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Underground Transformer Explosions and Life Safety Risks

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Abstract

Transformers are crucial to power generation, transmission and distribution systems. They can also be a life safety risk because of their ability to catastrophically fail, ignite and explode. This includes the possibility of a secondary explosion if the transformer is contained in an underground vault.

During a transformer catastrophic failure, quantities of explosive gases can be released in enclosing underground vaults. Unless the vaults are provided with adequate explosion relief vents, enormous explosive pressures can build up and be released into the surrounding environment. The consequences include loss of energy supply, high repair costs, environmental contamination, and threat to life to those within the path of the explosion.

Transformer design in Australasia generally adopts the prescriptive design guides from Australian Standards, Energy Australia Network Standard, National Fire Protection Association, Institute of Electrical and Electronic Engineers Standards, International Electro-technical Commission Standards or FM Global design recommendations. Although these prescriptive design guides may provide some guidance, they do not offer specific solutions for all existing underground transformers and their installation configurations in relation to explosions.

This paper examines the effects of an unvented transformer explosion and the radius of effect to life safety this may cause. Recent research has provided more up to date data on the probability of catastrophic transformer failure. The paper will examine catastrophic failure statistics and taking account the age of the transformer, bushings type, maintenance quality and other relevant factors, provide examples of failure probabilities. The probability of fatalities based on examples of new and near end of life transformers, incorporating occupancy statistics, will be discussed. Example F-N cumulative probability of fatality curves comparing industry tolerability limits with transformer catastrophic failure causing fatalities will be calculated. Mitigation strategies for transformer catastrophic failure and occupants' safety will be discussed in the conclusions.

Introduction

In 2018 [1] Martin and Watson undertook a comprehensive review of transformer catastrophic failures relating to fires and explosions. Catastrophic failure being defined as fires that resulted in the scrapping of the transformers. Looking at further industry data reveals the spread of probability of transformer catastrophic failure from previous studies and publications.

This paper outlines the methodology for calculating the probability of fatalities using the transformer catastrophic failure probability with the following inputs;

1. Facility occupancy statistics, specifically relating to the radius of effects area;
2. Transformer condition, maintenance, design, age, and failure history;
3. Transformer fault current;
4. Chemical properties of the transformer oil; vapourisation energy, and explosive energy released.

Radius of explosive effects use an equivalent TNT calculation method as outlined in FM Global Data Sheet [2]. This is modified for use in underground installations using a pressure wave adjustment factor as outlined by Weggel [3], to account for congested spaces.

An assessment of cumulative fatality probabilities, (i.e. more than one fatality), using F-N methodology and research of worker tolerability statistics is discussed. This can be used as a comparison against other industries and governmental type risk criteria. A table of risk probabilities of other industries is provided.

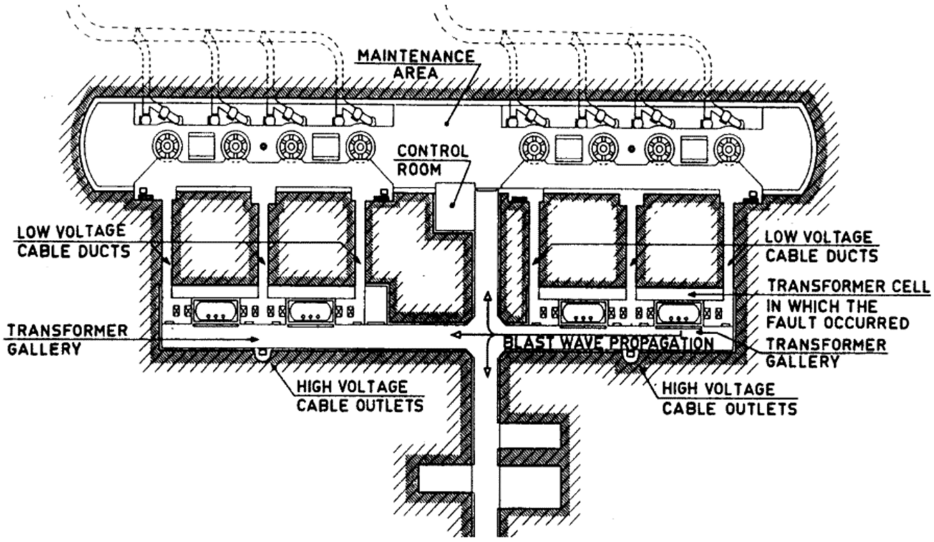
Finally, a table of risk mitigation options for existing underground transformers is provided as a summary.

Radius of explosion calculation and effects

In a typical existing underground power station or other facility, transformer specific explosion venting does not exist because it was not considered in the original design. Retrofitting explosion relief is impractical and prohibitively expensive in most cases.

Transformer secondary explosion from a vault is a credible scenario and has been modelled by Cadore et al[4], who found that up to 5.5 Bar pressures could be generated. Transformers are known to have secondary explosions and explosion venting is a criterion considered important to consider. Giuseppetti, G.Mazza, F.Chille, A. Sala [19] provide several actual examples of vault explosions. In this example Figure 1 from Roncovalgrande hydroelectric plant, “the discharge caused the pyrolisis of part of the oil contained in the junction box and the production of a gaseous mixture which deflagrated in contact with air. The deflagration gave rise to a pressure shock wave which propagated throughout the plant causing some damage to the equipment and civil structures but fortunately no damages to the personnel present in the underground plant at the moment of the accident”[Sic].

Figure 1 Roncovalgrande hydroelectric plant explosion



Typical vault construction provides around 2 bar using practical means of construction. It is credible to expect vaults to explode, with the resulting debris and pressure waves causing fatalities to those close by. The methodology to assess these pressures and their three-dimensional influence is described below.

Step 1 is to calculate the energy released (MJ) by the explosion. The detail of this calculation involves combustion chemistry which is best provided by an appropriately qualified chemical engineer. The input required to complete the calculation is listed as follows.

Note that energy released is equal to reacting vapour quantity in mol multiplied by enthalpy of combustion (kJ/mol). Reacting vapour quantity comes from the amount of oil vaporised by the fault energy, so is independent of vault room volume. Hence room volume is not part of the energy released equation.

Table 1 Summary of example inputs for a transformer energy release calculation

Input	Value
Transformer Fault Energy (MJ)	Specific to transformer
Ambient temperature	Typically 20°C
Ambient pressure	Typically 95kPa
Heat of combustion of	9.95 MJ/mol is used for Hexadecane fuel
Oil boiling temperature	284 °C
Heat of vapourisation	53,000J/mol
Average specific heats at ambient and boiling,	605J/molK
Stoichiometric oxygen to fuel mol ratio	24.5
Atmospheric oxygen molar concentration	0.2095

Step 2 is to calculate the radius of effects.

This uses the methodology as outlined in FM Global Data Sheet [2] using a TNT equivalent to MJ released and the calculation is quite straightforward using the following formula.

