BARRIER DESIGN FOR TORNADO-GENERATED MISSILES

A. K. KAR
Ebasco Services, Inc.,
21 West Street, New York, N.Y. 10006, U.S.A

SUMMARY

Nuclear powerplant facilities and many other structures need protection against missiles generated by tornados and explosions. The missile impacts result in both local and overall effects on barriers or targets. The local effects are characterized by penetration, perforation, and backface spalling or scabbing of the target material. The overall effects of missile impact on structural stability are commonly evaluated in terms of the flexural and shear behavior of the target. Empirical formulas are presented to determine the local effects on concrete and steel barriers. Procedures are given for determining the design loads for overall effects. Design methods are described.

The local effects resulting from missile impact depend on the material properties of both the missile and the target, and on the missile weight, shape, size, and impact velocity. The penetration on the front face is independent of the target thickness, whereas perforation and backface spalling are dependent on it.

Empirical formulas containing the parameters which influence the local effects are presented for concrete barriers. Predicted depth of penetration and target thickness to prevent perforation and scabbing of target are compared with all available test results. The comparisons are very good for all acceptable test results. These tests were on missiles of various weights, sizes, shapes, materials, and impact velocities. The target properties also varied significantly. A single set of formulas is applicable for impacts by bullets traveling at supersonic velocities, steel rods, timber poles, and steel pipes of various sizes. When perforation is prevented, punching failure does not present a problem.

The empirical formula for steel barriers is based on the Ballistic Research Laboratory formula. The modifications include consideration for the material properties of the missile and for the hardness and density of the barrier material.

The design loads resulting from missile impacts are governed by the absorption of kinetic energy from the missile by the target at its maximum deflection. These loads are limited by the yield, buckling, crushing, or local destruction of the missiles. Formulations based on the principle of colliding bodies are given for the impactive load. This load is dependent on the material and stiffness properties of the missile and the target and on the impacting velocity and mass of the missile. Comparisons of the calculated missile deceleration and barrier reaction show excellent correlation with test results.

The barrier response to missile impacts depends on available ductility. Analysis of test results shows very limited ductility if backscabbing is to be prevented. Recommendations are made on the limited ductility.

Procedures for obtaining shear and flexural strengths of concrete barriers are provided. The depth-span ratios of the barriers are considered for this purpose.

Empirical formulas are given for the prediction of local effects of missile impacts. Comparisons with test results demonstrate their superiority over all existing formulas. The analytical method for determining design loads and missile deceleration yields values which show excellent correlation with test results. Recommendations are made on available ductility for barriers and on design for flexure and shear.

1. Introduction

Nuclear power plant facilities have structures, systems, and equipment designed to contain possible radioactive releases and to permit safe shutdown. They must be protected against the damaging effects of various internal and external missiles. Walls, slabs, and other barriers are designed to withstand the dynamic effects of missile impact. Although these barriers can be of any structural material, this paper primarily examines reinforced concrete slabs or walls. In addition, steel barriers are treated briefly.

Among the external missiles are tornado-generated missiles. In the United States, the spectrum of tornado-generated missiles includes the utility pole, wood plank, automobile, steel rod, steel pipe, etc. [1]. Among these missiles, the utility pole and wood plank are soft. The steel sections are hard. The automobile is considered flexible because of its high initial deformability, followed by almost rigid behavior. This paper specifically treats hard and soft missiles.

Upon impact, missiles can produce two types of effects on the target. The local effects are characterized by penetration, perforation, and backface spalling or scabbing of the target material. The overall effects of missile impact on structural stability are commonly evaluated in terms of the flexural and shear behavior of the target.

This paper presents empirical formulas to determine the local effects on concrete and steel barriers. Procedures are given for determining the design loads for overall effects. The missile deceleration is obtained in a semiempirical manner. A method is given for the overall design of barriers.

