The reduction of blast noise with aqueous foam

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Experiments were performed to investigate the potential of water-based foams to reduce the farfield noise levels produced by demolitions activity. Measurements of the noise reductions in flat-weighted sound exposure level (FSEL), C-weighted sound exposure level (CSEL), and peak level were made for a variety of charge masses, foam depths, and foam densities (250:1 and 30:1 expansion ratio foams). Scaling laws were developed to relate the foam depth, foam density, and charge mass to noise reductions. These laws provide consistent results for reductions in the peak level, FSEL and CSEL up to a dimensionless foam depth of 2.5. A two part model for the mechanisms of sound level reductions by foam is suggested.

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INTRODUCTION

To date, most research into mitigating demolition effects has concentrated on nearfield phenomena, particularly the damaging effects of the blastwave (the nearfield is the region within a few hundred explosive charge radii of the explosive). Little has been done to measure and evaluate blast effects in the farfield, but it is the farfield effects of blasts which are becoming a serious environmental issue, i.e., annoyance and damage complaints from individuals and communities subjected to increased environmental noise levels can restrict, or eliminate, blast producing activities.

To address this problem of the farfield effects of demolition (and related activities), we have considered several methods of reducing blast noise, including the use of water-based foams as a mitigating agent. This paper describes an experimental investigation into the use of both low and high density aqueous foams to quiet blast noise in the farfield. The data is used to develop scaling laws for the foam so that the level of noise reduction can be predicted for various amounts and densities of foams. We also discuss past nearfield investigations when they can be related to our farfield measurements. Finally, a two mechanism model for the reduction of sound levels by foam is proposed.

I. METHOD

Two test series were performed using different expansion ratio foams. The expansion ratio is the ratio of foam volume to liquid content volume. To simplify the data analysis, simple lightweight cubical or near cubical foam enclosures were used. For all but the initial tests, these enclosures were constructed of a wooden frame with polyethelene sheeting for the walls. The charges were centered in the cube on crushable plastic posts (Fig. 1). Spheres of Composition Four (C-4) plastic explosive were used in all tests. During all tests, the charges were set in pairs: a test charge under foam and a reference charge without foam. For cases where the enclosure was slightly noncubical, the geometrically averaged foam depth was used in the data analysis

$$d = \tfrac{1}{2}(l \times w \times h)^{1/3}, \qquad (1)$$

where l, w, and h are the foam dimensions in meters.

In all tests, the flat-weighted sound exposure level (FSEL), C-weighted sound exposure level (CSEL), and the peak level were measured at four microphone positions, two each on opposite sides of the explosive. The standard microphone distances used in most tests were 60 and 120 m (Fig. 2). Two trials were performed for each configuration. The levels were read using a True Integrating Environmental Noise Monitor and Sound Exposure Level Meter, designed and constructed by the U.S. Army Construction Engineering Research Laboratory. The signals were recorded for later analysis on an AMPEX 2230 14-track FM recorder. The peak level, defined as

$$20 \log(p/p_0),$$

where $p_0 = 20\ \mu\text{Pa}$, is commonly used to identify excessive noise levels around explosive facilities and to identify when the possibility of structural damage exists. The sound expo-

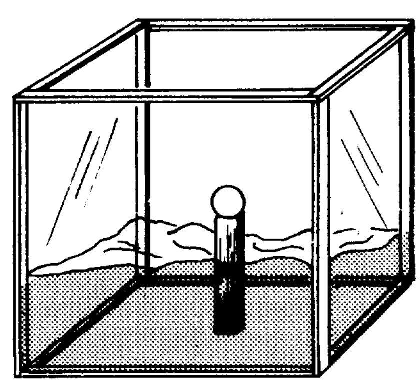

FIG. 1. Experimental setup for unconfined explosives test.

