# QUANTITATIVE RISK ASSESSMENT ON FIRE AND EXPLOSION IMPACTS FOR NUCLEAR POWER PLANTS

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# QUANTITATIVE RISK ASSESSMENT ON FIRE AND EXPLOSION IMPACTS FOR NUCLEAR POWER PLANTS

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To my beloved family

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# ABSTRACT

The International Atomic Energy Agency (IAEA) requires all nuclear power plant operators to identify, assess and evaluate potential hazards either internal or external, including the potential of human-induced events that can directly or indirectly affect the safety, security, and safeguard of the nuclear power plant (NPP). One of the external hazard that the operator of a licensed nuclear reactors has to consider is that of external explosion with potential for consequential damage to the site. In this study, effects of jet fuel (dedocane and butane) and hydrogen gas induced external explosion from aircraft impact on nuclear plants were investigated and analyzed A turbulence model based on Reynolds-averaged Navier-Stokes in the computational fluid dynamic (CFD) solver called Flame Acceleration Simulator (FLACS) and empirical correlations were used to determine the explosion parameters within the plant vicinity. The influence of obstacle separation distance on explosion severity was investigated with the aim of obtaining the minimum safety distance between buildings. The results of the FLACS simulation and empirical data were analysed and evaluated in order to demonstrate the safety assessment based on two generic plants (Fukushima and Horizon nuclear plants). The simulation results of key explosion parameters for hydrogen show a deflagrative overpressure, $P_{max}$ of 0.37 bar, and impulse load of 0.022 bar · s at the exterior walls of building structures. The findings showed that the local temperature of about 1523 K and flame speed of 266 $m \cdot s^{-1}$ from the hydrogen-air explosion. Butane/air explosion causes an overpressure, $P_{max}$ of 0.27 bar, with a maximum positive pressure impulse of 0.015 bar · s. An elevated local temperature of 2030 K and a flame speed of 44 $m \cdot s^{-1}$ are recorded for this fuel. It was found that for a safety consideration regarding the explosion of these fuel gases, a physical distance of 150 m between the explosion source and the target structure should be sufficient to provide protection against their potential hazards. The computed overpressure and impulsive loadings observed are capable of causing substantial structural damages and vulnerabilities. A significantly elevated flame temperature recorded would have a harmful effect on the safety function of structures, systems and components that are needed to execute reactor shutdown. The analysis also showed that consequential damage of explosion overpressure is strongly dependant on the global load of flammable gas volume and plant layout. In this case, 5000 $m^3$ of hydrogen/butane explosion is sufficient to produce a blast load wave for total plant destruction. The findings of this study may be used to evaluate the safety improvement needed at NPP site with regards to risks and consequences associated with external explosion due to aircraft impact. It is also useful in designing the layout of the NPP and placement of relevant items important to safety.