2. Local Effects

Missile barriers are constructed of concrete and occasionally of steel. The local effects depend largely on the relative material properties of the missiles and the target. Upon impact on steel barriers, ordinary missiles may richochet or disintegrate. They may also penetrate into or perforate the target. The relative damage depends upon the impact velocity of the missile. For concrete barriers, local damages in the form of spalling of material from the front and backfaces of the target, and penetration into or perforation of the barrier are generally characteristic of impact by a hard missile. The soft missiles cannot cause penetration or perforation, except at extremely high hypothetical velocities. They can cause backface cracking and scabbing; however, this scabbing will be less than the scabbing which would occur if the missiles were hard. The effects of impact of a flexible missile are intermediate to those of the hard and soft missiles. There may be some chipping off of material from the front surface and some cracking and scabbing of the backface.

Many formulas have been developed to evaluate the local effects of missile impacts. Most of the work was initiated in conjunction with military defense. Much of the available information is based on research for high-velocity, low-mass missiles. Recently, tests have been made using missiles with characteristics resembling those of tornado-generated missiles. Formulas based on test results are presented here to determine the local effects of missile impact on concrete and steel barriers. These formulas are for head-on impacts of missiles. Modifications for oblique hits are also indicated. The formulas are applicable to missiles of all types, whether high or low velocity or large or small mass. Though excellent correlations with results from tests involving supersonic velocities have been observed, without further verifications the formulas may not be used for impact at these velocities.

3. Concrete Barriers

Recent tests [2, 3] have shown that the Modified Petry [4], Ballistic Research Laboratory [4], Ammann and Whitney [5], and Modified NDRC [6] formulas are inadequate to predict the local effects of concrete barriers due to impact by tornado-generated missiles.

New formulas are here proposed to calculate the local effects of impact by tornado-generated missiles on concrete barriers. The formulas have their basis in test results [2, 3, 7], and they follow the format of the Modified NDRC Formulas [6]. The new formulas consider the cross-sectional areas as well as the outside dimensions and shapes of the missiles, the material properties not only of the targets but also of the missiles. They also consider, among other variables included in other formulas, the size of coarse aggregate in concrete. The existing formulas do not consider all of these. After a consideration of the important parameters, the new formulas have been developed by a nonlinear solution of the test results.

The depth of penetration x (measured in inches) in concrete structures is determined from eq. (1) as follows:

$$G_{(x/d)} = \alpha K N \frac{W}{D} \left(\frac{V_o}{1{,}000d} \right)^{1.80} \qquad (1)$$

where

$$G_{(x/d)} = \begin{cases} \left(\frac{x}{2d}\right)^2 & \text{for } \frac{x}{d} \leq 2.0 \\ \left(\frac{x}{d} - 1\right) & \text{for } \frac{x}{d} \geq 2.0 \end{cases}$$

In eq. (1), α is a constant and is described later in this paper.

The factor N is a missile shape factor. For practical cases, the following values may be used:

$$N = 0.72 \text{ for flat-nosed solid bodies} \tag{2}$$

$$N = 0.72 + 0.25(n - 0.25)^{0.5} \qquad \leq 1.17 \tag{3}$$

for missiles with special nose; n is the ratio of the radius of the nose to the diameter of the missile.

$$N = 0.72 + \left\{(D/d)^2 - 1\right\}\overset{0.0306}{(\cancel{0.36})} \qquad \leq \overset{1.0}{\cancel{1.17}} \tag{4}$$

for hollow circular sections (pipe) or irregular sections.

The factor K is a penetrability factor which is a function of the material properties of the missile and the target. The value of K is determined from the following:

$$K = \frac{180}{\sqrt{f'_c}}\left(\frac{E}{29{,}000}\right)^{1.25} \tag{5}$$

where E is the modulus of elasticity of the material of the missile (kips/inch^2), and f'_c is the ultimate compressive strength (psi) of concrete test cylinder. For other test samples of concrete, the value of K should be modified by the relationship between strengths of different types of test samples.

