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Current Knowledge and Research Opportunities in Nuclear Fire Safety: A Technical Overview on Aircraft Impact upon Nuclear Containment

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Abstract

Objective: This paper scrutinizes the available literature and presents a comprehensive overview of nuclear fire safety, acknowledging some areas for future research. **Methods/Statistical Analysis:** Relevant literatures on the aircraft impact upon nuclear reactor containment were reviewed. Scope, findings and limitations of major researches in this field were presented and possible areas of future research were highlighted. A statistical analysis on the number of scientific publications on nuclear fire safety per five years which present the progress in the subject matter was reported. The analysis considered 1968 and 2015 as the base and end years respectively. **Findings:** In general, some of the identified challenging issues and limitations of nuclear fire studies are: (i) there are limited experimental data on real nuclear fire (ii) studies which considered the impact of external events like aircraft crash on containment gave little or no considerations to tendon gallery, openings and penetrations as in most cases, crash were hypothetically assumed to occur at the midpoint of the cylindrical portion of the containment and near the junction of dome without making recourse to the other portions of the containment e.g. roofing and reactor base (iii) Most reactor fire analysis do not consider material properties at elevated temperatures (iv) in the hazard analysis concerning aircraft impact, assessment of hazards from fireball and pool fire are yet to be fully considered (v) there are very limited data concerning structural failure modes caused by near-field explosive loading. **Application/Improvement:** The findings of this article could be used to improve the existing methodologies of nuclear fire safety assessment in order to address some of the identified challenging issues.

Keywords: Fire Hazards, Nuclear Reactor, Nuclear Power Plant, Nuclear Accident, Nuclear Safety

1. Introduction

The incessant ramifications of global warming which has been caused by emission of greenhouse gases to the environment has been a major driver in the decision of both the developed and developing nations to embrace nuclear energy- which is a clean source of power. With this growing interest in nuclear energy, there is the need to improve all aspects of nuclear safety especially fire safety. Fire safety assessment of infrastructures such as nuclear power plant (NPP) is important in ensuring safety to the plant, plant's personnel, public and the environment.

The safety philosophy guiding the design, construction, and operation of nuclear power plant relies heavily on

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concept such as defense-in-depth and redundancy. For nuclear fire safety, the defence-in-depth means that attempts have been made to avert fire ignition and limit its consequences[1–4]. This concept requires the use of multiple active and passive fire safety measures to curtail any single failure which may lead to the release of radioactive materials that could readily initiate fire. It also requires the incorporation of large design safety margins to overcome any lack of precise knowledge about the capacity of barriers in normal condition or accident.

The concept further emphasizes the basic requirement of quality assurance in reactor design and manufacture, operation within predetermined safe design limits as well as continuous testing and inspection to preserve original design margin[5].

NPP safety is defined as the ability of the nuclear reactor to withstand a fixed set of prescribed accident scenarios judged by the International Atomic Energy Agency (IAEA) experts as the most significant adverse events in a nuclear power plant[5]. The argument is that if the plant can withstand the design basis accidents, it can also handle any other accidents. The attempt to eliminate the possibility of reactor failure from fundamental design flaws (and worst possible accidents should not be underestimated). However, the basic consideration of 'incredible events' such as the catastrophic failure of the reactor pressure vessel or multiple independent failure events were excluded in the definition of defense-in-depth[5].

A report on fire statistics in NPP by[6] revealed that a German nuclear power plant can experience an average of 15 fires during its life time of about 40 years and about 55% of nuclear accidents in U.S.A were caused by fire. The severity of external fire or explosion in an NPP depends on a number of factors such as magnitude of the impact force on the critical component of the plant, design capacity of the components, interaction of the subsystems with one another, duration of shock wave interaction with structures, fuel type and stoichiometry, type of ignition source and its location, time to ignition and detection, initial turbulence level in the plant, blockage ratios size, shape and location of obstacles, scale of plant (single or multi-unit reactor site), early response, sophistication and availability of firefighting equipment[7].

A standard practice to assess the consequences of fire and any form of explosion in the nuclear power plants is through risk assessment, but it appears that 'incredible events' were not included in the probabilistic risk assessment. The Fukushima Daiichi NPP incident (March 11, 2011), Aircraft attack on the World Trade Centre (WTC) (September 11, 2001) and Pentagon buildings are examples of initiating incredible events. These incidents attracted interest on the reliability and safety of nuclear reactor containment against any similar event[8–11]. For instance, in some fires related to NPP accidents like Chernobyl, the containment acts as a barrier and reduces the releases of hazardous isotopes to the environment[9,12–14]. The consequences of hydrogen explosion in the Fukushima and Chernobyl are much more dangerous than the WTC incident. The radioactive release from the formers present a greater damage to both human health and environment, and thus, it should be taken into account on the initiating events in probabilistic risk assessment.

Studies on the aircraft impacting a hard target revealed that such incident are usually associated with the explosion and evolution of fireball, which often occurred immediately after the explosion. This type of incident could result in devastating consequences, including intense fires and explosions with an influence over several kilometres. Strong blast waves could propagate beyond the immediate vicinity, and pollutants could disperse over a greater distances. Fire may challenge multiple redundant engineered protection systems if it penetrates through the barriers between redundant parts of the NPP[15]. For accidental aircraft crash on NPP, jet oil may enter the NPP sewage system, tunnel (housing electric and IC cables), and the vents to the reactor; and this could ignite fire in the reactor building. The internal fire may damage electrical and IC cables and could jeopardize the functionality of safety-related reactor auxiliaries.