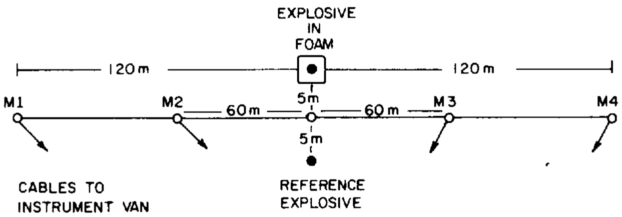

FIG. 2. Microphone positions for foam tests.

sure level (SEL) is defined as

$$10 \log\left(\int p^2 \, dt / p_0^2 t_0 \right),$$

where p_0 is defined above, $t_0 = 1.0$ s and the integral is performed over the entire duration of the transient. The FSEL is performed with no frequency weighting, the C-weighted SEL with a standard C-weighting filter in the system before the integration is performed.

The CSEL is important for the environmental assessment of blast noise since it can be used to calculate the C-weighted average day/night level (CDNL). The CDNL is recommended by the Committee on Hearing, Bioacoustics, and Biomechanics of the National Research Council[1] to assess the environmental impacts of high-energy impulsive noise and is used by the Department of Defense to assess blast noise.[2]

II. SERIES 1: HIGH EXPANSION FOAM

The first series of tests investigated the noise reducing properties of high expansion foam. The foam was made with a National Foam System WP-25 generator using National's $1\frac{1}{2}\%$ High Expansion Foam solution. When water is provided (by a fire truck) at 1400–1700 kPa, this generator produces foam with a nominal 250:1 expansion ratio. The expansion ratio varies slowly with time, but samples taken 30 s after generation were usually within 20% of the nominal value. The individual bubbles were approximately 1 cm in diameter. This type of foam was stable and usable for 10–15 min after generation in low wind conditions.

A. Test 1

The first test was a feasibility test. Two charge sizes and two foam configurations were used. In one case, the charges were set in a 3.0 m × 3.0 m × 1.85 m pit; the foam in the pit was piled about 0.30 m above ground level. In this partially confined case, the reductions in all noise metrics were about 14 dB for the 0.57-kg charge, and about 9 dB for the 2.37-kg charge.

The second configuration was an enclosure 2.4×2.4×1.7 m high, constructed as described in Sec. I. This enclosure produced reductions of about 10 and 5 dB in all metrics (peak level, FSEL, CSEL) for the 0.57- and 2.37-kg charges, respectively.

The results of test 1 established that significant environmental noise reductions could be achieved. These reductions were similar for all metrics measured, but did not provide enough information to allow foam thickness and charge size to be related to the reduction in sound levels.

B. Test 2

Test 2 investigated the dependence of CSEL, FSEL, and peak level on foam depth for two charge masses. The enclosure dimensions varied from 0.30 m to 1.5 m in 0.30-m steps. Charges masses of 0.57 and 0.061 kg were used. Plots of foam depth versus reduction for all three metrics were linear within the accuracy of the data. The data, along with those for tests 3 and 4, for the test are displayed in Fig. 3 ($\Delta = 0.061$ kg, $\odot = 0.57$ kg) as reductions in CSEL, FSEL, and peak level versus the cube root scaled foam depth. The results of these six experiments show that all three sound levels are reduced linearly up to the largest scaled foam depth, approximately 2.9 m/kg$^{1/3}$. At that depth, the reduc-