In eq. (1), d is the projectile diameter (inches) for solid slug-type missiles. For projectiles of other shapes, d is the diameter of a projectile that has the same contact surface area as that of the actual missile. D is the outside diameter (inches) of the actual missile in the case of a circular section. This is equal to d in the case of a rectangular section and equal to the diameter of circles inscribed within the boundary formed by joining the extremities of impacting ends of angular, I, or any irregular section. The minimum value of D is equal to that of d.

W is the weight of missile in pounds.

V_o is the impact or striking velocity (feet/sec) of the missile. For oblique impact, the normal component of the impact velocity is used in eq. (1).

When the different quantities are in the FPS units, as described in the preceding, α equals 1.0.

If D is expressed in cm, d is expressed in cm, E is expressed in kN/m^2, V_o is expressed in m/sec, W is expressed in kg, x is expressed in cm, then $\alpha = 0.01063$ in eq. (1).

The depth to prevent perforation, and the thickness s to prevent backface scabbing are determined by the following:

$$\left(\frac{e-a}{d}\right) = 3.19\left(\frac{x}{d}\right) - 0.718\left(\frac{x}{d}\right)^2 \qquad \text{for } \frac{x}{d} \leq 1.35 \tag{6}$$

$$\beta\left(\frac{s-a}{d}\right) = 7.91\left(\frac{x}{d}\right) - 5.06\left(\frac{x}{d}\right)^2 \qquad \text{for } \frac{x}{d} \leq 0.65 \tag{7}$$

where

$$\beta = \left(\frac{29,000}{E}\right)^{0.2} \tag{8}$$

a = (maximum aggregate size in concrete)

In eqs. (6) and (7), the units of a, e, and s are the same as those of d and x. In eq. (8), $\beta = 1$ for steel missiles.

For x/d ratios larger than those shown in eqs. (6) and (7),

$$\left(\frac{e-a}{d}\right) = 1.32 + 1.24\left(\frac{x}{d}\right) \qquad \text{for} \quad \left(3 \leq \frac{e}{d} \leq 18\right) \tag{9}$$

$$\beta\left(\frac{s-a}{d}\right) = 2.12 + 1.36\left(\frac{x}{d}\right) \qquad \text{for} \quad \left(3 \leq \frac{s}{d} \leq 18\right) \tag{10}$$

There is normally no penetration for missiles of materials with hardness numbers less than those of the barrier materials. However, there may still be scabbing on the backface. Therefore, x should still be determined from eq. (1) only for use in eq. (6) or (10).

Eqs. (1) to (10) have been used to compare predicted values with results from full-scale tests with missiles having characteristics not too different from those of tornado-generated missiles. Comparisons have been made also for tests with bullets. Some of these comparisons are presented in Fig. 1, and Tables I and II. Fig. 1 and Table II contain comparisons for predicted depths of penetrations by other formulas also. The comparisons show the superiority of the proposed formulas over other existing formulas.

4. Steel Barriers

There are some qualitative differences between the local failure mechanisms in steel and concrete barriers. For mild-to-medium-hard homogeneous steel plates, the barrier may have a ductile failure. For plates with Brinell hardness numbers above 350, failure by plugging may occur. For inferior quality steel, flaking may occur on the backface.

When using good quality steel, backface phenomena do not generally influence the depth of penetration; therefore, penetration or thickness to prevent perforation is given by the following:

$$y = \lambda\left(\frac{E}{29,000}\right)\left(0.72 + N\right) k_p \frac{\left(MV_o^2\right)^{0.667}}{1,067(D+d)} \tag{11}$$

where M is the mass of the missile (pound-sec^2/feet); V_o (feet/sec), D (inches) and d (inches) are as defined for eq. (1).

The penetrability coefficient k_p in eq. (11) is determined from the following:

$$k_p = \left[(0.632\ \text{BHN} + 94.88)/275\right] \tag{12}$$

In eq. (12), BHN is the Brinell Hardness number of the barrier material. The value of the quantity within the brackets is limited to between 0.37 and 1.0. For values less than 0.37 or greater than 1.0, 0.37 or 1.0 are used respectively.

