RELIABILITY OF MAIN TRANSFORMERS

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ABSTRACT

Key equipment for the electric power transmission is the transformer. Because of the high failure frequency and the resultant reliability and safety implications in particular of main transformers, an in-depth assessment is necessary. Main transformers are considered as a critical equipment because of the large quantity of oil in contact with high voltage elements. Experience has shown an increasing number of transformer explosions and fires in all types of power plants worldwide. Therefore, these phenomena have been investigated in more detail and are discussed with regard to potential root causes for these events such as potential influence of the age of the transformers. Moreover, possible diagnostic measures to avoid such events and enhance the reliability are shortly described. For investigating the current status of the reliability of transformers different types of databases have been evaluated.

1 INTRODUCTION

A broad spectrum of events such as design defects, voltage surges, lightning strikes, structural damage, rapid unexpected deterioration of insulation, sabotage, and even maintenance errors can lead to transformer fires and explosions. Experience has shown that the consequences of such events can be severe.

In particular, a fire of an oil-cooled transformer that contains several thousand litres of combustible insulating oil can result in severe damage to nearby power plant structural components such as concrete walls and damage or destroy electrical components such as nearby transformers, bus work, and circuit breakers (US Department of the Interior 2005). A one-year research project led to the discovery of 730 transformer explosions in the USA only. Many experts anticipate that the number of failures per year will increase significantly in the near future to 2%. In addition, the shorter lifetime of new transformers will sharply increase above this rate after 2010. Because about 115 000 large transformers are in operation in the US and about 400 000 worldwide, the number of impacted transformers is high, even when only in some cases fire and explosion lead to a total damage (Berg & Fritze 2010).

Power transformers with an upper voltage of more than 100 kV are necessary for the undisturbed operations of a developed society. In electricity generation plants, power transformers transform the voltage of the generator to a higher level for the transmission of electricity in the main grid. The voltage of the main grid must again be transformed to a lower voltage, so that the electrical energy can be utilized in numerous purposes (Valta 2007).

Electric power is normally generated in a power station at 11 to 25kV. In order to enable the transmission lines to carry the electricity efficiently over long distances, the low generator voltage has to be increased to a higher transmission voltage by a step-up transformer, i.e. 750 kV, 400kV, 220kV or 110kV as necessary. Supported by tall metal towers, the lines transporting these voltages can run into hundreds of kilometres. The grid voltage has then to be reduced to a sub-transmission voltage, typically 26kV, 33kV or 69kV, in terminal stations (also known as power substations).

Sub-transmission lines supply power from terminal stations to large industrial customers and other lower voltage terminal stations, where the voltage is stepped down to 11kV for load points through a distribution network lines. Finally, the transmission voltage is reduced to the level adapted for household use, i.e. 415V (3-phase) or 240V (1-phase) at distribution substations adjacent to the residential, commercial and small to medium industrial customers. Figure 1 shows a typical electrical network system, in which power is transformed to the voltages most suitable for the different parts of the system.

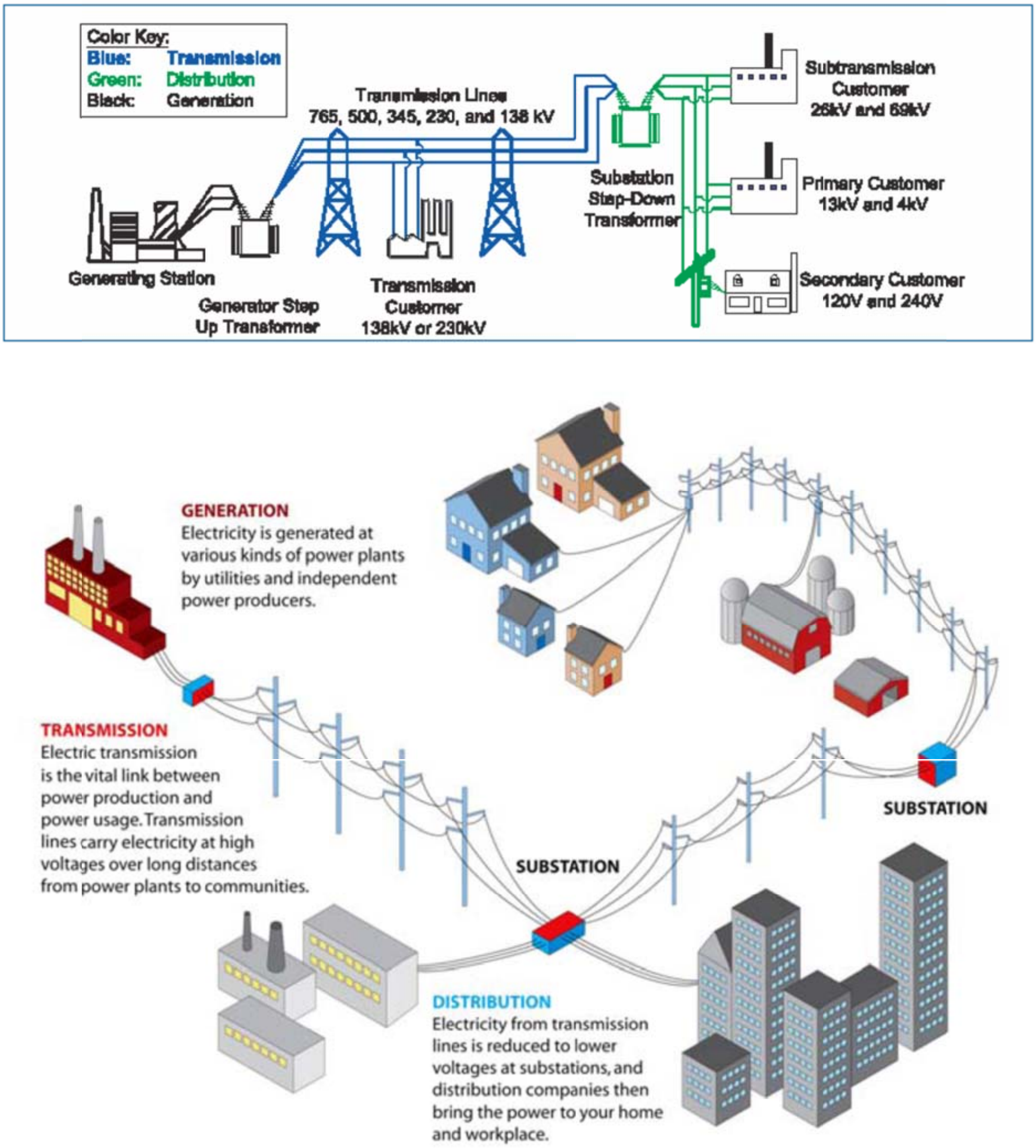

Figure 1. Typical electrical power network

At every point where there is a change in voltage, a transformer is needed that steps the voltage either up or down. There are essentially five levels of voltages (United States Department of Energy 2006) used for transmitting and distributing AC power (Table 1): Ultra-High Voltage

(UHV, 1100 kV), Extra-High Voltage (EHV, 345 to 765 kV), High Voltage (HV, 115 to 230 kV), medium (or sub-transmission) voltage (MV, 34.5 to 115 kV), and distribution voltage (2.5 to 35 kV). The UHV, EHV, HV, and MV equipment is mainly located at power plants or at electric power substations in the electric grid, while distribution-level transformers are located in the distribution network on poles, in buildings, in service vaults, or on outdoor pads.

