Risk Mitigating Strategies of Transformer Fires

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Abstract: The consequences of transformer fires can include loss of energy supply for a period of 18 months or more, power system instability, high repair and replacement costs, environmental contamination, and loss of reputation, and threaten the safety of site personnel. Therefore, having an effective risk mitigation strategy for transformer fires is crucial to all stakeholders in the use and operation of transformers. In recent times, oil containment systems have been widely implemented around New Zealand. While such systems are helpful in the event of a benign oil spill such as during oil processing or transformer maintenance, they can contribute to a serious pool fire if oil is released during a catastrophic transformer failure, and in many cases, providing an adequate radiation shield that is specifically analysed can significantly reduce the consequences of the fire.

In Australasia, power generation companies generally adopt the prescriptive design guides such as National Fire Protection Association (NFPA) of the United States or FM Global design recommendations. Although the prescriptive design guides may reduce the fire risk to a certain extent, they do not work for all transformers and their installation configurations, and they do not specifically consider the quantity of fuel or the ambient conditions such as the external influences of wind.

This paper presents the performance of radiation shields as generically specified by NFPA and FM Global design recommendations and comments on their efficiency of performance by calculating radiation from transformer fires. Case studies will be given for three transformer sizes. As examples, radiation shields that provide more effective fire radiation damage limitation will be considered for each of these cases.

1. INTRODUCTION

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 whom do not understand the possibility of explosion or ignition in certain machinery. Understanding and reducing consequential loss is therefore highly important. New Zealand is currently going through major upgrade and replacement of transformers in the electricity generation and distribution areas, and this is the period when a specific fire risk analysis is most useful as risk mitigation measures can still be included in the overall design.

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. It is almost always the case that large transformers 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 has a flash point and fire point approximately of 110 to 170^{o}C [2], which is almost guaranteed to be exceeded during an internal transformer fault. 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.

Transformer failures are relatively uncommon. Based on Bartley's analysis, between 1997 and 2001 there were only 94 reported failures of transformers rated at 25MVA and above in the world [3]. Not all of these failures led to transformer fires. However, out of the 94 incidents, 24 were caused by insulation failure, 5 were caused by overloading, 4 were by line surge and 3 were related to direct exposure to fire/explosion from external sources. All of these failure mechanisms provide ignition sources that can lead to fires. The likelihood of both insulation and short-circuit failures increases with the age of the transformer [3,4].

Because of the large amount of refined mineral oil with a high heat of combustion in the transformer, the size of a transformer fire can be tremendous and incur significant damage to the adjacent equipment and structures, threaten lives and cause both tangible and intangible losses. For example, in the year 2000, a single transformer fire in Virginia destroyed two transformers and damaged the third, incurred a US$10 Million in damages [5]. In 1994, a transformer fire in New York spread to the turbine building, generator station and the boiler towers causing significant damage to the plant, and the fire from the unprotected transformers overwhelmed the sprinkler system in the neighbouring buildings [6]. In the case of generator step up transformers where a spare is not available it is often the lost generation revenue that dwarfs even the high repair and replacement costs of the transformer itself. In such a case it would be typical for the generator to be out of service for at least 18 months.

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. There are several studies in this field to investigate how to minimise the risk of transformer fires from different angles. Hansen et al. looked into reducing the flammability of the transformer oil vapour mixture prior to ignition in order to reduce the likelihood for ignition [4]. The Hydroelectric Research and Technical Services Group of Bureau of Reclamation in Denver, Colorado of U.S Department of the Interior advised to replace mineral oil to ester-based insulating fluid which has higher flash and fire points, and use both active and passive fire protection systems on transformers in accordance with NFPA 851 [7].

The business risk associated with transformer fires can be reduced either by decreasing the likelihood of a fire, or by minimising the consequences. While the former option is extremely important and receives considerable attention in modern asset management practises; the focus of this paper is on the latter option and looks into relying on radiation shields to protect the buildings and equipment adjacent to the transformers.

2. BACKGROUND INFORMATION

In New Zealand, the Building Code sets the performance objectives of the fire design. However, if the power generating plants are designed only to meet the Building Code, there will be no asset protection or any measures to sustain the business continuity, not to mention the subsequent loss incurred to the society during the down time of the electricity supply. Therefore, most of the power generating plants and critical substations have additional safety measures in place to provide the extra level of protection.