In eq. (11), y is in inches and $\lambda = 1.0$ when the different quantities are expressed in the FPS units, as described previously.

If D is expressed in cm, d is expressed in cm, E is expressed in kN/m^2, M is expressed in $kg\text{-}sec^2/m$, V_o is expressed in m/sec, y is expressed in cm, then $\lambda = .0035$ in eq. (11).

5. Design Load

For overall design of barriers, it is necessary to determine the impactive load, imparted by the missile. Design loads resulting from missile impacts are governed by the absorption of kinetic energy from the missile by the target at its maximum deflection. These loads are limited by the yield, buckling, crushing, or local destruction of the missiles. In this section, formulations based on the principle of colliding bodies are given for the impactive load, as the missile hits a concrete barrier. This load is a function of the material, shape, size, weight, and impact velocity of the missile and the material properties and stiffness of the barrier. The actual design load is the smallest of the loads calculated for the different modes of failure of the missile and those necessary for the conservation of momentum or energy.

From the principle of colliding bodies the velocity V of the missile at time t can be obtained as

$$V = V_o \exp\left(- \frac{\rho_c A C_c t}{M}\right) \tag{13}$$

where ρ_c is the density of concrete, A the cross-sectional area of the missile, and C_c the speed of sound in concrete. C_c is obtained from

$$C_c = \left(\frac{E_c}{\rho_c}\right)^{0.5} \tag{14}$$

where E_c is the modulus of elasticity of concrete.

The contact pressure σ at the interface of the missile and the barrier is given by

$$\sigma = \rho_c V_o C_c \exp\left(- \frac{\rho_c A C_c t}{M}\right) \tag{15}$$

The contact period between the missile and the target is equal to the time required for the stress pulse to travel the length of the missile and return to the impacting end. The stress pulse travels at the speed of sound in the missile material. The duration of contact is also the load duration. For a 13.73 feet long (4.19 m) missile, the load duration is approximately equal to .002 sec. This includes effects of lateral vibration and plastic deformation.

From a consideration of the stress pulse, given by eq. (15), and material properties of a tornado-generated pipe missile, it is found that for V_o = 202 feet/sec (61.61 m/sec), the missile breaks at the impacting end. This matches with observations from test No. 4 in Ref. [2].

The load on the barrier is contributed by the force necessary to break the missile and the change in linear momentum. The first part P_1 is given by

$$P_1 = A f_{du} \tag{16}$$

where f_{du} is the dynamic ultimate compressive stress of the missile material. In determining P_1, the dynamic response of the missile is considered.

The second part of the load is given by

$$P_2 = 0.5\ m\ V^{2} \tag{17}$$

where m is the mass of the missile per unit time, and V is the velocity of the uncrushed portion of the missile. From practical considerations, V can be assumed to be equal to V_o.

The results predicted by the method proposed here are compared with those from test No. 4 in Ref. [2]. The test panel is a 15-foot-square (4.58 m) slab, 18 inches (0.458 m) thick. From Fig. C-1 of Ref. [2], the effective period T of the target system, i. e., the fundamental period for transverse vibration, is estimated as .044 sec. From considerations of the loading pulse and period of the structure, the equivalent static missile load is calculated to be 359.6 kips (1600.2 kN). In Ref. [3], the peak value of the total support reaction has been measured as 356 kips (1584 kN). The same design load can be calculated by considering the elastic stiffness properties of the barrier and the available ductility beyond this elastic range.

With appropriate changes in the physical parameters in the preceding derivations, it is possible to determine the impactive load for a steel barrier.

