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U.S. NUCLEAR REGULATORY COMMISSION

REGULATORY GUIDE

OFFICE OF STANDARDS DEVELOPMENT

REGULATORY GUIDE 1.91
EVALUATIONS OF EXPLOSIONS POSTULATED TO OCCUR ON TRANSPORTATION ROUTES NEAR NUCLEAR POWER PLANTS

A. INTRODUCTION

General Design Criterion 4, "Environmental and Missile Design Basis," of Appendix A, "General Design Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Licensing of Production and Utilization Facilities," requires that nuclear power plant structures, systems, and components important to safety be appropriately protected against dynamic effects resulting from equipment failures that may occur within the nuclear power plant as well as events and conditions that may occur outside the nuclear power plant. These latter events include the effects of explosion of hazardous materials that may be carried on nearby transportation routes. This guide describes methods acceptable to the NRC staff for determining whether the risk of damage due to an explosion on a nearby transportation route is sufficiently high to warrant a detailed investigation. Acceptable methods for evaluating structural adequacy when an investigation is warranted are also described. This guide is limited to solid explosives and hydrocarbons liquified under pressure and is not applicable to cryogenically liquified hydrocarbons, e.g., LNG. It considers the effects of airblasts on highway, rail, and water routes but excludes pipelines and fixed facilities.

B. DISCUSSION

In order to meet General Design Criterion 2, "Design Basis for Protection Against Natural Phenomena," of Appendix A to 10 CFR Part 50 with respect to tornadoes, the structures, systems, and components important to safety of a nuclear power plant must be designed to withstand the effects of a design basis tornado, including wind, pressure drop, and the effects of missiles, without causing an accident and without damage that would prevent a safe and orderly shutdown. In addition, those structures, systems, and components must be designed to accommodate the vibratory ground motion associated with the Safe Shutdown Earthquake.

The effects of explosives that are of concern in analyzing structural response to blast are incident or reflected pressure (overpressure), dynamic (drag) pressure, blast-induced ground motion, and blast-generated missiles. It is the judgment of the NRC staff that, for explosions of the magnitude considered in this guide and the structures, systems, and components that must be protected, overpressure effects are controlling. Drag pressure effects will be much smaller than those due to the wind loading assumed for the design basis tornado. The effects of blast-generated missiles will be less than those associated with the blast overpressure levels considered in this guide. If the overpressure criteria of this guide are exceeded, the effects of missiles must be considered. The effects of blast-induced ground motion at the overpressure levels considered in this guide will be less than those of the vibratory ground motion associated with the Safe Shutdown Earthquake.

This regulatory guide describes a method for determining distances from critical plant structures to a railway, highway, or navigable waterway beyond which any explosion that might occur on these transportation routes is not likely to have an adverse effect on plant operation or to prevent a safe shutdown. Under these conditions, a detailed review of the transport of explosives on these transportation routes would not be required.

A method for establishing the distances referred to above can be based on a level of peak positive incident overpressure (designated as P_{so} in Ref. 1) below which no significant damage would be expected. It is

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Comments and suggestions for improvements in these guides are encouraged at all times, and guides will be revised, as appropriate, to accommodate comments and to reflect new information or experience. However, comments on this guide, if received within about two months after its issuance, will be particularly useful in evaluating the need for an early revision.

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the judgment of the NRC staff that, for the structures, systems, and components of concern, this level can be conservatively chosen at 1 psi (approximately 7 kPa). Based on experimental data on hemispherical charges of TNT cited in Reference 1, a safe distance can then be conservatively defined by the relationship

$$R \geqslant kW^{1/3} \tag{1}$$

where R is the distance in feet from an exploding charge of W pounds of TNT. When R is in feet and W in pounds, k = 45. When R is in meters and W in kilograms, k = 18.

