U.S. REGULATORY REQUIREMENTS FOR BLAST EFFECTS FROM ACCIDENTAL EXPLOSIONS

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SUMMARY

This paper is limited to accidental explosions external to nuclear power plants. Procedures for deciding if the risk of damage due to an accidental explosion is sufficiently high to warrant detailed study and methods for assessing structural capability when detailed study is needed are described.

In the United States, accidental explosions are excluded from the design basis for nuclear power plants if the likelihood of occurrence is less than 10^{-7} per year. Accidents which produce blast overpressures less than 1.0 psi are also excluded from the design basis. Regulatory judgment is that, because nuclear power plants must be designed for certain prescribed extreme environmental conditions such as tornadoes and earthquakes, and abnormal load occurrences such as the loss of coolant accident, U.S. nuclear power plants have an inherent strength to resist blast overpressures of at least 1.0 psi. Effects of accidental explosions include blast generated overpressure, wind, missiles and ground shock. Dynamic drag pressure due to wind will ordinarily be negligibly small when compared to overpressure at accident conditions having probabilities greater than 10^{-7} per year.

Missile hazards from accidental explosions will normally be less threatening than tornado generated missiles at the overpressure levels likely to occur and, as a result, are commonly ignored. Ground shock from accidental explosions of the type considered are usually slight when compared to earthquake motions except for high frequency content. However, the high frequency content is not readily transmitted through the relatively low frequency structures, systems and components and consequently, apart from equipment mounted directly to foundations, ground shock is not significant. Thus overpressure tends to dominate the safety evaluation of nuclear power plants subjected to accidental explosions.

The dynamic blast load effect may be estimated by a simplified static procedure. The regulatory staff permits use of a dynamic load factor of 2 applied to the overpressure or reflected pressure, as appropriate, and the assumption that structures and structural elements will deform dynamically as though the loads were applied statically. This assumption allows the designer to compute stresses, moments and shears without reference to the distribution of inertial forces within the structure. Blast pressure should be considered to act both inward and outward to account for dynamic stress reversal. Overturning and sliding stability as well as the ability of supporting structures to carry loads transmitted from the directly loaded exterior surfaces must be assessed. A detailed dynamic analysis in which force-time histories and the stiffness and mass properties of the structures are employed is also acceptable. Damping is not important for air blast effects. The regulatory staff requires that blast effects be resisted elastically. This is consistent with regulatory philosophy that global loading situations should not be permitted to cause global damage. Appendix C to ACI-349, "Code Requirements for Nuclear Safety Related Concrete Structures", in conflict with regulatory requirements, permits a ductility of 3 for blast loadings.

1. SCOPE

General Design Criterion 3 of Appendix A to Title 10, United States Code of federal Regulations, Part 50, requires that "Structures, systems and components [of nuclear power units] important to safety shall be designed and located to minimize ... the effects of fires and explosions". General Design Criterion 4 states further "... structures, systems and components shall be appropriately protected against dynamic effects... from events and conditions outside the nuclear power unit". On the other hand, 10 CFR 50.13 states "an applicant... is not required to provide design features... for protection against the effects of attacks and destructive acts, including sabotage, ... by an enemy of the United States...". This paper is limited, according to the intent of 10 CFR, Part 50, to accidental explosions external to nuclear power plants. A good majority of such explosions will occur along routes transporting hazardous materials, including highways, railways and waterways. Pipeline and aircraft accidental explosions can also threaten the safety of nuclear power plants; however, risk assessment from these latter causes are treated somewhat differently than the former causes.

This paper treats procedures for deciding if the risk of damage due to an accidental explosion is sufficiently high to warrant detailed study, and in addition describes methods for assessing structural capability when detailed study is required.