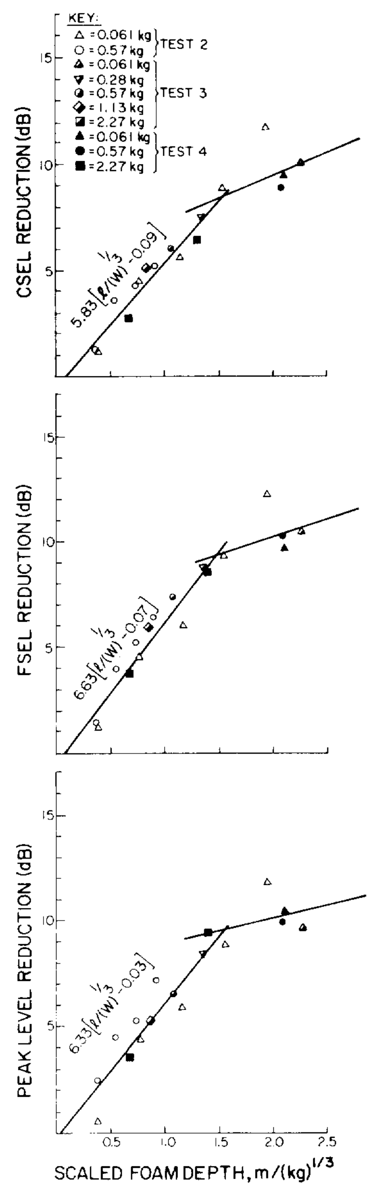

FIG. 3. CSEL, FSEL, and peak level reductions versus scaled foam dept[h] high expansion-ratio foam tests.

tions are uniformly about 12 dB. (In explosives work, it is common to use either energy or mass scaling to display data. In this case, the scaling used is the foam depth in meters divided by the cube root of the charge mass. This technique will be discussed further after the other tests are described.)[3]

C. Test 3

Test 3 investigated the effect of charge size for a constant foam depth. The enclosure used in this experiment was 1.8 m on a side. Charge masses of 0.061, 0.28, 0.57, 1.13, and 2.27 kg were fired. These data are also displayed in Fig. 3 (▽ = 0.28 kg, ◑ = 0.57 kg, ◊ = 1.13 kg, ◪ = 2.27 kg). Because the wind knocked the foam depth down by 0.08 to 0.15 m before the explosive was fired, the geometric average of 1.7, 1.8, and 1.8 m was used in the data analysis. When the sound level reductions are plotted versus the cube root scaled foam depth, the plots increase linearly up to 1.2 m/kg$^{1/3}$; at larger scaled foam depths, the reductions appear to level off.

D. Test 4

When the data from tests 2 and 3 are plotted together, it is not clear which results correctly describe the behavior of the reduction at large scaled foam depths. The test 3 data show a clear break in the rate of reduction above 10 dB—the test 2 data do not. To investigate further, three experiments were performed.

(1) A 0.061-kg charge was detonated in a $1.6\times1.6\times1.5$-m enclosure. Microphones were placed at 15 and 30 m—much closer to the charge than in tests 2 and 3—to determine if over land propagation differences could be the cause of the saturation and/or discrepancy in results.

(2) A 0.57-kg charge was centered and detonated in a $3.7\times3.7\times3.7$-m enclosure with the microphones at 60 and 120 m.

(3) A 2.37-kg charge was centered and detonated in a $3.7\times3.7\times3.7$-m enclosure with microphones at 60 and 120 m. Again, these results are shown in Fig. 3.

E. Discussion of tests 2–4

All data from tests 2–4 are plotted in Fig. 3 versus scaled foam depth. The foam depths used are the geometrically averaged foam depths or their equivalents. The lines shown are linear least squares fit to portions of the data. The first segment of the line is fitted to the data points from 0.0–1.6, the second segment from 1.2–2.5. From Fig. 3 it is apparent that:

(1) All the data obey the cube root scaling law, with the exception of the single data point from test 2, which lies well above the fitted line. This point is for a small charge mass, 0.061 kg, and such charges are generally unreliable. All of the other data points are within 1.5 dB of the lines.

(2) The maximum possible reduction is limited to about 10 dB. There appears to be a transition from a rapid increase in reduction under 1.2 scaled m to a much slower reduction over 1.2 scaled m. A similar saturation at 1.5 scaled m has been reported by Dadly *et al.*[4] in their investigation of the reduction of blast overpressures.