This paper reviews fire safety assessment of NPP based on deterministic (modelling) practices with the special emphasis on aircraft crash upon outer containment of the nuclear reactor. The scope, techniques, results, strengths and limitations of relevant literatures on NPP fire safety are highlighted. This paper aims to focus on the fire safety issues within the NPP vicinity, narrowing the research gaps available and embarking on further research in nuclear safety and emergency preparedness.

The paper is organized as follows:

- The first section introduces the regulatory requirements for NPP fire safety assessment set by IAEA and United States Nuclear Regulatory Commission.

- NPP fire assessment methods and a brief description of fire safety models will be the next discussion.
- The last part of the paper presents a general review on the aircraft impact analysis upon outer containment of nuclear reactor plant.

1.1 Regulatory Requirements for Fire and Explosion Safety Assessment due to Aircraft impact

The IAEA requires the verification and fire safety assessment due to external fires e.g. involving aircraft impacting a nuclear power plant structures. These regulatory requirements are contained in the safety guides GS-G-4.1, NS-G-1.2, NS-G-1.5, and NS-G-3.1. Section 5 of NS-G-3.1 requires that the chance for aircraft crashes that may affect the plant site should be considered at the early stages of the site evaluation process and it should be assessed over the entire lifetime of the plant. Section 5.16 of NS-G-3.1 and section 4.23 of NS-G-1.5 directly deals with fire hazards caused by aircraft fuel and reads as follows: "The following possible consequences of the release of fuel from a crashing aircraft should be taken into account":

- burning of aircraft fuel outdoors causing damage to exterior plant components.
- the explosion of part or all of the fuel outside buildings
- entry of combustion products into the ventilation or air supply systems
- entry of fuel into buildings through normal openings or holes caused by the crash or as vapor or aerosol through air intake ducts, which often lead to subsequent fire, explosions or side effects.

Section 5.18 of NS-G-3.1 elaborates further that the evaluation should consider the type and quantity of fuel involved in the crash in order to quantify the fire interaction effects and correlate them with potential structural damage[16]. Section 4 of NS-G-1.5 specifically deals with the aircraft crash. It is emphasize in this document that analysis of steps taken to limit the consequences to an acceptable level should be carried out and the evaluation should give consideration to global and local structural damage, the effect of fuel initiated fires and functional failures of structures, systems and components (SSCs) to be protected against external initiating events. In the evaluation of aircraft loading, the characteristics of the aircraft such as class, velocity at impact, mass, stiffness, size and location of the impact region and consequences in conjunction with single impact (e.g. secondary missiles or fuels spills) has to be explicitly defined[17].

Countries such as USA have their national guidelines for the analysis of the aircraft fire hazard and acceptance criteria. For example section a (1) and a (2) of US NRC 10 CFR 50.150 "Aircraft impact assessment" requires that structures, systems, and components (SSCs) important to safety be assessed for aircraft impact. The assessment must be based on beyond-design basis impact of large, commercial aircraft; and aircraft characteristics such as fuel type and quantity involved. Impact angle, impact speed as well as experience of the pilot should also be considered in the assessment. In addition to performing a local and global structural analysis, it is also necessary to evaluate the effects of fire and shock that can cause damage to important systems utilized for fuel cooling.

2. Fire Safety Assessment Methods in the NPP

Available methods for estimating the severity of fire in the nuclear power plant can be divided into two: performance-based and risk-based. Both methods estimate the potential consequences of possible catastrophes and accidents. Fire safety standards by the regulatory bodies are designed based on the outcome of these two assessment methods.

2.1 Performance-Based Assessment Method

This is a deterministic based approach that is, computational analysis of actual fire models. It involves the use of performance-based practices which are used in performance design. In principle; deterministic analysis identifies fire hazard which may result in core damage or release of significant radiation level. The fire hazard results are used in addressing countermeasures against deviation from normality. The main aim of this method is to determine the expected outcome of designed fire scenario such that: (i) potential occurrence of accident is minimized with no significant release of radioactive materials (ii) critical safety systems are not damaged by the fire and (iii) minimize economic loss. The designed fire scenario must include characteristics that may affect fire and smoke spread such as building features, occupants, and fire characteristics. It should be noted that the predicted fire hazard is strongly a function of the design fire scenarios analyzed.

It was reported in the study by[18] that performance-based assessment methods have some noteworthy merits and demerits associated with its use in NPP fire assessment. They reported that many key principles based on deterministic considerations, such as safety margins, defense-in-depth, diversity, redundancy and independence have served the backbone of nuclear power plant safety today. These key principles are very useful concepts, and as a result, are expected to continue to play a greater role in keeping nuclear power plant safe. These authors noted the following notable drawback of the fire hazard approach: (i) safety arguments are primarily made on the basis of design basis events that were defined somewhat arbitrary by combining initiating events with single failures and coincidence occurrences (ii) the accident sequences identified as design basis events (DBEs) do not have a strong basis for credibility because no systematic process is provided for the sequence identification.

