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Consequence Assessment of Vapour Cloud Explosion Involving Large Commercial Airliner Crash upon Nuclear Reactor Containment

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This work concerns with the consequences analysis of vapour cloud explosion (VCE) on the nuclear reactor plant due to accidental aircraft crash. The International Atomic Energy (IAEA) requires the operator of each licensed nuclear power plant to demonstrate that the site is acceptably safe from the perspective of the internal and external risk of exposure to workers, visitors and third parties who are working within the site vicinity. One of the potential external hazards is the unintentional aircraft accident with the potential on consequential damage to the site through impact, fuel fire and other effects. The fire and explosion overpressure resulting from the accident have the potential to damage the nuclear structural components and gave a challenge to a safe reactor shut down. The equivalent TNT, TNO multi energy and Baker-Strehlow models were used to estimate the overpressure from the explosion within the distances of 50 - 410 m from the first impact location of nuclear reactor. The structural damage at varying distances from the fire and explosion hazards was estimated using Probit equation. Analysis of the results shows that the control room at a distance of 210 m would be highly damage with a probability of 99 %. The probability for major structural damage at a radial distance of 410 m is 93 %. The findings of this analysis may be used to evaluate the safety improvements required on the nuclear power plant on the risk associated with aviation-related hazards and provide an insight on the safe design and the sitting of the existing facilities and/or new nuclear installations.

1. Introduction

Fire incidents on critical nuclear plants' components have been studied in the last few decades and keeping in mind the disastrous nature the effect may have. The studies indicate that it may be impossible to carry out a full-scale experiment in order to assess the fire consequences on a typical Nuclear Power Plant (NPP) structures due to the complexity in fire dynamics behaviour and the cost in carrying out the experiment (Iqbal et al., 2012). The complexity of fire studies arises due to the complex interaction between fire turbulence, buoyancy, material combustion, heat release rate, ventilation, geometry and etcetera which in turn controls fire growth and smoke movement. A standard practice to assess the impact of fire and explosion in the nuclear power plants is through risk assessment, but it appears that the consequences of 'incredible events' were not fully considered in this assessments method. This is strongly underlined by the aircraft attack on the World Trade Centre on September 11, 2001 and Pentagon buildings as well as Fukushima Daiichi NPP incident. These incidents attract interest in the reliability and safety of nuclear reactor containment against any similar event (Jeon et al., 2012). The September 11 attack refute the notion that larger aircrafts cannot be maneuverer with higher velocities near the containment structure (Kukreja, 2005).Therefore, analysis of possible VCE that immediately occurred after the crash is of utmost importance. Fire and smoke from the crashing plane can enter through vents, openings and cable tunnel, and may challenge safety redundant systems and safe reactor shutdown. Studies on the impact of aircraft crash on containment are given little or no considerations to the effect of explosion overpressure to auxiliary buildings. In most cases, the analysis is concerned only with the dynamic loadings of the aircraft. Ignition of jet fuel from the crashing plane could result in devastating consequences, including intense fires and explosions with blast over several km. Strong

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shock waves could propagate beyond the immediate vicinity, and pollutants could disperse to a greater distances. The nuclear reactor building is the most important structure in the NPP and in fires related incidents, it acts as barrier and reduce the release of hazardous radiation to the environment. Hence, the consequence of VCE due to aircraft crash on this important structure should not be overlooked.
Explosion may have several effects on structures and human, depending upon the scenario by which it occurred. Some major causes of damage due to explosion are overpressure, energised projectiles, debris damage, thermal radiation, cratering and ground shock. Most of the damage by an explosion to structures, people, and vehicles, however, is done by the overpressure in the blast wave, rather than by the fireball (Dorofeev, 2007). Figure 1 shows the probable consequences of VCE induced by aircraft impact on nuclear containment. This work aims to estimate the blast pressure and pulse duration in order to determine the blast loading that may be experienced by the reactor containment and control-room walls for the hypothetical scenario described in the paper. Accidental commercial airliner crashed, resulting in a large release of jet fuel is assumed. The equivalent TNT, TNO model and Baker-Srehlow-Tang models were used to estimate the overpressure resulting from the incident. Probit equations were used to estimate the impact of explosion on structures.