The concept of TNT equivalence, i.e., finding the mass of substance in question that will produce the same blast effect as a unit mass of TNT, has long been used in establishing safe separation distances for solid explosives. A test program is required to establish that equivalence (Ref. 2). For solid substances more efficient in producing blast effects than TNT, equivalents are known by the manufacturers. For solid substances not intended for use as explosives but subject to accidental detonation, it is conservative to use a TNT equivalence of one in establishing safe standoff distances, i.e., use the cargo mass in Equation (1).

Application of the TNT equivalence concept to possible detonations of vapor clouds formed after an accidental release of hydrocarbons is not as well documented. However, investigations of accidents that resulted in blast damage have used this concept in attempts to estimate, based on blast damage, the effective yield of the explosion (Ref. 3). Most assessments of this type have led to estimates that less than one percent of the calorific energy of the substance was released in blast effects. Since the ratios of heat of combustion of hydrocarbons to that of TNT are typically about 10, this corresponds to an equivalence on a mass basis of 10 percent. However, there have been accidents in which estimates of the calorific energy released were as high as 10 percent. The blast energy realized depends, in great measure, on phenomena that are accident specific, i.e., the rate of release of the substance and the way in which the cloud is ignited. A reasonable upper bound to the blast energy potentially available based on experimental detonations of confined vapor clouds is a mass equivalence of 240 percent (Ref. 4). A detailed analysis of possible accident scenarios for particular sites, including consideration of the actual cargo, site topography, and prevailing meteorological conditions may justify a lower effective yield. But, when establishing safe stand-off distances independent of site conditions, use of an upper bound is prudent.

Determination of the maximum probable quantity of hazardous cargo is dependent on both the transportation mode and the vehicles utilized. The maximum probable hazardous solid cargo for a single highway truck is 50,000 pounds (23,000 kg). Similarly, the maximum explosive cargo in a single railroad box car is approximately 132,000 pounds (60,000 kg). The largest probable quantity of explosive material transported by ship is approximately 10,000,000 pounds (4,500,000 kg). For illustrative purposes, the safe distances, as defined by inequality (1), are shown in Figure 1 for these quantities of TNT. When shipments are made in connected vehicles such as railroad cars or barge trains, an investigation of the possibility of explosion of the contents of more than one vehicle is necessary.

In cases where the distances from the transportation route to the structures, systems, and components that must be protected are not sufficiently great to allow a conclusion (based on conservative assumptions) that the peak positive incident overpressure would be less than 1 psi (approximately 7 kPa), an analysis of the frequency of hazardous cargo shipment may show that the attendant risk is sufficiently low. It is the judgment of the NRC staff that, if the exposure rate, r, defined in Equation (2) can be shown to be less than 10^{-7} per year, the risk of damage due to explosions is sufficiently low.

$$r = nfs \tag{2}$$

where r = exposure rate,

n = explosion rate for the substance and transportation mode in question in explosions per mile,

f = frequency of shipment for the substance in question in shipments per year, and

s = exposure distance in miles (see Figure 2).

If the substance in question is shipped on more than one transportation mode near the plant, exposure rates calculated for the modes should be summed.

If an adequate data base for estimating the explosion rate for a substance is lacking, an estimate can be made by utilizing nationwide statistics for the particular transportation mode, i.e.,

$$n = n_1 n_2 \tag{3}$$

where n_1 = accidents per mile for the transportation mode, and

n_2 = cargo explosions per accident for the transportation mode.

Because of the low frequency of occurrence of the events under consideration, estimates based on average frequency may have wide confidence bands, and conservative estimates may be preferred. If estimates of explosion rate, frequency of shipment, and exposure distance are made on a realistic or best estimate basis, an exposure rate less than 10^{-7} per year is sufficiently low. If conservative estimates are used, an exposure rate less than 10^{-6} per year is sufficiently low.