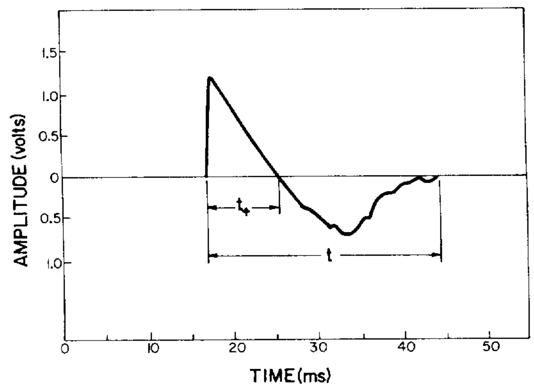

FIG. 4. Positive and total duration of a transient waveform typical of an explosion at close range.

(3) All metrics, CSEL, FSEL, and peak level, are reduced by roughly the same amount. The initial slopes are 5.8, 6.6, and 6.3 dB per scaled m, respectively. The small difference between the peak level slope and the FSEL slope indicates that the foam causes little duration change in the wave form, since the FSEL is a function of an integral over the duration of the wave.

To examine this more closely, the positive phase duration and total duration of the wave were monitored directly using a Bruel and Kjaer type 7502 Digital Event Recorder to display the transients on a screen. The positive and total durations were measured from this display (see Fig. 4). When plotted versus scaled foam depth, the positive phase duration was reduced by about 5% by the foam; the total duration was reduced by about 20%. Although there was great scatter, the total duration change tended to become smaller as the foam depth increased.

To check whether our farfield data agreed with past nearfield work, Winfield and Hill's data[5] were scaled out to 60 m using a design chart of pressure versus distance.[3] This technique is at best crude, since at close ranges energy is still being fed into the shock wave by the expanding detonation products, and the foam certainly must affect these energy transfers. This calculation also neglects the reflection of the shock wave at the foam/air interface. Still, the results of this calculation agree reasonably well with the data from our study. The initial slope of the peak pressure reduction versus scaled foam depth line is 8.6 vs 6.3 dB per scaled m measured in the present study. This difference may be due to the denser foam used by Winfield and Hill,[5] or to the placement of their pressure transducers near the bottom of the foam volume, where the foam may be denser.

III. SERIES 2: LOW EXPANSION FOAM

A Mearl Corporation OT 10–5 generator was used for the dense foam experiments. The generator was adjusted to produce a stiff 30:1 expansion ratio foam at a reasonably high flow rate; the foam was made from a 5% solution of National Foam Systems $1\frac{1}{2}$% high expansion foam solution. The bubble diameter in this foam was on the order of a millimeter. The low expansion foam was quite stable; no drainage or subsidence was noticeable in the first hour after generating the foam.

The experimental set up for the 30:1 foam tests was the same as that described for the high expansion foam. The knowledge gained from the high expansion foam results allowed a simpler experiment for the low expansion foam.

Three charge masses were used: 0.11, 0.57, and 2.37 kg. Three cubical enclosures were used with the 0.11-kg charge: 0.31, 0.91, and 1.5 m on a side. Five cubical enclosures were used with the 0.57-kg charge: 0.31, 0.61, 0.91, 1.2, and 1.5 m. Two cubical enclosure sizes were used with the 2.27-kg charge: 0.91 and 1.52 m. The enclosures were oversized by 0.2 m on length and width; thus, the foam depth used in the data analysis was the geometric average of the enclosure dimensions divided by two.

The reductions in noise level from the various trials and microphones were averaged. These are plotted in Fig. 5.