Table 1. AC voltage classes

Transmission Voltages		**Distribution Voltages**	
Class	**kV**	**Class**	**kV**
Medium voltage (MV)	34,5	2.5	2.4
	46	5	4.16
	69	8.66	7.2
	115	15	12.47
High voltage (HV)	115	25	22.9
	138	35	32.5
	161		
	230		
Extra-High voltage (EHV)	345		
	500		
	765		
Ultra-High voltage (UHV)	1100		

For the different activities of changing voltage, the following two types of transformers are commonly used:

- dry type transformers and
- liquid insulated transformers.

Dry type transformers are transformers containing solid or gas insulation material. The fire hazard of dry type transformers is generally considered to be lower compared to liquid type transformers because the amount of combustible materials present in the transformers is limited.

Liquid insulated type transformers are usually subdivided from a fire hazard point of view into less flammable liquid transformers and flammable liquid transformers.

Less flammable liquid (e.g. silicone oil, ester) is expected to have a high fire point (above 300°C) and, hence, such a transformer is more difficult to ignite. Transformers which are insulated with flammable liquid such as mineral oil are considered to have the highest fire hazard because of the combustible liquid oil and its relatively lower fire point (100°C to 170°C).

Today, liquid-filled main transformers are widely used in power distribution systems. Most are outdoors, where the risk of property damage associated with a flammable liquid dielectric is lower.

When flammability must be reduced, alternative liquids are needed which lead to other problems (toxicity) resulting from PCB. Therefore, the majority of main transformer is still oil-insulated.

2 MAIN COMPONENTS OF A TRANSFORMER

The major components of a transformer are the coils (windings), the core, the tank or casing, the radiator, and the bushings as shown in Figure 2. Generally, transformer coils are made of copper because it has a lower resistance and is more efficient compared to other metals. Each winding is wrapped with an insulating material such as paper. The primary winding is usually wound around the transformer core and the secondary winding is then wound on top of the primary winding. Between each layer of the windings, another layer of insulating material is wrapped to provide extra insulation between the windings. There are ten major transformer components (Ng 2007).

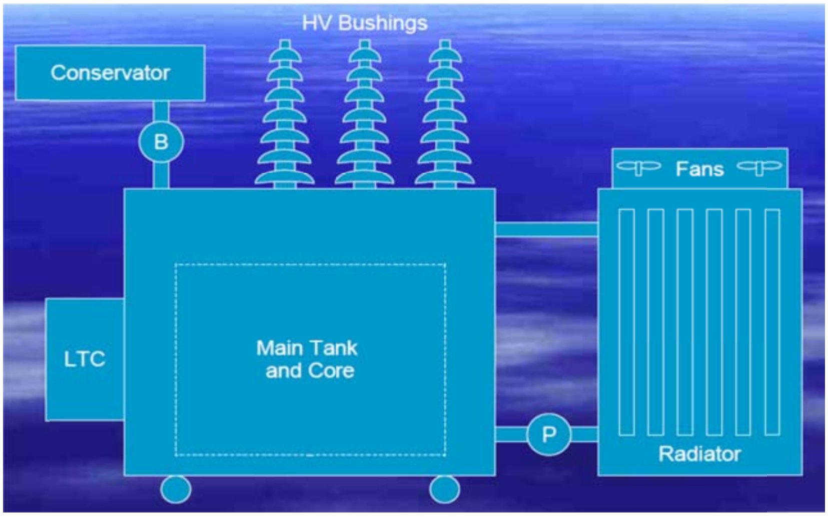

Figure 2. Main transformer components

These components can briefly be described as follows:

1) Core is a ferromagnetic material (commonly soft iron or laminated steel) that provides a path of high magnetic permeability from the primary circuit to the secondary circuit.
2) Windings allow a secondary voltage to be induced in the secondary circuit from the alternating current (AC) voltage in the primary circuit. The change in magnetic field in the transformer core caused by applying primary AC voltage causes an induced magnetic field and, hence, voltage on the secondary winding.
3) Tank or casing, which is usually a reinforced rectangular structure in these transformers, contains the dielectric material, the core and the windings.
4) Dielectric material is a substance that is a poor conductor of electricity but an efficient supporter of electrostatic fields. It can be fluid oils, dry solids or gases.
5) The expansion tank or conservator containing dry air or dry inert gas is maintained above the fluid level.
6) Bushing is an insulating structure that provides a conducting path though its centre, its primary function is to insulate the entrance for an energised conductor into the tank.
7) Pressboard barriers, between the coils and between the coils and core, are installed to increase the dielectric integrity of the transformer.
8) The tap changer is a connection point along a transformer winding that allows the number of turns to be selected, or so-called voltage regulating device.
9) The radiator provides a heat transfer path to dissipate the internal heat generated in the transformer.
10) The pressure relief device is used to protect the tank against excessive pressure release inside a transformer tank.

An oil-insulated transformer is made up of a steel tank, which includes windings and the transformer's iron core. During the manufacturing phase, the windings are covered with insulation paper and electrical insulating board. The steel tank is full of transformer oil and it impregnates the insulation paper, during which time the combination of paper and oil and the electrical insulating board form a necessary electrical insulation.

Basic core and winding configurations differ little between dry and oil-insulated transformers. However, air is a much poorer insulator than dielectric fluid; hence, clearances between conducting surfaces can be much smaller in a liquid-filled transformer, allowing operating voltages to be much higher than with dry-type design.

To ensure that the transformer can operate without failure for at least 30 years and that the life expectancy of the transformer can be correctly estimated the properties of the transformer oil and insulating paper must be kept at a specific level.

3 RESULTS FROM INTERNATIONAL DATABASES

3.1 OECD FIRE Database

One application of the OECD FIRE Database has been an analysis of events associated with explosions (Berg et al. 2009 and 2010a) base on the database issued March 2009. A query in the Database on the potential combinations of fire and explosion events has indicated a significant number of explosion induced fires. Most of such event combinations occurred at transformers on-site, but outside of the NPP buildings or in compartments with electrical equipment. Approximately 50 % of the fires were extinguished in the early (incipient) fire phase before the fire had fully developed. As a consequence of these indications, improvements concerning the fire protection of transformers are intended in Germany. As there is no specific coded field in the database to indicate explosions, the main source of information is provided by the event description field.