# ABSTRAK

Agensi Tenaga Atom Antarabangsa (IAEA) mensyaratkan semua operator loji kuasa nuklear untuk mengenal pasti, memeriksa dan menilai potensi hazad sama ada dari punca dalaman atau luaran, termasuk potensi peristiwa yang disebabkan oleh kecuaian manusia yang boleh menyebabkan kesan secara langsung atau tidak langsung terhadap keselamatan, kesejahteraan dan perlindungan loji kuasa nuklear (NPP). Salah satu faktor bahaya luaran yang perlu diberi perhatian oleh operator reaktor nuklear berlesen ialah letupan dari sumber luaran yang boleh menyebabkan kerosakan teruk kepada tapak loji. Dalam kajian ini, kesan bahan api jet (dedokana dan butana) dan gas hidrogen dalam letupan luar akibat daripada impak pesawat terhadap loji nuklear telah diselidik dan dianalisis. Satu model pergolakan berasaskan kepada purata-Reynold Navier-Stokes dalam penyelesaian pengiraan dinamik bendalir yang dikenali sebagai “Flame Acceleration Simulator” (FLACS) dan korelasi empirik telah digunakan bagi menentukan parameter letupan di persekitaran loji. Pengaruh jarak pemisahan antara objek penghalang terhadap kesan letupan telah diselidiki dengan tujuan untuk mendapatkan jarak selamat minimum di antara bangunan. Hasil simulasi FLACS dan data empirik telah dikaji dan dinilai untuk mempamerkan pentaksiran keselamatan berdasarkan dua loji generik (loji nuklear Fukushima dan Horizon). Keputusan simulasi untuk parameter utama letupan gas hidrogen menunjukkan tekanan deflagrasi, $P_{maks}$ bernilai 0.37 bar, dan beban impuls adalah 0.022 bar·s telah dikenakan pada dinding luar struktur bangunan. Hasil dapatan mendapati bahawa suhu setempat adalah setinggi 1523 K dan kelajuan ambatan api adalah selaju 266 $m \cdot s^{-1}$ akibat daripada letupan hidrogen-udara. Letupan dari gas butana/udara menunjukkan tekanan lampau, $P_{maks}$ adalah 0.27 bar, dengan tekanan impuls positif maksimum selaju 0.015 bar·s. Suhu setempat telah direkod setinggi 2030 K dan kelajuan perambatan api adalah 44 $m \cdot s^{-1}$ telah dicatat bagi bahan api ini. Simulasi juga menunjukkan bahawa untuk tujuan pertimbangan keselamatan berkaitan dengan letupan bahan api gas ini, jarak fizikal 150 m di antara punca letupan dan struktur sasaran adalah memadai bagi memberikan perlindungan daripada potensi hazad. Tekanan letupan yang dikira dan beban impuls yang dicerap mampu menyebabkan kerosakan sebahagian struktur dan kawasan sekitar. Suhu api yang dicatat adalah lebih tinggi dan melampaui suhu yang digunakan untuk mereka bentuk kebanyakan komponen loji nuklear, sekaligus menyebabkan kegagalan struktur dan komponen keselamatan yang diperlukan untuk melaksanakan penutupan operasi reaktor. Analisis menunjukkan kemusnahan akibat dari letupan amat bergantung kepada beban keseluruhan isipadu gas mudah terbakar dan susun atur loji. Bagi kes ini, letupan hidrogen/butana sebanyak 5000 $m^3$ adalah mencukupi untuk menghasilkan gelombang beban letupan untuk kemusnahan loji secara keseluruhan. Hasil kajian ini boleh digunakan untuk menilai penambahbaikan sistem keselamatan yang diperlukan oleh tapak NPP bagi menghadapi akibat dan risiko yang berkaitan dengan letupan dari sumber luaran akibat impak pasawat. Ia juga berguna dalan merancang susun atur sesebuah NPP dan penempatan peralatan yang penting untuk keselamatan.

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$\beta$ - Porosity in grid cell

$D$ - Plant-to-airport distance

$E$ - Energy released by explosive

$\varepsilon$ - Dissipation rate of turbulent kinetic energy

$F_{w,i}$ - Flow resistance due to walls

$F_{o,i}$ - Flow resistance due to subgrid

$f_E$ - TNT yield factor

$G_s$ - Flow Shear stress

$G_w$ - Wall shear stress

$G_b$ - Buoyancy

$G_o$ - Sub-grid objects

$\xi$ - Transport equation for mixture fraction

$I$ - impulse

$\bar{I}$ - Scale impulse

$H$ - Enthalpy

$L_T$ - Length scale

$N$ - Number of moles

$M$ - Mass

$\dot{m}$ - Mass loss rate

$M_f$ - Mass of fuel

$M_{TNT}$ - Equivalent TNT mass

$\rho$ - Density

$\Delta H_C$ - Heat of combustion of explosive

$P$ - Pressure

$P_a$ - Ambient pressure

$P_k$ - Production of turbulent kinetic energy

$P_s$ - Overpressure of the shock wave/ Sach-scaled ovepressure

$P_r$ - Probit function

$\bar{P}$ - Scale overpressure

$PROD$ - Combustion product mass fraction

$R$ - Universal gas constant

$r'$ - Sach-scaled distance

$k$ - Turbulent kinetic energy

$P_{max}$ - Maximum pressure

$c_p$ - Specific heat

$C_s$ - Speed of sound

$u^{'}$ - Turbulent flow

$u_i$ - Velocity in the $x_i$ direction

μ - Effective viscosity

$c_\mu$ - Constant in $k-\varepsilon$ equation ($c_\mu$=0.09)