2.2 Risk-Based Assessment Method

This is a probabilistic approach where frequency of fire occurrence and consequence are quantitatively obtained for a given scenario. Basically, fire hazard analysis is a part of the fire risk analysis as the information from former will go into the latter. Fire risk analysis play a prominent role in making a safety case for the siting, design, construction, operation, and decommissioning of nuclear power plants for several years. This method highlights some key reliability features of nuclear power plant. It identifies the components and systems performance. Further, it exposes the deep distrust and fear among the public on anything nuclear. Risk information and insights from probabilistic safety assessment (PSA) may be applied in decision making process for plant design-safety-analysis to complement deterministic approach[18]. So risk analysis has been applied to develop licensing requirements for different forms of reactors and also in the verification of reactor design. In this approach, accident scenarios are systematically analyzed using event trees with careful considerations of nuclear components interactions, common caused failure events, operating errors, success and failure criteria rather than conservative assumptions used in deterministic approaches. The likelihood of occurrence of unwanted events and its consequences are analyzed. With this approach, an operator will gain an idea on the weaknesses and strength for safety systems. This could help to properly correct important safety problems. Probability is assigned to each accident scenario and its associated frequency is estimated. In[19] acknowledged that a design feature and characteristics that reduce the frequency of a given fire incident are considered as contributing to prevention. Those that prevent or reduce the level of fire consequences as viewed from particular point along the accident scenarios are considered as contributing to mitigation.

In[20] highlighted five major steps for PSA of nuclear power plants. The steps are: (i) develop and screen scenario (ii) develop models (iii) estimate parameter ranges and uncertainties[1] perform calculations and (v) interpret results.

It has been a tradition in this method for an analyst to ask questions such as: what can go wrong? How likely is it? And what are the consequences? These questions demand answers which have to be obtained through risk analysis.

In[19,20] are on the opinion that probabilistic risk assessment of NPP is superior to deterministic as the former can provide more detailed information on the problems inside a given zone based on the in-depth analysis of every possible fire origin and the associated fire frequency. In[18] recognized that fire risk analysis for the NPP have the advantage in that risk insights can significantly help to make a more informed and robust decision making as compared to the deterministic approach.The authors elaborate further that the approach can take advantage of the PSA technique where plant safety is thoroughly evaluated with explicit consideration of system interactions, success criteria, human errors, common cause failures and so on. Though, the risk-based assessment method have been in used for a long time to supplement and change licensing requirements by the regulatory bodies, the authors of this article noted that the technique is limited by the state-of-art and quality of the available risk analysis. Therefore, proper integration of the method to deterministic insights is needed to be established. The technique is also associated with uncertainties regarding input data and modeling assumptions that cannot be easily quantified.

This paper is concerned mainly with the analysis of performance-based safety researches.

3. Fire Assessment Models

Deterministic and Probabilistic fire models are the two modeling tools used in nuclear power plant fire safety assessments. They are designed to measure the performance of nuclear power plant components in confronting the hazards associated with various accidents and catastrophes. Life-threatening impacts, environmental and property damages are the main concern in these models.

The intention of this section is to briefly discuss on these models and point directly at their strengths and weaknesses.

3.1 Deterministic Fire Models

Deterministic models simulate hazardous conditions and quantify their risk. These models are developed and maintained by various organizations to predict fire and smoke conditions in the nuclear power plant environment, dwelling compartments and elsewhere. In these models, a set of empirical equations (conservation and fluid flow equations) which predict state variables (pressure, temperature, layer height) as a function of time are solved using "first principle".

Obviously, similar computer programs, using zone or computational fluid dynamics (CFD) modeling are employed for fire hazard analysis in compartments or generic nuclear power plant components. The key factor in determining which models are suitable to a given situation is through the understanding of the assumptions and limitations of the individual model and these relates to the condition in question[21]. The basic assumption used to formulate a zone model is that each enclosure is divided into two layers: an upper hot layer and the lower, cool layer. Since these layers represent the upper and lower parts of the enclosure, conditions within it can only change from floor to ceiling. The hotter and cooler zones interact by exchanging mass and energy[22,23]. However, in the field model, the compartment is divided into numerical grid cell or discrete point. Physical quantities such as temperature, density, velocity, pressure, flame height, plume temperature, heat flux, mass loss rate as well as chemical composition and other quantities are computed within each cell at each discrete time.

It has been reported in the literature that simulation using field models requires much more computing time and processing speed than in zone models[4, 20, 24, 25]. However, detailed information on fire-induced flows and temperature field in both obstructed and unobstructed space of arbitrary geometry are effectively obtained with the field model. Field models can also be used for fire hazard analysis outside the enclosure, such as fuel tank fires, offshore rig fire safety assessment and in the analysis of fireball from aircraft crash[4, 20, 24, 25]. Conversely, zone models cannot be used for the analysis of thermal environment outside enclosure, and provide information only based on two fire zones. Furthermore, human behavior and residence reliability accrued from fire are not interpreted in most zone models. So for a quick estimation of the smoke layer height and temperature induced in compartment of simple geometry, zone models can be used. For more detailed analysis of the thermal environment of complex geometry, field models are preferable.