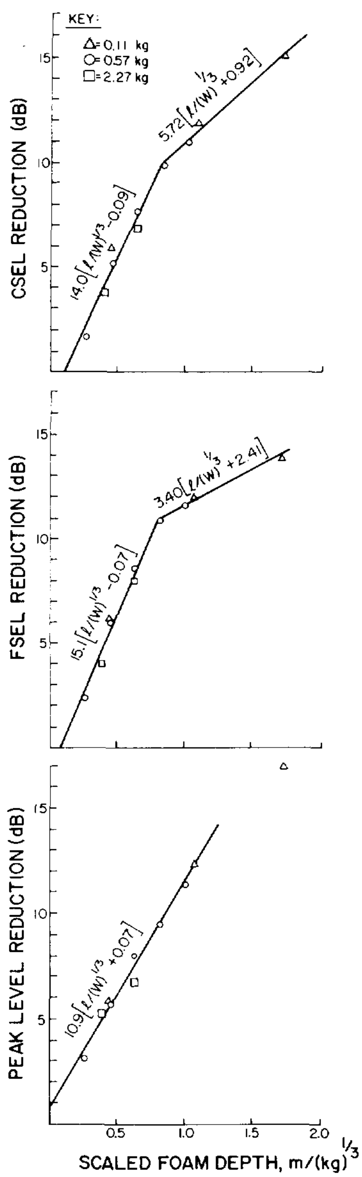

FIG. 5. CSEL, FSEL, and peak level reductions versus scaled foam depth; low expansion-ratio foam tests.

Three features in Fig. 5 are of interest.

(1) The data scale rather well; all the points lie close to the best fit lines when reduced to scaled coordinates. None of the points lie further from the fitted lines than 1.0 dB.

(2) As in the low expansion foam, the reduction in FSEL is not linear over the full range of scaled foam depth, but has a break point at about 0.80 scaled m. The first segment on the FSEL curve is fit to the points from 0.0–0.9 scaled m; the second segment is fit to the points from 0.8–1.3 scaled m. The CSEL has a similar break point near 0.82 scaled m. The peak level reduction does not display as clean a break point; however, the point corresponding to the largest scaled distance is under the curve fit to the rest of the points. In each case where present, the break point does occur at a 10–11-dB reduction—similar to the break points in the series I tests.

Above the break point, the rate of reductions in the low expansion ratio foam is greater than in the high expansion ratio foam.

(3) As with the high expansion foam, the low expansion foam reduced the FSEL more than it reduced the peak level. The initial slope of the peak level curve is about 11 dB per scaled m, while the initial slope of the FSEL curve is about 14 dB per scaled m. This again indicates that the foam slightly reduces the time duration of the waveforms.

To further investigate the characteristics of this reduction, positive and total durations were measured in several of the tests. Like the high expansion foam test data, the low expansion foam data displayed great variation in duration reductions. The dense foam reduced the positive duration by about 20%; the reduction in total duration was about 30%, with changes scattered down to 0% and up to 44%. Even for identical tests, the changes varied from 5%–30%. There is a small tendency for the duration change to get smaller as the foam depth increases, as in the case of high expansion foam. The 30% reduction in total duration corresponds to a 1.5-dB difference between peak and FSEL reduction, if no change in shape occurs.

IV. EFFECT OF FOAM DENSITY

Test series 1 and 2 considered only two different foam expansion ratios: 250:1 (high expansion ratio foam) and 30:1 (low expansion ratio foam). For each foam, a cube root scaled foam depth was used to organize the test results for widely varying charge sizes into a single set of curves for each sound level metric. The success in scaling the results for different charge masses in this way indicated that perhaps the two sets of data could be combined if plotted against a scaled variable which include the foam density. To pursue this possibility, the literature on blast scaling was examined.

An explosives scaling law which includes the density of the surrounding media is Lampson's earth shock scaling law[6]

$$(p_1 - p_0)/p_0 = h(\rho_0 R^3/w), \quad (1)$$

where

$h(\ )$ is a function only of $\rho_0(R^3/w)$
ρ_0 is the density of the medium surrounding the charge
R is the distance from the charge center
w is the mass of the charge.