$\mu_{eff}$ - Effective viscosity

$dP/dt$ - Rate of pressure rise

$dt$ - Time step

$S_f$ - Flame speed

$S_L$ - Laminar burning velocity

$S_T$ - Turbulent burning velocity

$\sigma_{i,j}$ - Shear tensor

$S_\alpha$ - Source term in chemical specie conservation term

$S_{Q,L}$ - Quasi laminar velocity

$Q$ - Total heat flux/emissive power

$t_p$ - Positive phase duration

$T_a$ - Ambient temperature

$T_g$ - Temperature of the gas flow

$T_{i,j}$ - Shear stress

$\bar{P}_s$ Dimensionless overpressure

$PIMP$ Pressure impulse

$x$ - Distance from the centre of explosion

$R$ - Flame radius

$R_{fuel}$ - Fuel reaction rate

$Z$ - Scale distance

$t'_p$ - Sach-scaled pulse duration

$\bar{R}$ - Energy scaled distance

$V$ - Flow velocity

$Y_\alpha$ - Mole fraction of specie $\alpha$

$Y$ - Fuel mass fraction

$\gamma P$ - Fuel dependent parameter

# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| BWR | - | Boiling Water Reactor |
| BLEVEs | - | Boiling Liquid Expanding Vapour Explosions |
| BR | - | Blockage Ratio |
| CFD | - | Computational Fluid Dynamics |
| CWS | - | Circulating Water Systems |
| DDT | - | Deflagration to Detonation Transition |
| FLACS | - | Flame Acceleration Simulator |
| HSE | - | Health and Safety Executives |
| HEPA | | Higher Efficiency Particulate Air |
| HAVC | | Heating, Ventilation and Cooling |
| IAEA | | International Atomic Energy Agency |
| INES | - | International Nuclear and Radiological Event Scale |
| LOCA | - | Loss of Coolant Accident |
| LPG | - | Liquefied Petroleum Gas |
| MIIB | | Major Incident Investigation Board |
| NPP | - | Nuclear Power Plant |
| NRC | - | Nuclear Regulatory Commission |
| PRIS | | Power Reactor Information System |
| PWR | - | Pressurised Water Reactor |

| | | |
|---|---|---|
| RCW | - | Reactor Building Cooling Water |
| SSCs | - | Structures, Systems and Components |
| TNT | - | Trinitrotoluene |
| TCW | - | Turbine Building Cooling Water |
| UVCE | - | Unconfined Vapour Cloud Explosion |
| VCE | - | Vapour Cloud Explosion |
| USEPA | - | United State Environmental Protection Agency |
| WTC | - | World Trade Centre |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background of Study

External hazards (e.g. aircraft impact, hurricane, flooding and earthquake) can be a significant risk contributors on Nuclear Power Plant (NPP) operation and pose serious hazards to public and environment due to release of hazardous radiation, resulting from fire-induced failures of important plant safety systems (Berg and Hauschild, 2012; Siu and Apostolakis, 1986). It may challenge the available emergency services and affect the mechanism for a safe reactor shutdown and this could lead to unsafe condition with the potential to cause reactor core damage. Therefore, hazard evaluations of external initiating events could help in minimising incidents and accidents that may involve loss of life and tremendous monetary costs.