Basis for the results provided in this section is the version March 2010 of the OECD FIRE Database. The 24 reported explosions amount to 6.5 % of all events reported up to date (see Figure 3).

Concerning the process of explosion distinction should be made between an explosion as a process of rapid combustion (chemical explosion) and an explosion as a physical process resulting from a sudden gas pressure rise by a high energy electric (arcing) fault (HEAF).

A chemical explosion was found for only three events (solvent vapor, diesel fuel, hydrogen). In the other 20 cases, HEAF events obviously took place at the same time indicating a physical explosion. In some of these cases the electric fault might have caused a fuel pyrolysis or fuel spread and acted as an ignition source for a chemical explosion, thus a HEAF event and a chemical explosion may have taken place simultaneously.

In one event, a fire led to the explosion of diesel fuel vapor while in another event a fire and an explosion occurred independently from each other in parallel. In all other cases explosions induced the fire).

Concerning the buildings/locations where the events took place it was found that 13 (54 %) events took place outside buildings, five inside electrical buildings.

A majority of 54 % of the reported explosions started at transformers. The other 11 events took place at electrical cabinets, other electrical equipment, or process equipment (three each representing 13 %). External fire brigades were needed in four of 24 cases (17 %). The 24 events were also evaluated concerning the fire duration with the following results shown in Table 2.

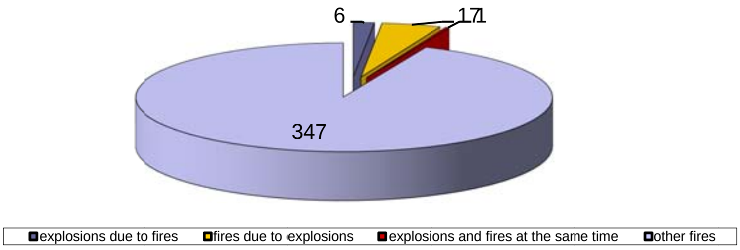

Figure 3. Results from the OECD FIRE Database

Table 2. Fire duration

Fire duration	Number of events
0 - < 5 min	11
15 - < 30 min	4
30 - < 60 min	4
> 60 min	3

For the remaining two events no information on the fire duration is provided. This is in good agreement with the fire durations recorded for all events, where for approx. 59 % of the events (154 out of 261 events with fire duration provided) a fire duration of less than 15 min could be found.

As one can see from Figure 4, fires of high voltage transformers contribute to about 8,9 % of all fires contained in the OECD FIRE database.

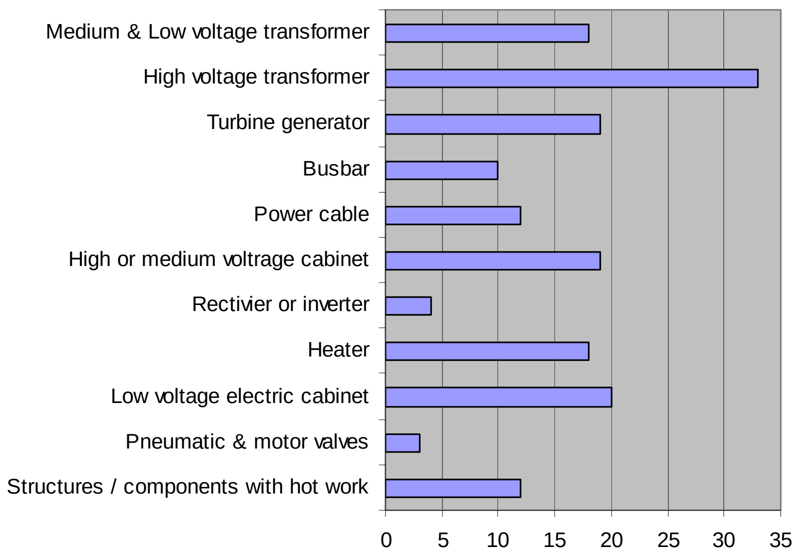

Figure 4. Components where the fire started

3.2 Statistics from EPRI Database

Within the document on fire PRA methodology (EPRI and USNRC 2005) some generic fire frequencies are provided based on the operational experience of US nuclear power plants:

- Catastrophic fire at transformer yard (includes events with rupture of transformer tank, oil spill and burning oil splattered a distance from the transformer): 6.0E-03 / reactor year.
- Non Catastrophic fire at transformer yard (includes events without oil spill outside transformer tank): 1.2E-02 / reactor year.
- Other fires at transformer yard (includes events associated with the transformers but not the transformers themselves): 2.2E-03 / reactor year.
- The above given mean values are based on 1674 reactor years and about 35 fire events in total.

The transformer yard fire frequencies estimated in the above mentioned report are comparable to the operating experience shown by OECD FIRE database. The number of transformer yard fires collected in the OECD FIRE project is also adequate for qualitative purposes. Quantitative analysis of the OECD FIRE data would still require additional information about number of transformer under consideration in each NPP to avoid using reactor years, which causes some uncertainty. Also additional information on the amount of burned transformer oil would be welcome to realize the necessary performance of fixed extinguishing systems and operative fire fighting measures (Lehto et al. 2010).

3.3 Statistics from non-nuclear industry

Transformers are used for stepping up or down the voltage.. High voltage equipment is mainly located at power plants and at substations representing high voltage electric systems facilities used to switch generators, equipment and circuits or lines of the system on and out. Substations can be large with several transformers and dozens of switches.

In 2003, the International Association of Engineering Insurers (IMIA) presented a research, which contained an analysis of transformer failures, which have occurred in IMIA member countries (see Bartley 2003 and Bartley 2005). During the period 1997 – 2001 a total of 94 failures occurred.

These 94 failures have been divided in Table 3 below according to age.

Table 3. Division of failure according to age of transformer 1997 – 2001

Age	Number of failures
0 – 5 years	9
6 – 10 years	6
11 – 15 years	9
16 – 20 years	9
21 – 25 years	10
Over 25 years	16
Age unknown	35

Insulation failures were the leading cause of failure in this study. The average age of the transformers that failed due to insulation was set to 18 years, in some cases leading to transformer fire and explosion. However, the high number of failures where the age is not known may indicate a tendency to higher transformer failures due to ageing.

During the normal use of a transformer, oil and insulation paper becomes old and at some phase they are no longer able to fulfil their tasks concerning electrical and mechanical strength.

The damage databases provide clear observations that transformer damages often arise due to defects in insulation that originate in the interior of the transformer. It is, therefore, necessary to monitor the ageing phenomena so that reliable information concerning potential faults can be obtained during the earliest phase possible.

More recent industry data show that in case of substation transformer 20 % of failures result in a fire. In Los Angeles, 97 transformer fires occurred in the first three month of 2006, averaging more than one per day.

