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The Reduction of Blast Overpressures from Aqueous Foam in a Rigid Confinement

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SUMMARY

Experiments were performed in order to quantify the additional attenuation provided by enclosing a blast reducing material (aqueous foam) in a rigid vessel (cylindrical metal culvert), open at one end to the atmosphere. The results are compared with previously reported data on aqueous foam where the culvert was not used. A total of eight configurations were investigated. Tests performed with a 0·91-m culvert section and ½ stick (0·285 kg) of C-4 explosive and with a 1·22-m culvert section with ½ stick and 1 stick of C-4. A third parameter varied in the trials was the amount of foam used (depth in culvert). Data are presented for FSEL, and CSEL and peak level reduction scaled according to a modified scaled foam depth dependent on the charge weight, and height and depth of the culvert. This modified scaling law illustrates the relative effectiveness of enclosure depth and width on the noise reduction.

1 INTRODUCTION

The research discussed in this paper deals primarily with the reduction of blast wave overpressures resulting from detonating high explosives. As reported in previous work,[1–6] potentially dangerous sound levels can be

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mitigated through the use of energy absorbing materials at the blast source. As a continuation of the earlier efforts to understand the reduction of intermediate (i.e. >150 dB) noise levels produced by detonating high explosives, the US Army Construction Engineering Research Laboratory (USACERL) has investigated the attenuation levels produced by surrounding an explosive charge with aqueous foam which is confined within a rigid cylindrical vessel. This research is similar to the work reported in Ref. 1 in which the sound absorbing material (aqueous foam) was supported by thin plastic sheeting, an enclosure design which presumably added no additional attenuation.

The experiments reported herein were performed in order to quantify the additional attenuation provided by enclosing the blast reducing material (in this case aqueous foam) in a rigid vessel, open at only one end to the atmosphere. The results are compared with the previously reported data on aqueous foam.[1] Scaling laws will illustrate the relative effectiveness of enclosure depth and width on the level of noise reduction. As in the previous work,[1,3] the range of charge weights is limited to $0{\cdot}28\,\text{kg} < C_\omega < 0{\cdot}57\,\text{kg}$.

2 EXPERIMENTAL SET-UP

The tests discussed in this paper were conducted at the Fort Leonard Wood, Missouri, demolitions training range. The physical layout of the test facility is similar to the one described by Raspet, Butler and Jahani.[3] As in the previous research, Endevco piezo-resistive microphones were mounted on tripods 1·2 m above ground level at various distances from the blast source. In all four microphones were used, two at 38 m from the charge and two at 76 m. Each pair was separated by 90° relative to the blast source. In each test case, three metrics were measured and recorded by the remote data acquisition system. The C-weighted sound exposure level (*CSEL*), the flat-weighted sound exposure level (*FSEL*) and the peak level (*PEAK*) were measured for each of the four stations, and the signals recorded on an Ampex 2230 14-track FM recorder. To assure reliable results, the system was calibrated prior to and after each test using a Bruel & Kjaer piston-phone. By definition, the peak sound pressure level (*PEAK*) and sound exposure level (*SEL*) are given as

$$PEAK(\text{dB}) = 20\log_{10}[(P_p - P_0)/P_0] \tag{1}$$

$$SEL(\text{dB}) = 10\log_{10}\left[\int P^2\,\mathrm{d}t/P_0^2 t_0\right] \tag{2}$$

where P_p is the peak thermodynamic pressure (Pa), P_0 is a reference pressure ($P_0 = 20\,\mu$Pa), and t_0 is a reference time ($t_0 = 1$ s).

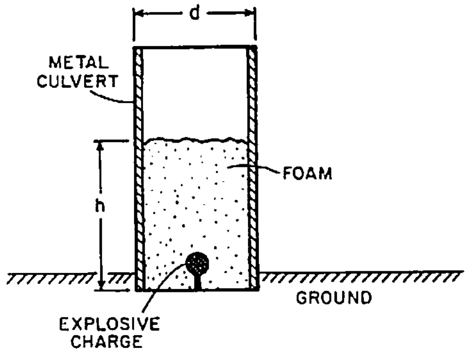


Fig. 1. Schematic of test configuration used in this work. The explosive charge is placed in a metal culvert filled with 30:1 expansion ratio aqueous foam.