2. CRITERIA FOR INCLUDING ACCIDENTAL EXPLOSIONS IN THE DESIGN BASIS

The concept of design basis is employed in the construction of nuclear power units in the United States [1]. In this procedure, operating, accidental and environmental loading conditions are combined in a prescribed manner using specific load factors and design allowables to arrive at a plant design safe against reasonably foreseeable events likely to threaten the nuclear power unit. Certain environmental conditions, such as tornadoes and earthquakes, and certain abnormal occurrences, such as high-energy pipe breaks, are presently included in the design basis of all US nuclear power units. Other environmental and accident conditions, such as aircraft impact, turbine missile impact, flood and accidental explosions are included in the design bases on an ad hoc basis, depending primarily on the likelihood of occurrence. In the United States, significant accidental explosions are excluded from the design basis for nuclear power plants if the probability of occurrence is less than about 10^{-7} per year.

Overpressure levels less than 1.0 psi are regarded as insignificant. Estimates of the probability of an accidental explosion causing significant effect due to the transport of a specific hazardous material along a transportation route may be made from the equation

$$p = nfs \qquad (1)$$

where

p = annual probability of an explosion causing significant effect from a specific hazardous material shipped along a generic transportation route.

n = number of explosions per mile of the specific material along the generic transportation route, based on historical records.

f = frequency of shipment for the hazardous material, in shipments per year.

s = length of transportation route where an explosion could occur and cause significant effects at the nuclear power unit, that is, cause an overpressure greater than 1.0 psi.

In determining the distance s, the maximum probable weight of hazardous cargo is conservatively used. Reference [2] shows that the distance R, in feet, at which an overpressure of 1.0 psi will be produced from a weight W, in pounds, of TNT is given by

$$R = 45W^{1/3} \tag{2}$$

For explosives other than TNT, the TNT equivalent is used. The length s is therefore the length of transportation route located within a distance R from the nuclear power unit perimeter, using for W the maximum probable weight of hazardous cargo appropriate to the transportation route in question. Mean values, rather than more conservative estimates, may be used for n and f.

When several hazardous materials are carried along transportation routes near a nuclear power unit the <u>sum</u> of all probabilities must be less than about 10^{-7} per year in order to exclude accidental explosions from the design basis. If the sum of all probabilities is greater than about 10^{-7} per year, the postulated design basis accidental explosion is located to maximize its effect on the nuclear power unit and the maximum probable weight of hazardous cargo is employed in the safety evaluation. It follows from this procedure that if no transportation route passes within the distance R from the plant perimeter then accidental explosions may be excluded from the design basis.

The selection of a 1.0 psi blast overpressure as the beginning of significant effects is based on U.S. regulatory judgment that, because nuclear power plants must be designed for prescribed extreme environmental conditions such as tornadoes and earthquakes, U.S. nuclear power units have an inherent strength to resist blast overpressures of at least 1.0 psi. Test evidence can be presented to demonstrate that damage to unreinforced concrete buildings begins at about 1.0 psi overpressure and that conventionally reinforced concrete buildings can withstand at least a few psi overpressure [3, 4]. In summary then, only nuclear power units for which the likelihood of an accidental explosion (having an expected overpressure greater than 1.0 psi) exceeds about 10^{-7} per year must include blast effects in the design basis. Probabilities of explosions from aircraft collisions and pipeline ruptures are handled, at present, on a case-by-case basis. A major difficulty with evaluating accidental explosions from these sources is estimating the overpressure levels and other blast parameters needed for structural evaluation.

3. <u>EXPLOSIVE EFFECTS</u>

Effects of accidental explosions include blast-generated overpressure, wind, missiles and ground shock. Dynamic drag pressure due to wind will ordinarily be negligibly small when compared to overpressure at accident conditions having probabilities greater than 10^{-7} per year. This results because peak overpressure levels seldom exceed a few to several psi. At overpressure conditions of 1.0 psi, the probability of any missile impact is generally negligible and, as a result, missiles are commonly ignored. Where explosion generated missiles must be considered it is required that essential systems susceptible to missile damage be protected by metal barriers which will stop the missile or by concrete barriers which do not scab. In virtually every case, however, tornado borne missiles postulated to occur in the design basis of every nuclear power unit impose more severe barrier design requirements and tend to govern the design.

Ground shock from accidental explosions of the type considered are usually slight when compared to earthquake motions, except for high frequency content. However, the high frequency content is not readily transmitted through the relatively low frequency structures and consequently, apart from equipment mounted directly to foundations, ground shock is not significant.