According to (Lord & Hodge 2008) the contribution of the different main components (as shown in Figure 2) to major failures are winding and tap changes with about 25 % each, whereas high voltage (HV) bushings are the cause in about 20 % to 40 % of failures depending on the underlying statistical basis. However, HV bushings provide the highest contribution to all transformer fires with about 70 % (see Figure 5).

These results are furthermore supported by the experience provided in Table 4 (Foata & Nguyen 2010) where the failure statistics for 735 kV transformers over 25 years is collected.

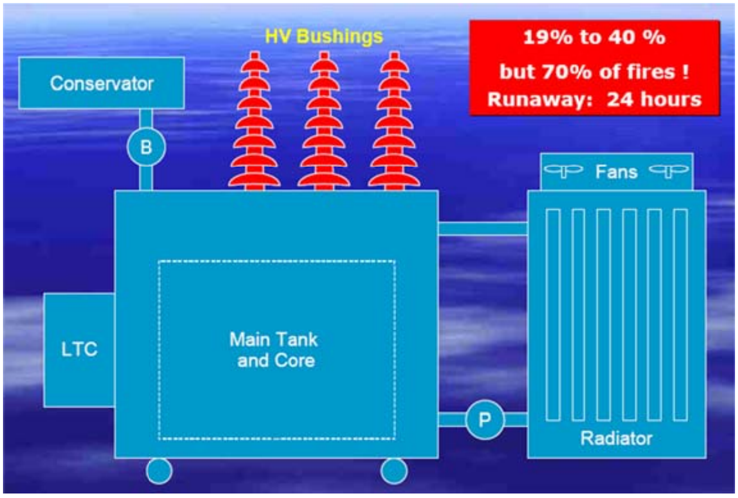

Figure 5. Contribution of Major Failures

This database contains 175 transformer failures that resulted in 110 high energy arcs causing in total 44 tank ruptures and 18 fires. In 13 of the 18 fires, the component HV bushings contribute to the transformer fires.

Table 4. Failure statistics for 735 kV transformers over 25 years

Component	Faults	Ruptures	Fires
HV bushing	41	19	13
Windings	57	21	3
Core	3	2	1
OLTC	2	1	0
Others	7	1	1

The large contribution of bushing failures to the transformer fire risk is also a result presented in the last transformer session of the International Council of Large Electric Systems (Foaka 2010) as shown in Figure 6.

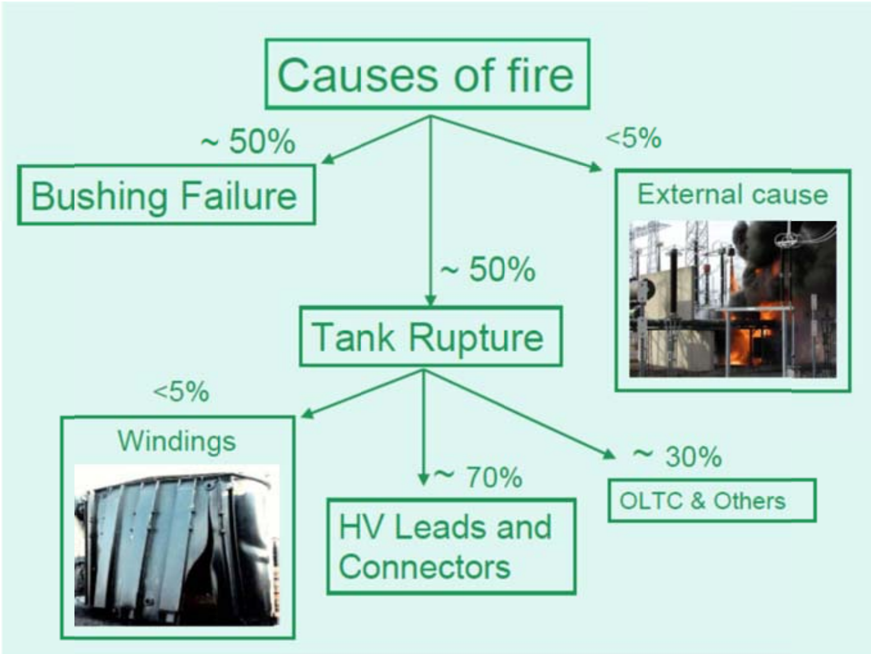

Figure 6. Causes of transformer fires (Foata 2010)

As in the case of the statistics provided in (Foata & Nguyen 2010) also other power utilities traditionally collect data and information on failure causes (Minhas et al. 1999). This information shows that in smaller transformers ageing related failures are dominant. In the medium power rating class, tap changer failures constitute the highest failure rate.

In the large transformers insulation coordination failures are the most common cause in the early service life of transformer (Mirzai et al. 2006), the influence of ageing could not be justified at present due to a lack of data.

However, one result provided in (Foata 2010) shows a correlation between the fire rate per year and the voltage which depicts an increasing probability for a transformer failure resulting in a fire for larger power transformers.

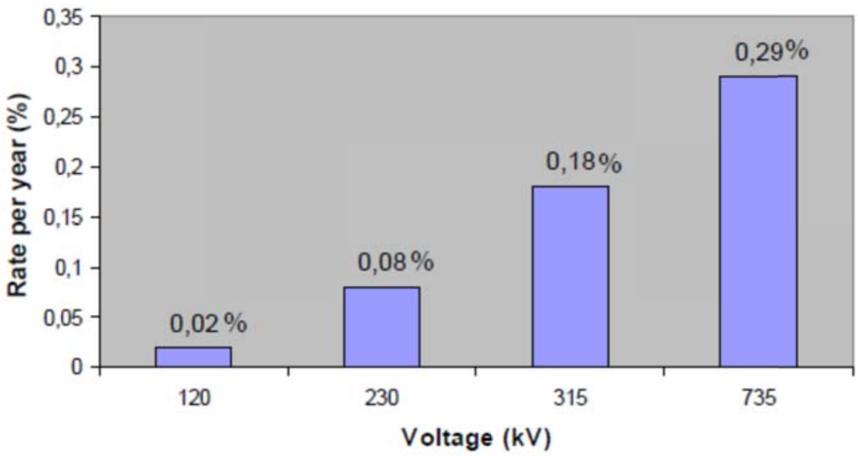

Figure 7. Fire probability vs. voltage

Figure 8 shows an example of a destroyed transformer, the root cause was an electrical arc, fortunately not resulting in a fire or explosion.

