

# Methodology for Assessing Safety Stand-off Distances for Postulated Offsite Explosion Accidents at NPP

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## 1. Introduction

To prevent offsite explosions from adversely affecting the safety of a nuclear power plant (NPP), it is essential to establish an adequate safety standoff distance. The primary parameter governing the impact of an explosion on NPP safety is blast overpressure. For postulated explosion scenarios, blast overpressure is typically evaluated by converting the energy of the explosive source into an equivalent mass of TNT. In this paper, overpressure is estimated using various correlation models derived from TNT test data. Based on these results, a methodology for assessing the safety standoff distance is proposed.

## 2. Methodology

The safety stand-off distance(L) is determined using the cube-root scaling law of Hopkinson (1915), as given in Eq. (1). In this equation, Z denotes the scaled-distance (m/kg<sup>1/3</sup>), and W represents the TNT equivalent mass of the explosive source.

$$L = Z \times W_{TNT}^{1/3} \quad (1)$$

As shown in Eq. (1), evaluating the safety stand-off distance requires the TNT equivalent mass and the scaled distance Z. The representative correlations of Z for blast overpressure are summarized in Table 1 [1] [2] [3].

Table 1. Blast Overpressure Correlations for Scaled Distance

Models	Formula for $\Delta P$ (MPa)
Newmark & Hansen (1961)	$\Delta P = \frac{0.6784}{Z^3} + 0.294 Z^{-3/2}$
Kinney & Graham (1985)	$\Delta P = P_a \left[ \frac{808 \left[ 1 + \left( \frac{Z}{4.5} \right)^2 \right]}{\left[ 1 + \left( \frac{Z}{0.048} \right)^2 \right]^{0.5} \left[ 1 + \left( \frac{Z}{0.32} \right)^2 \right]^{0.5} \left[ 1 + \left( \frac{Z}{1.35} \right)^2 \right]^{0.5}} \right]$
Wu & Hao (2005)	$\Delta P = 1.059 Z^{-2.56} - 0.051 \quad (0.1 \leq Z \leq 1)$ $\Delta P = 1.008 Z^{-2.01} \quad (1 \leq Z \leq 10)$
Iqbal & Ahmad (2009)	$\Delta P = 1.026 Z^{-1.96} \quad (1 \leq Z \leq 12)$
Vannucci (2017)	$\Delta P = \left( 1 + \frac{1}{2e^{10Z}} \right) e^{0.14 - 1.49 \ln Z - 0.08 \ln Z^2 - 0.62 \sin(\ln Z)} \quad (Z \leq 40)$

Characterization of blast waves for TNT equivalent mass is performed using multiple empirical correlation models, which are summarized in Table 1. However, US NRC regulatory guidance adopts, as a conservative approach, correlation developed from TNT explosion test data documented in the US Department of Defense (DoD) Uniform Facilities Criteria (UFC) [4] [5] [6]. The UFC provides regression-based correlation equations for blast characteristics (such as overpressure, impulse, duration time and arrival time) as a function of scaled distance, as given in Eq. (2). The coefficients a, b, and c in Eq. (2) are listed in Table 2

$$\log P = \sum_{i=0}^n c_i (a + b \log Z)^i \quad (2)$$

Table 2. Parameters for calculating the blast wave characteristic correlation.

constant	range	Overpressure P <sup>0</sup> (kPa)	Impulse i <sub>p</sub> (Pa·s)	Duration time t <sub>d</sub> (ms)	Arrival time t <sub>a</sub> (ms)
	1	0.0674 ≤ Z ≤ 40	0.0674 ≤ Z ≤ 0.955	0.178 ≤ Z ≤ 1.01	0.0674 ≤ Z ≤ 40
	2		0.955 ≤ Z ≤ 40	1.01 ≤ Z ≤ 2.78	
	3			2.78 ≤ Z ≤ 40	
a	1	-0.214362789	2.067619087	1.929461541	-0.202425716
	2		-1.947088467	-2.124925252	
	3			-3.536262181	
b	1	1.3503425	3.076032967	5.250991939	1.377842236
	2		2.406977454	9.299628861	
	3			3.463497456	
c <sub>0</sub>	1	2.780769166	2.524556209	-0.61422276	-0.059163429
	2		1.672816459	0.315409246	
	3			0.686906642	
c <sub>1</sub>	1	-1.695898874	-0.502992764	0.130143718	1.357064963
	2		-0.384519027	-0.029794427	
	3			0.09330553	
c <sub>2</sub>	1	-0.154159377	0.171335645	0.134872512	0.052492799
	2		-0.026081671	0.030632955	
	3			-0.000584942	
c <sub>3</sub>	1	0.514060731	0.045017696	0.039157428	-0.196563954
	2		0.005957988	0.018340557	
	3			-0.00226885	
c <sub>4</sub>	1	0.098855437	-0.011896463	-0.004759337	-0.060177005
	2		0.014544526	-0.017399647	
	3			0.002959089	
c <sub>5</sub>	1	-0.293912623		-0.004281446	0.069636027
	2		-0.006632893	-0.00106322	
	3			0.001480297	
c <sub>6</sub>	1	-0.026811235			0.021529749
	2		-0.002841893	0.0056206	
	3				
c <sub>7</sub>	1	0.109097496			-0.016165893
	2		0.001364482	0.000161822	
	3				
c <sub>8</sub>	1	0.001628468			-0.00232532
	2			-0.000686019	
	3				
c <sub>9</sub>	1	-0.021463103			0.001477521
	2				
	3				
c <sub>10</sub>	1	0.000145672			
	2				
	3				
c <sub>11</sub>	1	0.001678478			
	2				
	3				