Safety philosophy guiding the design, construction, and operation of NPP relies heavily on a concept such as defense-in-depth and redundancy (Matala and Hostikka, 2011; Sofu, 2013). This concept requires the use of multiple active and passive fire safety measures to curtail any single failure that may lead to the release of radioactive materials. It also incorporates large design safety margins to overcome any lack of precise knowledge about the capacity of barriers in normal or accident conditions and operation within predetermine safe design limits (Keller and Modarres, 2005). Probabilistic risk assessments have been the conventional method for assessing the risk and consequences of a fire or any form of an explosion in the NPP. Safety standards issued by the regulatory agencies are dependent on the outcomes of these form of analysis. It is interesting to note that the consequences from the occurrence of 'beyond-design-basis accidents' were not fully addressed in the probabilistic risk analysis which amongst other external threats should be a priority for the analysis. For instances, the Fukushima Daiichi NPP incident of March 11, 2011, and World Trade Centre (WTC) aircraft attack on September 11, 2001 (Dundulis *et al.*, 2007; Jeon *et al.*, 2012; Luther and Müller, 2009; Siddiqui *et al.*, 2003). These incidents attract interest on the reliability and safety of reactor containment and auxiliaries against any similar event. Based on Health and Safety Executive (HSE) report (HSE, 2008), industries including NPPs still encounters frequent fire and explosion hazards. The accidents may occur for different reasons ranging from malfunctioning of safety systems and equipment to human operational error. Depending on the source of release, flammability limit and availability of ignition source, ignition of the flammable gas cloud may lead to a severe explosion which has been referred to as Vapour Cloud Explosion (VCE) (Drysdale, 2010; Taveau, 2012).

Although, there are few documented records of significant hydrocarbon fuels induced external fires or explosion at the nuclear plant site, however, these could be initiated in many ways, including storage, reloading, transport accidents and vicious attack using higher-profile explosives. In addition, fabrication and handling of explosive materials at a close distance to NPP could be a potential initiating event. The aircraft crash may occur at the site as result of takeoff or landing operation at a nearby civilian airport or owing to the air traffic in the federal airways and military flight zones. Example of transportation accident was the train derailment in June 2009 at Viareggio, Italy which led to a flash-fire, destroying several houses and 31 causalities (Pontiggia *et al.*, 2010). This kind of accident might give devastating consequences if occurs near the NPP site. One significant accidental aircraft crash is reported to have occurred near the vicinity of nuclear islands, sometimes with the detached engine skids up to 300 m, with the damage to industrial and residential facilities (IAEA, 2003b) and this motivates a different landscape from the safety point of view when accessing the risk assessment and evaluation on NPP and its vicinity. The relevant studies on the topic aircraft impact upon nuclear containment have been described elsewhere (Abbas *et al.*, 1995, 1996; Frano and Forasassi, 2011; Iqbal, 2009; Joseph *et al.*, 2009; Lee *et al.*, 2013).

The consequences of VCE on the nuclear island pose domino effect condition; high explosion overpressure, thermal radiation from the fireball, toxic gas dispersion and effect of explosion-generated fragments. For consequence analysis, the effect of overpressure is of greater interest rather than that of thermal radiation and the fragments. The explosion overpressure and blast waves could propagate several kilometres and pollutants could disperse over greater distances. In addition, fuel may enter through the vents openings, air exhausts vents of reactor and diesel buildings, sewage system, and tunnel. This may result into subsequent fires or explosions which will affect personnel or cause the plant to be malfunctioned such as electrical faults or failures in emergency diesel generators. Fireball could propagate rapidly and engulf reactor platform, leading to affect multiple redundant engineered safety systems if it penetrated between redundant parts of the NPP (Safaei *et al.*, 2010). All these could constitute a significant safety threat to the operation of the plant as it would distress the emergency services, safe reactor shutdown mechanisms, and critical safety equipment. A comprehensive safety assessment is essential to be carried out to determine the appropriate countermeasures in order to maintain an inherently safer operation of the NPP. It should be conducted under various services and extreme conditions, both natural and produced by vicious man activities (Frano and Forasassi, 2011). Thus, this work aims to investigate the hazard evaluation for an external explosion caused by jet fuel from commercial aircraft to NPP. This includes structural damage and safety distance analyses. Of particular interest to this research is the congestion level and location of obstacles relative to ignition location. These are directly related to the spatial arrangement of structures and may have a strong influence on the evolution of fireball, pressure build-up, and flame propagation.