6. Deceleration Time History

By differentiating eq. (13) with respect to time, the deceleration of the missile $\dot{V}$ is obtained as

$$\dot{V} = V_o \ \exp\left(-\frac{\rho_c\, A\, C_c\, t}{M}\right)\left(-\frac{\rho_c\, A\, C_c}{M}\right) \tag{18}$$

Because of limited rigidity of the barrier, the effective deceleration $\dot{V}_{eff}$ is assumed to be given by

$$\dot{V}_{eff} = \dot{V}\psi \tag{19}$$

where

$$\psi = 0.5924\left(\frac{k_{barrier}}{k_{missile}}\right)^{0.16055} \leq 1.0 \qquad (20)$$

The stiffness of the missile $k_{missile}$ is given by

$$k_{missile} = \frac{AE}{L} \qquad (21)$$

where L is the length of the missile. In eq. (20), $k_{barrier}$ is the stiffness of the barrier acting as a spring. In determining $k_{barrier}$ the uncracked properties of the barrier are considered.

It is proposed that the magnitude of the deceleration starts from zero at t = 0, linearly increases and peaks at time $\tilde{t}$ given by

$$\tilde{t} = 4\left(\frac{\text{depth of penetration in feet}}{V_o^{1.8}}\right) \qquad (22)$$

After reaching the peak, the missile decelerates as shown by eq. (23)

$$\dot{V}_{(t-\tilde{t})} = \dot{V}_{eff} \exp\left[-\frac{\rho_c A C_c (t-\tilde{t})}{4M}\right] \quad \text{for} \quad t \geq \tilde{t} \qquad (23)$$

For the missile in test No. 4 of Ref. [2], the calculated peak deceleration is 1025.6g, where g is the acceleration due to gravity. The calculated peak deceleration compares exactly with the test deceleration of 1025.6g [3]. The method of deceleration has been used also for projectile penetration into earth media. Comparisons between predicted and test results have been found to be very excellent.

7. Design of Barrier

The barrier is designed for the equivalent static load determined in section 5 of this paper. The design is necessary to verify the adequacy of the barrier in flexure and reaction shear. Design for punching shear is unnecessary if perforation of the barrier is prevented. This is because for punching failure the full thickness of the barrier is involved, whereas front and backface spalling presents a smaller thickness of the barrier to be perforated.

For reaction-shear design for very transient missile loads, considerations should be given to the size of the missile or loading dimensions, ratio of loading dimension and barrier thickness, and span-depth ratio.

Conventionally, the design for flexure is performed by using the yield line theory. Refs. [2, 3] show that under impact by missiles there is scabbing of material from the backface before any yield line can be initiated. Tests with statically applied concentrated loads also show that yield line patterns may not always form. Also tests [2, 3, 8] have shown that the available ductility is small if backface scabbing is to be avoided. This ductility is smaller for dynamically applied concentrated loads than for distributed loads. For test No. 4 of Ref. [2] the ductility has been calculated to be approximately 3.36, and there has been undesirable spalling.

It is recommended that for design for flexure for impactive loads from missiles, the ductility ratio be limited to $0.8(3.1-1.7p)\geq 1$ in concrete barriers. p is the percentage of reinforcement. The equivalent static load for design for flexure can be determined based on this ductility. The design for flexure is then performed by determining elastic moments for the concentrated load. Using this approach, it has been possible to verify the test results reported in Refs. [2, 3]. For shear and compression, the ductility ratios are smaller than those for flexure. For shear, carried by concrete alone, the permissible ductility ratio shall be 1.3. For shear, carried by concrete and stirrups or bent bars, the permissible ductility ratio shall be 1.6. However, it shall not exceed that for flexure. For shear, carried completely by stirrups, the permissible ductility shall equal that for flexure.

In the design, dynamic increase factors appropriate for the strain rates involved are applied to static strengths of the barrier materials.

References

[1] "Missiles Generated by Natural Phenomena," United States Nuclear Regulatory Commission, Standard Review Plan, Sec. 3.5.1.4, Rev. 1.

[2] "Full-Scale Tornado-Missile Impact Tests," NP-148, Interim Report, Sandia Laboratories, Tonopah Test Range, Tonopah, Nevada, April, 1976.