3.2 Probabilistic Fire Safety Models

Probabilistic fire safety models predict fire growth, temperature rise, smoke generation and propagation using statistical rules and logic in quantifying hazards for a particular event or sequences of events. Probabilities are assigned to each transfer point based on analysis of relevant experimental data and historical fire incidents.

In NPP, these models can be used to identify level 1 PSA (contributors to core damage) and level 2 PSA (containment failure during a severe accident which leads to the release of nuclear radiations). It can also be used for level 3 PSA (quantification of risk in terms of release consequences to the public and environment). Probabilistic models are used for the analysis of both internal and external initiating events that may lead to accident. For fire and explosion safety, these models can effectively be used to evaluate the effect of fire on safety-related cables and equipment, and quantify probability of fire occurrence at a specific position, fire detection and suppression, as well as quantify consequences. The common-cause or common-mode failures events are difficult to model with PSA fire safety modeling tools.

4. Review of the Relevant Literature

Fire incidents on NPP have been studied in the last few decades keeping in mind the disastrous nature the effect may have. An available study indicates that it may be inevitable to carry out a full-scale experiment in order to assess the fire consequences on a nuclear power plant structures. This is due to complex interaction between fire turbulence, material combustion, heat release rate, compartment geometry, ventilation and buoyancy which in turn control fire growth and smoke movement[12,22].

Nuclear reactor containment is the most important structure in a nuclear power plant. Its protection against external aggression such as aircraft crash, vapor cloud explosion, flooding, tornados, missiles and fires is crucial to keep public and environment from radiation hazards[26]. The basic aims of aircraft impact protection is to maintain integrity of reactor containment and spent fuel pool, core and spent fuel cooling, and to prevent the release of radioactive materials to the environment[27].

An aircraft crash impact is a short duration dynamic load that could involve very large structural deformations and damage to both NPP reinforced concrete structure and the aircraft itself[28]. Several safety researches on aircraft crash impact which varies according to their techniques and scopes have been performed since the last few decades. An attempt was made in this section to analyze the contributions of major studies on the Aircraft impacting an important nuclear power plant component. Analysis of the procedure, scope and limitations of these major studies were described. It is not intention of this review to cover fire safety researches on probabilistic aspects and nuclear power plant internal fires or explosion. The probabilistic safety approach differs from the deterministic safety assessment and procedures in analyzing the internal fire scenarios may quite differ from the external fire scenarios. These aspects would be addressed in another review article by the authors.

4.1 Aircraft Impact Analysis

Various analytical and numerical techniques have been proposed for the assessment of aircraft impact force on given target. However, the uncertainty in the result of complex interactions between aircraft (missile) and concrete containment (target) coupled with complexity in predicting fire dynamics behavior placed more demand for a more robust research in this area.

The force-time history curve for an impact of large aircraft against a rigid surface was proposed by[29]. The author assumed a normal impact at a speed of 103 m s^{-1} for Boeing 720 and 707 aircrafts. Maximum response curve for elastic, undamped, one-degree of freedom system were evaluated based on these aircraft data. It was shown in Riera's study that for a large structures with a fundamental period T smaller than 0.2 s, the maximum dynamic load frequency is close to unity.

The effect of the engine and landing gear is considered to be an integral part of the crushing aircraft fuselage in the work of[29]. However, aircraft crash analysis requires that the engine should be considered as an independent missile. As stated by[30], the assumption of normal impact results in the highest missile stiffness making the Riera method conservative. In a later study[31], clarified some of the questions raised concerning his earlier findings by presenting some new data on the study. The authors demonstrated that force-time curve can be approximated by an idealized shape function which is scaled according to the velocity. It was further demonstrated that velocity, angle of incidence at the impact region and the number of engines greatly affect reaction-time curve. In[32] extends the work of[29] by presenting (i) finite element computer program of free vibration of flat slab. The program can treat arbitrary boundary conditions which idealized more realistically the actual edge supports of a slab (ii) a consistent mass finite element computer program for static slab bending analysis. This program is not limited to simply supported boundary conditions and can predicts more actual maximum response of rectangular associated structures (iii) a numerical method of solution which combines the advantage of finite difference approach and direct integration for static and vibration analysis of rotationally symmetric shells subject to non-symmetric loads. Study by[32] addresses the problem of higher dynamic response of structure which is associated with the Riera's method. The over-prediction in structural response could lead to a very expensive design.