$R_g = Z_g(W_e)^{1/3}$

R_g = Radial Distance from Energy Released Epicentre (m) at some overpressure.

Z_g = Scaled Ground Distance (m/kg($^{1/3}$))

W_e = TNT Mass Equivalent (kg)

TNT Equivalent 0.239005736 conversion factor from MJ.

Scaled ground distance Z_g (m/kg($^{1/3}$)) is taken from a table in [5] or by using data in [2]. A selection of critical pressures is provided. These are critical in terms of damage and life safety criteria to formulate the radius.

This calculation assumes an uncongested building arrangement. In reality most underground facilities have corridors or linked areas that create reflective pressure waves. These can also increase pressures in an explosion. To account for this, a factor for the overpressures can be applied, whereby the distances calculated remain the same, with a higher damaging pressure applied. The "Weddell" factor [3] for congestion is used, with a conversion factor of 1.75 for shock- wave adjustment.

Examples of the pressures and how they affect the environment and occupants are illustrated in Table 2 which is referenced from Zipf and Cashdollar; *"Effects of blast pressure on structures and the human"* [6]. Note there are three effects causing the fatalities: the pressure wave closer to the explosion, the structural failures and the projectiles. A further table is provided in NFPA 921 Guide for Fire and Explosion Investigations [17] listing similar effects taken from similar references.

Table 2 Effect of blast pressure on structures and human occupants.

Pressure (Bar)	Comment
3.79-4.48 (55-65 PSI) 1	May cause 99% fatalities from the pressure wave
3.1 (45 PSI)	99% occupant ear drum rupture from the pressure wave
2.41-3.1 (35-45 PSI)	May cause 1% fatalities from the pressure wave
1.38 (20 PSI)	Heavily built concrete buildings are severely damaged or demolished. Fatalities approach 100%, i.e. occupants survive the pressure wave effects on the human body, but failure of structures and projectiles cause fatalities.
1.03 (15 PSI)	Threshold for lung damage blast overpressure – pressure wave effect.
0.69 (10 PSI)	Reinforced concrete buildings are severely damaged or demolished, most people killed, i.e. occupants survive the pressure wave effects on the human body, but failure of structures and projectiles cause fatalities.
0.34 (5 PSI)	Most buildings collapse, injuries are universal, fatalities are widespread, i.e. occupants survive the pressure wave effects on the

Pressure (Bar)	Comment
	human body, but failure of structures and projectiles cause fatalities.
	Blast pressure will rupture eardrums in about 1% of occupants
0.21 (3 PSI)	Residential type structures collapse serious injuries, fatalities may occur, i.e. occupants survive the pressure wave effects on the human body, but failure of structures and projectiles cause fatalities.
0.14 (2 PSI)	Moderate damage, windows and doors blown out, Injuries by flying glass and debris.
0.07 (1 PSI)	Window glass shatters, light injuries from fragments

Example results presented in Table 3 provide a brief summary as to how real the effects might affect occupants. The results assume a congested pressure adjustment.

The examples given are to provide a general context of the issue with some interpretation required. If transmission and generation constructions are generally significantly reinforced concrete structures within the vicinity of the transformers, structural collapse is less likely. Lightweight construction of partitions and unreinforced concrete blockwork can create projectiles. The consideration of residential structure collapse is relevant as it is comparatively similar with light-weight partition or unreinforced masonry construction. Pressure waves and projectiles would be the predominant life safety risk rather than structural collapse.

Table 3 Transformer Fault Energy Explosion and effect of blast pressure on structures and the human – specific example calculations

Transformer Fault Energy MJ	MJ released	Pressure developed 1		Pressure distance (m)	Effect
		Bar	PSI		
3.6	170	0.14	2	44	Moderate damage, windows and doors blown out, Injuries by flying glass and debris.
		0.34	5	23	Most buildings collapse, injuries are universal, fatalities are widespread, i.e. occupants survive the pressure wave effects on the human body, but failure of structures and projectiles cause fatalities.
					Blast pressure will rupture eardrums in about 1% of occupants.
		0.69	10	14	Reinforced concrete buildings are severely damaged or demolished, most people killed, i.e. occupants survive the pressure wave effects on the human body, but failure of structures and projectiles cause fatalities.
		3.8-4.5	55-65	6	May cause 99% fatalities from the pressure wave.

Transformer Fault Energy MJ	MJ released	Pressure developed 1		Pressure distance (m)	Effect
		Bar	PSI		
10.9	509	0.14	2	63	Moderate damage, windows and doors blown out, Injuries by flying glass and debris.
		0.34	5	34	Most buildings collapse, injuries are universal, fatalities are widespread, i.e. occupants survive the pressure wave effects on the human body, but failure of structures and projectiles cause fatalities.
					Blast pressure will rupture eardrums in about 1% of occupants.
		0.69	10	20	Reinforced concrete buildings are severely damaged or demolished, most people killed, i.e. occupants survive the pressure wave effects on the human body, but failure of structures and projectiles cause fatalities.
		3.8-4.5	55-65	8	May cause 99% fatalities from the pressure wave.

There is cube relationship in the calculation of radius distance, whereby twice the distance requires eight times the explosive energy release. This is useful in understanding the fault and released energies on radius distances.

Probability Discussion

Transformer catastrophic failure probability requires a thorough knowledge of the design of the main components – particularly bushings, on load tap changers and windings. Specific manufacturer and maintenance regimes must also be considered. For existing transformers, the probability is a subjective assessment that must seek input from all stakeholders as well as a review of the relevant statistics.

Probabilities are calculated on a percentage per year. The example inputs listed are as per Table 4.

Table 4 Inputs for fatality probability calculations

Probability Factor	Input data chosen	Reference
Example transformer in mid-life with a recent history of failures or near miss catastrophic failures for that transformer type	0.015% (1 in 6,667 years)	Assesses the maintenance, recent failures, protection, age and other condition factors. Multiplier used on base probability. This example represents a high degree of risk in continuing to operate the transformer from catastrophic failure.
New transformer probability failure factor	0.0021% (1 in 47,619 years)	Considered at the lower end range of a number of publications. 0.0021%, is conservative and considers; - new transformer supplier is unknown, and the risk of failure can be manufacturer dependent. - "Infant" mortality data is not available on new transformer failures where

Probability Factor	Input data chosen		Reference
			failures occur in service and not during Factory Acceptance Testing.
Martin & Watson [1] upper limit	0.02380% (1 in 4,202 years)		This study included transformers down to 1 MVA. As such much data would have been collected from distribution level transformers that include many technical differences to Generator Step Up and high voltage transmission transformers.
Lower end from literature	0.00210% (1 in 47,619 years)		This probability results from the lowest rate of transformer failures to transformer catastrophic failures in the published literature, that of 1 in 42.
Number of Transformers in the same vicinity	7 transformers		
Occupancy (from a year operation)	Persons	Total	
	1	10.44%	
	5	20.01%	
	10	2.40%	
	20	1.20%	
	30	0.40%	
	50	0.96%	

The example outputs are shown in Tables 5 and 6 with the two options of a high failure probability, compared with new transformer failure probability. It is assumed for this study that a catastrophic failure could result in the containing vault exploding.

