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IDENTIFICATION OF POTENTIAL FOR EXPLOSIONS IN NUCLEAR POWER PLANT

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ABSTRACT

Structures, systems and components (SSC) that are essential for the safe operation and shutdown of the nuclear power plant may be subject to a variety of loads. Examples of such loads are jet impingement, reactor vessel sub-compartment pressurization, pipe whip restraint reaction and blast pressure. Various United States Nuclear Regulatory Commission (USNRC) Regulatory Guides and Standard Review Plans specify required loads and provide acceptable methods for structural design. The design of concrete structures, subject to impulse and impact loads is governed by the ACI-349 Code. Acceptable analysis techniques vary from simplified quasi-static methods for single degree of freedom systems, to detailed computer analysis techniques accounting for material and geometric non-linearities.

The identification of potential for explosions is an ongoing process due to additions, modifications or other changes that are being implemented in operating Nuclear Power Plants. The purpose of this paper is to present an overview of the various impulsive loads e.g. accidental explosions, intentional explosions, jet impingement, pipe whip restraint action, tornado induced pressure drop. The limitations in the analysis and design procedures used to protect the safety related SSC's from the effect of these loads have also been investigated.

Keywords: explosions; ductility; nuclear power plants

1. INTRODUCTION

Nuclear power plant structures, systems and components may be subject to a variety of impulsive loads caused by accidental explosions and or high energy pipe ruptures. The United States Code of Federal Regulation 10CFR50, Appendix A provides General Design Criteria for the design of Nuclear Power Plant facilities. Criteria 2, 3 and 4, Design Basis for Protection against natural phenomena, Fire Protection and Environmental and missile design bases, require that the safety related SSC's be designed to withstand the effect of natural phenomena, fire, explosions and postulated accidents that may result from equipment failures and from events and conditions outside the nuclear power plant.

Impulsive loads caused by explosions and/or high energy pipe ruptures are one category of loads that require consideration. Explosions may occur due to a variety of reasons that need to be identified and for which the probability of occurrence may need to be quantified. In the United States, explosions that have a probability of occurring of less than 10^{-7} per year do not need to be considered in the design(O'Brien, 1977). Several U.S. Nuclear Regulatory Commission Standard Review Plans and Regulatory Guides e.g RG 1.147 (2003) , DG-1122 (2002) etc specify loads and provide acceptable methods for analysis and design of the safety related SSC's.

The identification of potential for explosions is an ongoing process due to additions, modifications or other changes that are being implemented in operating Nuclear Power Plants. (Kennedy,1986). The purpose of this paper is to present an overview of the impulsive loads and the analysis and design procedures used to protect the safety related SSC's from the effect of these loads.

2. IMPULSIVE LOADS

In consideration of impulsive loads in the design of safety related structures, the following load types are discussed:

- Accidental Explosions
- Intentional Explosions
- Jet Impingement
- Pipe Whip Restrain Action
- Tornado Induced Pressure Drop

Each of these load types, as well as characteristics of each type, is discussed in the following sections.

2.1 ACCIDENTAL EXPLOSIONS

A possible source of an accidental explosion is the release of explosive liquefied gas from off site storage tanks during transport or land storage. The released gas when combined with air forms a vapor could which can be ignited, resulting in a deflagration or an explosion. Examples of explosive gases include the hydrocarbon gases such as Ethylene, Ethylene oxide, methane, butane, ethane, propane and propylene. The transportation mode may be gas tankers for sea or inland waterway traffic, railway tank cars, tank trucks, or pipe lines. The gases may also be stored in storage areas of the industrial complexes close to the nuclear plant facilities.