[3] "Full-Scale Tornado-Missile Impact Tests," Sandia Laboratories, Tonopah, Nevada, distributed at Washington, D. C., Nov. 19, 1976.

[4] Gwaltney, R. C., "Missile Generation and Protection in Light-Water-Cooled Power Reactor Plants," ORNL NSIC-22, Oak Ridge National Laboratory, Oak Ridge, Tennessee, for the United States Atomic Energy Commission, Sept., 1968.

[5] "Structures to Resist the Effects of Accidental Explosions," TM 5-1300, Department of the Army, Washington, D. C., July, 1965.

[6] Kennedy, R. P., "A Review of Procedures for the Analysis and Design of Concrete Structures to Resist Missile Impact Effects," presented at the Sept., 1975 Intl. Seminar on Extreme Load Conditions and Limit Analysis Procedures for Structural Reactor Safeguards and Containment Structures, Berlin, West Germany.

[7] Barber, R. B., "Steel Rod/Concrete Slab Impact Test (Experimental Simulation), Bechtel Corp., San Francisco, Oct., 1973.

[8] Denton, D. R., "A Dynamic Ultimate Strength Study of Simply Supported Two-Way Reinforced Concrete Slabs," TR 1-789, U. S. Army Engineers Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi, July, 1967.

TABLE I.- Comparison of Calculated and Measured Depth of Penetration, Occurrence of Perforation and Thickness to Prevent Scabbing - 12 Inch Schedule 40 Pipe

Test Identification (1)	Test Reference (2)	Target Thickness t (inches) (3)	Velocity of Impact V (feet/second) (4)	Weight of Missile W (pounds) (5)	Compressive Strength of Concrete f'_c (pounds/inch^2) (6)	Depth of Penetration x (inches) (7)	Thickness to Prevent Perforation e (inches) (8)	Does Perforation Occur (9)	Thickness to Prevent Scabbing s (inches) (10)	Does Scabbing Occur (11)	Size of Aggregate in Concrete (inches) (12)
ID 12B18-3	9	18	201	743	3480	7.0		No		Yes	1.5
						(6.84)[1]	(15.6)	(No)	(19.9	(Yes)	
ID 12B18-4	9	18	202	743	3600	6.8		No		Yes	1.5
						(6.80)	(15.6)	(No)	(19.9)	(Yes)	
ID 12B24	9	24	202	743	3795	6.8		No		No	1.5
						(6.71)	(15.5)	(No)	(19.8)	(No)	
	10	18	202	743	3350	7.0		No		Yes	1.5
						(6.92)	(15.8)	(No)	(20.0)	(Yes)	
	10	18	198	743	3560	6.9		No		Yes	1.5
						(6.73)	(15.5)	(No)	(19.8)	(Yes)	
	10	18	203	743	4535	7.5		No		Yes	1.5
						(6.44)	(15.2)	(No)	(19.4)	(Yes)	
	10	18	213	743	4690	9.1		No		Yes	1.5
						(6.58)	(15.4)	(No)	(19.9)	(Yes)	
	10	18	143	743	4320	5.0		No		No	1.5
						(5.23)	(13.6)	(No)	(17.8)	(No)	
	10	18	152	743	4205	5.3		No		No	1.5
						(5.48)	(13.8)	(No)	(18.0)	(No)	
	10	18	157	743	4255	4.1		No		No	1.5
						(5.57)	(14.1)	(No)	(18.2)	(Yes)	
	10	12	143	743	3680	12.0		Yes		Yes	1.5
						(12.0)	(13.9)	(Yes)	(18.0)	(Yes)	
	10	12	98	743	3595	4.5		No		Yes	1.5
						(4.33)	(12.2)	(Yes)	(16.5)	(Yes)	
	10	12	92	743	3350	3.5		No		No	1.5
						(4.23)	(12.0)	(No)	(16.4)	(Yes)	

[1] The quantities within parentheses are calculated values using Eqs. (1) to (6). The corresponding quantities outside parentheses are test results. Since penetrated surfaces are very irregular, approximately half of the aggregate size may be added to or subtract- from the measured quantity to derive the correct depth of penetration.