The main characteristics (incident overpressure, reflected overpressure, impulse, etc.) based on the TNT explosion test data are as shown in Fig 1.

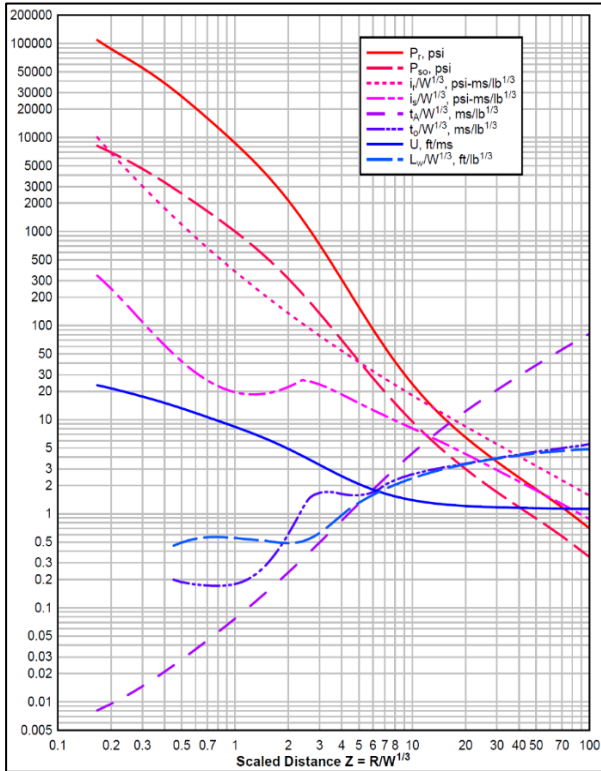


Fig. 1. (UFC) TNT explosion characteristics plot

### 3. Examples

The results of plotting the scaled-distance regression models for predicting blast overpressure listed in Table 1 are shown in Fig. 2. In Fig. 2, the UFC curve is obtained by calculating blast overpressure as a function of scaled distance Z using Eq. (2) with the coefficients provided in Table 2.

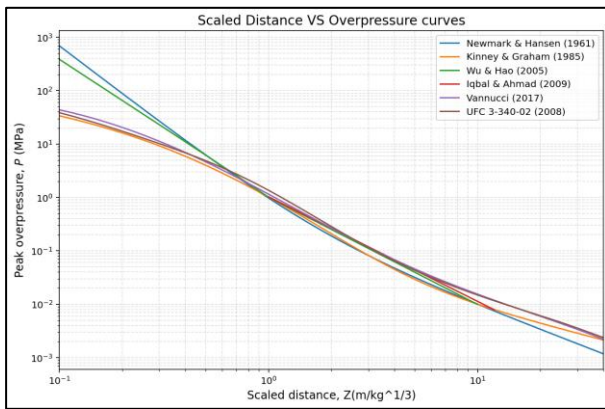


Fig 2. TNT-equivalent blast overpressure curves as a function of scaled distance.

Using Fig. 2, the scaled distance Z corresponding to a specified overpressure can be determined for each TNT-based regression model. By applying Hopkinson's cube-root scaling law (Eq. (1)) to the obtained Z, the safety stand-off distance for a given TNT equivalent mass can be calculated.

### 3.1 Safety Stand-Off Distance Estimation at Blast Overpressures for an Specific TNT Equivalent Mass

Fig. 3 shows the resulting safety stand-off distances as a function of specified overpressure for an assumed TNT equivalent mass of 1 ton, comparing the selected methodologies.

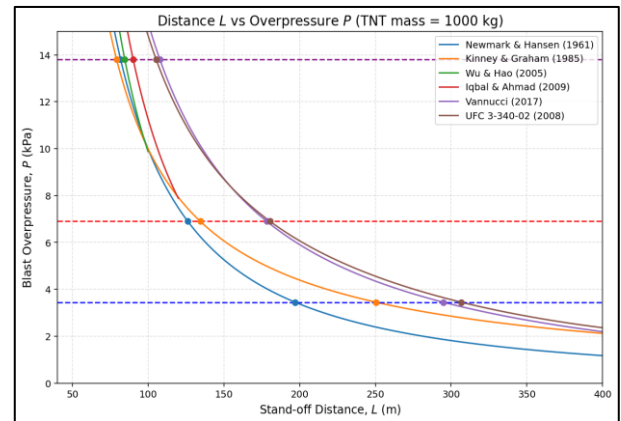


Fig 3. Comparison of safety stand-off distances by TNT blast-wave characterization methodology.