All test results described in the following section (see Table 1) were performed with aqueous foam supported by a metal culvert section. This particular configuration is shown in Fig. 1. Two charges were used in each test; a control charge set on a 0·9-m high crushable post, and a test charge set at the center of the cylinder on a 4-cm high post. The culvert sections were sunk into the ground about 6 cm to reduce the propagation of noise under the cylinder. To some extent, this phenomenon did occur since the culvert section was driven into the air by the blast. A total of eight different configurations were investigated. This included tests that were performed with the 0·91-m culvert section and $\frac{1}{2}$ stick (0·285 kg) of C-4, and with a 1·22-m culvert section with $\frac{1}{2}$ stick (0·285 kg) and 1 stick (0·57 kg) of C-4. The third parameter varied in the trials was the amount of foam. In all cases, the experimenters attempted to keep the foam expansion ratio, α, fixed at a value of 30:1 (total volume:liquid volume).

The material referred to as C-4 is a military explosive (91% RDX + 6% TNT + 3% other) with a detonation pressure $P_{CJ} = 25{\cdot}7$ GPa, detonation velocity $D_{CJ} = 8{\cdot}4$ mm μs^{-1} and theoretical heat of detonation of $E_{ch} = 5{\cdot}86$ MJ kg^{-1}.[7] For comparison, it is about 1·36 times as energetic as TNT.

3 TEST RESULTS

As discussed earlier, the series of tests were performed in order to study the effect of external confinement on the blast reduction produced by aqueous foams. A schematic of the test configuration is shown in Fig. 1. The confining vessel is a cylindrical metal culvert, open at the top end. During all tests, the explosive charge was first set in the test cylinder and then the cylinder was filled with a 30:1 expansion ratio foam produced with a Mearl OT 10 batch foamer. By definition,[1] the expansion ratio is

$$\alpha = V_t/V_l \tag{3}$$

where V_t represents the total volume occupied by the foam, and V_l is the liquid volume. For future comparisons, the test configuration used by Raspet and Griffiths[1] is shown in Fig. 2. Here the aqueous foam is contained in a less-confining plastic cube surrounding the explosive.

In the present investigation, tests were performed with $\frac{1}{2}$ stick of explosives (0·285 kg) in the 0·91-m culvert with two foam depths (0·86 and 0·55 m), and with $\frac{1}{2}$ stick and 1 stick in the 1·22-m diameter culvert with three foam depths (1·16, 0·86 and 0·55 m). One stick of C-4 has a mass equal to 0·57 kg (0·78 kg TNT equivalent). Table 1 contains the results of these tests. In addition to the C-4 mass and foam dimensions (d = diameter, h = height), *CSEL* reduction ($\Delta CSEL$), *FSEL* reduction ($\Delta FSEL$) and peak noise level reduction ($\Delta PEAK$) are listed for the three different combinations of charge size and culvert size.

The *CSEL*, *FSEL* and *PEAK* reductions were determined from the difference between a control charge and the test charge, so that variations due to charge mass, composition and temperature would be minimized. This is the same test procedure as used in Ref. 1.

Three qualitative features of the blast wave reductions can be seen from the results in Table 1. First, increased foam depth for a given culvert and explosive configuration results in increased noise reduction. This feature is evident in the comparison of test 101a with 101b, as well as the comparison of the set including tests 102a, 102b, 102c, 103a, 103b and 103c. A second observation is that an increased culvert diameter for a fixed depth results in greater noise reduction. Finally, increased charge mass results in decreased noise reduction. These dependences are the same as those found in Raspet and Griffiths[1] for unconfined explosives. To display those similarities and

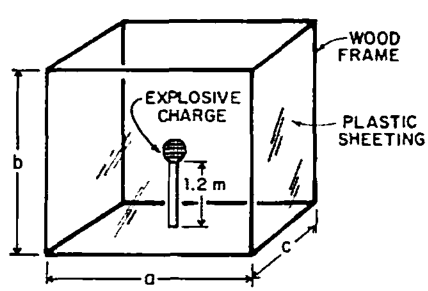


Fig. 2. Schematic of test configuration used by Raspet and Griffiths.[1] Here the foam is confined by plastic sheeting rather than the rigid metal culvert.