The results of containment response study by[33] provides the following conclusions: (i) structural damping leads to smaller response and the effect is more pronounced as the distance to the impact point is increased (ii) Riera's and lumped elasto-plastic model agrees extremely well for all impact velocities in the force-time curve (iii) mass build-up shift the frequency of peak spectral response. In[34] reports that at highest frequency close to 150 Hz, the curves from Riera analysis give higher frequency spectra, likely due to harder hit with smaller displacement. This result agrees with the previous findings by[32]. Detailed results such as consequences versus speed, weight and wall thickness were not reported in the research work by[34]. In[35] pointed out some inconsistencies in the derivation of load-time history of aircraft crashing into structure by Riera. They argued that the velocity distribution in the crushing region should decrease to zero in order to match the velocity at the point of contact of the rigid structure, otherwise the structural response may be overestimated. The authors developed a simplified reaction-time history curve for a fast-flying aircraft impact using the approaches from both particle and continuum mechanics. It was shown in their research that the reaction is not affected by the manner in which the velocity distribution in the crushing region of the aircraft decreases to zero at the contact point with the target. The peak reaction for the chosen example is 40% lower than the one obtained through Riera's formulation, meaning that Riera's approach gives higher structural response. In another study by[36,1], it was reported that Riera's reaction-time history approach can be used with confidence in the impact analysis of crushable objects. It was further reports that striking angle, target geometry and velocity greatly influenced impact force and impulse force. And an effect due to impact position and tendon pre-stress does not have much significant to reaction-time curve. Similar results was obtained by[1]. The advantage of the proposed method by[1] over that of[31] is that it can be used for load calculation of complex building geometries for different crushing scenarios. The present authors observed that the reaction-time history developed by[29, 31] served as the basis for the aircraft impact loading analysis that was used by many researchers. In our opinion, impact velocity in their formulation may not be representative of velocity from an accidental commercial airliner (about 250 m s^{-1}), and hence, may not represent the worst case scenario. Results and information from Riera's study may over-predict the maximum stresses and displacements on nuclear structure as reported in various studies.

The local behavior of concrete slabs was investigated by[37]. Analysis of their results confirmed the following: (i) the impact resistance of a double reinforced concrete slab is inferior to single reinforced concrete slab (ii) the greater the thickness of the reinforced slab, the smaller the degree of damage (iii) the higher the missile velocity, the greater the damage to the slab[38] the existing empirical formula for evaluating critical thickness at which perforation and scabbing occur (e.g. Chen and Li's empirical correlations, not reported in this work), gives conservative results. We noted that the thickness of the slab (6-24 cm) and impact velocity (100-200 m s^{-1}) of projectile used in this study may not represent the scenario condition for a commercial aircraft impact. Variation of certain parameters to impact force from Phantom model aircraft was studied by[39]. It was observed that the overall behavior of the total force is nearly insensitive to variations of certain parameters. Therefore, for safety considerations, only one force versus time history curve may be used as proposed Riera. The present authors observed that the response and behavior of critical structures to dynamic and impact loading may be somewhat affected by the aircraft data.

A comparative study between Riera's method for aircraft impact loading and a realistic aircraft finite element model revealed that Riera's model can provides an adequate approximation to the total load history profile obtained in the finite element analysis[38]. The only basic difference between the two models is that finite element method provides more details in both spatial and temporal localized loading variations. However, the Riera approach considerably under-predicted the overall damage for a deformable reinforced concrete structure. In a similar study by[28], it was observed that the total impulse measured on the basis of Riera's formulation is higher than that obtained using finite element approach with LS-DYNA software. At low impact velocity of about 112 ms^{-1}, the forces LS-DYNA predicted were 33% lower than the Riera forces. However, at higher impact velocity of about 215 ms^{-1}, the impact forces LS-DYNA predicted were 4 percent lower than the Riera forces. The difference in the two results is due to the approximate crush force used in the Riera's calculations. In[40] argued that the reaction time response obtained on the basis of the rigid target assumption is not only unrealistic but also non-conservative in some cases. The sensitivity test by these authors refutes the common assumption that variation in crushing strength has very little effect on the reaction from the target. It was found here that both linear mass density and crushing strength are sensitive in affecting the reaction from the target, depending upon the characteristics of the missile and the target. Similar results was obtained by these authors in their later study[13].Therefore, it is undesirable to use load-time response obtained on the basis of rigid target assumption for this type of analysis. The results by[28, 38, 40] indicates that it is undesirable to use reaction-time response obtained on the basis of rigid target assumption as proposed by[29] for designing of NPP structure as is the usual practice. Conclusions drew by the authors of these references have triggered interest in knowing the actual relationship between crushing strength and reaction from the target. In[11] observed that the idea of rigid target is unrealistic and conservative; as the effect of the target yielding was found to be dependent upon the characteristics of the projectile and target structure. This is in contradiction to the observation made by[40]. They argued that the assumption of rigid target disregards stiffness and inertia of the target and can only be applied in cases that indicate no perforation and relatively small deformation. It was elaborated further that strain rate influenced the magnitude of deformation and local failure of the containment.

A notable experimental study on the aircraft impact was carried out by[41]. The results of their full-scale aircraft impact test and target response shows that (i) the existing Riera approach for load-time history, with slight modification, is a good way of estimating the impact loading (ii) the acceleration response versus time, crushing load versus time and impact force versus time curves for the test and simulation results agrees closely (iii) simulation test shows that the engines detached from the fuselage when their heads touched the target and then hits the target independently. This study confirmed an earlier claim by other researchers who hypothesized that the aircraft engine should be considered as independent projectile when performing crash analysis. The findings also strengthened the most recent study by[33, 1] as they demonstrated that Riera's load curve can provide a good estimate for aircraft dynamic impact studies. It was reported in the work of[13] that cracking strain of the reinforced concrete structure is the most important parameter which should be measured with precision in the response studies. In[11] reported that the highest damage area of the building was the area adjacent to center point of the plane-impacted area. The results of these researches shows the importance of material strain in limiting cracks and gives an insight on the locations that are vulnerable to collapse by the aircraft impact. We noted that degradation of material due to fire and effect of fireball were not considered in the analysis. We opined that similar analysis should be carried out on other reactor auxiliary.