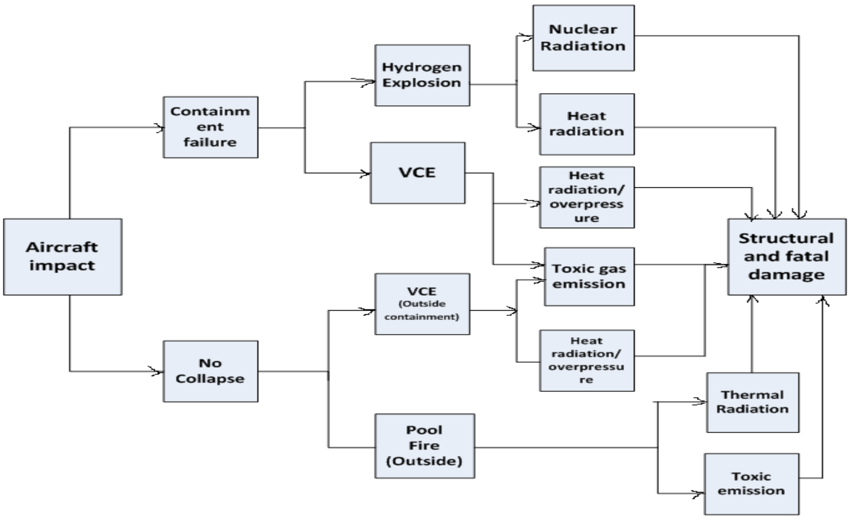

Figure 1 : Probable consequences resulting from an aircraft impact on nuclear containment

1.1 Theoretical Description of Empirical Equations for VCE Assessment

Determination of the detailed explosion impact and analysis on structures and people is economically costly, technically difficult, and comes with a degree of uncertainty due to varying loading conditions, which can make complex analysis methods unpractical. Several methods i.e. approximate method of analysis, numerical method, experimental and experimental scaling can be used to determine the impact of an explosion on a structure. This research work uses widely known empirical models (TNT, TNO and BST) to estimate the strength and consequences of the blast wave produced by VCE as a function of distance from the cloud centre.

1.1.1 Equivalent TNT mass Method

This uses an empirical method to measure the blast impact and blast overpressure at a specific location from the explosion centre. In this method, explosive power of vapour cloud is expressed as an equivalent mass of TNT (tri-nitrotoluene) that would produce the same explosive power (Baker et al., 1983). The method is based on the assumption that the entire flammable mass is involved in the explosion and that the explosion is centred in a single location.
For TNT calculation, the Hopkinson-Cranz cubic-root scaled distance is given as

$$Z = x/\left(M_{TNT}^{\frac{1}{3}}\right) \tag{1}$$

where Z is the scaled distance (mkg$^{-1/3}$), M_{TNT} is the equivalent TNT mass (kg) and X is the distance (m) from the centre of explosion. The equivalent TNT overpressure of the shock wave resulting from the VCE is given by Eq(2) (Baker et al., 1983).

$$P_s = 808[1 + (Z/4.5)^2]/\left(\sqrt{1 + (Z/0.048)^2}\sqrt{1 + (Z/0.32)^2}\sqrt{1 + (Z/1.35)^2}\right) \tag{2}$$

1.1.2 TNO Multi Energy Method

Multi-Energy method is based on the assumption that detonation in the unconfined parts of a vapour cloud can be ruled out. The congested regions will contribute to a higher strength explosion blast (van den Berg, 1985). Unobstructed parts of the cloud will slowly burn, without a serious contribution to the strength of the blast (Mercx et al., 2000). This assumption is supported by vast experimental data, including (Van den Berg, 1984). The method takes into account the variability of the blast strength by expressing the explosion as a number of sub-explosions each with individual characteristics taking place inside specific area of the cloud.
The calculation of the over pressure requires the knowledge of cloud dimensions, approximate volume of the obstructed region, energy of explosion and Sachs-scaled distance. The blast overpressure (MPa) is given by