TABLE 1
Test Data and Scaled Foam Depths

Test number	*Explosive mass (kg)*	*d (m)*	*h (m)*	$\Delta PEAK$	$\Delta CSEL$ *(dB)*	$\Delta FSEL$ *(dB)*	$\hat{X}$	$\bar{X}$
101a	0·28	0·92	0·86	20·6	18·5	17·8	0·71	3·75
101b	0·28	0·92	0·55	16·8	14·4	14·0	0·61	2·77
102a	0·28	1·22	1·16	24·9	21·6	19·4	0·95	4·99
102b	0·28	1·22	0·86	23·3	22·2	20·8	0·86	4·09
102c	0·28	1·22	0·55	18·0	15·8	15·1	0·74	3·04
103a	0·57	1·22	1·16	22·0	20·4	19·8	0·75	3·96
103b	0·57	1·22	0·86	21·1	19·8	19·2	0·68	3·25
103c	0·57	1·22	0·55	16·1	14·4	14·3	0·59	2·41

any differences in a quantitative manner, it is necessary to apply scaling laws to these data.

4 DISCUSSION OF RESULTS

These tests were performed so that the scaling laws developed in Raspet and Griffiths[1] could be applied to cases where the foam is supported by rigid walls. Data presented in Ref. 1, where unconfined aqueous foam was used as the blast reducing agent, indicated that a scaled foam depth

$$\hat{X} = l(C_w^{1/3}) \tag{4a}$$

scaled foams of the same density, and that a dimensionless foam depth defined as

$$X = l(\rho_f/C_w)^{1/3} \tag{4b}$$

scaled foams of different densities quite well. In eqns (4), ρ_f represents the foam density, l represents the geometrically averaged pit depth (see Fig. 2), and C_w is the mass of explosive in equivalent kilograms of TNT. This is also the same form of the scaling used in Ref. 3, where fiberglass, steel wool and other materials were used in place of foam. Since all the experiments reported in Refs 1 and 3 were for the cubic arrangement shown in Fig. 2, the geometrically averaged foam depth was given as

$$l = \tfrac{1}{2}a \tag{5}$$

where a is the dimension of the cube shown in Fig. 2.

Because the current experimental layout is somewhat similar to that reported in Refs 1 and 3, and because the observed trends are also similar, a scaling law such as eqn (4b) is a prime candidate for these new data.

Before this can be accomplished, a reasonable way of adjusting for charges at the bottom of the foam volume, rather than centered in the volume, must be developed. Theoretically, there are two counteracting effects. First, the energy from the charge propagates into a solid angle of 2π rather than 4π, thus increasing the effective charge by a factor of two. Second, energy is absorbed by the ground, which results in a reduction of the effective charge weight. We can use the results of two experimental tests to guide us in choosing an effective weight. Tests at Fort Leonard Wood in conjunction with earlier tests[8] indicated that charges on the ground were quieter by 3 dB *FSEL*.

Measurements of the sound level reduction from charges set in the culvert with no blast noise reducing materials are given in Table 2. It is interesting to

TABLE 2
Reductions with No Foam in Culvert

Metric	*d* (*m*)	*Reduction* (*dB*)
PEAK	0·91	−0·3
FSEL	0·91	1·0
CSEL	0·91	1·0
PEAK	1·22	1·3
FSEL	1·22	2·5
CSEL	1·22	2·5

note that the system of culvert plus ground has a larger reduction on the energy measures than on the peak levels. This indicates that the dissipation in this case is possibly due to multiple reflections after the initial shock front develops. In view of the variation in data and the sparsity of data, the best adjustment is the simplest. We will use the geometrically averaged foam depth divided by the cube root of the charge weight. This is equivalent to assuming that half the energy of the charge is propagated into the ground. We will scale the data using this simple model and note any variations which might be caused by this particular choice.

For comparison with the previous data, the scaled foam depths ($\hat{X}$) for each of the current tests are listed in Table 1. The *CSEL* reduction versus scaled foam depth is displayed in Fig. 3a, the *FSEL* reduction in Fig. 3b and the peak reduction in Fig. 3c. Also displayed on these figures are the lines fitted to the unconfined data in Ref. 1.