The present authors acknowledged that penetrations, openings, and tendon gallery were not modeled in the analysis by[12, 40].We are in the opinion that smoke and fireball may enter through these openings which were not model in the analysis, and this may affect the outcome of the output data. Therefore, for fire and explosion safety considerations, reactor openings should be included in the analysis. We also observed that impact speed (100-200 m s^{-1}); interface area of 10-15% and assumption of rigid target that is commonly used in the previous studies may not represent the actual scenario for an aircraft impact on NPP structure. The impact speed of 100-200 m s^{-1} is below the landing speed for a deliberate attack into an important national structure as observed in September 11 event of World trade Centre and Pentagon. Impact speed here was estimated to be around 235 m s^{-1} and 293 m s^{-1} respectively. These speed exceeds the landing speed limits (<100 m s^{-1}) of a typical civilian airliner. Moreover, the assumption of rigid target disregard inertia and stiffness of target structure thereby target response to an impact loading cannot accurately be predicted.

As the reactor safety systems continue to grow in size and complexity, a new method of analysis is needed to produce reasonably more accurate risk estimates particularly from jet fuel. In[10] used the idea of boiling liquid expanding vapors explosion (BLEVE) to analyze the potential hazard of fuel fireball from a hypothetical commercial airliner on generic nuclear power plant using Fire Dynamic Simulator (FDS). Their FDS result was validated with BLEVEs experiment where 5.9 tons propane was burnt in the German BAM experiment. The validation shows a good agreement. Analysis of their modeling results showed that: (i) in the early phase of fire, the fireball is cool, rich in fuel and lean in oxygen and the highest temperature $\approx 2000^{o}C$ is reached after the fireball has risen above the NPP structure (ii) building structures have a strong effect on the fireball evolution and that local turbulence caused by obstacles may result in "hot spots". It was noted that the subsequent pool fire hazards from the crash is not considered here and is left as a task for feature work in the field. In the work of[26], it was shown that for an explosion overpressure received by the target structure due to aircraft crash, the failure points lie either within the lowest 10 m region or at top of the shell dome. The results further indicates that for an accurate prediction of damage to a reinforced concrete structure due to nearby external explosion, simultaneous measurement of ground shock and air-blast pressure time history parameters is necessary. On simultaneous application of air blast and ground shock, an increase of 5-20 MPa occurs as compared to that of air-blast only. The approach by this authors appears to be more accurate as it considered both pressure load and induced vibration on containment structure. It is however noted that the effects of jet fuel fires on structural components and safety related equipment (air baffles, ventilation systems and containment opening) were not addressed in this work.

The study by[11] on the local effect of aircraft engine revealed that a 1 m thickness of reinforced concrete wall is sufficient to prevent perforation. However, a recent article by[42] stated that a 2 m thickness of reactor vessel is needed to avoid perforation in the case of a larger commercial airliner like Boeing 747-400. The author highlighted that a research problem which remains unsolved is on the strong shaking of NPP structures which may affect the internal containment. In the author's later study, In[43] an attempt was made to address this problem. The author suggested a design which requires connecting critical parts of NPP structures to the foundation slab with restraints having an adequate degree of deformability; this will minimize the transmission of higher frequency impacts forces from other parts of the structure. The scenario in which the inner structure was decoupled from the same base foundation slab using seismic-isolators was found to be more effective in minimizing the shock waves intensity inside the isolated part of the inner containment. In another study by[44], it was demonstrated that the impact due to Boeing 747 class will cause penetration depth of about 1 m into the outer containment but the overall stability of the inner containment will be maintained. The sensitivity analysis also shows that if the outer containment is less than 1 m (minimum acceptable thickness by the IAEA), the impact from a large commercial airliner will lead to perforation of the outer containment with a significant debris from the collapsed region to hit the inner containment walls. This result does not agree closely with that of[34] but agrees closely to that of[42] who predicts about 2 m thickness as a requirement to prevent perforation by this type of aircraft impact.[8] demonstrated in their study that both mass of an aircraft and impact velocity have great effect on the containment reliability. In addition, the diameter of reinforcement and distance from the airport are directly related to the containment reliability. In a recent communication by[14], it was shown that the reactor containment could not withstand the crash impact of Boeing 767 and 747 airplanes owing to their higher momentum and speed used in the scenario. It was shown here that the containment structure suffered rupture around the impact region leading to global failure. The magnitude of stress in the reinforcement for 747 aircraft was found to be 940 MPa and 733 MPa for the inner and outer containment respectively. And local deformation of the concrete wall equal to 998 mm. However, it was demonstrated in the work of[45] that the double wall of outer containment and inner containment would be capable enough to sustain the full impulsive load of the two aircrafts. The current authors noted that reactor openings and vents were not modeled in these researches; fire or smoke can enter through such openings and may challenge safety shut-down. Moreover, properties of the concrete at intense fire temperatures were not taken into cognizant and the assessment considered only flexural behavior neglecting axial behavior.

