional fire risk mitigation. Obviously due to cost, available space and other practicalities; such ideal risk mitigation cannot be always implemented. Hence following the Fire Protection Design Basis, (specifically engineered fire risk study), as recommended by NFPA is desirable.

In addition, the study did not investigate the fire effects of indoor transformers, which is another separate area of interest. Generally larger transformers are installed outdoors, although underground power stations, and in building location can have large transformer installations which pose different needs, such as longer fire durations due to ventilation limited fire constraints and explosion venting.

## Conclusions

Transformers are crucial to power generation and distribution systems. Unfortunately, transformers are one of the most likely components in an electrical distribution system or generation plant to catch fire. Because of the large quantity of fuel, resulting fires can emit significant amounts of heat damaging critical neighbouring equipment, plant and structures. The consequences of a transformer fire can be disastrous, so that having an effective risk mitigation strategy for transformer fires is very important.

While many excellent oil containment systems have been implemented in Australasia, some of these could lead to open pool oil fires. Providing an adequate radiation shield that is specifically designed and analysed can significantly reduce the consequences of the fire. Three transformers and different fire scenarios are assessed in this paper. The results show that depending on the level of risk the asset owner and stakeholders are willing to accept, neither the prescriptive guidelines in NFPA 850 or AS 2067 can provide an absolute consequence-free or conservative solution, and the ideal situation is to have the engineers, asset owners, and stakeholders establish an appropriate risk matrix to assist in the decision making and engineering design processes. The outcome from this is an appropriate engineering design of the fire resisting structure and possible oil containment and drainage measures to specifically cater for the risks present and the site conditions.

## References

1. P. Kiameh, *"Power Generation Handbook: Selection, Applications, Operation, and Maintenance"*, Martingsburg; McGraw-Hill, 2003.

2. A.K-L. Ng, *"Risk Assessment of Transformer Fire Protection in a Typical New Zealand High-Rise Building"*, Master's Thesis, Christchurch; University of Canterbury, 2007.

3. S.G. Badger, *"Large-loss Fires of 2000"*, NFPA Journal, November/December, 2001, pp. 57-64

4. W.H. Barley, *"Analysis of Transformer Failure"*, International Association of Engineering Insurers 36th Annual Conference, Stockholm, Sweden; 2003

5. O.R. Hansen, B. Wilkins, and K. Eckhoff, *"Explosion Protection in Transformer Rooms"*, Bergen, Norway; GexCon Report, 2005

6. *"NFPA 851, Recommended Practice for Fire Protection for Hydroelectric Generating Plants"*, Quincy, Massachusetts; National Fire Protection Association, 2010.

7. *"NFPA 850, Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations"*, Quincy, Massachusetts; National Fire Protection Association, 2010.

8. *"AS2067, Substations and High Voltage Installations Exceeding 1 kV A.C"*, Sydney; Standards Australia, 2008.

9. *"FM Global, Property Loss Prevention Data Sheets 5-4 – Transformers"*, USA; Factory Mutual Insurance Company, 2010.

10. B. Karlsson, and J. Quintiere, *"Enclosure Fire Dynamics"*, Boca Raton, Florida; CRC Press, 2000.

11. C. Beyler, *"Fire Hazard Calculation for Large, Open Hydrocarbon Pool Fires"*, The SFPE Handbook of Fire Protection Engineering, 4th Edition, Quincy, Massachusetts; National Fire Protection Association, 2008, p.3-271 to 3-319.

12. C.L. Tien, K.Y. Lee, and A.J. Stretton, *"Radiation Heat Transfer"*, The SFPE Handbook of Fire Protection Engineering, 4th Edition, Quincy, Massachusetts; National Fire Protection Association, 2008, p.1-74 to 1-90.

## Biography

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