The explosion of vapor clouds can evolve in the form of deflagration waves with a limited over-pressure. A deflagration with its slow burning speed is characterized by a pressure pulse with relatively long duration and low amplitude. In the deflagration process, turbulent flame acceleration also may lead to a blast type pressure pulse. There is also a possibility that under adverse circumstances a detonation rather than a deflagration could occur (Geiger, 1977) that generates substantial pressure shock wave. A detonation causes a blast wave with sudden pressure rise and high peak value but short duration. Several studies have been done on the characteristics of the vapor cloud explosion of various concentrations with different ignition sources (Drenckhan,1981, Widerman,1981,Hendricks,1983) ,. Most studies conclude that the concentrated hydrocarbons in a free cloud deflagrative ignition will not result in a detonation.

The storage and transportation of other high explosive dangerous, material such as dynamite and other munitions close to a Nuclear Power Plant is a concern and has been the subject of various studies (Gobert, 1981). Studies on the accumulation and burning of hydrogen for long period of time in the Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) containments during a postulated core melt accident scenario (Bracht, 1983) show that there is potential for a hydrogen detonation condition for small containments.

Such detonation is likely to cause pressure waves with maximum pressure several times design levels. The hydrogen detonation is not presently postulated in the design of containments. To minimize the risk of hydrogen detonation, the characteristically smaller BWR containments are inerted during plant operation, by replacing the atmosphere with a mixture of nitrogen.

BWR plants have storage facilities for hydrogen and oxygen in the gas or liquid states. Hydrogen is used to prevent the corrosion of stainless steel piping in BWR's. Addition of hydrogen into the feedwater piping reduces the aggressiveness of water toward the piping material. Oxygen is injected into the condensate and feedwater systems to regulate reactor feedwater-dissolved oxygen and to minimize corrosion of the carbon steel in the condensate and feedwater system components. The rupture of storage vessels or tanks containing gaseous of liquid hydrogen results in a turbulent release of the gas that leads to hydrogen explosion with blast waves propagating outward from the vessel or tank rupture site (Kennedy, 1986). Accidental rupture of other pressurized vessels inside the containment structure and other safety related structures, causes-compartment pressurization that is considered in the design of the safety related structures, systems and components.

2.2 INTENTIONAL EXPLOSIONS

Although the U.S. Regulation does not require consideration of explosions due to terrorist attack and other act of war in the design of Nuclear Power Plant structures, other countries postulate and consider such explosions (Peretz, 1983, Kivity, 1981). Studies have been performed for the event when a penetrating warhead is detonated inside containment. Also a pressure wave in the form of blast loading is prescribed by various codes to postulate the detonation of explosives close to the Nuclear Power Plant structure. The blast loading is supposed to envelop the intentional and accidental explosions in the vicinity of the power plants. The air blast phenomenon is characterized by an air pressure time variation with an instantaneous rise time to a maximum pressure, followed by a decline to sub-atmospheric pressure, then a gradual return to the normal atmospheric pressure. The below atmospheric pressure portion (the negative phase), is less important than the above atmospheric (the positive phase), and is neglected for design. The postulated blast loads are idealized forcing functions with a rapid rise in pressure, a small drop and then a constant pressure for a short duration.

2.3 JET IMPINGEMENT

Jets resulting from a postulated rupture of high pressure piping exert an impulsive load on the affected area. The ruptured pipe may contain steam water mixture, steam or sub cooled water. (Mohammadadian, S., L. Sleger 1983, ASCE Manual 58, 1980). Studies have been performed to quantify the impulse load considering the flow divergence between the point of discharge and the point of impact. The USNRC Standard Review Plan (SRP) 3.6.2, gives guidelines for determination of the forcing function of the jet thrust and jet impingement. The impulse load due to jet impingement is localized to the affected area.

2.4 PIPE WHIP RESTRAINT REACTION

Postulated breaks in high energy piping which result in the escape of fluid or gas from the pipe will induce motion to the pipe. The “whipping” pipe may impact other pipes and/or other SSC’s. Impulsive forces are developed at the anchor or restraining of the whipping pipe during impact or rebound. Also the momentum of the escaping fluid or gas from the pipe induces impulsive forces at the pipe restraints. Standard Review Plan 3.6.2 provides guidelines for calculation of impulsive loads due to pipe break. The pipe whip anchor/restraint reactions are localized loads.