Table 5 Example Outputs for fatality probability calculations 0.015%, 1 in 6667 years

Probability Item		Probability of Fatality - based on Transformer Catastrophic Failure Probability of 0.015% (1 in 6667 years)	
		Percentage per year	One in "X" Years
Transformer vault explosion	1 fatality	0.0110	9,122
	5 fatalities	0.0210	4,760
	10 fatalities	0.00252	39,683
	20 fatalities	0.00126	79,365
	30 fatalities	0.0004	238,095
	50 fatalities	0.0010	99,206

Probability Item		Probability of Fatality - based on Transformer Catastrophic Failure Probability of 0.015% (1 in 6667 years)	
		Percentage per year	One in "X" Years
	More than 1 fatality	0.0262	3,817

Table 6 Example Outputs for fatality probability calculations 0.0021%, 1 in 47,619 years

Probability Item		Probability of Fatality - based on Transformer Catastrophic Failure Probability of 0.00210% (1 in 47,619 years)	
		Percentage per year	One in "X" Years
Transformer vault explosion	1 fatality	0.00153	65,160
	5 fatalities	0.00294	33,997
	10 fatalities	0.00035	283,447
	20 fatalities	0.00018	566,893
	30 fatalities	0.00006	1,700,680
	50 fatalities	0.00014	708,617
	More than 1 fatality	0.00367	27,265

F-N Curve Probability Methodology

The American Institute of Chemical Engineers, Inc., Guidelines for Developing Quantitative Safety Risk Criteria [7] provides a very useful document explaining the methodology and the criteria for judging the tolerance to risk using F-N curves.

For the cumulative frequency basis called F-N curves the value plotted on the y-axis is the cumulative frequency of experiencing N or more fatalities.

To construct the F-N curve, a list of all events (E_x) and their associated frequencies (f_x) and consequences (N_x) is sorted by decreasing values of N.

The final graph takes this data along with worker or societal risk criterion when plotted on a log basis. Typical worker or societal risk criteria uses a F-N slope of -1, termed as risk averse. In this case the risk criterion would dictate that the frequency of an event that results in 100 or more fatalities must be 10 times lower than the frequency of an event that results in 10 or more fatalities and so on. In other words, risk averse means the risk criteria reflects a greater concern with for events causing a larger number of fatalities.

The "anchor" points for calculating the comparative worker or societal risk is something that many industries do not like to define, because an acceptable fatality probability is assigned to a human life.

For the example shown, the following the tolerability limits, fatalities per year selected are;

a. Upper High Risk = 1 x 10^{-3} (1 in 1,000) – Such as that managed on a congested oil platform with highly managed risks [8] and [11], and individual Risk Tolerability Limits for workers. [9]

b. Upper acceptable risk = 1 x 10^{-4} (1 In 10,000) Typical Ranges for Individual Risk per Annum [10] and used typically an anchor point of 10 fatalities x 10-3/year [7].

c. Lower Acceptable Risk = 1 x 10^{-6} (1 In 1,000,000) Risk Tolerability Limits for workers [9]

F-N Results

Figure 2 F-N Curve for 0.015% probability of Catastrophic Failure (1 in 6667 years)

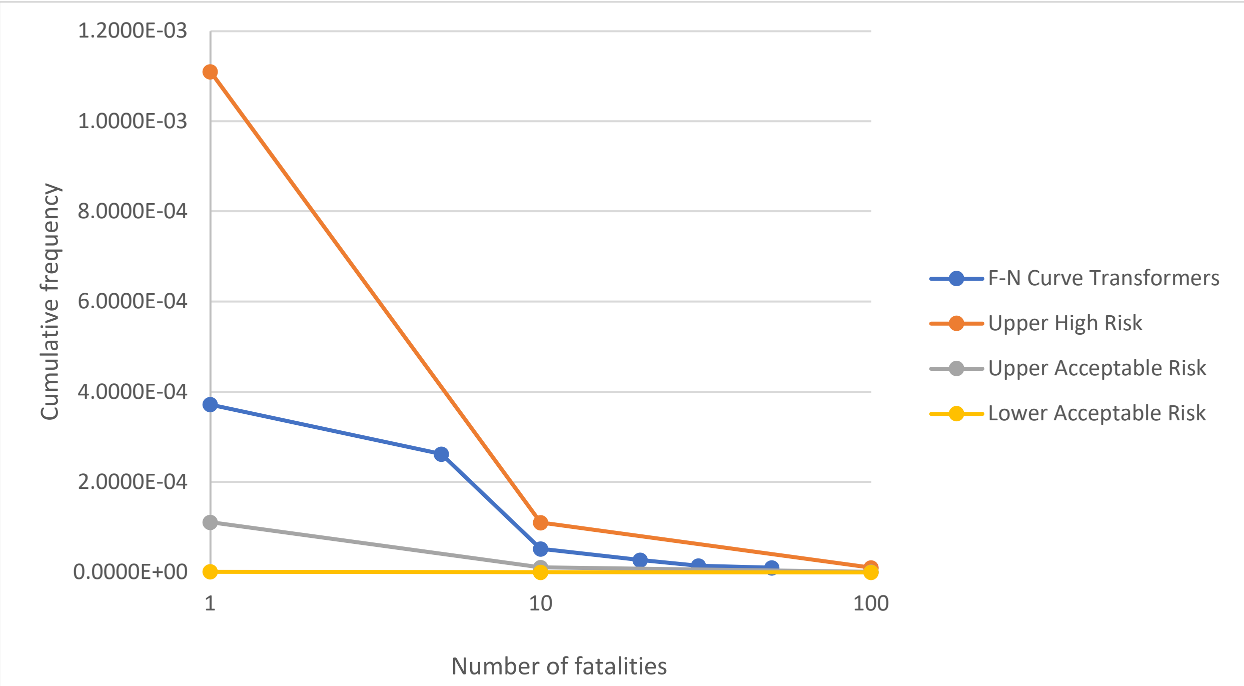


Figure 2 shows that the number of fatalities places the facility into the category of highly managed risk. This is similar to oil platforms with "congested" risks and is above the acceptable worker risk value chosen.