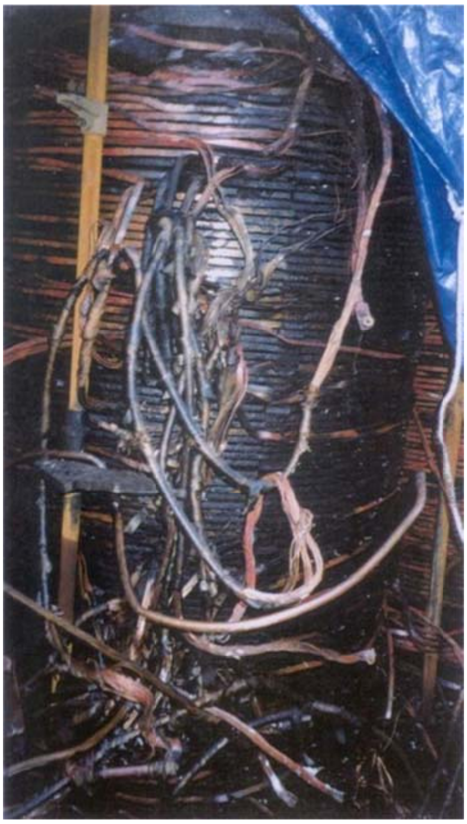

Figure 8. Example of a destroyed transformer

10 EXAMPLE OF A TRANSFORMER FIRE IN A NUCLEAR POWER PLANT

A fire started in the transformer building leading to a short circuit to occur in the transformer. The resulting electric arc – a spark – set fire to the oil in the transformer.

A simplified diagram showing the main components of station service supply and the grid connection of the nuclear power plant is provided in Figure 9.

The short circuit was recognised by the differential protection of the generator transformer, and the circuit-breaker between the 380-kV grid connection and the affected generator transformer (AC01) as well as the generator circuit-breaker upstream of the unaffected transformer (AQ02) were opened. At the same time, de-excitation of the generators was actuated. The short circuit was thereby isolated. In addition, two of the four station service supply bus bars (3BC and 4BD) were switched to the 110-kV standby grid (VE in Figure 9).

Within another 500 ms, the generator protection system caused the circuit-breaker between the second 380-kV grid connection and the intact generator transformer (AC02) to open. Subsequently the two other station service supply bus bars (2BB and 1BA) were also switched to the standby grid. After approx. 1.7 s, station service supply was re-established by the standby grid. Due to the two short under voltage on station service supply bus bars (signal "Voltage of unit bus bars BB and BC<70%") the reactor protection system triggered reactor trip.

Due to the damage caused by the fire in the transformer, the plant was shutdown. The fire of the transformer showed the normal behaviour of a big oil-filled transformer housing, the fire lacks combustion air and produces a large amount of smoke (see Figure 10).

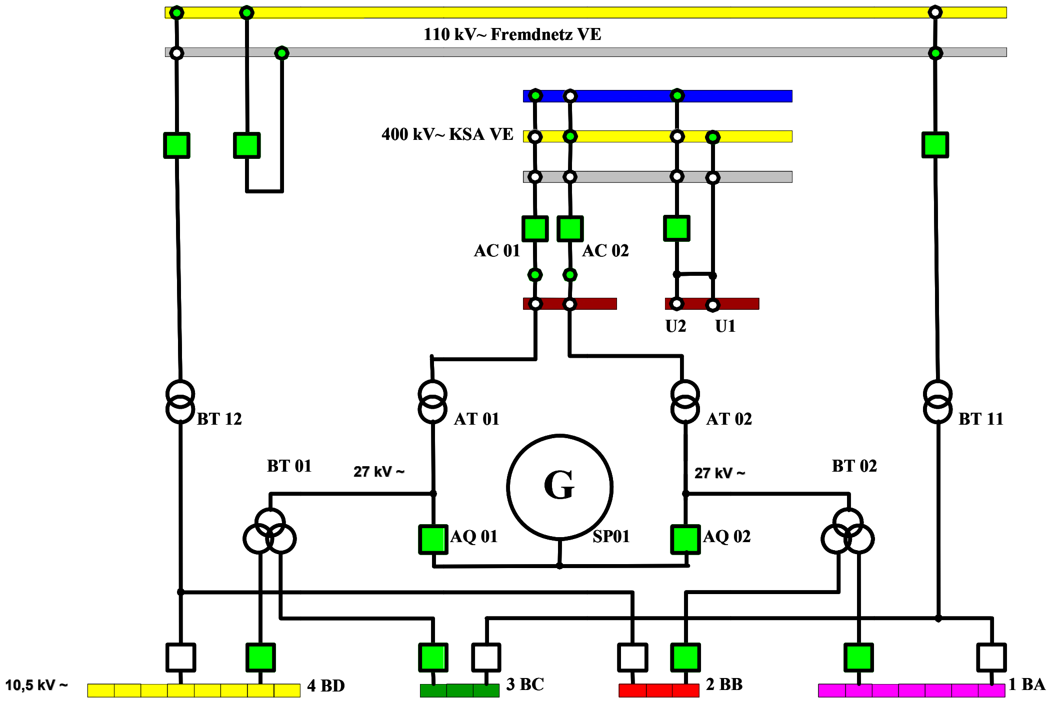

Figure 9. Simplified diagram of the station service supply
and the grid connection of the nuclear power plant

The fire extinguishing activities start with an automatic fire extinguishing system, followed by activities of the on-site fire brigade, later supported by external local fire fighters (see Figure 11).

Figure 10. Flames and smoke occurring at the 2007
generator transformer fire at a German NPP

After the end of the fire fighting operations, a foam attack and later a flooding of the transformer vessel has been started to cool down the spools.

The time, until the fire in the transformer housing was extinguished, lasted nearly seven hours, approx. 70.000 kg transformer oil were ignited.

The long duration of the extinguishing phase is due to the large amount of fire loads involved and the exceptional heat capacity of the transformer core and windings (approx. 350.000 kg of iron and copper).

Figure 11. Fire extinguishing activities supported by the external local fire fighters

All fire fighting equipment worked as designed. Because of the non chloride oil the influence on the environment is low.

The root cause analysis of this event was not successful due to the total damage of the transformer. Therefore, one alternative is to perform a simulation of the event which has to couple electromagnetic, thermal and hydrodynamic phenomena. For that purpose, one has to:

- determine the magnetic field created by the inductance and/or arc in the surrounding field versus the injected current per phase;
- calculate the induced currents and the Joule and Eddy current local dissipated power;
- calculate the temperature by using the resulting above values as heat sources.
- Such a calculation can be done using four sub models as described in (Scheurer et al. 2007a and 2007b).

The analysis has been based on the information that an electric arc was the starting point of the event sequence. The electrical arc is a high temperature plasma. Therefore, at this heat level, the oil cracking process generates sufficient gas to create an overpressure. The vessel maximum tolerated pressure was determined to be above atmospheric pressure, but the pressure relief valves are inefficient for such pressures.

11 APPLICATION OF DIFFERENT METHODOLOGIES

In order to determine the risk of potential transformer failures leading to damage, a typical HAZOP analysis should be performed and possible risk categories can be defined.

Figure 12 shows exemplary input data needed for evaluating possible risks and risk categories to be taken into account (Stiegemeier 2007).