## 1.2 Problem Statement

Although previous studies have developed and adopted different verified methodologies on reactor safety and fire hazards, studies that considered the impact of external events like aircraft crash on the NPP structures are very limited and gave little or no considerations to the effect of fuel that initiated fires and/or explosions. In most cases, the assessment of aircraft-induced events pay emphasis to local and global structural damage which follows one of the three reference analytical methods such as energy balance, load–time history and missile–target interaction (Abbas, *et al.*, 1996; Dundulis, *et al.*, 2007; Iqbal *et al.*, 2012; Kukreja, 2005; Petrangeli, 2007; Petrangeli, 2010; Siddiqui, *et al.*, 2003). Despite the regulatory requirement for evaluation of hazards related to chemical explosion from the jet fuel fires and other sources in the vicinity of NPP, most attention has been focused on internal explosion to plant, only a few specific evaluation data on explosion outside the plant have been reported. The assumption that external fire or explosion last for a very short duration or low occurrence frequency may be the reasons of why it has lesser attention. Security issues may also be additional reasons for not reporting such research findings to the public. Yet, ignition of gas cloud in the vicinity of NPP could result in fire and/or explosions that could affect the safety functions of SSCs needed to resume and maintain the nuclear installation to a safe condition (IAEA, 2002, 2003a). The blast could travel over several kilometres, which might extend beyond the immediate vicinity and pollutant could be dispersed over greater distances. Therefore, the consequence of the external fire and explosion should not be overlooked and should be determined against the nuclear plant.

Literature scrutiny revealed limited experimental and real accidents data that can be directly referred to in assessing external explosion hazards on the operation of the nuclear plant. Studies by Luther and Müller (2009) and Jeon, *et al.* (2012) did not address the minimum stand-off distance as part of protection measures against the effects of the explosion. The influence of obstacle separation distance on gas explosion severity has been extensively explored for the process plant (Kindracki *et al.*, 2007; Lee and Moen, 1980; Na'inna *et al.*, 2014; Park and Lee, 2012). However, there is hardly found in the literature on experimental or modeling research on the influence of obstacle separation distance for the aircraft impact induced explosion in the vicinity of NPP. It is the aim of this study to extend the investigation into the influence of obstacle spacing on gas explosion severity with a view to determine the minimum stand-off distance between containment structure and other building structures for the postulated jet fuel release.

## 1.3 Research Questions

(i) What is the magnitude of explosion severity (in terms of overpressure, impulse, temperature, flame speed) on the operation of NPP?

(ii) How the building structures does influences the explosion severity in the NPP?

(iii) How much damage done to the exterior walls of the surrounding buildings and the hazards posed by the fireball/flame front propagation of fire/explosion at fictive openings (air intake vents & exhaust)?

(iv) How to verify the design strength of the reactor containment and other critical components of NPP are strong enough to withstand the blast loading from an aircraft crash (intentional or accidental) or close proximity blast using high profile explosives?

## 1.4 Research Hypothesis

(i) The magnitude of explosion pressure and impulse loadings will cause the collapse of structures housing the important safety components thereby leading to unsafe condition in the plant.

(ii) The distance between reactor building and the nearest structures is small. This minimum distance may significantly enhance overpressure and cause the blast waves to propagate beyond the immediate vicinity.

## 1.5 Objectives of the Research

The primary objective of this research is to undertake, in a structured manner, a hazard assessment of key explosion parameters that may affect the operation of the NPP with a view of determining the appropriate countermeasures for a hypothetical aircraft accident scenario. The specific objectives include the following:

(i) To compute the VCE parameters such as pressure, P, flame speed, $S_f$, the temperature of the gas, $T_g$, the rate of pressure rise, dP/dt, pressure impulse, (PIMP), and blast effect distance at pre-selected monitor points within the bounds of the NPP complex.

(ii) To estimate the severity of explosion in terms of overpressure and impulse loadings, flame speed as well as the fireball temperature in the NPP taking into account the specific site layout and distance between operational units.

(iii) To assess the influence of building obstacle separation distance on the explosion severity with a view to determine the minimum safety gap between units of operation.

(iv) To estimate the vulnerability of building structures using empirical models and compare the results with numerical data obtained using validated commercial software, FLACS (Flame Acceleration Simulator), version 10.6r3.

## 1.6 Scopes of the Research

The research work was conducted within the following scopes:

(i) A hypothetical aircraft impact scenario for the NPP is simulated with FLACS Computational Fluid Dynamics (CFD) model.

(ii) A homogeneous mixture of 100% (v/v) butane-air, dodecane-air and hydrogen-air at a near stoichiometric concentration were used as fuels to compare the explosion characteristics.