Figure 3 F-N Curve for 0.0021% probability of Catastrophic Failure (1 in 47,619 years)

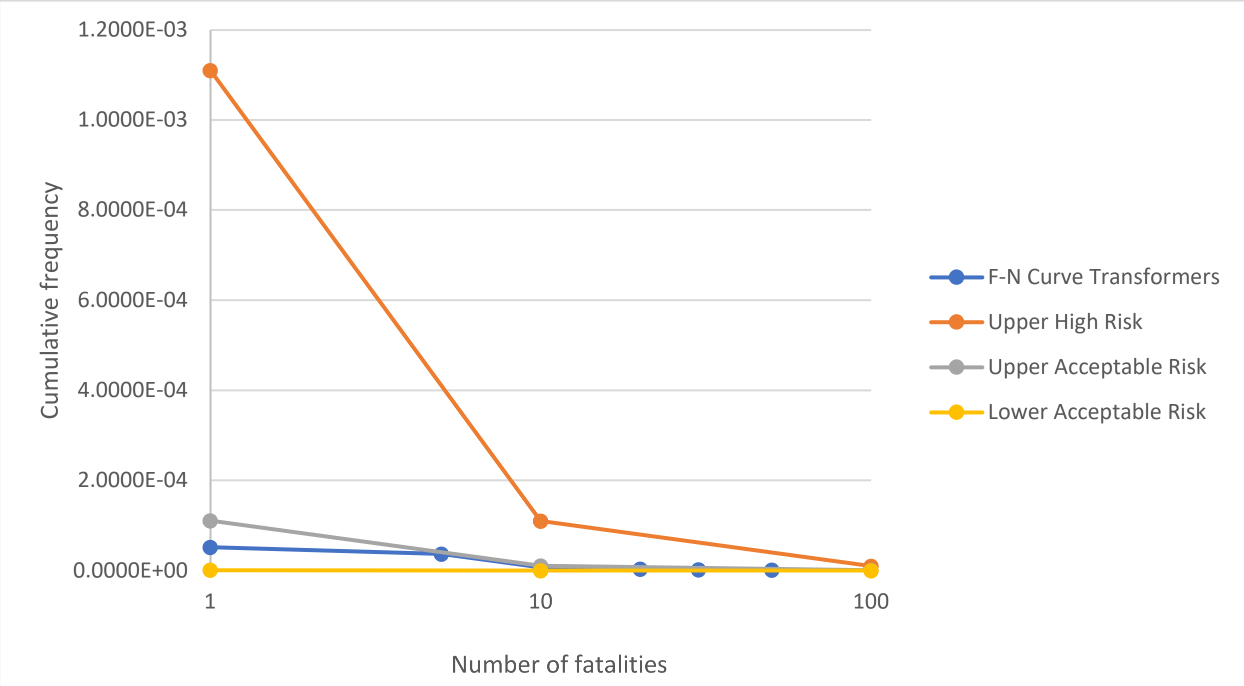


Figure 3 shows that with the new transformers the worker tolerability limits are below the level of worker upper acceptable risk level.

It is noted that the appetite for risk acceptance is a matter for the management of the facility to determine. Whilst these are examples, the values used for probabilities and occupant tolerability limits are realistic. They do give benchmarks for how the cumulative risks can be presented and are representative of industry norms.

Practical Risk Mitigation Strategies – what can be done?

Table 7 lists explosion mitigation options from a review of relevant codes and standards.

Transformer life safety risk-management is site specific and should be assessed individually as to what are the appropriate levels of controls. Table 7 is targeted at the issues surrounding underground transformer locations. It also discusses options that are recommended by relevant codes and not typically viable.

Table 7 Specific and Generic Risk Mitigations for Existing Underground Transformers

Item	Comment	Reference
Proximity and Access Controls	Access for performance operational and maintenance tasks should be restricted to authorised and qualified staff and limited to the degree necessary for operating and maintaining the transformers and ensuring entrapment does not occur. Proximity and access to the transformers for the public should be restricted to the very minimum, if not eliminated altogether. Painting of zones on the floor is an easy way of identifying zones for limited access and control of activities within those zones. These could be solid painting, strip marking or similar.	CIGRE 537 June 2013, *Guide for Transformer Safe Practices*, 7.3.1 Minimising The Risk of loss of Life to Humans [12]
Projectile Management	Relating to the explosion zone to reduce harm of explosions picking up objects; Treat all equipment that handles energetic materials, as well as rooms or buildings where these can be present, as having an explosion hazard. Implement a comprehensive energetic materials fire and explosion awareness program, including education, understanding of the hazard and consequence. Check equipment for loose objects and tightness, use shadow boards for tools. Inspect all equipment for loose objects and tools after repairing, testing, maintenance. Account for all tools using during maintenance operations by maintaining a list to check the tools in and out of the area.	FM GLOBAL Property Loss Prevention Data Sheet; *7-28 Energetic Materials*, Section 2 Loss Prevention Recommendations [13]
Transformer Replacement	The life safety fatality probability is significantly reduced by replacing the transformers that have an unacceptable risk profile with new transformers.	N/A
Transformer component replacement and maintenance.	Certain types of designs such as service aged bushings lend themselves to an unacceptable failure condition which could result in a catastrophic failure being likely. Some components can be replaced that lead to extended life of the transformer and lower catastrophic risks can be implemented. Transformer on-load tap-changers can be regularly maintained in accordance with the original equipment manufacturer's instructions.	N/A
Multi Gas Calisto on line DGA monitoring	Adding Multi Gas on line DGA monitoring may improve fatality risks by providing early warning for many developing incipient fault types. .	Product Information
Nitrogen injection and	A Nitrogen injection and rapid pressure relief system such as SERGI technology could be a good mitigation technique for transformer explosion relief if these can be installed.	Product Information

Item	Comment	Reference
rapid pressure relief		
Transformer Walls upgrading	Improvements in the transformer walls to upgrade pressure ratings for a full vault explosion should be carefully considered as explosive pressures may overcome the upgraded construction anyway. Fire rating and projectiles from transformer primary explosions are risks that must be mitigated and managed through fire walls and rated walls. FM Global Property Loss Prevention Data Sheet; *1-44 Damage-Limiting Construction* Table 4 [14] indicates quite low pressures comparatively for vented enclosure design of between 0.03 and 0.1 bar. This would indicate for exploding parts from a transformer upgrading from standard masonry construction can be contained by design wall pressures of 0.03 to 0.1 bar.	FM Global Property Loss Prevention Data Sheet; *1-44 Damage-Limiting Construction* Table 4 [14]
Suppression Systems	Ultra-High-Speed deluge systems activation with 100 milliseconds (ms) (0.1 second), could be considered but may not be fast enough for explosion forces which may happen in 10 ms (0.01 seconds). Management of the deluge water and oil, in an underground and potentially burning environment is commonly complicated.	FM GLOBAL Property Loss Prevention Data Sheet; *7-28 Energetic Materials*, [13]
Continuous ventilation	Cause B.5.3.2 discusses the factors involved , and smaller enclosed areas or of very slow release rates. The upshot is that the ventilation of the transformer vaults is impractical for explosion prevention.	AS/NZS 60079.10.1:2009 *Explosive Atmospheres Part 10.1 Classification of areas – Explosive gas atmospheres* [15]
Explosion relief venting	This is discussed in many references. In existing underground facilities, venting is not practically able to be installed.	FM Global Property Loss Prevention Data Sheet; *1-44 Damage-Limiting Construction* [14]
AS 2067	Has no specific life safety considerations for existing underground transformer installations that can be applied to existing underground transformers.	AS 2067 2016 *Substations and high voltage installations exceeding 1kv a.c* [16]

Discussion and Conclusions

The effects of an explosion in underground transformer installations indicate that it is essential to manage the explosive effects on site as a highly managed risk environment where a transformer catastrophic failure is possible or probable.