If it cannot be shown that the distance to the transportation route is great enough or that the exposure rate is low enough to render sufficiently low the risk of damage to a structure housing a system or component that must be protected, an analysis of the blast load effects may be made. The loading combination to be considered may be limited to:

$$C = D + L + T_0 + R_0 + B \qquad (4)$$

where
- C = combined load effect,
- D = dead load effect,
- L = live load effect (not including wind or snow loads),
- T_0 = thermal load effect during normal operating or shutdown conditions,
- R_0 = pipe reaction effect during normal operating or shutdown conditions, and
- B = blast load effect, with the explosion source positioned to maximize the load combination for the structural element under consideration. Only the incident (or, if appropriate, reflected) pressure loading need be considered.

Either a static analysis using twice the appropriate pressure loading or an elastic analysis using dynamic load factors (Ref. 5) is acceptable for computing blast load effects. The blast pressure should be considered to act both inward and outward in order 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.

C. REGULATORY POSITION

In the design of nuclear power plants, the ability to withstand the possible effects of explosions occurring on nearby transportation routes should be considered. The following methods are acceptable to the NRC staff for ensuring that the risk of damage due to an explosion on a nearby transportation route is sufficiently low.

1. When carriers that transport explosives can approach vital structures of a nuclear facility no closer than the distances computed using Figure 1, no further consideration need be given to the effects of blast in plant design. In calculating TNT equivalents, assumptions of 100 percent TNT (mass) equivalence for solid energetic materials and 240 percent TNT (mass) equivalence for substances subject to vapor phase explosions are acceptable upper bounds when effective yields generated from test data do not exist. Lower effective yields may be justified by analyses accounting for reaction kinetics, site topography, and prevailing meteorological conditions when the hazardous cargos can be identified.

2. If transportation routes are closer to structures and systems important to safety than the distances computed using Figure 1, the applicant may show that the risk is acceptably low on the basis of low probability of explosions. A demonstration that the rate of exposure to a peak positive incident overpressure in excess of 1 psi (7 kPa) is less than 10^{-6} per year, when based on conservative assumptions, or 10^{-7} per year, when based on realistic assumptions, is acceptable. Due consideration should be given to the comparability of conditions on the route to those of the accident data base.

3. If transportation routes are closer to structures and systems important to safety than the distances computed using Figure 1, the applicant may show that the risk to the public is acceptably low on the basis of capability of the safety-related structures to withstand blast and missile effects associated with detonation of the hazardous cargo. In assessing the capacity of structures to resist blast loads, a simplified quasi-static analysis of blast effects using the load combination of Equation (4) is acceptable. Effective yields based on analyses accounting for reaction kinetics, site topography, and prevailing meteorological conditions can be used when justified.

D. IMPLEMENTATION

The purpose of this section is to provide guidance to applicants and licensees regarding the NRC staff's plans for utilizing this regulatory guide.

Except in those cases in which the applicant proposes an alternative method for complying with specified portions of the Commission's regulations, the method described herein will be used in the evaluation of construction permit applications docketed on or after February 24, 1978.

If an applicant wishes to use this regulatory guide in developing submittals for applications docketed on or before February 24, 1978, the pertinent portions of the application will be evaluated on the basis of this guide.

REFERENCES

1. Department of the Army Technical Manual TM 5-1300, "Structures to Resist the Effects of Accidental Explosions," June 1969.

2. Napadensky, H. S., and L. Jablansky, "TNT Equivalency Investigations," Proceedings of the 16th Annual Explosives Safety Seminar, Department of Defense Explosives Safety Board, Washington, D.C., September 1974.

3. Strehlow, R. A., and W. E. Baker, "The Characterization and Evaluation of Accidental Explosions," NASA CR-134779, June 1975.

4. Eichler, T. V., and H. S. Napadensky, "Accidental Vapor Phase Explosions on Transportation Routes near Nuclear Power Plants," Final Report J 6405, IIT Research Institute, Chicago, Illinois, April 1977.