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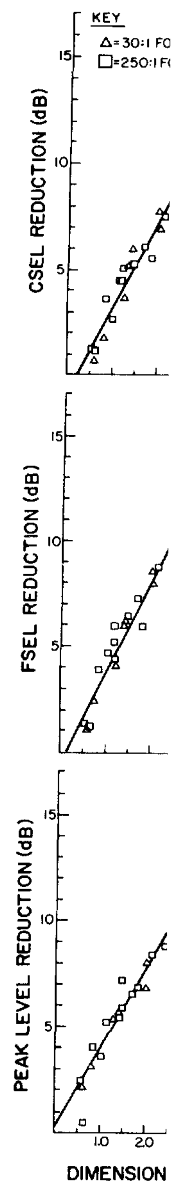

FIG. 6. CSEL, F
depth.

Since the reduction data from the tests of high and low expansion foams scaled well as a function of $(l^3/w)^{1/3}$, Lampson's scaling law suggests that plotting both sets of data as a function of $(\rho_l^3/w)^{1/3}$, where ρ is the foam density, may result in a unification of the predictions.

All of the data from test series 1 and 2, except for the data from test 1 of series 1, are plotted versus dimensionless foam depth in Fig. 6. The dimensionless foam depth used in this figure is the geometrically averaged foam depth multiplied by the cube root of the foam density in kilograms per cubic meter and divided by the cube root of the charge mass in kilograms of TNT. (When charge mass is used in scaling laws, it is common to express it in terms of an equivalent mass of TNT. The C-4 used in our experiments is about 1.34 times as energetic as TNT; to agree with scaling conventions, our charge masses were adjusted by that factor.) The dimensionless foam depth is

$$X = (\rho l^3/w)^{1/3}, \tag{3}$$

where

ρ is the foam density in kg/m^3
l is the geometrically averaged foam depth
w is the mass of explosive in kilograms of TNT.

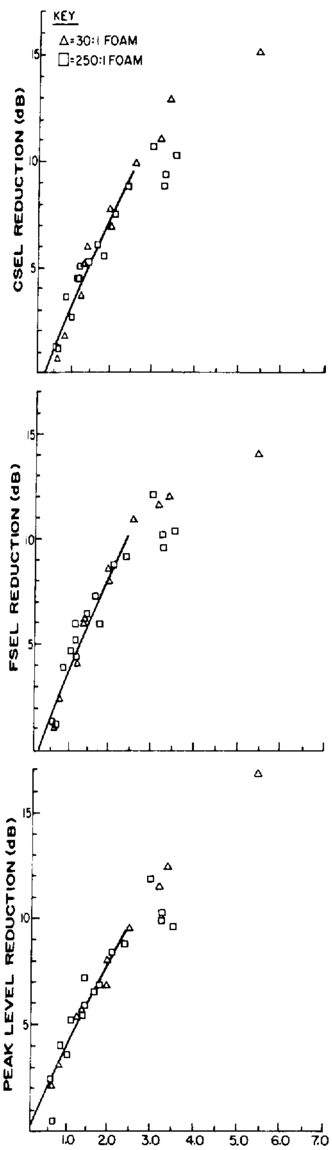

FIG. 6. CSEL, FSEL, and peak level reductions versus dimensionless foam depth.

The density of the foam is given by the density of water (1000 kg/m^3) divided by the expansion ratio.

From Fig. 6, we see that the data scale well for all metrics up to a dimensionless foam depth of 2.5. Little or no systematic differences were detected between the high and low expansion foam results. Thus the foam scaling laws and Fig. 6 can be used to predict the reduction produced by varying foam densities, foam depths, and charge masses. However, there are not enough data at different foam densities to establish that the foam scaling laws hold for widely varying foam densities. For example, in the extreme case of pure water (expansion ratio 1:1), the foam scaling laws do not hold. The reductions produced by water were measured by detonating a 0.57-kg charge of C-4 in the center of a 0.39-m cube. The dimensionless foam depth calculated for this experiment was 2.22, which by Fig. 6, would result in reductions of 8.0, 8.7, and 8.2 dB in CSEL and FSEL, and peak level, respectively. The actual average reductions, measured by microphones at 30, 60, and 120 m and averaged, were only 3.8, 3.7, and 5.7 dB.