2.5 TORNADO INDUCED PRESSURE DROP

The tornado loads, postulated for design of safety related SSC, consist of a sustained pressure due to rotational and translational wind speed and the tornado generated missiles. In addition, the effect of the pressure drop when the lower pressure center of the tornado passes over a building , is considered in the design. The forcing function of the pressure drop is of a transient type with the pressure dropping up to 3 psi (depending on tornado intensity region in US) in 1.5 seconds and then going back to the normal pressure in 1.5 seconds. The total duration of the forcing function is 3 seconds which is relatively large compared to the impulse loads due to blast loads. Other forcing functions with durations of 8 seconds are also used.

Considering that most of the safety related buildings are normally constructed of reinforced concrete with natural frequencies higher than 8 cps, and the long duration of the tornado pressure drop forcing function, the maximum pressure drop is normally applied to the non-vented structure without any dynamic load factors. However, for buildings with lower frequencies, the tornado pressure drop is treated the same as other impulse loading. For vented structures, the tornado pressure drop forcing function is used to calculate the maximum pressure difference between various compartments of the building considering the area of the openings in the building.

3. EFFECT OF IMPULSIVE LOADS ON SAFETY RELATED STRUCTURES

Safety related systems and components are normally protected from the potential impulsive loads by barriers. As a result, the effect of impulsive loads on the safety related structural elements such as beams, slabs and walls which act as barriers has been the subject of various experimental and theoretical studies (Salomoni(2003), Saeed & Javed (2003) Widerman, 1981, Stangenberg, 1981, Amman, 1981,Reynen ,1981, Florence, 1977, Turula, 1977, Kot, 1977)). In addition, the effect of impulsive loads due to explosions on the containment structure has been studied (Cybulskis, 1981, Brcht, 1983,). These studies deal with the determination of the forcing function in the vicinity of the structures and the response of the structures to the applied load.

The impulsive loads have a local and global effect on the structural elements. The local effect such as spalling or flaking of concrete surface due to jet impingement or scabbing (spalling of back face) of the concrete due to blast loading, normally do not impair the structural integrity of elements. Scabbing is caused by the free surface reflection of the shock wave induced in the wall by high pressure blast and occurs whenever the dynamic tensile rupture strength is exceeded. The effect of scabbing on the design of other safety related SSC should be considered, or the structural elements subjected to the blast load should be designed to prevent scabbing .

The global effect is the overall deformation of the structural element due to the impulsive load which induces bending moments, shear and in plane forces. The structural element is normally designed to absorb the applied energy by Plastic deformation. In addition the overturning, sliding of the structure, and propagating of the blast wave through the structure, are all global effects of the impulsive loads that are considered in the design.

4. ANALYSIS AND DESIGN APPROACH

The approaches commonly used to design safety related structures, systems or components in Nuclear Power Plants against the effects of impulsive loads are:

- Duplication
- Protection
- Separation
- Strength

A combination of those approaches is often utilized. Each of these approaches is briefly described in the following paragraphs.

4.1 Duplication

In this approach, redundant systems are designed such that the failure of one system will not affect the safe operation of the other. For example, impulse loads due to jet impingement may damage or destroy a sensitive piece of equipment but will not affect the safety of the plant due to the existence of a redundant component. This method is used for design of safety related components are systems.

4.2 Protection

In this approach the SSC's are protected from the effect of the impulsive load by a strong barrier. The barrier, which may be of thick steel plates or thick concrete elements, absorbs the forces of the impulse with limited or no damage. An example of this approach is when a piece of equipment is placed in a bunker or hardened compartment. Systems that have a potential for generating impulsive loads are located outside of the barrier. This approach is used for design of many safety related components and systems. The barriers are designed using the strength methods.