This is reinforced by F-N calculations of tolerability limits for the example situations of this type, which indicate where this occurs. These must be highly managed work environments. These environments should not be considered as low risk.

Effective management includes loose tools and plant being excluded as far as practical from areas where pressure waves can pick them up. Only necessary work should be undertaken in the hazard zones indicated. Painting of floor zones is an effective method of easily identifying risk areas. Occupancy should be excluded from the hazard zones, unless there is an essential need to visit them, especially when transformers are energised.

The use of a TNT calculation methodology has been adopted as a reasoned approach and recommended by FM Global methodology [2] modified for congested environments. More sophisticated modelling elemental techniques are available, which may refine the results. Elemental modelling would not change the reality that areas nearby will be hazardous from pressure waves and explosion debris. There could be more refinement of longer distance effects and how the actual construction affects the pressure wave and pressures generated. The overall conclusions and risk management would remain as recommended regardless of the analysis methodology.

The example probabilities for the existing and improvement options have been selected using the industry data available. The probability 0.015% (1 in 6667 years) for high probability of catastrophic failure indicates that probability of fatalities recommended above those for normal worker exposure would be exceeded. These environments require highly managed risk and compare with congested risk management on industries such as oil platforms. This level of probability is likely to occur in transformers that have experienced catastrophic failures or near-miss failures particularly related to end of life factors and design, construction and commissioning faults.

New transformer failure statistics 0.0021% (1 in 47,619 years) were selected which provided probability of fatalities at risk levels of a more typical value for workers. Risk management recommendations as per Table 7 for underground installations should still be applied. This figure is higher, (more risky) than readers might expect. The reason this value is selected is that the authors have no knowledge of the particular design, rigour of manufacture, installation and commissioning for a new transformer, and these matters can vary widely in modern transformer purchases.

Appendix A Tolerability Summaries

Table 8 Upper Tolerability Workers

Upper Tolerability Limit (Fatalities per year)	Upper Tolerability Limit (One in "X" Years)	Comment	Reference
10^{-3}	1,000	These are individual Risk Tolerability Limits for WORKERS.	Commission for Energy Regulation, *ALARP Guidance Part of the Petroleum Safety Framework and Gas Regulatory Framework Guidance Document CER/16/106 3rd November 2017 Version 3.1, Dublin, Republic of Ireland*
5×10^{-6}	200,000	Petroleum and Gas industries developments at their boundaries for non-residential neighbours. FOR LAND USE PLANNING	
10^{-6}	1,000,000	Petroleum and Gas industries developments at their boundaries for	

Upper Tolerability Limit (Fatalities per year)	Upper Tolerability Limit (One in "X" Years)	Comment	Reference
		residential neighbours. FOR LAND USE PLANNING	
10^{-6}	1,000,000	UK, Holland, Western Australia for the general public. FOR LAND USE PLANNING	
10^{-3}	1,000	Offshore industries such as oil and gas sea platforms, with congested infrastructure on the platforms. For WORKERS. High degree of risk controls is typically in place.	UK Health and Safety Executive*, Guide on Risk Assessment for Offshore Installations, Offshore Information Sheet 3/2006***.** (Specifically page 9.)
10^{-4}	10,000	People off site (Public) LAND USE PLANNING	UK Health and Safety Executive *Reducing Risks, Protecting People (R2P2), HSE Decision Making Process, HSE 2001*
10^{-7}	10,000,000	Public Risk at the boundary of Developments. This value not to be exceeded. Has no legal status. LAND USE PLANNING	Safe Work Australia: *SAFETY CASE: DEMONSTRATING THE ADEQUACY OF SAFETY MANAGEMENT AND CONTROL MEASURES GUIDE FOR MAJOR HAZARD FACILITIES*
10^{-3}	1,000	For the high hazard environment of a congested offshore oil platform. For WORKERS. "The risk for a less congested on-shore facility should be much lower than this. It is likely that the regulator would challenge an operator if it appeared from the risk matrix that a risk of 10-3 per year or higher was considered low risk, or in the lower end of medium risk. These criteria are offered for reference purposes only, so it is not mandatory that they be met. However, if operators choose to meet different criteria, it is important that whatever criteria are adopted is justified as appropriate." Has no legal status.	
5×10^{-4}	2,000	Typical Ranges for Individual Risk per Annum.	ALARP Engineering website
1×10^{-4} (EXAMPLE ONLY)	10,000	Uses typically an anchor point of 10 fatalities x 10^{-3}/year and slope of -1 for the F-N Curve.	Centre for Chemical Process Safety – American Institute of Chemical Engineers, Inc., Guidelines *for Developing*

Upper Tolerability Limit (Fatalities per year)	Upper Tolerability Limit (One in "X" Years)	Comment	Reference
			Quantitative Safety Risk Criteria
1×10^{-6}	1,000,000	Nuclear Power Plants WORKERS	IAEA Nuclear Graphite Knowledge Base

Table 9 Lower Tolerability Workers

Lower Tolerability Limit (Fatalities per year)	Lower Tolerability Limit (One in "X" Years)	Comment	Reference
10^{-6}	1,000,000	These are individual Risk Tolerability Limits for WORKERS.	Commission for Energy Regulation, *ALARP Guidance Part of the Petroleum Safety Framework and Gas Regulatory Framework Guidance Document CER/16/106 3rd November 2017 Version 3.1, Dublin, Republic of Ireland*

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16. AS 2067 2016 “Substations and high voltage installations exceeding 1kv a.c”

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Biography

Gilbert Gordon

Gilbert is the Technical Director of *Gordon Risk & Fire.* He has been working in the Power Industry as a fire and risk consultant for 15 years. He has a specialist interest in transformer fire issues.

In 2019 he set up his own consultancy, after being the manager of *Holmes Fire Christchurch* for 14 years.

He is a Chartered Fire Engineer (CPENG), and member of Engineering New Zealand CMEngNZ. He has a bachelor's degree in mechanical engineering and a diploma in fire engineering both from the University of Canterbury.

Gilbert has presented papers on transformer fire issues and specialist fire extinguishing systems at previous TechCon and EEA conferences.

Dr Wade Enright

Wade is director of *Viva Technical Solutions (Vivatech)* and senior electrical engineer. Vivatech is his own consultancy and he has been working in this industry for 28 years.

He is a member of Engineering New Zealand, Electricity Engineers Association and CIGRE and has many publications and articles.

Wade has a PhD from the University of Canterbury in transformer models for electromagnetic transient studies with particular reference to HVDC transmission.