For the cylindrical geometry of the culvert, the characteristic foam depth l

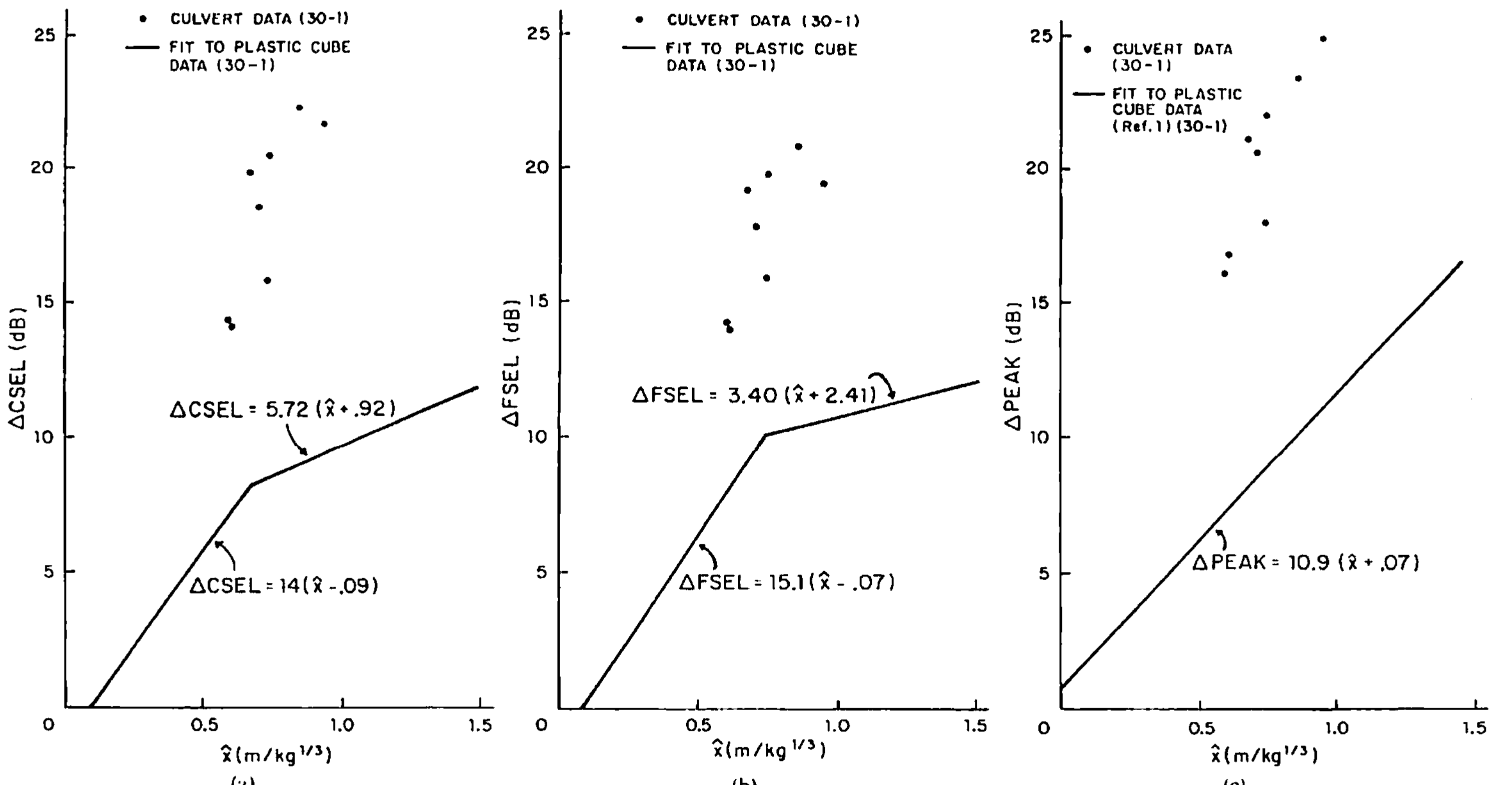


Fig. 3. (a) *CSEL* reduction scaled to foam depth $\hat{X}$ as defined in Ref. 1. (b) Scaled *FSEL* reduction: the solid line represents the data from Ref. 1, where the foam is confined in a plastic cube. (c) Peak level reduction scaled to foam depth $\hat{X}$.

is given as the equivalent radius of a sphere with the same volume as the cylinder. That is,

$$l = (\tfrac{3}{16} d^2 h)^{1/3} \tag{6}$$

Obviously, these tests are not extensive enough to provide detailed scaling laws giving reduction as a function of diameter, depth and charge size. However, these tests do provide an engineering estimate of the reduction produced by confined charges.