The risk of a short circuit failure is based on the assessment of the short circuit strengths of the windings and clamping structure. The thermal condition of the winding is based on the condition of the paper insulation; brittle insulation is more likely to fail under the mechanical and electrical stress conditions. The risk of dielectric failure is based on the assessment of the dielectric withstand capability of the transformer insulation system (oil, paper, etc.) and the electrical stress imposed by the power system and naturally occurring events. Accessory failures are failures of a bushing, pump or tap changer which may cause a failure of the transformer. Miscellaneous risk covers other failures including random ones.

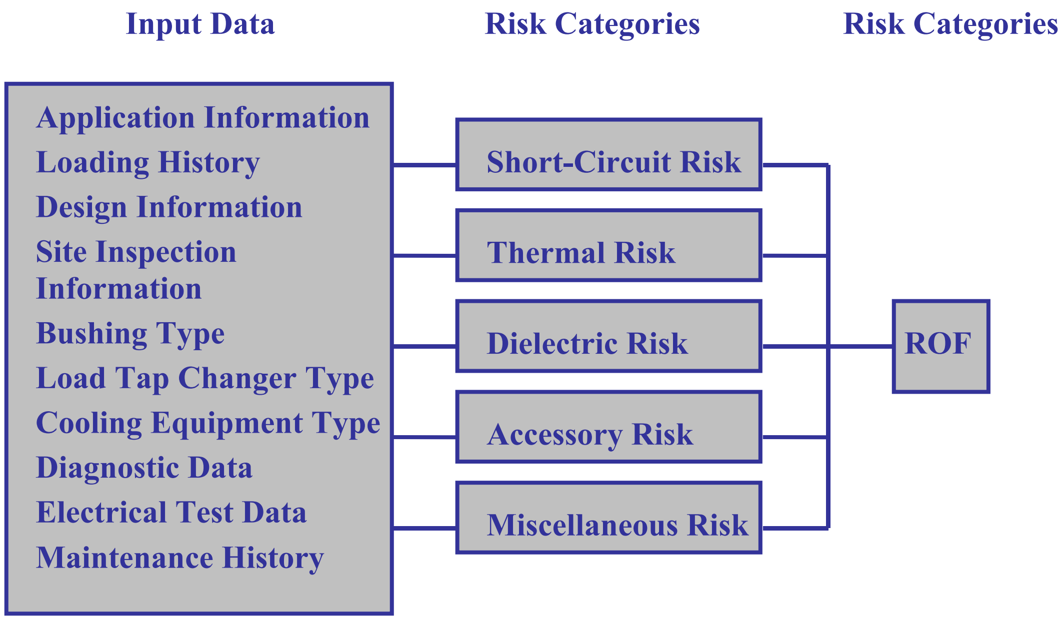

Figure 12. Risk of failure resulting from different risk categories

Such risk considerations can be performed for a single unit but also for a fleet of transformers if the boundary conditions are comparable.

In order to assess the risk of power transformer failures caused by external faults such as short circuit, a fuzzy risk index has been developed and applied (Flores et al. 2009). The risk index is obtained by comparing the condition of the insulation paper with the probability that the transformer withstands the short circuit current. This probability and the value of the degree of polymerization of the insulating paper are used as inputs of a fuzzy logic system in order to assess the failure risk.

Recently, the failure mode and effect analysis methodology has been applied to transformers, as a first step for a comprehensive project on lifetime modelling and management (Franzen & Karlsson 2007). The fault trees developed for the transformer result form discussions with experts on transformers and from a literature study. In order to analyze the transformer and to develop a fault tree the transformer has been subdivided into different sub-components such as windings, bushings, insulation, cooling and tap changer.

The objective of the above mentioned project is to develop a quantitative probabilistic model, based on both failure statistics and measurements, for the lifetime of transformer components. First models for lifetime estimation of transformers and measurement techniques will be studied. Then an improved model will be developed. Finally, the model developed will be implemented into a maintenance planning problem. Work has also been carried out on developing a statistical method for lifetime estimation based on results from Dissolved Gas Analyses. The project started in June 2009 and will be completed in September 2014.

12 CONCLUDING REMARKS

6.1 Further investigation

It has been found that main transformer failures require an in-depth assessment because of the high failure frequency and the resultant reliability and safety implications (USNRC 2010).

A lot of events in all types of power plants and substations has shown that ageing transformers are a matter of concern. Thus, transformer age might be an important factor to consider when identifying candidates for replacement or rehabilitation. Age is one important indicator of remaining life and upgrade potential to current state-of-the art materials. During transformer life, structural strength and insulating properties of materials used for support and electrical insulation (especially paper) deteriorate (US Department of the Interior 2003). Ageing reduces both mechanical and dielectric strength. All transformers are subject to faults with high radial and compressive forces. Clamping and isolation can then not longer withstand short circuit forces which can result in explosions and fires.

Although actual service life varies widely depending on the manufacturer, design, quality of assembly, materials used, maintenance, and operating conditions, the designed life of a transformer is about 40 years, but in practice industry has noted that they last 20 to 30 years.

However, in some cases the transformer are younger as in the case of the transformer fire at the Diablo Canyon plant in 2008 where the transformer was only nine years old.

The most mostly applied method for obtaining this information is to take oil samples from the transformer oil and carry out a so called Dissolved Gas Analysis. Certain gases are formed in transformer oil as a result of the transformer's age but they are also formed as a result of different over-loading situations, partial discharges and electric arc phenomena, etc. This method will now implemented in several nuclear power plants to avoid recurrence of a fire event.

However, the effectiveness of the current practice of oil sampling to predict the failure of power transformers has been checked within a research project. It was found that the current method of oil sampling using dissolved gas analysis alone is not as effective as usually perceived. An average of only 1,7% of transformer failures were actually predicted by this method. Thus, alternative mitigating strategies have to be developed to manage the risk of transformer failures (Visser & Brihmohan 2008).

One approach might be a combined use of gas and optical sensing technologies for the testing of transformer oil. The performance of such a method was evaluated to-date only on a small database of transformer oil samples and has to be further validated (Amrulloh, Abeyratne & Ekanayake 2010).

A further aspect which needs to be taken into account is the fact that the detection method Dissolved Gas Analysis is not able to measure the amount of the gases that are inside the solid insulation.

However, temperature variations can cause the generated gases to migrate into the solid insulation or more gases come out from the solid insulation into the liquid. This could generate error in Dissolved Gas Analysis measurements or trigger a false alarm. A mathematical model can be used to convert the Dissolved Gas Analysis results to the real amount of gas present in the system based on the current gas concentration in the oil and the system temperature. A possible approach is provided in (Shahsiah, Degeneff & Nelson 2006).

6.2 Countermeasures

The four main types of transformer failures are well known:

- arcing or high current break down;
- low energy sparking or partial discharges;

- localized overheating or hot spots;
- general overheating due to inadequate cooling or sustained overloading.