5. Biggs, J. M., "Introduction to Structural Dynamics," McGraw-Hill, New York, 1964.

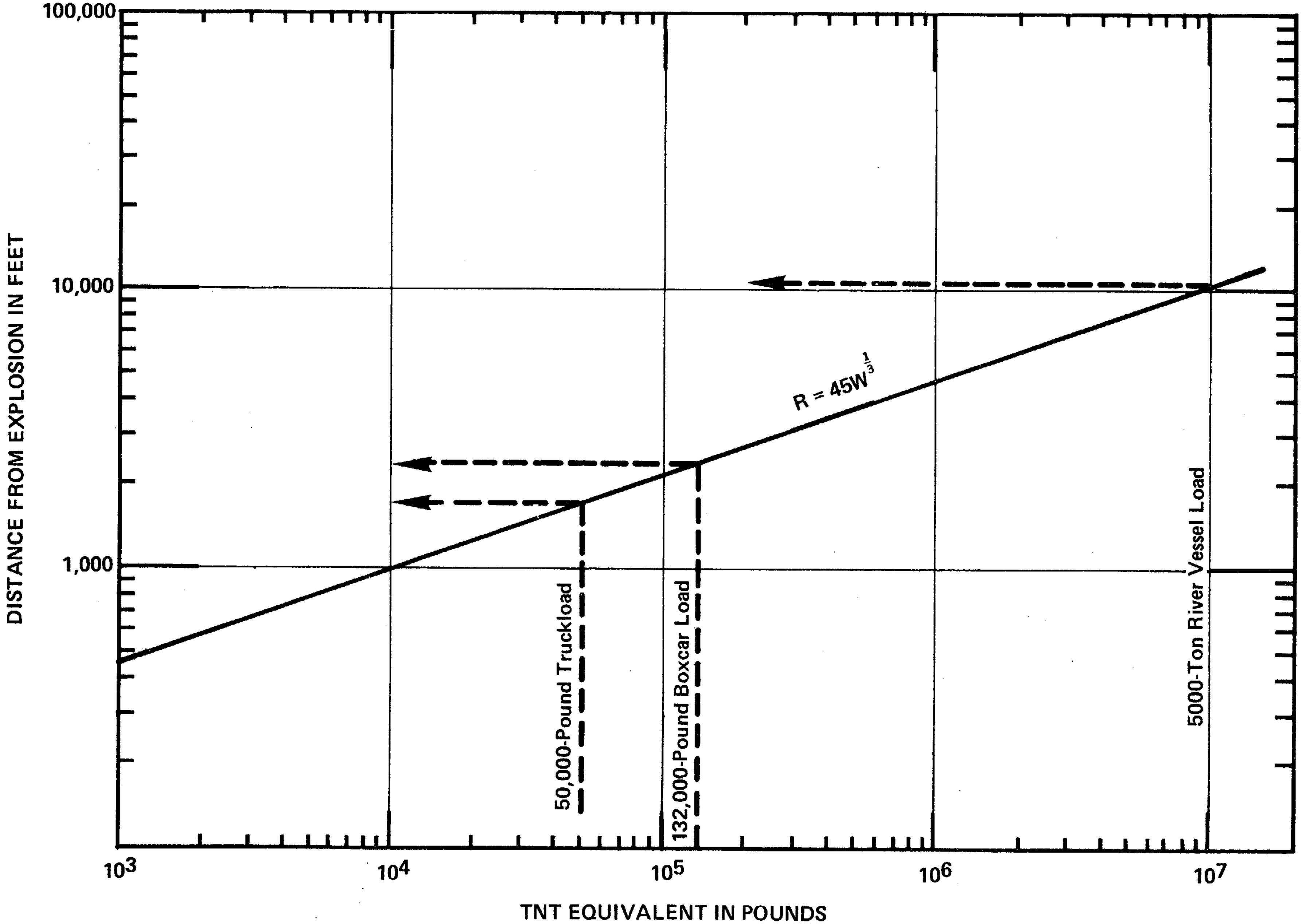

Figure 1. Radius to Peak Incident Pressure of 1 PSI.