$$P = P_s^{'} * P_a \tag{3}$$

where, P_s' the Sachs-scaled overpressure (dimensionless) and P_a is the ambient pressure (0.1 MPa). Using the above information, a blast over pressure at any given Sachs-scaled distance r' from the centre of explosion can be estimated from the curves consisting of scaled over pressure as a function of scaled distance.
The time duration of positive phase t_p (s) is given by the equation:

$$t_p = (t'p/C_s)(E/P_a)^{\frac{1}{3}} \tag{4}$$

where t'p is the Sachs-scaled positive phase duration from the curve consists of positive phase duration as function of scaled distance, Cs - the velocity of sound in air (340 ms^{-1}), E is the energy released (MJ) and P_a is the ambient pressure (0.1 MPa). A step by step on using this method has been described by (van den Berg, 1985). It was noted that the overpressure values obtained by TNO multi energy method are much closer to the experimental values based upon the damage that could occur from explosion (Marc and Konstantinos, 2010). Therefore, values of explosion overpressure obtained on the basis of multi energy approach were used for vulnerability estimation.

1.1.3 Baker-Strehlow-Tang Method

This technique has some similarities with TNO multi-energy method. Baker-Straw-Tang method is based on the assumption that the strength of the blast wave is proportional to the maximum flame speed achieved within the cloud. The important parameter in the selection of the intensity of the explosion blast in this method is the flame propagation speed (Soman and Sundararaj, 2012). Explosion intensity is determined by factors such as (i) the reactivity of the fuel (ii) the way the flame front propagates (iii) the density of the obstacles and (v) the degree of confinement. The procedure from TNO method was adopted in determining the vapour cloud dimension and energy released during explosion. The scaled overpressure P_s' can be calculated from the curve consisting of scaled overpressure as a function of scaled distance, with the flame speed (in form of March number, M_f) as a parameter described in (Baker et al., 1996). The reactivity of jet fuel is higher, so it is assumed in this study that flame expansion is 2D and the flame speed is 1.77.

2. Description of the Scenario

A generic site plan of a “hypothetical nuclear power plant” is shown in Figure 2. The plan dimensions are 1.0 km × 0.6 km. A concrete containment composed of a circular base slab, an upright cylindrical walls and torispherical dome is placed between control room and stack. The thickness of inner containment is 1 m and outer containment wall (as well as dome) is 1.2 m. The height of the outer containment building is 62 m and 42 m inner radius. The control building that houses the main control room is located on the central location as the hub of the plant operating staff's activities. The control room is 6 m long, 3 m wide and 2 m high (must have visual observation capability of both areas). The congested area consisting of turbine and heat exchanger buildings, service building and light oil storage tank has the average dimensions of 40 m × 15 m × 12 m. The arrangement of the building structures is shown in Figure 2.

2.1 Load Assumptions

The worst case scenario is defined by the maximum aircraft impact velocity and maximum fuel capacity. Also of important is the congestion level. Both velocity and congestion will determine the propagation of overpressure and its interaction with structures as well as flame spread in the vicinity of the plant. The following load assumptions are used in this study.

i. The impact is from Airbus A380 or Boeing 747. Specific dada for these airplanes adapted from (Luther and Müller, 2009) are shown in Table 1.
ii. The two wings of the aircraft contribute to explosion and in the evolution of fireball.

iii. The maximum fuel mass in the two wings is 180 t kerosene equivalent to 43 GJ/t assuming the typical value of hydrocarbon heat of combustion of 43 MJ/kg. A maximum fuel mass of 120 t (to account for losses from the airport to the NPP and spilled oil which will result in a subsequent pool fires after the crash) is consumed in the explosion.
iv. The impact velocity of the aircraft is assumed to be at 250 m/s.
v. An inclined impact into the gap between the containment dome and the control building from the direction of the diesel building is considered.
vi. A jet fuel with approximate shape of mixed cloud as indicated in Figure 1 is assumed to form after the crash. Electrical spark/friction is the main ignition source.