Underground Transformer Explosions and Life Safety Risks

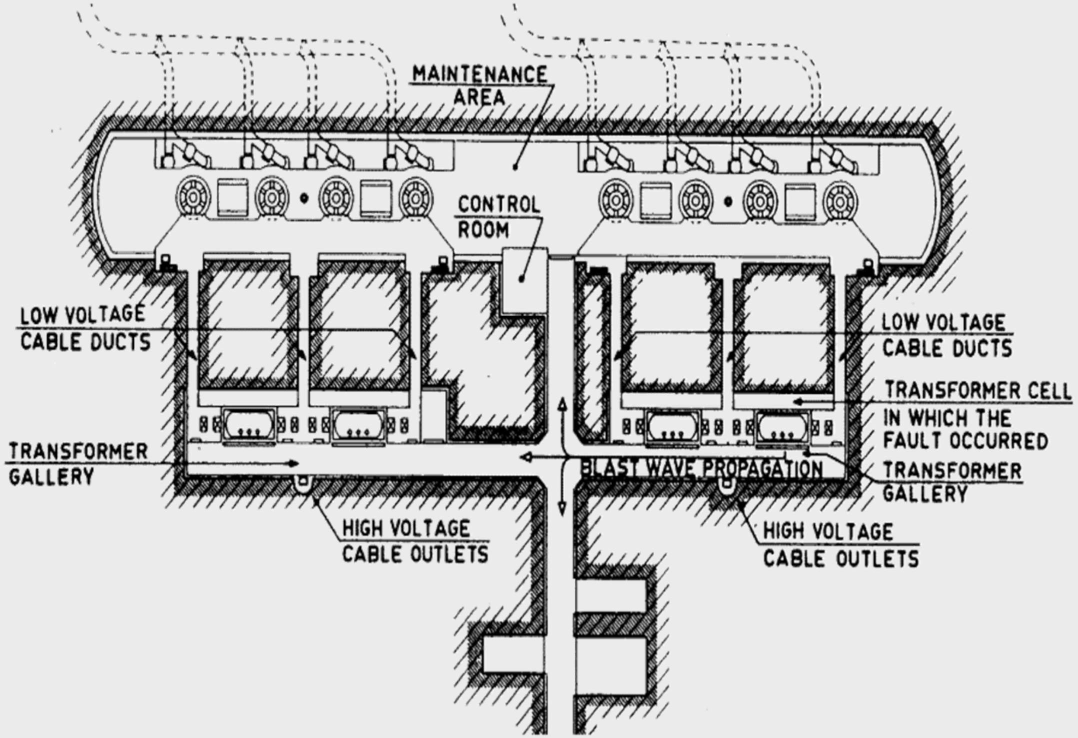
Gilbert Gordon – Gordon Risk & Fire
Dr Wade Enright – Viva Consultants

Introduction

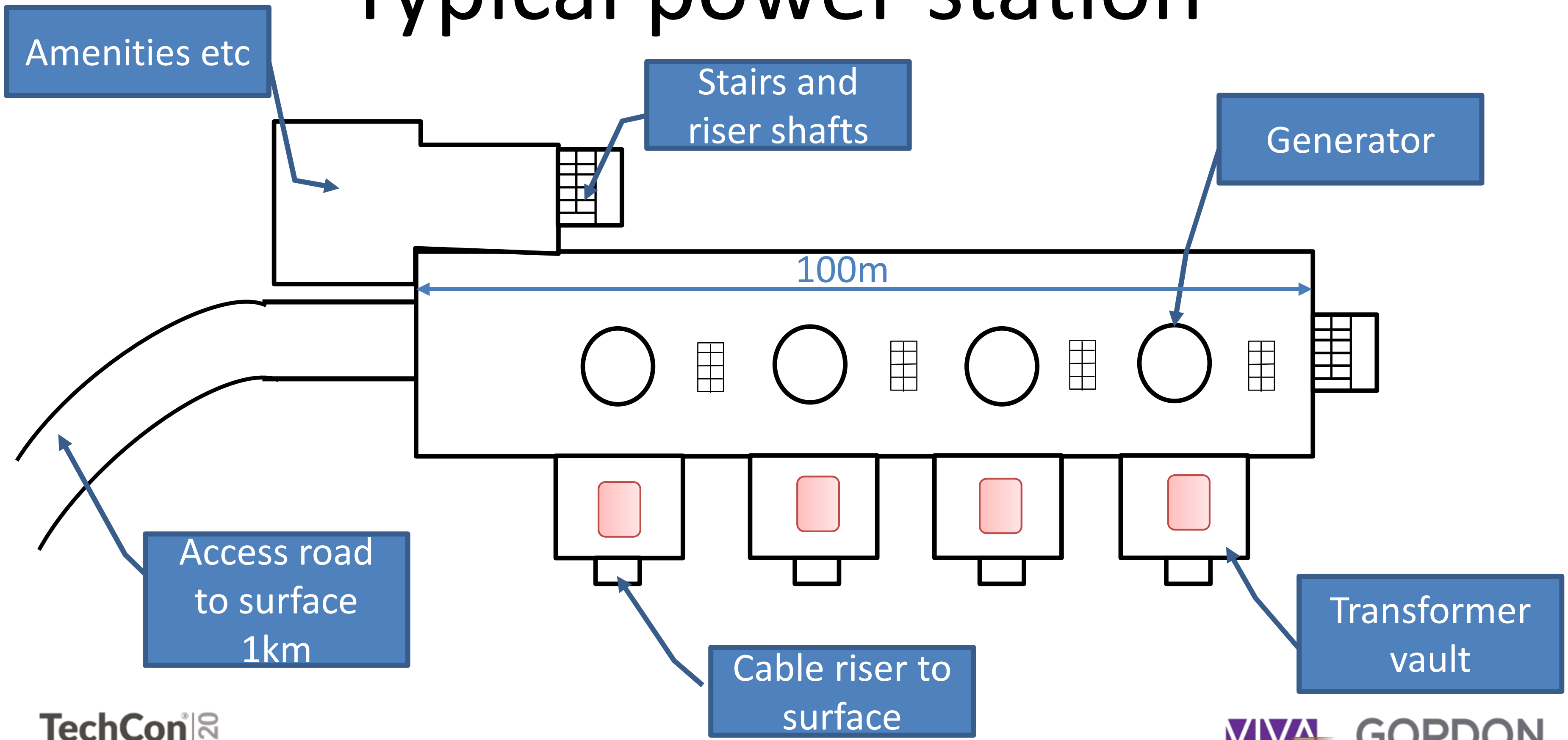
- Secondary Transformers in underground power stations
- Explosion effects
- Explosion probability
- Fatality probability
- How to mititgate effects