A notable feature of this data is the tendency of the dB reduction to saturate for the larger depths. There is a large change in reduction from 0·55 to 0·86 m depth, and a smaller change in reduction from 0·86 to 1·16 m depth. Since the foam is unconfined in the vertical directions, perhaps vertical saturation is beginning to occur at these depths.

It appears that equivalent depth variations produce larger changes than equivalent diameter variations. That is, if the foam volume is kept constant so that the scaled foam depth is constant but the depth increased and diameter decreased, the reduction will increase. A more accurate theory may need to divide the volume dependence of scaling into an area dependence and a depth dependence.

Figures 4a, b and c show the *FSEL* reduction, *CSEL* reduction and peak level reduction plotted as a function of a modified scaled foam depth $\bar{X}$, defined as

$$\bar{X} = A^{1/6} h^{2/3} (\rho_f / C_w)^{1/3} \tag{7}$$

where A is the surface area of foam and h is the depth of foam. The scaled data shows good agreement, with the exception of one erroneous data point (103b). When one excludes this data point along with the data point that appears to be in the saturation region, a linear regression analysis gives reasonable results. These are displayed in Table 3 for all three metrics. Here the reductions are 4·17, 4·05 and 4·54 dB/scaled distance for *PEAK*, *FSEL* and *CSEL*, respectively.

TABLE 3
Linear Regression Calculations for Experimental Data Less 102a and 103b: $Y = A\bar{X} + B$

Variable Y (dB)	*Correlation coefficient*	*A*	*B*
$\Delta PEAK$	0·99	4·17	5·53
$\Delta FSEL$	0·96	4·05	3·44
$\Delta CSEL$	0·96	4·54	2·43