Table 1: Comparison of Airbus 380 and Boeing 747

Type	Airbus A380-800	Boeing 747-400
Maximum Velocity (m/s)	303	306
Travel vel. (impact vel.) (m/s)	253	253
Maximum fuel capacity (t)	256 (313,300 L)	162 (198,300 L)
Maximum passengers	555	416
Maximum take-off weights (kg)	560,000	396,890
Wing span (m)	79.60	64.44
Fuselage diameter (m)	7.14	6.49

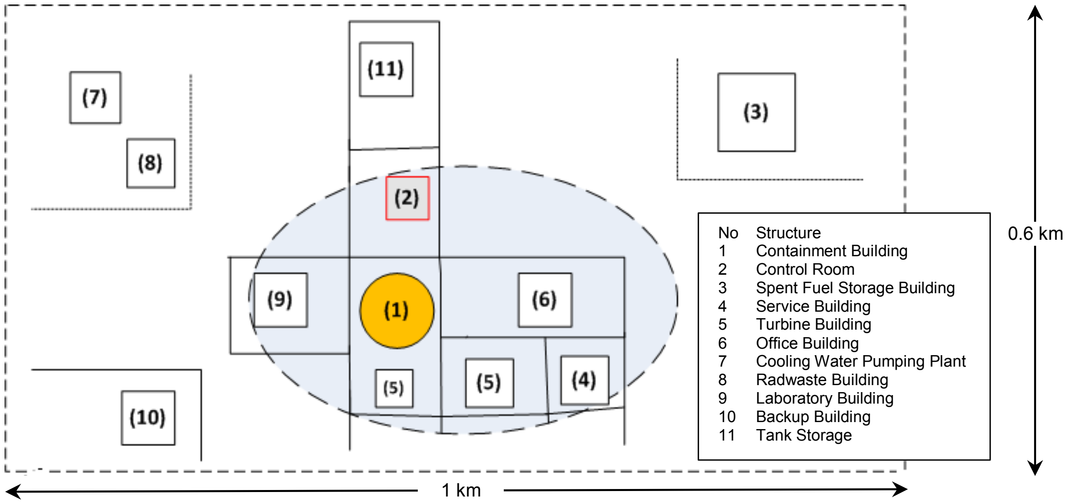

Figure 2: The plant layout

2.2 Vulnerability Estimation

The vulnerability of persons and structures to the effects of explosion generally follows the Probit probabilistic approach. The magnitude of the physical effects is observed to be a strong function of the overpressure released and its positive phase duration. In this study, probit equation developed by (Prugh, 1999) was employed in the calculation of percentage for major and minor structural damage at a specific location from the centre of explosion. The probit equation for structural damage calculation is given by:

$$P_r = 5.0 - 0.26\, log_e\, V \tag{5}$$

For major structural damage, $V = (17{,}500/P_s)^{8.4} + (290/i_s)^{9.3}$ (6)

For minor structural damage, $V = (4{,}600/P_s)^{3.9} + (110/i_s)^{5.0}$ (7)

where i_s is the impulse $\left(\frac{1}{2}p_s t_p\right)$, p_s is the peak overpressure (Pa) and t_p is the positive phase duration (s).

3. Results and Discussions

3.1 Variation of the Overpressure with Distance

Table 2 shows the summary of computed overpressure and positive phase duration at a detonation distance of 50 - 410 m for a fictional scenario of an aircraft impacting a nuclear containment building. Analysis of the results showed that there is extremely very higher blast pressure and long positive phase duration even at a distance above 400 m from the explosion centre point. The observed overpressure measured at a detonation distance of 410 m was 0.32 bar. This value is within those considered to cause total destruction of most common buildings (Santamaría and Braña, 1998). This analysis further indicates that irrespective of the method used, the explosion of 120 t which account for 67 % of the maximum fuel capacity for A380 series deserved serious measures to limit its consequences.