In[9] used ABAQUS explicit finite element tool to assess fire resistance of a nuclear containment. The intensity, distribution and duration of the fire based on aircraft analysis and characteristics of jet fuel were considered. Fire resistance of the structure was assessed by comparing the fire-induced section forces with the section resistance using the load-moment strength interaction diagram. An analysis of the fire curve shows a very rapid elevation of temperature, up to 1100 °C. The predicted temperature is beyond the design temperature of nuclear power plant. It was shown in this work that, for more accurate and realistic assessment of fire resistance of containment, both axial force and bending moment should be accounted for, instead of considering only the bending moment in the conventional assessment. The authors predicted further that reinforced concrete sections of the postulated nuclear power plant structures will maintain the fire endurance time of over 3 h. A 3 h endurance time is quite sufficient to execute safety measures. The current authors noted that this study is limited only to containment and auxiliary building; detailed assessment of fire resistance on various parts of the structure (e.g. roofing, apex of the dome, dome-cylinder discontinuity zone) was not considered. Moreover, explosive spalling of concrete was not also evaluated.

The previous study by[11] indicates that 1 m reinforced concrete wall is sufficient to prevent perforation by the aircraft but[42] reports about 2 m wall's thickness. This means that additional 1 m thickness is required to prevent perforation, hence additional cost in design. We noted that the discrepancy in the two results may be due to difference in the scenario in which the two authors performed their analysis. As shown in the previous researches, the severity of the impact depends on factors such as mass of the plane, impact speed, and impact angle as well as impact position. Subsequent fire or explosion can also deteriorate the concrete structure depending on the fire intensity, distribution and duration. Target characteristics such as tendon pre-stressing and shape are also important factors that will determine the possibility of perforation. In a nutshell, the target response is strongly affected by the target and missile characteristics.

4.2 Advantages and Disadvantages of Aircraft Impact Modelling Techniques

Previous researches on the subject aircraft crash upon outer reactor containment had adopted various verified modelling techniques, each with their own strengths and weaknesses. Generally, it was observed that the modelling approaches discussed in the previous section follows one of the three reference analytical methods for evaluation of global structural damage such as energy balance, load–time history and missile–target interaction analysis. A brief capabilities and limitations of these modelling analysis are described in the IAEA document "External events excluding earthquakes in the design of nuclear power plant". For example, the load–time history method developed by[29], is widely applied in the analysis of dynamic structural behavior of the containment. This method uses the mass distribution, velocity and crush force of an aircraft to compute an equivalent impact load resulting from the crash impact[28]. The force-time history which derived from the missile and target characteristics is used to study the structural behavior. Though, Riera's method compared favorably to various modeling and an experimental technique on impact analysis, this technique is limited by the assumption of rigid target. So, application of this history to a flexible or elastic structure may not provide accurate results in terms of the structural capability, since accounting for target flexibility or plasticity may reduce the effective aircraft loading. Moreover, the idea of rigid target disregard stiffness and inertia of target structure which rendered the technique to be used only in cases that shows no perforation of structure and relatively minimal deformation. In addition, lack of sufficiently detailed data concerning mass distribution and crush force along the length of the aircraft may affects the use of this method. This limitation is also noted by[28, 30].

The energy balance method correlates the initial kinetic energy of the missile with the strain energy of the missile during impact and the kinetic and strain energy of the target during the impact. The method is good for the evaluation of overall behavior of the structural response and helpful for preliminary design considerations. However, detailed results such as time histories of motion for equipment evaluation cannot be produce with this method[17].

In the missile–target interaction analysis, a non-linear material behavior and the geometry of the projectile and target are modelled. The impact is defined by the initial velocity of the projectile and upon impact the behavior of the combined system is modelled in the time domain. The result of this analysis will provide the structural behavior of the target such as deformations and displacements, velocities and accelerations[17]. In all these modelling techniques, sensitivity studies is necessary to determine the level of consequences and the most sensitive parameters.

5. Lesson Learnt from the Study and Areas of Improvement

Figure 1 shows the number of publications on nuclear fire safety per five years based on keywords search in Scopus and Web of Science. The figure reveals that the number of scientific publications increased by 84% in the last 22 years (from 1993). The analysis considered 1968 and 2015 as the base and end years respectively. When carefully looked at the trend, the reader realized the significant of explosive incidents in NPP within 1993-1997 publications and from 2003 (2-years after September 11 attack) to date. Within the period 2003-2012 (10 years interval) only, there was 58% increase in the number of researches. This increase in the number of publications may be connected to the demand by the regulating bodies, WTC attack of September 11, 2001 and the Fukushima Diachii NPP accident of March, 2011.

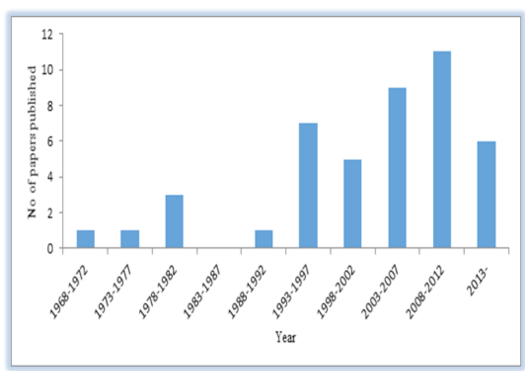

Figure 1. Number of publications on nuclear fire safety per 5 years (Source: from the Literature).