Generally, prescriptive design guides such as NFPA850 [8] and NFPA851 [9] from the National Fire Protection Association of the United States, AS 2067 [10] or FM Global design recommendations [11] are used for design by power generation companies in Australasia. 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 hidden in these assumptions. Besides, each power generating plant or transmission location is different and more than likely located in a remote area with an unusual surrounding environment, and have an odd configuration in relation to existing buildings and other plant. A generic prescriptive design may not always be the conservative design option.

The most recent editions of NFPA 850 and 851 appear to give stronger emphasis to the "Fire Protection Design Process". This process recognises that the recommendation of these codes is to incorporate the experience and knowledge of persons familiar with fire protection engineering and those familiar with the plant item of concern. To be precise, the plant specific analysis and evaluation taking into account the particular equipment, its configuration and layout and operating requirements. It is also anticipated that the design is formulated taking into account the risk profile and risk acceptance levels across a range of consequences.

In terms of the fire separation between outdoor oil-insulated transformers and its adjacent structures, NFPA 850 requires 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 default generic calculation method for designing the 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 wind tilting effect.

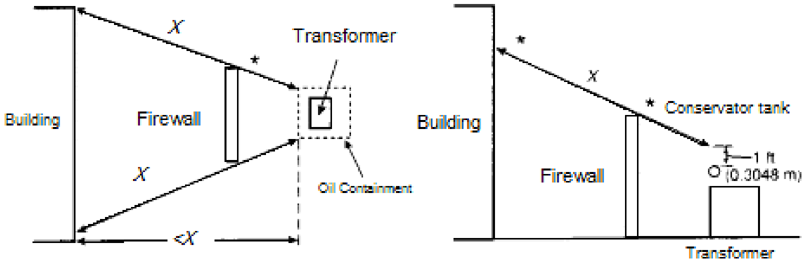

Figure 1 Illustration of Oil-Insulated Transformer Separation based on NFPA850

AS 2067 [10] adopts a different approach. 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. However, a minimum height of the firewall is not specified as in NFPA 850.

FM Global [11] provides a similar calculation methodology to AS 2067 as shown in Figure 2. The recommended fire separation distance is approximately twice of the distance required by NFPA850. However, the flame height and the wind tilting effect made in the assumptions are still unclear.

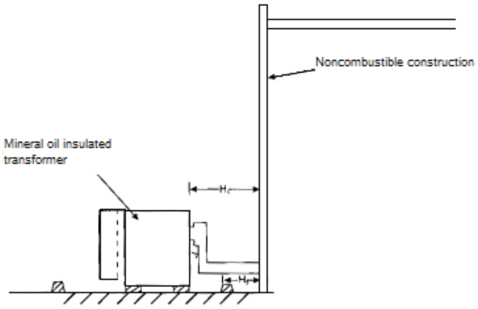

Figure 2 Illustration of Oil-Insulated Transformer Separation based on FM Global

Without getting into explosion science, the heat generated from a transformer fire and the likely flame height can be calculated in a practical manner using fundamental fire engineering equations, and 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.

3. ASSESSMENT METHODOLOGY

Babrauskas [13] discusses the mechanisms as to how transformer fires initiate. The mechanisms can involve arcing faults resulting in the ejection of oil aerosols, yielding mostly ethane, ethylene, methane, acetylene and small quantities of hydrogen. These ejections are possibly accompanied by the explosion of the transformer main tank and result in fire. Meanwhile, dislodgement of the transformer lid and hatch covers can be triggered, resulted from failures of the connection bolted sections and edges.

Case studies have indicated that the ruptures are mostly along the bolted seams of the transformer 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 the fire can have significant time duration due to the abundant fuel source. It must also be remembered that within the transformer there are tons 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 for new transformers, especially 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, although 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 endeavour to model these scenarios by assuming a pool fire at the base equal to the bund area and another pool fire equal to the top plate area of the transformer. The calculation methodologies are well established for pool fires [12, 14] Using the methods established by Tien et al. [15], the radiation effect on to surrounding structures and equipment, with or without considering the tilting of the flame caused by the wind, can be calculated.

From the designer's point of view, the outcome of this exercise is to be checked against the acceptable level of received heat flux at the neighbouring structures or machinery. In many situations the neighbouring structures are not very sensitive to the heat flux, 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, as high temperature or heat flux could cause 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 machinery also depends on the stakeholders, and consideration should include the importance and reinstatement cost of these structures or machinery, the redundancies and the risk of operation discontinuity.