Therefore, protecting transformers against explosion and fire has becomes a high priority taking into account

- worldwide privatization programs of electricity production and distribution companies have resulted in a reduction of investments,
- today's competitive markets demand longer life, greater production, which results in ageing equipment and overloaded transformers.

However, transformer failures and transformer fires are not only important for operational reasons but could lead to significant safety-relevant consequences.

Therefore, a working group of the International Council of Large Electric Systems was initiated in 2007 which deals with transformer fire safety practices. Results of this working group are expected in 2011.

Detection techniques serve as a warning system to developing abnormalities in a transformer or one of its components. Detection techniques are comprised of parametric measurements and visual inspection.

The parametric measurements most often used are the current, the voltage, the internal pressure of the tank, the oil level, the oil and winding temperature, gas in oil analysis, and winding power factor, to name a few. The least frequently used measurements include the load tap changer acoustic vibration, acoustic surveillance of partial discharge, etc.

Visual inspection of the transformer exterior reveals important condition information. For example, valves positioned incorrectly, plugged radiators, stuck temperature indicators and level gauges, and noisy oil pumps or fans. Oil leaks can often be seen which may indicate a potential for oil contamination, loss of insulation, or even environmental problems. Physical inspection requires staff onsite experienced in these techniques.

Existing diagnosis concepts for power transformers are traditionally categorized by the underlying measurement technique (online vs. offline). The subdivision into physical subsystems (e.g. mechanic subsystem, dielectric subsystem, thermal subsystem) is a first step for a model-based approach. Interpretation methods for measurement results and the integration of the subsystems into a common diagnosis scheme are missing links on the way to a model-based diagnosis concept (Hribernik et al. 2008).

A further approach in addition to protective measures is the implementation of a structured description for different scenarios which can occur and their consequences in a plant, in particular in the case of power increase.

An example is a coal-fired plant in Australia with four 660 MW generating units which has planned a capacity increase to 750 MW for each unit. In the framework of a comprehensive risk analysis of this project, a specific fire safety study has been performed for four main scenarios: steam generator oil fire, generator hydrogen fire, boiler explosion and fire as well as generator transformer explosion and fire (Fire Risk Solution 2009).

Figure 13 summarises in a simplified manner the steps of the assumed scenario "transformer explosion resulting in fire" including the normal fire control processes in place and the worst case for a transformer fire if the foreseen measures fail.

Such a flow diagram should be complemented by a more detailed list of risk reduction strategies in place (technical and procedural measures).

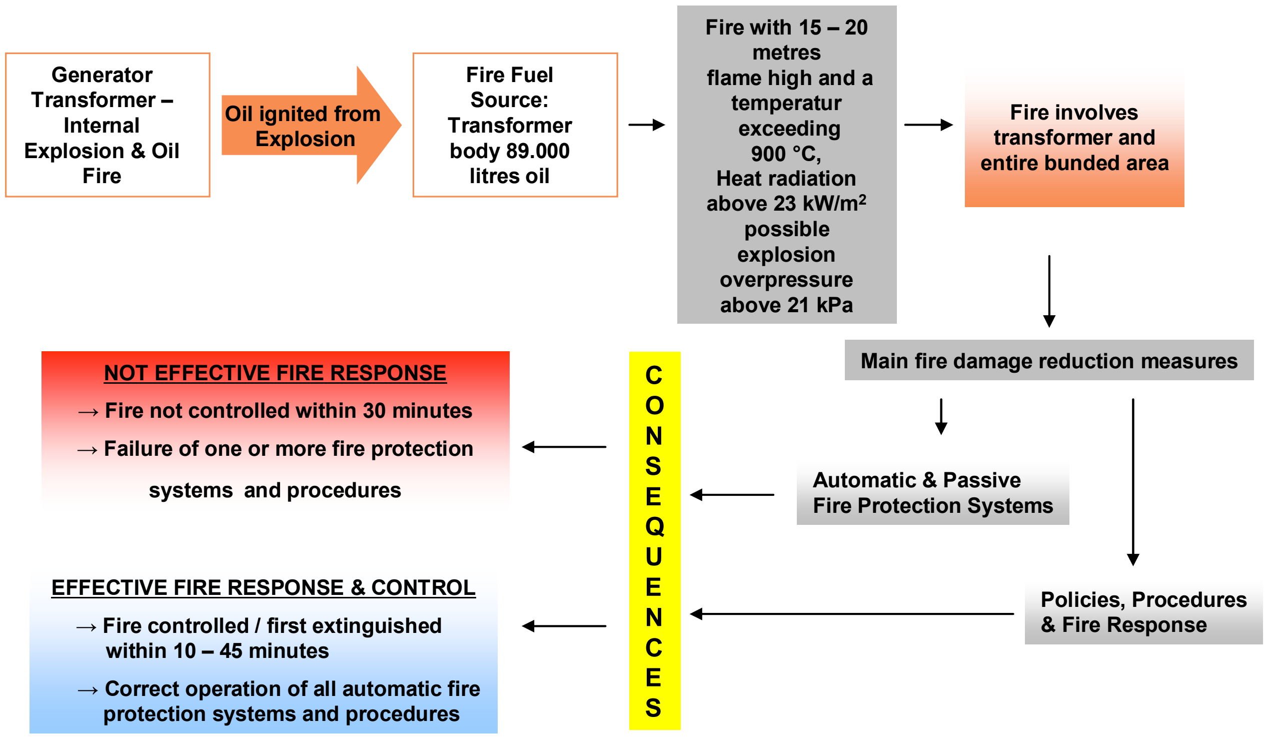

Figure 13. Flow diagram for an assumed generator transformer internal explosion and resulting fire.

13 OUTLOOK

Transformer are considered as vulnerable equipment because of the large quantity of oil in contact with high voltage elements since they can result in dangerous spillages, expensive damages and possible environmental pollution.

In particular, worldwide experience has shown an increasing number of transformer explosions and fires in all types of power plants. Therefore, these phenomena have been investigated and discussed in more detail in this paper with regard to causes for these events, potential influence of the age of the transformers and possible diagnostic measures in order to avoid such events. For that purpose, different types of databases have been evaluated.

However, the different databases have to be used very carefully, since the underlying criteria are not known in all cases or they are different, which requires a careful interpretation. Even the OECD FIRE Database providing data in a well structured manner is not homogeneous enough due to different reporting criteria in the member countries ranging from reporting every type of fire to reporting only fires with safety significant consequences according to their national regulations. In addition, databases of insurance companies or industries provided only a selected picture, e.g. collecting data in IMIA member countries (see Bartley 2003 and 2005) or investigating manufacturer specific transformer types (Petersson et al. 2008). Moreover, the population of transformer investigated is sometimes different.