Thus overpressure tends to dominate the safety evaluation of nuclear power units subject to accidental explosions. It is not appropriate to use nuclear weapons scaled distance relations to describe the effects of high explosive detonations. Specific high explosive data correlations, as for example, that presented in reference [2], should be used. Moreover, unless justification can be provided for assuming otherwise, it is necessary to postulate a surface burst rather than a free air burst.

4. METHODS OF STRUCTURAL ANALYSIS

Analyses for the effects of accidental explosions focus on overpressure loadings with the tacit recognition that on very rare occasions it may be necessary to investigate missiles, ground shock and dynamic drag pressure. The loading combination required by the US Regulatory Staff is:

$$C = D + L + T_o + R_o + B \tag{3}$$

in which

C = combined load effect

D = dead load effect

L = live load effect

T_o = thermal load effect during normal operating or shutdown conditions

R_o = pipe reaction effect during normal operating or shutdown conditions

B = blast load effect, with the explosion positioned to maximize the load combination for the structural element under consideration.

For a large number of structural elements affected by blast loadings T_o and R_o will not be significant.

The dynamic blast load effect, B, may be estimated by a simplified static procedure. An acceptable simplified and conservative static procedure for verifying the adequacy of non-vented structures and structural elements to air blast loading utilizes a dynamic load factor of 2 and the assumption that the structure or structural element will deform dynamically as though the loads were applied statically. This assumption allows the designer to compute stresses, moments and shears within the structure by the principles of statics without reference to the distribution of inertial forces in the structure. In this procedure the peak reflected pressure is multiplied by 2 to obtain the equivalent static pressure on all surfaces which can receive an incident blast wave. If the surface is oriented in such a way that it can not be struck by an incident blast wave, or if the angle of incidence is more than about 85°, then the equivalent static pressure is set equal to twice the peak overpressure. The equivalent static pressure so obtained should be considered as acting both inward and outward. Local and overall forces on both flat and curved surfaces are conservatively obtained by multiplying the equivalent static pressure by the full projected area of the structure or structural element. Justification for reducing the equivalent static pressure on curved surfaces are considered on an ad hoc basis. The maximum equivalent static base shear and overturning moment should be computed by considering that only the blast side of the structure is loaded with the equivalent static pressure. For vented structures, in which the blast wave is permitted to enter into the structure, no reduction in equivalent static pressures should be allowed in the simplified static procedure.

In lieu of the simplified static procedure, a detailed dynamic analysis in which force-time histories and the stiffness and mass properties of the structures and components are employed is acceptable to the Regulatory staff. The dynamic model may be the same as that used for seismic analysis. Dynamic models with fewer degrees-of-freedom may also be used if it can be shown that these models adequately describe response to air blast loads. Damping will ordinarily not play as significant a roll in air blast response as in seismic response because of the relatively short duration of the air blast loads.

Reference [5] furnishes suitable methods for computing external blast loads on structures. These procedures and methods are required to determine average side and roof loading, average back face loadings, net horizontal loading and average front face loadings as functions of time.

The regulatory staff requires that blast effects be resisted elastically. This is consistent with regulatory philosophy that global loading situations should not be permitted to cause global damage. The proposed Appendix C to ACI-349, "Code Requirements for Nuclear Safety Related Concrete Structures", permits a ductility ratio of 3 for blast loadings. The ACI requirement reflects a less conservative opinion on the level of safety that should be provided.

5. REFERENCES

[1] Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants, NUREG-75/087 LWR Edition, September 1975, US Nuclear Regulatory Commission, Section 3.8.

[2] Structures to Resist the Effects of Accidental Explosions, Department of the Army Technical Manual TM5-1300, June 1969.

[3] The Effects of Nuclear Weapons, US Atomic Energy Commission, 1962.

[4] STREHLOW, R. A.,BAKER, W., Characterization and Evaluation of Accidental Explosions, NASA Report CR-134779, June 1975.

[5] BIGGS, J. M., Introduction to Structural Dynamics, McGraw-Hill, Inc., 1964.