Note: 1 pound = 0.453 kg; 1 inch = 2.54 cm; 1 foot/second = 0.305 m/second; 1 pound/inch^2 = 6.9 kN/m^2

Table II. - Comparison of Predicted Depth of Penetration Versus Test Results for Tornado-Generated Missiles

Missile	Test Reference	Target Thickness (inch)	Impact Velocity (Feet/Second)	Test Result (inch)	Depth of Penetration (inch)									
					Kar		Ammann&Whitney		Army Corps of Engrs		Modified NDRC		Modified Petry	
					Predicted	Ratio Pred/Test	Predicted	Ratio Pred/Test	Predicted	Ratio Pred/Test	Predicted	Ratio Pred/Test	Predicted	Ratio Pred/Test
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1 inch Dia Rod		9	213	1.71	1.82	1.06	1.33	0.78	3.44	2.01	1.70	0.99	>9	large
		6	213	1.60	1.81	1.13	1.31	0.72	3.40	2.13	1.83	1.14	>6	large
		3	218	>3	>3	1.0	1.37	0	>3	1.0	>3	1.0	>3	1.0
		6	220	1.98	1.84	0.93	1.39	0.70	3.54	1.79	1.88	0.95	>6	large
		6	322	1.68	1.60	0.96	1.30	0.77	3.03	1.80	1.82	1.08	>6	large
		9	235	2.34	1.92	0.82	1.56	0.67	3.84	1.64	2.15	0.92	>9	large
		9	217	1.84	1.93	1.05	1.50	0.82	3.80	2.07	1.96	1.07	>9	large
		6	150	1.23	1.53	1.24	0.77	0.63	2.40	1.95	1.40	1.14	>6	large
		18	303	3.6	2.61	0.72	3.13	0.87	6.73	1.87	3.01	0.84	>18	large
Mean						0.99		0.66		1.81		1.01		large
13.5 inch Utility Pole		18	204.6	0.0	0.0	1.0	2.67	infinity	13.10	infinity	9.70	infinity	5.92	infinity
		12	204	0.0	0.0	1.0	2.57	infinity	12.72	infinity	>12	infinity	9.02	infinity
Mean						1.0		infinity		infinity		infinity		infinity
12 inch Schedule 40 Pipe		24	202	6.8	6.71	0.99	1.43	0.21	9.66	1.42	10.45	1.54	3.23	0.48
		18	201	7.0	6.84	0.98	1.48	0.21	9.78	1.40	>18	large	3.20	0.46
		18	202	6.8	6.80	1.0	1.47	0.22	10.32	1.52	>18	large	3.23	0.48
		18	198	6.8	6.71	0.99	1.40	0.21	9.66	1.42	>18	large	3.11	0.46
		18	203	7.5	6.44	0.86	1.30	0.17	9.40	1.25	>18	large	3.26	0.43
		18	213	9.1	6.58	0.72	1.39	0.15	9.57	1.05	>18	large	3.56	0.39
		18	143	5.0	5.23	1.04	0.71	0.14	8.21	1.64	7.41	1.48	1.69	0.34
		18	152	5.3	5.48	1.03	0.80	0.15	8.41	1.59	7.89	1.49	1.90	0.36
		18	157	4.1	5.57	1.36	0.84	0.20	8.50	2.07	8.09	1.97	2.02	0.49
		18	202	7.0	6.92	0.99	1.50	0.21	9.86	1.41	>18	large	3.23	0.46
		12	143	>12	>12	1.0	0.77	0.	8.36	0	>12	large	1.69	0
		12	98	4.5	4.33	0.96	0.39	0.09	7.51	1.67	>12	large	0.81	0.18
		12	92	3.5	4.23	1.20	0.36	0.10	7.45	2.13	>12	large	0.72	0.21
Mean						1.01		0.16		1.43		large		0.36

Note: For the Ammann & Whitney, Army Corps of Engineers, and the Modified Petry Formulae, the outside diameter of the missiles have been considered. For the Modified Petry Formula the value of concrete coefficient has been selected as .00426.