The safety stand-off distances corresponding to the specific blast overpressure point (the marked point in Fig. 3) for each characterization methodology are summarized in Table 3. Blank entries in Table 3 indicate cases where the value could not be evaluated, as the corresponding scaled distance (Z) falls outside the applicable range of the respective methodology.

Table 3. Safety stand-off distances for specified blast overpressures by Each Evaluation methodology

Overpressure Methodology	13.80 kPa (2 psi)	6.90 kPa (1 psi)	3.45 kPa (0.5 psi)
Newmark & Hansen (1961)	81.8 m	126.1 m	197 m
Kinney & Graham (1985)	79.1 m	134.4m	250.4 m
Wu & Hao (2005)	84.6 m	-	-
Iqbal & Ahmad (2009)	90.1 m	-	-
Vannucci (2017)	107.7 m	178.3 m	294.8 m
UFC 3-340-02 (2008)	105.3 m	180.5 m	306.7 m

### 3.2 Safety Stand-Off Distance for the Regulatory Overpressure Limit

US NRC RG 1.91 specifies 1 psi (6.9 kPa) or less as the allowable blast wave pressure, i.e., explosion overpressure, that would not adversely affect the safety of a nuclear power plant. For each evaluation methodology, the scaled distance (Z) corresponding to the peak explosion overpressure specified in the regulatory guideline was determined, and the results are presented in Table 4. However, the Wu & Hao and Iqbal & Ahmad methodologies were excluded from this evaluation because the scaled distance corresponding to the specified overpressure condition cannot be determined using these methods.

Table 4. Safety Stand-Off Distances for TNT Equivalent Mass by Each Evaluation Methodologies (6.9 kPa)

Methodology	Scaled Distance (Z, m/kg <sup>1/3</sup> )
Newmark & Hansen (1961)	12.62
Kinney & Graham (1985)	13.443
Vannucci (2017)	17.82
UFC 3-340-02 (2008)	18.07

Based on the scaled distances for each methodology presented in Table 4, Fig. 4 shows the safety stand-off distances for TNT equivalent mass corresponding to the regulatory guideline (6.9 kPa).

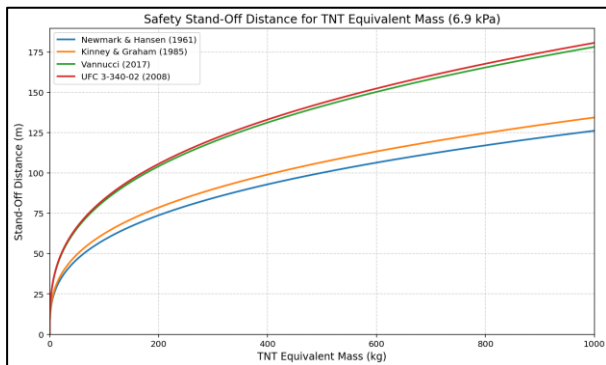


Fig. 4. Safety Stand-Off Distance for TNT Equivalent Mass by Evaluation Methodologies (6.9 kPa)

As presented in the examples, when the TNT equivalent mass and the target blast overpressure are specified, the safety stand-off distance can be quantitatively estimated for each evaluation methodology, and the required safety stand-off distance corresponding to the allowable overpressure limit in the regulatory guideline can also be determined. Furthermore, by comparing the differences in the calculated results among the methodologies, the conservatism and applicability of each model can be assessed. Accordingly, the proposed approach enables a more systematic evaluation of safety stand-off distances for hypothetical explosion accidents in the vicinity of nuclear power plants (NPP).

### 4. Conclusions

This study presented a methodology for estimating safety stand-off distances for postulated offsite explosion accidents near nuclear power plants using TNT-equivalent blast overpressure characterization models. By applying various TNT-based correlations, scaled distances and safety stand-off distances corresponding to target blast overpressures were derived, and the applicability of the methodology was confirmed through example evaluations. The proposed methodology can be used to quantitatively assess the effects of potential offsite explosion accidents from hazardous facilities near nuclear power plants on reactor buildings and safety-related structures, systems, and components (SSCs), and to determine safety stand-off distances that do not adversely affect plant safety. In addition, because the methodology reflects both regulatory criteria and TNT-based explosion evaluation approaches, it can serve as a useful technical basis for safety evaluations, safety stand-off distance determination, and licensing activities. Therefore, the proposed methodology is considered to have practical engineering and regulatory applicability for evaluating offsite explosion safety around NPP.

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