(iii) Key explosion parameters such as blast pressure, P, pressure impulse, PIMP, flame speed, $S_f$, and temperature $T_g$, blast effect distance at the exterior walls of building structures were estimated using FLACS.

(iv) Empirical modeling methods such as Trinitrotoluene (TNT), multi-energy (TNO) and Baker-Strehow-Tang (BST) were used to compute overpressure and positive phase duration within the distances of 50 m to 600 m from the first impact location.

(v) The effects of building obstacle separation distance on the evolution of fireball and overpressure development are investigated with a view of establishing the minimum safety gap between units of operation.

(vi) Damage to structures was estimated using Probit methodology.

## 1.7 Limitations of the Study

The main limitations of the study are as follows:

(i) The work presented in this research is based on the hypothetical scenario of aircraft impacting a nuclear containment. The NPP site scenarios are retrieved from the references (Hitachi, 2014b; INPO, 2011). It should be noted that the layout of the NPP were followed the original layout however, the building dimensions were made by assuming the normal building dimensions and some complied with IAEA regulation and standard i.e. reactor building.

(ii) The analysis relied only on FLACS simulation and empirical data calculated using explosion prediction methods. No data for the actual scale (in terms of width, length and height of building) of the NPP geometries used. These geometries are hypothetically assumed and used in the simulations.

(iii) The research work uses information that are freely available in the IAEA safety standards and relevant safety documents for vulnerability/damage analysis.

(iv) Physical effect due to the ejection of fragments, cratering, ground shock wave and resulting effects from the pool fire and smoke are not included in the analysis.

## 1.8 Significance of the Research

This study explores the deterministic approach on the consequences of VCE involving aircraft crash on the nuclear island. The knowledge of the explosion characteristics and its impact on of Structures, Systems, and Components (SSCs) is important in determining the appropriate countermeasures in order to maintain safer operation of the nuclear station. Furthermore, conducting details and comprehensive research on the effects of explosion parameters on the operation of NPP will contribute in perspective and diagnostic studies regarding NPP fire and explosion safety, particularly on the human-made threat. Some significances of the study are given below:

(i) With the information on explosion modeling, the managers can take preventive steps to ensure plant's safety.

(ii) Provides decision makers with additional information regarding the placement of animate and inanimate objects. Therefore, personnel can be located or relocate to areas with least risk for sustaining explosion damage.

(iii) The determination of minimum safety distance from the target unit to other equipment and occupied building could be applied to offshore and onshore facilities as well as large industrial vessels.

## 1.9 Thesis Organization

This thesis is classified into five different chapters. Chapter 1 describes the background of the research, problem statement, research question, and research hypothesis, objectives of the research, scope of the research, limitation of the study and significance of the research aimed to highlight the introduction aspect of the research work. In Chapter 2, the regulatory guides on external explosion assessment were discussed. It also discusses on structural safety and design against external missiles. Further, the typical layout of nuclear plant followed by a brief explanation on functions and features of common civil structures in the NPP were briefly highlighted. Descriptions of external hazards affecting the NPP operation as well as major effects of the gas explosion were highlighted in this chapter. It also discusses the mechanisms of VCE, factors affecting the severity of VCE as well as detailed description of three widely empirical methods for VCE modeling. The chapter further describes the FLACS CFD tool that was used in the simulation. A highlight on vulnerability analysis was made. The chapter ends with a comprehensive literature review covers the general overviews on explosion safety assessment in the process plant and NPP and highlights on safety distance as defined by some selected regulatory guides. Chapter 3 explained the methodology and assumptions made on modelling simulation works. It particularly discusses the research approach and how the work is performed to achieve all research objectives. The tasks include setting the scenario, running the simulation using FLACS model and analysing time-history or distance-history graphs for various scenarios and plant arrangements. The simulation results from FLACs and probit/empirical analysis were discussed in details under Chapter 4, and probit/empirical results are discussed in Chapter 5. The comparison analysis made on empirical model calculation was also examined under this chapter. Finally, conclusions were made based on the results obtained from the CFD simulation and empirical data. Recommendations of further investigation based on the research vacuums acknowledge during this study were mentioned and highlighted in Chapter 6.

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