4.3 Separation

The principle in the separation approach is to assure that the man made hazards that have the potential of generating impulsive loads are kept far from the safety related SSC's. the separation is calculated to either reduce the effect of the impulsive load on the SSC's to values comparable to other loads that the SSC's are designed to withstand or to reduce the effect to nominal forces that can be neglected. An example of such an approach is locating the safety related structures far enough from the railway, highway or navigable waterway such that any explosion that might occur on these transportation routes does not have any adverse effect on plant operation or prevent the plant to achieve a safe shutdown if required. U.S. Regulatory Guide 1.91 provides safe distances for the carriers that transport explosives depending on the TNT equivalent of the explosive material on board.

No further consideration need to be given to the effect of blast in plant design if the distances given in this Reg. Guide are complied with. Otherwise, it should either be shown that the probability of explosion is very low (less than 10^{-7} per year) or the critical plant structures are strong enough to withstand the impulsive loads from the explosion. Studies have been performed (Held, 1981, Lannoy, 1977), to determine the TNT equivalent of explosive materials.

The separation approach is also used in locating storage facilities that have a potential for explosion. The distance of the storage facilities from the safety related structures is calculated as a function of vessel size in the storage facility. Design graphs have been generated that show the required separation from a typical nuclear power plant building wall which is designed to resist other loads, such as tornado pressure and seismic loads. The building wall is checked for the effect of the impulsive load due to explosion at the storage facility. For example, Kennedy, (1986) and EPRI NP-5283-SR-A (1987) provide such design graphs for liquid hydrogen storage tank for various explosion scenarios and wall thicknesses. The walls (structural elements) are checked and/or designed for the effect of the explosion using the strength methods described above.

4.4 Strength

In the strength approach, the structural elements (walls, slabs, columns, barriers, doors etc.) are designed to withstand the impulsive loads. The analysis and design of structural elements of impulsive loads is similar to the design for loads due to impact. While it may be possible to design the elements on an elastic basis using allowable stresses specified in codes, the severe local nature of these loads can make such design very costly. The structural elements are allowed to deform beyond the elastic limit as long as the localized plastic deformation is controlled and the overall integrity of the structure is not impaired.

The limits applied to plastic deformation are specified in terms of allowable ductility ratios which is defined as the maximum permissible deflection to the deflection at effective yield of the structural system. The approach is acceptable to the USNRC for all impulsive loads except the tornado pressure drop which is not classified as an impulsive load. The allowable ductility ratios for flexure, compression, tension and shear as applicable to concrete and steel structures are given in Appendix A to the Standard Review Plan (SRP) 3.5.3 and Regulatory Guide (RG) 1.142. ACI 349-90 provide allowable ductility ratios which are more liberal than the SRP 3.5.3 but are widely used and in certain applications, may be acceptable to the NRC if justified. Pfortner (1977) & Held (1981) also provide requirements, guidelines and procedures for analysis and design of structural elements subjected to impulsive loads.

The conventional analysis technique is based on an idealization of the impulse load time history to a simple mathematical form, and the structure is simplified to a single degree of freedom system with idealized material behavior. Based on these assumptions a set of graphs is generated that relate the ductility, dynamic load factor and the ratio of the impulse load duration to the structure period. The graphs are used to calculate the design force for the structure based on the allowable ductility ratios.

For cases where the simplifying assumptions described above are not accurate or lead to uneconomical design, more complex techniques based on finite element or finite difference analysis are used. These methods, which can account for material and geometric non-linearities are also used when time-history and/or response spectra at selected locations in the building are required. The response spectra are required for the design and qualification of sensitive and/or safety released equipment found in Nuclear Power Plants.

CONCLUSIONS

This paper presented a brief summary of the impulsive loads which must be considered in the design of safety related structures, systems and components in Nuclear Power Plants Facilities. The source of the impulsive loads, its effect on safety related structures and a brief description of the analysis and design approaches used have been presented. References at the end of the paper will provide a source for additional technical information.

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