Table 2: Variation of overpressure and time of positive phase with distances

TNT Method			TNO Method			BST Method
x (m)	Z (m kg$^{-1/3}$)	P_s (bar)	r' (bar)	P_s (bar)	t_p (ms)	P_s (bar)
50	1.05	8.98	0.13	-	-	-
70	1.47	4.21	0.19	-	-	10.00
90	1.89	2.35	0.24	10.20	163.77	9.00
110	2.31	1.47	0.30	7.92	174.69	6.50
130	2.73	1.01	0.35	6.00	196.52	6.00
150	3.15	0.73	0.40	3.10	218.36	3.10
170	3.57	0.56	0.46	2.80	218.36	2.32
190	3.98	0.45	0.51	2.23	196.52	2.25
210	4.40	0.37	0.57	2.10	207.44	2.00
230	4.82	0.31	0.62	1.20	272.95	0.92
250	5.24	0.26	0.67	1.10	283.87	0.90
270	5.66	0.23	0.73	0.90	305.70	0.70
290	6.08	0.21	0.78	0.82	327.54	0.64
310	6.50	0.18	0.84	0.71	349.37	0.48
330	6.92	0.17	0.89	0.68	382.13	0.44
350	7.34	0.15	0.94	0.48	414.88	0.40
370	7.76	0.14	1.00	0.38	436.72	0.36
390	8.18	0.13	1.05	0.40	458.55	0.32
410	8.60	0.12	1.10	0.32	480.39	0.30

Figure 3 presents a functional relationship between explosion overpressure and distance from the explosion centre. The TNO method predicts higher overpressure as compared to other two methods. A good agreement is achieved between the TNO and BST models at a distance higher than 110 m. The study by Lobato et al. (2006) reports a higher values of overpressure for the TNT model in contradiction to our findings. The difference in the measurements may be attributed to variation in the assumptions and scenarios analysed.

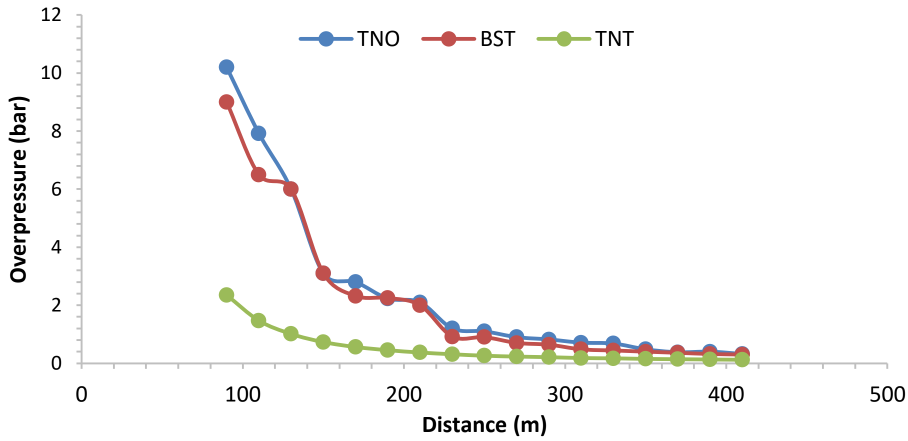

Figure 3: Overpressure as a function of distance

The blast pressure measured at a detonation distance of 210 m for the TNT, TNO and BST methods were 0.37 bar, 2.1 bar and 2.0 bar. These values are extremely high to withstand by any engineering structures (Santamaría and Braña, 1998). The vulnerability estimate shows that the probability of major structural damage at a distance of 370 m and 410 m distances were 97 % and 93 %. The vulnerability estimates are supported by the values of explosion overpressure shown in Table 2. With these calculated values of overpressures, one could confidently conclude that the model NPP site would suffer total demolition. Another important safety concern in this scenario is the observed long positive phase duration of explosion overpressure. The minimum value of positive phase duration t_p (s) recorded at a distance of 90 m was 163.77 ms and maximum is 480.39 ms at a distance of 410 m. This translates to an explosion speed of 550 m/s and 853 m/s, which means that a detonation has taken place on the whole region.

4. Conclusions

This study presents the results of consequence analysis of VCE carried out for the accidental release of 120 t kerosene equivalent in NPP. A hypothetical scenario of aircraft crash is assumed to be a source of the release. The TNO model predicts higher explosion overpressure at the same distance than the other two models for all the data points. The three models predicted that both containment building and control room would suffer destruction with various probabilities depending on the distance. The overpressure estimated from TNT, TNO and BST methods at a detonation distance of 410 m were 0.12 bar, 0.32 bar and 0.30 ba. These values are within the range considered to cause failure of concrete block wall and major damage to steel frame building. Therefore, taking into account our scenario, a 1 km × 0.6 km area is not sufficient enough for the safe positioning of NPP structural components.

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