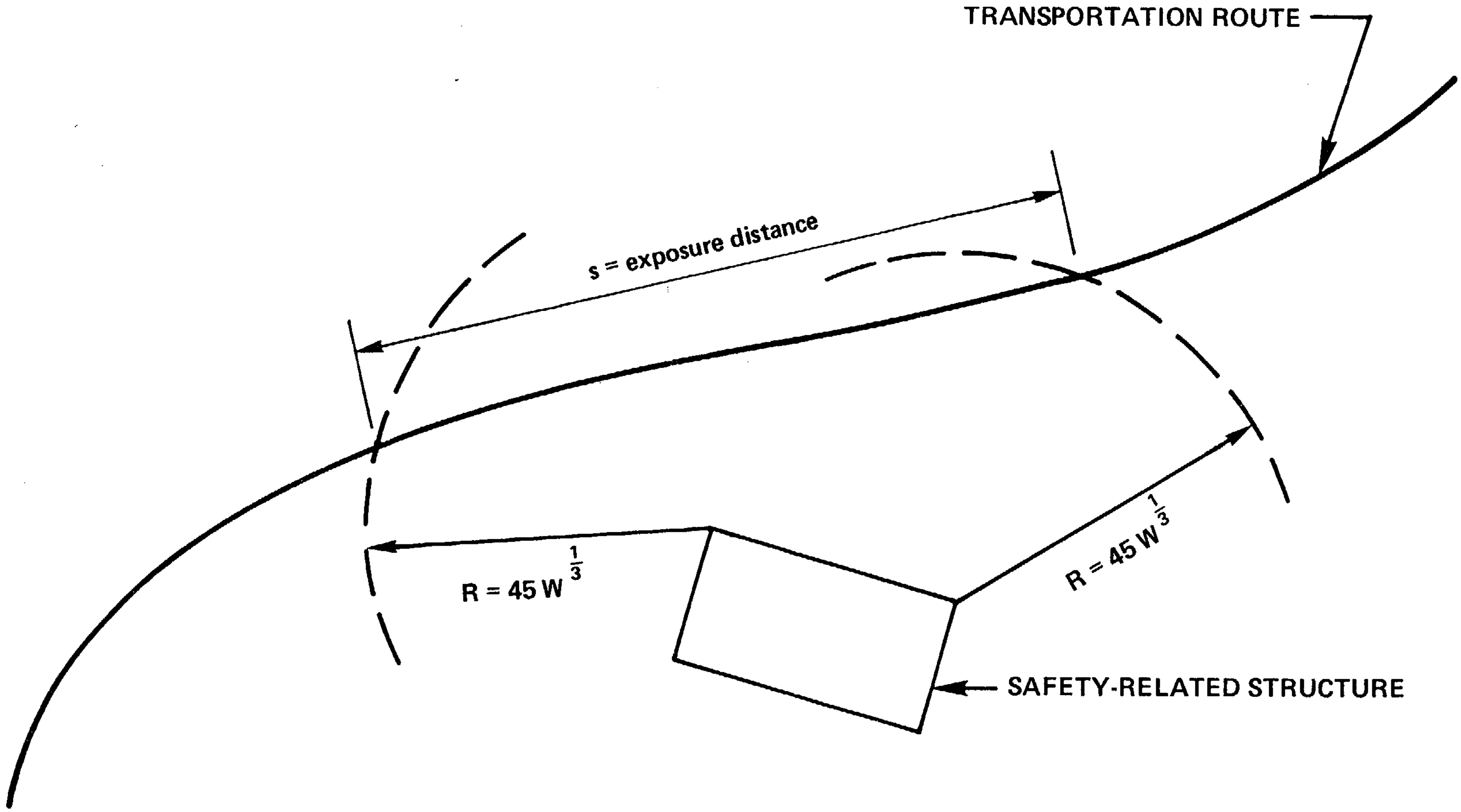

Figure 2. Exposure Distance Calculation