Typical Issues

Roncovalgrande Power Station



Typical power station



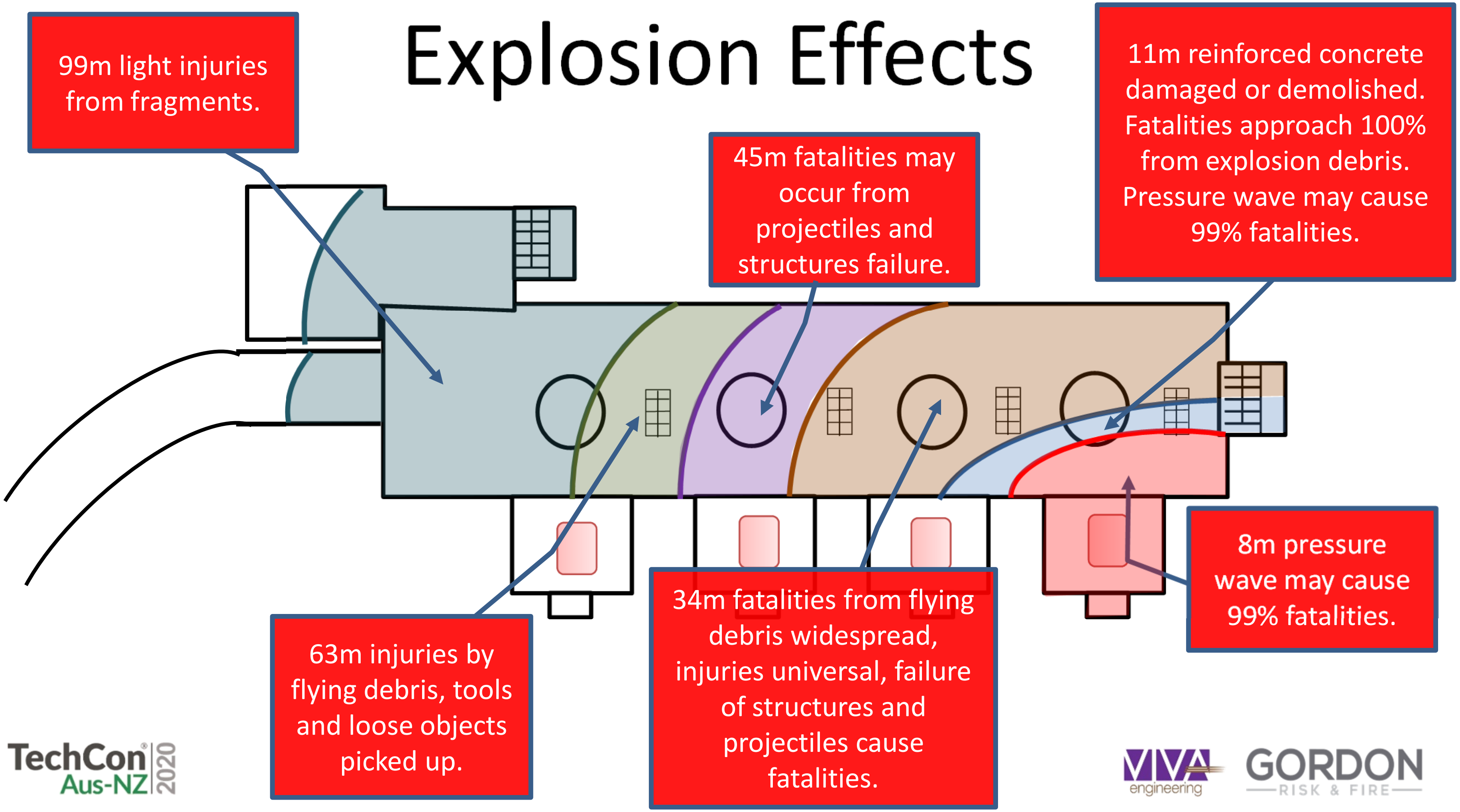
Methodology

- Equivalent TNT method has been used.
- Damage and injuries to be expected in an explosive event, based on the size of the explosion, distance from the event, and assumptions about building construction.
- For a given blast at twice the distance requires eight times the explosive energy release. So differences in energy not necessarily critical?

Methodology

- TNT equivalent with a 1.75 multiplier for congested spaces – walls can magnify forces because of reflection.
- The extent and severity of damage and injuries in an explosive event cannot be predicted with perfect certainty!

Explosion Effects



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Probability of explosion

- Industry survey data on transformers.
- Range 0.015% (1 in 6,667 years) to 0.0021% (1 in 47,619 years).
- History of the specific transformer type catastrophic failure – explosion that results in scrapping of the transformer.
- Maintenance and that is relevant – bushing failure can be independent of main transformer.

F-N Cumulative Probability of fatality

- Way of judging the tolerability of risk.
- Cumulative frequency basis, sorted by decreasing value of N.
- The cumulative frequency of all events causing at least N fatalities.

F-N Cumulative Probability of Fatality

Event	Event frequency (per year)	Event consequence	Cumulative frequency (per year)
E_1	f_1	N_1	$F_1 = f_1$
E_2	f_2	N_2	$F_2 = f_1 + f_2$
E_3	f_3	N_3	$F_3 = f_1 + f_2 + f_3$
E_4	f_4	N_4	$F_3 = f_1 + f_2 + f_3 + f_4$
…..	….	….	…..
E_n	f_n	N_n	$F_n = f_1 + f_2 + f_3 + f_4 + \dots F_n$

Tolerability Limits @0.015% at least

Consequence Description	Cumulative Frequency Probability %	1 in "X" years
50 fatality	0.000010	99206
30 fatalities	0.000014	70028
20 fatalities	0.000027	37202
10 fatalities	0.000052	19201
5 fatalities	0.000262	3814
1 fatality	0.000372	2690