4. EXAMPLE TRANSFORMERS

Three transformers are assessed based on the requirements of NFPA 850, FM Global and fundamental fire engineering equations. The first assessment is based on an actual 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.

Table 1 Dimensions of Example Transformer 1

Transformer Type	100MVA, 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.

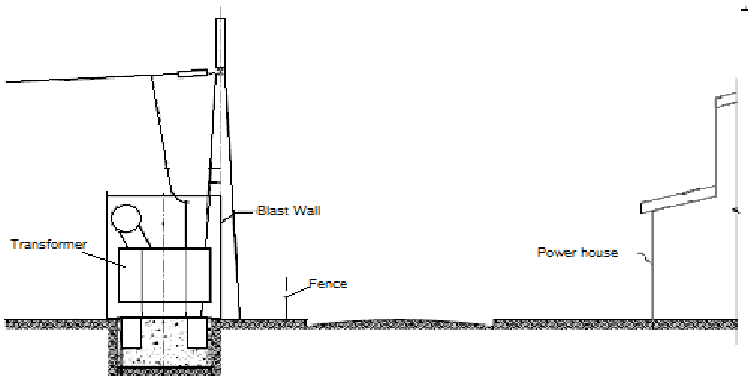

Figure 3 Schematic Drawing of the Layout of Example Transformer 1

Example Transformer 1 is a 14-year old 100 MVA generator step up transformer which exploded one night in 2008. 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 content 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 has caused all bushings shattered, aluminium casting melted, and complete destruction of external facilities. 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.

The other two transformers are typical realistic examples. Table 2 shows the key parameters of the transformers.

Table 2 Dimensions of Example Transformers 2 & 3

	Example Transformer 2	Example Transformer 3
Transformer Type	95MVA, 33-110kV	230MVA, 11-220kV
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 46MJ/kg [11], and a flash point 140^{o}C [2]	65000 litres of mineral oil, assumed heat of combustion is 46MJ/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, 56km/hr	

5. CALCULATIONS & DISCUSSIONS

In simplistic terms 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. The first fire scenario only considers a pool fire at the bund; the second scenario has pool fires both at the bund and 30% of the top lid area; and the third scenario has pool fires both at the bund and 100% of the top lid area, assuming the entire top lid has ruptured or the conservator tank has spilled oil over the top of the transformer. Table 3 shows the fire size from all three example transformers under the three scenarios, calculated using the method mentioned in Section 3.

In the calculation the ambient temperatures is assumed to be 20°C, and the atmospheric pressure 760mmHg. Both ambient temperature and atmospheric pressure are within the normal range experienced in New Zealand and have only a small influence in the final results. Altering the ambient temperature by 20°C for instance has a difference of less than 5mm on the flame height.

Table 3 Emitted Heat Flux of Studied Example Transformers

	Transformer 1	**Transformer 2**	**Transformer 3**
Scenario 1 – Pool fire at the bund			
Pool fire area (m^2)	26 (41-15)	47.7 (89-41.3)	45 (79-34)
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
Scenario 2 – Pool fires at the bund and 30% of top lid area of the transformer			
Pool fire area (m^2)	43.9 (bund: 26; top lid: 4.5)	60.1 (bund: 47.7; top lid: 12.4)	55.2 (bund: 45; top lid: 10.2)
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 transformer fire: 10.3	bund fire: 8.3 transformer fire: 11.1	bund fire: 8.5 transformer fire: 11.5
Emissive Power (kW/m^2)	bund fire: 70.4 transformer fire: 110	bund fire: 53.4 transformer fire: 94.5	bund fire: 56.0 transformer fire: 97.9
Scenario 3 – Pool fire at the bund and 100% of top lid area of the transformer			
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 transformer fire: 12.7	bund fire: 8.3 transformer fire: 14.6	bund fire: 8.5 transformer fire: 14.7
Emissive Power (kW/m^2)	bund fire: 70.4 transformer fire: 91.0	bund fire: 53.4 transformer fire: 70.3	bund fire: 56.0 transformer fire: 74.5

It is apparent that Scenario 1 is not as severe as Scenarios 2 and 3. Between Scenarios 2 and 3, although the emissivity power of the transformer fire is less in Scenario 3, 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.