1 inch = 2.54 cm; 1 foot/second = 0.305 m/second

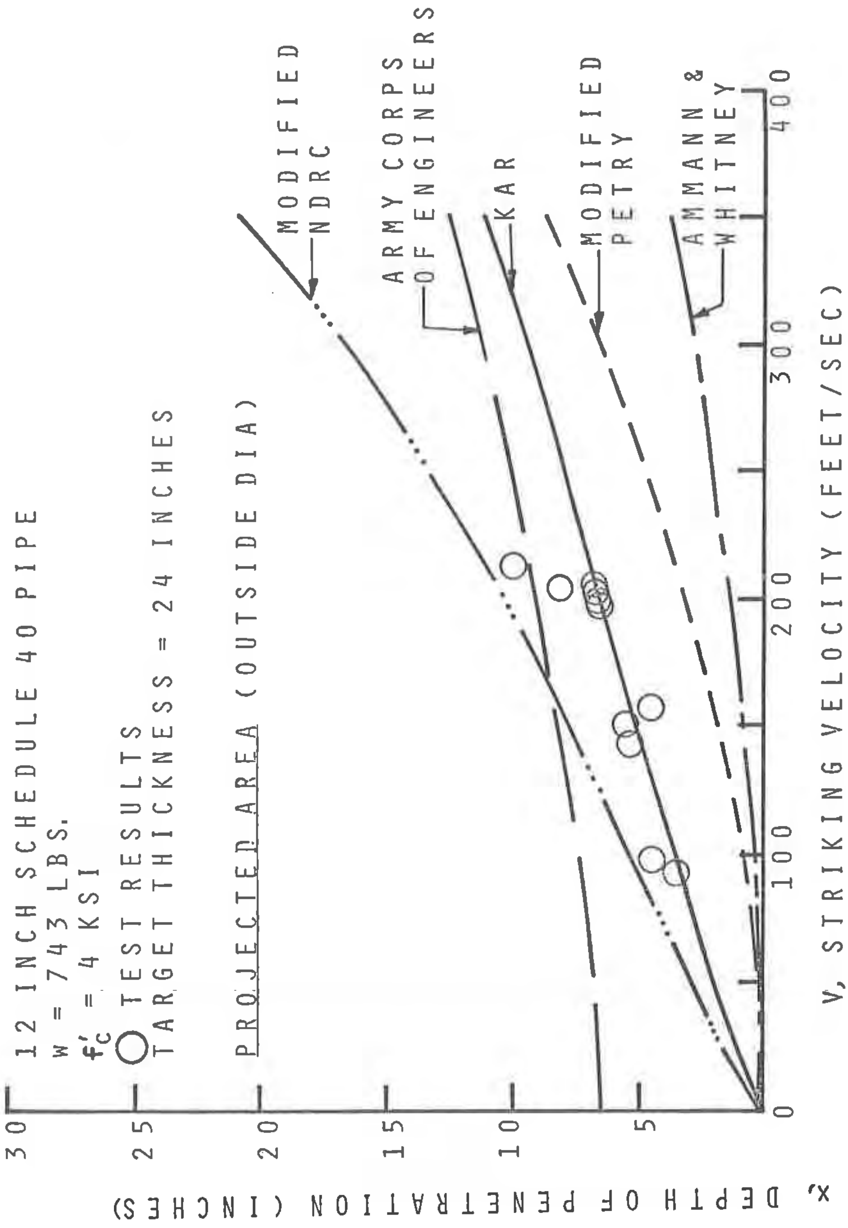

Fig. 1. Comparison of Penetration Formulae for 12 Inch Schedule 40 Pipe (1 in = 2.54 cm)