Both offline and online diagnostics of transformers can be extremely successful to avoid significant events.

Besides monitoring the condition of the transformer, it might be possible to limit the consequences of a transformer explosion, e.g. by protective walls surrounding the transformers to limit the propagation of the explosions while sprinklers extinguish the induced fire. Nevertheless, despite of these equipments, transformers still explode like in the case of the example shown in section 4.

A further important task for receiving the required risk informed insights is to compare the distinguishing parameters of transformers such as their insulation type, number of phases, adjustability, core/coil configuration and winding configurations, oil content, design against overpressure, maintenance and monitoring features. In addition, the fire extinguishing systems installed in the locations of transformers have to be considered which may also affect the fire duration. Such investigations are intended in the future. For that purpose, exemplary experiences are also helpful.

As a result of the German transformer fire outlined in this paper the regulatory authority is mulling the inclusion of transformers outside reactor buildings into the routine supervisory activities although these transformers are operational components with no direct safety significance.

14 REFERENCES

Amrulloh, Y., Abeyratne, U. & Ekanayake, C. (2010). Gas and optical sensing technology for the field assessment of transformer oil. *International Journal of Emerging Electric Power Systems*, Vol. 11, Issue 4, August 2010.

Bartley, W.H. (2003). Analysis of transformer failures. *Proceedings 36th Annual Conference of the International Association of Engineering Insurers*, Stockholm 2003.

Bartley, W.H. (2005). Analysis of transformer failures …the insurance company perspective. *Proceedings AVO New Zealand International Conference*, Methven, New Zealand, April 19 – 21, 2005.

Berg, H.P., Fritze, N. (2010). Power plant transformer explosion and fire. *Journal of Polish Safety and Reliability Association, Summer Safety & Reliability Seminars*, Volume 1, Gdynia, Poland, June 20 – 26, 2010, 35 - 42

Berg, H.P., Forell, B., Fritze, N. & Röwekamp, M. (2009). First national applications of the OECD FIRE Database. *Proceedings of SMIRT 20, 11th International Seminar of Fire Safety in Nuclear Power Plants and Installations*, August 17 – 19, 2009, GRS-A-3496, Paper 3.19.

Berg, H.P., Forell, B., Fritze, N. & Röwekamp, M. (2010a). Exemplary applications of the OECD FIRE Database. *Compact of the Annual Meeting on Nuclear Technology*, 4 – 6 May 2010, Berlin, paper 306.

Berg, H.P., Fritze, N., Forell, B. & Röwekamp, M. (2010b). Risk oriented insights in transformer at nuclear installations. *Proceedings of ESREL 2010, September 5 -11, 2010*, 351 – 361.

EPRI and USNRC. (2005). *EPRI/NRC-RES Fire PRS Methodology for Nuclear Power Facilities; Volume 2: Detailed Methodology*. EPRI TR-101/1089 and NUREG/CR-6850, Electric Power Research Institute and U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research.

Flores, W.C., Mombello, E., Jardini, J. A. & Ratta, G. (2009). Fuzzy risk index for power transformer failures due to external short-circuits. *Electrical Power Systems Research*, 79 (4): 539 – 549.

Foata, M. (2010). Transformer fire risk and mitigation. *CIGRE A2 Transformers Session*, 2010.

Foata, M. & Nguyen, V. N. (2010). Transformer tank rupture and mitigation – Hydro-Quebec perspective, Presentation, September 29, 2010.

Franzen, A. & Karlsson, S. (2007). *Failure modes and effects analysis of transformers*. Royal Institute of Technology, KTH, Stockholm: TRITA-EE 2007:040.

Fire Risk Solution. (2009). *Earing Energy – Power Station Upgrade Fire Safety Study,* March 2009.

Hribernik, W., Kubicek, B., Pascoli, G., & Fröhlich, K. (2008). Verification of a model-based diagnosis system for on-line detection of the moisture content of power transformer insulations using finite element calculations. *International Conference on Condition Monitoring and Diagnosis, Bejing, China, April 21-24, 2008*.

Lehto, M., Marttila, J. & Virolainen, R. (2010). Risk informed insights from transformer fires at NPPs. *Proceeding of PSAM 10 - 10th International Probabilistic Safety Assessment & Management Conference, June 7-1, 2010.*

Lord, T. & Hodge, G. (2008). On-line monitoring of transformers as a strategic tool.

Minhas, M., Reynders, J. & de Clerk, P. (1999). Failure in power system transformers and appropriate monitoring techniques. *High Voltage Engineering Symposium, 22 – 27 August 1999*, Conference publication no. 467, IEEE.

Mirzai, M., Gholami, A. & Aminifar, F. (2006). Failures analysis and reliability calculation for power transformers. *J. Electrical Systems*, 2-1, 1 – 12.

Ng, K.-L. A. (2007). *Risk assessment of transformer fire protection in a typical New Zealand high-rise building*. Thesis, University of Canterbury, Christchurch, New Zealand.

Petterson, L., Melzer, L., Bengtsson, C., Fantana, N. (2008). Transformer challenges. *ABB Review* 1: 29 – 33.

Scheurer, D. et al. (2007a). Study and design of power plant transformer explosion and fire prevention Part I, *Electricity Today*, October 2007.

Scheurer, D. et al. (2007b). Study and design of power plant transformer explosion and fire prevention Part II, *Electricity Today*, November 2007.

Shahsiah, A., Degeneff, R.C. & Nelson, J.K. (2007). Modeling dynamic propagation of characteristic gases in power transformers oil-paper insulation, *IEEE Transactions on Dielectrics and Electrical Insulation*., Vol. 14, Issue 3, 710 – 717.

Stiegemeier, C.L. (2007). Power transformer analytical assessment - The micro approach. *IEEE/IPES Transformer Committee Tutoria*l, March 13, 2007, Dallas.

United States Department of Energy (2006). *Benefits of Using Mobile Transformers and Mobile Substations for Rapidly Restoring Electrical Service,* Report to the United States Congress pursuant to section 1816 of the Energy Policy Act of 2005, August 2006.

United States Department of the Interior (2003). *Transformer Diagnostics*. Facility Instructions, Standards and Techniques, Volume 3 – 31, June 2003.

United States Department of the Interior (2005). *Transformer Fire Protection*. Facility Instructions, Standards and Techniques, Volume 3 – 32, January 2005.

U.S. Nuclear Regulatory Commission (2010). *Resolution of Generic safety issues: issue 107: main transformer failures (Rev. 3)*. NUREG-933, Main report with supplements 1 – 32, January 15, 2010.

Valta, V. (2007). Oil-insulated power transformers. *If's Risk Management Journal,* 2/2007, 13 – 15.

Visser, K. & Brihmohan, Y. (2008). The effectiveness of oil analysis for failure prediction of power transformers. *Electricity Distribution Maintenance Summit*, June 10, 2008.