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 4kW/m^2 is assumed in the calculation, which generally would raise the temperature of a steel plate to approximated 400^{o}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 4 Emitted Heat Flux of Studied Example Transformers for Scenario 2

	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 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)	2.9	6.2	6.4

The high received radiation heat flux from Transformers 2 and 3 are caused by the wind tilting effect (approximately 60 degrees) and also the relatively short separation distance (15 m). Based on the New Zealand Building Code acceptance criteria, 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. This acceptance criterion does 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 4kW/m^2.

Table 5 Emitted Heat Flux of Studied Example Transformers for Scenario 3

	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 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 5 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 effect drawing the flame closer to the neighbouring building. The wind effect is not a variable addressed in the standards. Therefore based on NFPA 850 and AS 2067, the transformers do not require a flame barrier. 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 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 power plants, and specific calculation may be required as Tables 4 and 5 demonstrated that neither NFPA 850 or AS 2067 are always suitable or conservative. Nevertheless, at the end it depends on the 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 2097 and FM Global specify for two hours fire rated structure as fire barrier. The two hours fire rating means the structure can sustain the ISO 834 standard fire for two hours, which has no real correlation with the burning duration of the transformer fire as described in AS 2097. 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 ISO fire, the risk associated with providing only a two hours fire rated wall should be clarified with all the stakeholders in the design.

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

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 can have large transformer installations which pose different needs, such as longer fire durations due to ventilation limited fire constraints and explosion venting.

6. 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 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 New Zealand, some of these could lead of open pool oil fires. Providing an adequate radiation shield that is specifically 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 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 and stakeholders establish the risk matrix and then design the fire resisting structure specifically to match the site conditions and accepted risk level.

7. REFERENCES

[1] Kiameh P., 2003, *Power Generation Handbook: Selection, Applications, Operation, and Maintenance*, McGraw-Hill, Martinsburg, USA.

[2] Ng, A.K-L., 2007, *Risk Assessment of Transformer Fire Protection in a Typical New Zealand High-Rise Building*, Master’s Thesis, University of Canterbury, NZ

[3] Barley, W.H., 2003, *Analysis of Transformer Failures*, International Association of Engineering Insurers 36th Annual Conference, Stockholm, Sweden.

[4] Hansen, O.R., Wilkins, B., Eckhoff, K, 2005, *Explosion Protection in Transformer Rooms*, GexCon Report, Bergen, Norway.

[5] Badger, S.G., 2001, "Large-loss fires of 2000", *NFPA Journal* (Nov/Dec), pp.57-64

[6] Sullivan, M.J., 1994, "Property Loss Rises in Large-loss Fires", *NFPA Journal* (Nov/Dec), pp.84-101

[7] Bureau of Reclamation - Hydroelectric Research & Technical Services Group, 2005, *Transformer Fire Protection*, FIST 3-32, Denvor, Colorado

[8] NFPA 850, 2010, *Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations,* National Fire Protection Association, Quincy, MA, USA.

[9] NFPA 851, 2010, *Recommended Practice for Fire Protection for Hydroelectric Generating Plants*, National Fire Protection Association, Quincy, MA, USA.

[10] AS 2067, 2008, Substations and High Voltage Installations Exceeding 1 kV A.C., Standards Australia, Sydney, Australia

[11] FM Global, 2006, Property Loss Prevention Data Sheets, Factory Mutual Insurance Company, USA.

[12] Karlsson, B., Quintiere, J., 2000, Enclosure Fire Dynamics, CRC Press, Boca Raton, FL, USA.

[13] Babrauskas, V. 2003, *Ignition Handbook: Principles and Application for Fire Safety Engineering, Fire Investigation, Risk Management and Forensic Science*, Fire Science Publishers, Issaquah, Wash., USA.

[14] Beyler, C. 2008, "Fire hazard calculation for large, open hydrocarbon pool fires", *The SFPE Handbook of Fire Protection Engineering*, 4th Edition, National Fire Protection Association, Quincy, MA, USA, pp. 3-271 to 3-319

[15] Tien, C.L., Lee, K.Y., Stretton, A.J., 2008, "Radiation heat transfer", *The SFPE Handbook of Fire Protection Engineering*, 4th Edition, National Fire Protection Association, Quincy, MA, USA, pp. 1-74 to 1-90