Within the period (1993-2015) a very large amount of knowledge have been gained and a wide range of technical issues concerning impact loading-history curve, dynamic structural response and development of various deterministic-based techniques for NPP fire assessment evolved. The current authors observed that there is limited experimental and real accidents data that can be directly referred to in assessing the fire resistance of nuclear power plant subject to a large aircraft crash or man-made explosive induced-fire. Majority of the researches dealt with the impact analysis based on the aircraft kinetic energy transferred and absorbed by the target containment. The possible aircraft fuel burning or explosions scenarios were not considered even though it spelled on IAEA policy on risk assessment practice. Fire and smoke from the crashing plane can enter through vents, openings and cable tunnel, and hence challenge safety redundant systems and safe reactor shut-down. The spilled oil or vapor may enter the building through normal openings and holes leading to subsequent fire and explosions. Furthermore, there are limited researches on the evaluation of fire hazards of fireballs due to close proximity blast. The most important parameters in the assessment of possible aircraft fuel hazards are explosion overpressure, positive-phase duration and flame speed. The consequence of accident involving large aircraft fuel should not be overlooked as the effect of explosion depends on so many factors.

5.1 Recommendations

The sections dealing with the assessment of aircraft impact in the safety guides are generally concerned with the evaluation of aircraft loading and fuel effects. For example, section 4.9 to 4.22 of the IAEA safety guide on "external initiating events excluding earthquake", dealt with evaluation of aircraft loading and section 2.23 is dealt with fuel effects. Analysis of the relevant literatures revealed the need for a more detailed analysis in the subject aircraft impact. The present authors recommend the followings:

(a) Some improvement need to be made on the previous studies[8–10, 12, 45] in establishing aircraft impact scenarios based on more realistic scenario, in obtaining nonlinear thermal stress (impulsive loading) and in evaluating fire endurance time. In the literature, tendon gallery, openings and penetrations were not modeled and crash was only considered to occur at the midpoint of the cylindrical portion and near the junction of dome without making recourse to the other portions (e.g. roofing and base). The current authors emphasize that auxiliary buildings should also be considered as the aircraft may hit positions other than reactor vessel. The inclined impact at the base of the containment may likely give the worst case scenario as the flame front can easily come in contact with structures and all openings.

(b) With the exemption of[9] other researches did not consider the material properties at elevated temperature. Degradation of materials (concrete, steel, and pre-stressing) properties at elevated temperature should be considered and the impact from larger airliners such as Antonov An-124 and An-225 should be assessed.

(c) There are very limited data on the assessment of external explosion caused by the aircraft falling on nuclear island. This assessment is necessary to ensure that the design strength of the containment and auxiliary buildings is capable to withstand the postulated overpressure (direct and drag) loading from the incident. The flame front and toxic gas may have serious adverse effects to the NPP operations.

(d) There are limited experimentally validated data on the aircraft crash upon reinforced concrete structure. Therefore, the use of conservative assumptions in the estimation of force due to aircraft impact on NPP structures left many questions unanswered which in turn affects the outcome of the analytical results.

(e) There are very limited literatures on the possible pool fires result from the aircraft accident and induced vibration or response of the containment.

(a) Studies on solid explosives induced fire on the NPP structures are very limited, possibly due to assumptions that external fire has a relatively short duration and does not have significant effect on the plant's components. However, structural failure modes caused by near-field explosive loading pose the necessity for this evaluation.

6. Conclusion

This paper reviewed the current literature on the aircraft impact upon reactor containment and presented the possible areas of future research on the subject matter. The authors presented the results of literature scrutiny on the impact loading assessment of NPP components that have been subjected to arbitrary aircraft crash and other possible external events. This review identified that there is the need to adopt a more systematic technique in evaluating fire resistance or fire endurance time for nuclear power plant structures in terms of external fire induced by aircraft crash or near-field terror attack with high profile explosives. The paper was able to observe that material properties at elevated temperatures have not been fully considered in impact analysis of reactor containment; attention was rather given to kinetic energy transferred and absorbed by the concrete target. It is also noted that there are no much emphasis on the hazards of jet fuel in the impact analysis involving aircraft crash on the NPP. The hazards from this should not be overlooked as the spilled fuel or vapor may enter the building through normal openings and holes leading to subsequent fire and explosions. Hence, there is a need to include these possibilities in future studies. There are very limited researches on solid explosives induced fires or explosions on the NPP structures. However, structural failure modes caused by near-field explosive loading pose the necessity for this evaluation.

An analysis of the number of publications on nuclear fire safety per five years based on keywords search in Scopus and Web of Science, revealed that the number of scientific publications (journal articles and conference papers) increased by 58% in the last 12 years (from 2003). The number of publications is expected to increase considerably by the end of 2017. The analysis considered 1968 and 2015 as the base and end years respectively. This considerable increase in the number of publications may be connected to the WTC attack of September 11, 2001 and the Fukushima Diachii NPP accident of March, 2011.

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