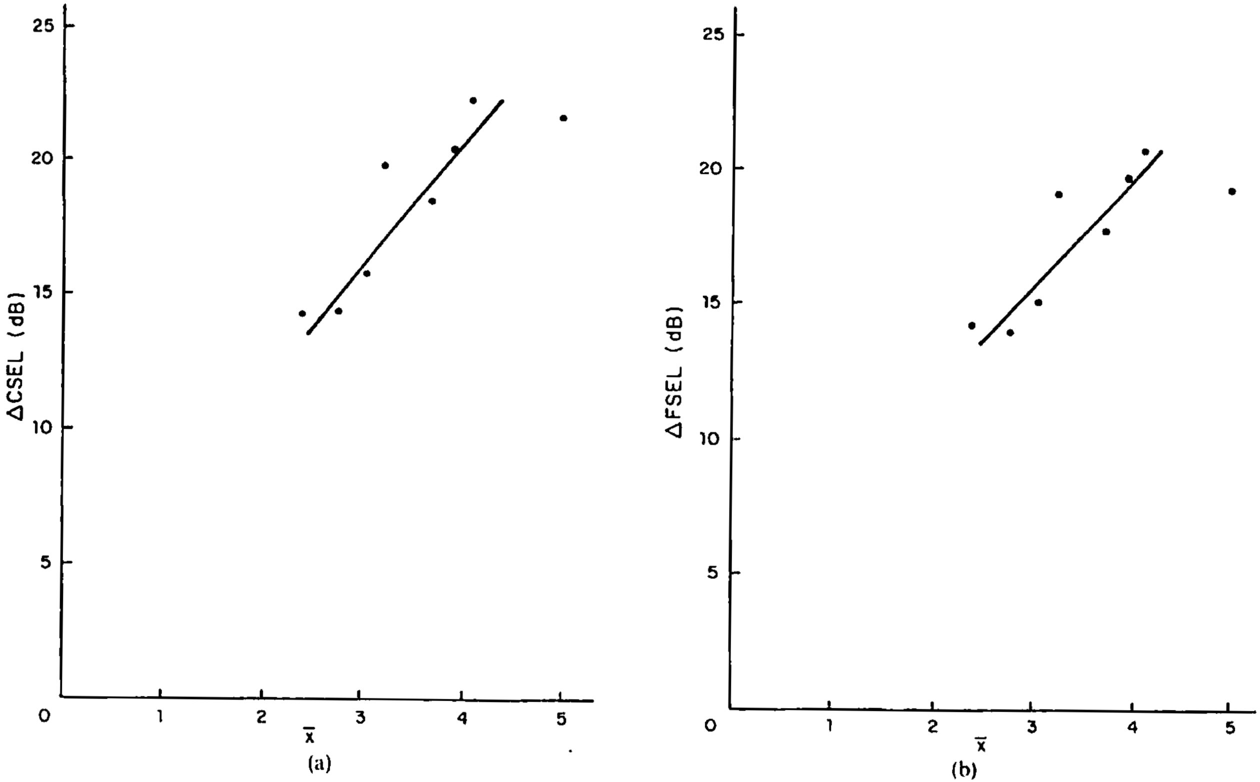
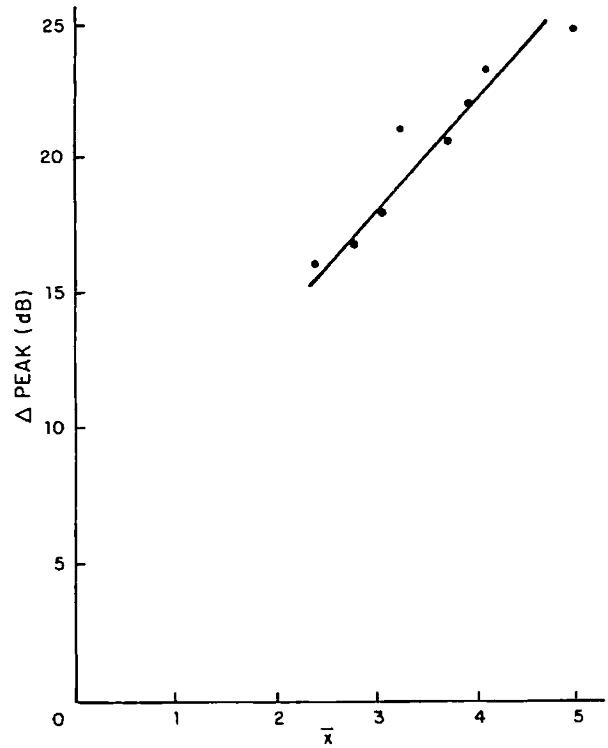


Fig. 4. (a) *CSEL* reduction scaled to $X = A^{1/6}h^{2/3}(\rho_f/C_w)^{1/3}$. (b) *FSEL* reduction for aqueous foam confined within a metal culvert: X is defined in Fig. 4a.



(c)

Fig. 4. (c) Peak level reductions for aqueous foam in a metal culvert.

5 CONCLUSIONS

In this work, we have investigated the attenuation effectiveness of aqueous foam confined in a rigid metal structure. When compared to previous data[1] for unconfined foam, it appears that the rigid confinement contributes to the attenuation process. It may be that the wave reflections off the internal walls, as well as the heterogeneous medium, dissipate energy. Previous data[1] showed that, for the unconfined case, the dimensionless material (foam) depth provided a reasonable scaling law. For the confined situation, it was shown that for several different configurations the best scaling was with foam depth raised to the $\frac{2}{3}$ power and surface area to the $\frac{1}{6}$ power in addition to the regular charge mass to the $-\frac{1}{3}$ power. The system of culvert plus ground has a larger reduction in the energy levels than in the peak levels. This indicates that the dissipation in this case is due to multiple reflections after the initial shock front develops. This is consistent with the wave reflection statement made above.

It should also be noted that the geometrical arrangement provided in these tests results in a focusing of the blast energy in the vertical direction. The degree of attenuation provided at distances greater than 76 m can only be determined by measurements, since it is not clear if the readings at 76 m are affected by this energy.

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