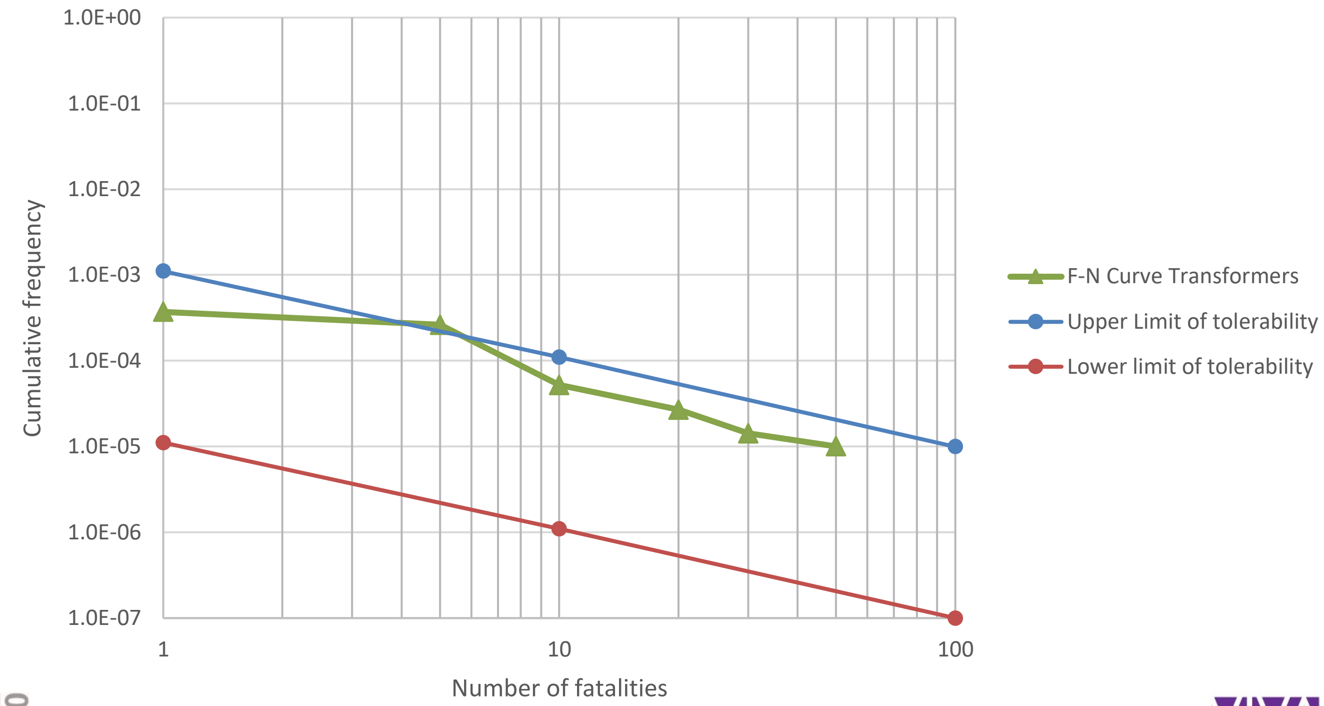
Tolerability Limits @0.0021% at least

Consequence Description	Cumulative Frequency Probability %	1 in "X" years
50 fatality	0.000001	708617
30 fatalities	0.000002	500200
20 fatalities	0.000004	265731
10 fatalities	0.000007	137152
5 fatalities	0.000037	27244
1 fatality	0.000052	19211

Tolerability Limits

- Challenge is to find the upper tolerability limit.
- Upper tolerability = 1×10^{-3} (1 in 1,000 years) – Such as that managed on a congested oil platform with highly managed risks, dam safety criteria.
- Lower Acceptable Risk = 1×10^{-5} (1 In 100,000 years) Typical value from dam safety engineering.

Probability of Transformer Catastrophic Failure 0.015%
(1 in 6,667 years)



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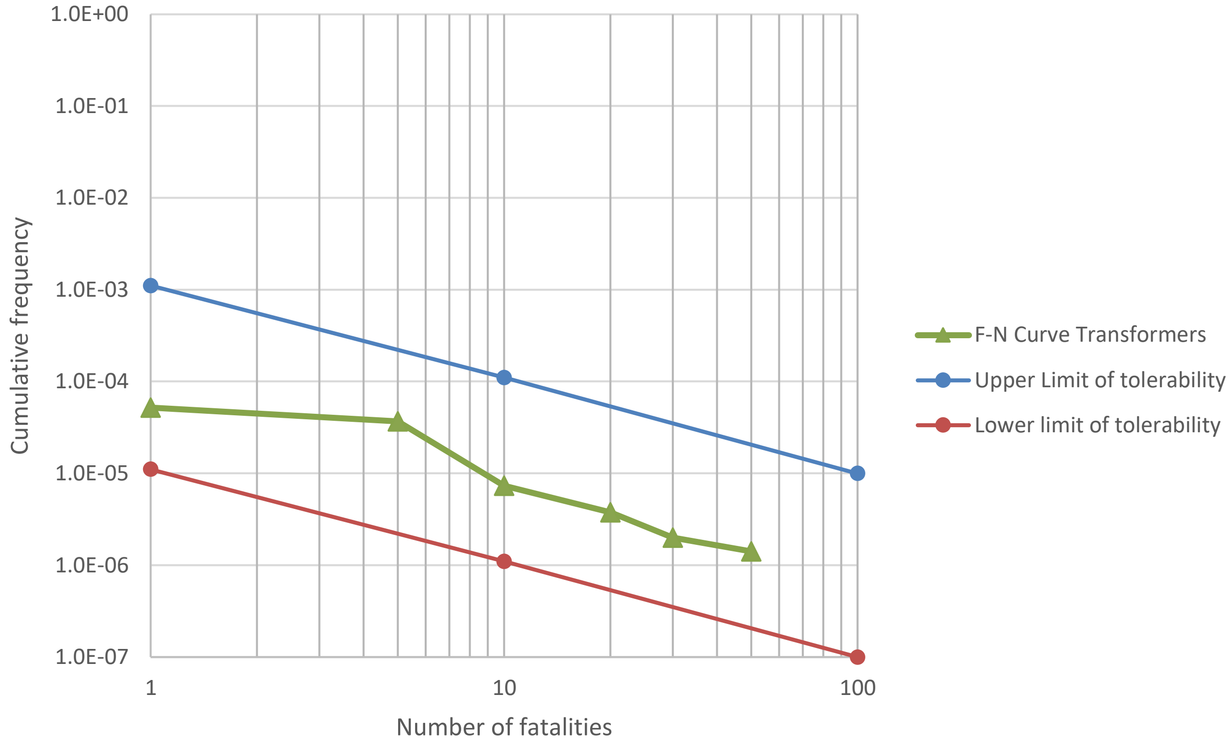
Probability of New Transformer Catastrophic 0.0021% (1 in 47,619 years)






What can NOT be done easily?

What can be done?

- Transformer Improvements.
- Prioritise end of life extension e.g. bushing replacement.
- Replace the transformers.
- Monitoring systems that are appropriate - Difficult with rapid effects of explosion.
- Highly managed facility.
- Tool and plant projectile management.
- Painted restricted zones.
- Occupants in the area only when necessary.
- More use of robot and drones for maintenance?

Transformer Risk Improvement

EXISTING

- e.g. double re-entrant bushings not manufactured anymore and cannot be replaced.
- All the standard maintenance and control features expected in industry are in place.
- Understanding why a failure has occurred elsewhere or on that plant.

Transformer Risk Improvement

New Transformers

- No statistics available on infant mortality.
- No statistics on utilisation factors of transformers in failure data and cold start effects.
- Catastrophic probability affected by manufacturer, installation and commissioning.

Risk Acceptability

What is the transformer acceptable fatality risk?

- 1 in 100,000 years?
- 1 in 10,000 years?
- 1 in 1,000 years?

Conclusion

- Underground transformers are a hazard if a secondary vault explosion occurs.
- Highly managed risk controls are required when risks of failure are beyond tolerability.
- Understand where the explosion effects radius is likely is important.
- Transformers with a catastrophic failure probability pose significant risks.

Questions

- Thanks for listening