The foam scaling laws do not hold for dimensionless foam depths greater than 2.5. Above 2.5, the denser foam produced greater reductions than the lighter foam.

V. DISCUSSION OF RESULTS

The results observed in these tests can be explained by a two mechanism model of blast noise reduction by foams. The noise reduction data clearly separates into two regimes, above and below a dimensionless foam depth of 2.5. Below 2.5, the data scales with density and displays a rapid reduction in noise level with increasing foam depth. Above 2.5 the rate of reduction is smaller and does not scale with density. The break point occurs at different scaled radii for the two foams, however, it occurs at about the same pressure. This pressure, calculated from the reduction data and the bare charge pressure[3] is on the order of a few hundred kPa. From independent tests of foam collapse, it has been found that these pressures are very close to the minimum pressure necessary to fracture the foam cells and so form a fine water mist.[7] With this knowledge it is evident that at least two distinct mechanisms of noise reduction are operative. (1) Strong wave decay through the water mist of the fractured foam; and (2) nonacoustic decay of the weak wave through the intact foam. The first mechanism is dominant close to the explosive, where peak pressures are very high; the second one dominates further out, in the low pressure regime.

In general, the decay of strong waves depends on the irreversible work performed on the fluid between its initial state (before the wave has arrived) and its final state (after the fluid has returned to ambient pressure).[8,9] This is often called the waste or lost work and is related to the entropy produced between the initial and final fluid states. For a homogeneous fluid, the source of lost work is viscous dissipation due to the very large strains across the thin wave front. In a two-component material like foam, however, other sources of irreversible work are also available; the slip and heat transfer between the air and water as the two components come to equilibrium are both irreversible processes. For high peak pressures, the water in the foam is broken into extremely fine droplets, each with a large specific surface area, so that the heat and momentum transfer between the two components is very rapid. This leads to substantial irreversible work in the small time available between the arrival of the front and passage of the wave. This may account for the observation that foams reduce sound levels more effectively than solid/air systems of comparable density. That is, solids cannot fracture into small particles that provide a very large surface area. In addition, the maximum possible strains are much larger in a foam than they are in air alone: the shock compression ratio in air is limited to about six; in dense foams, the rapid heat transfer from the air to the water permits a maximum compression ratio of about 30. Consequently, foams may exhibit enhanced strain-dependent entropy production.

Note that this intercomponent transport mechanism cannot be responsible for the observed reductions at large foam depths. At the small peak pressures in the foam at large depths, the particle velocity and temperature rise are so small that heat and momentum transfer between the air and water cannot generate significant irreversible work.

At large scaled foam depths, the peak pressures are very small. In this regime, a wave propagating in a homogeneous material would experience acoustic decay with (for spherical geometry) its characteristic inverse distance effect on the sound levels. Thus, if the foam were homogeneous, some finite scaled depth would provide the maximum attainable benefit available from a given foam. At larger scaled depths, the sound levels would decay at the same rate in air and in the foam and so no further reductions would be obtained; the data in such a case would break to form a horizontal line. Since the data show a continued small increase in reductions beyond the break point, we conclude that at large scaled foam depths the waves are experiencing a dispersive, slightly nonacoustic decay in the additional foam. A weak wave propagating through the foam is partially reflected at each interface. This partial reflection results in nonacoustic attenuation and dispersion of the wave.[10] We will further examine the dispersion when we discuss the foam induced changes in the pulse duration.

We note that the combined scaling of Fig. 6 supports our two mechanism model. Below a dimensionless foam depth of 2.5 the data scale with density. Since the foam is shattered by the passing shock, the reduction depends only on density and not on details of foam dimensions or cell structure. We expect the scaling to hold in this range provided that the isothermal compressibility of the air/water mixture remains approximately that of air and that direct interaction between water particles (in the compressed state) is not significant.

We likewise expect that the density scaling law should fail for large foam depths since our proposed farfield mechanism of low pressure weak decay depends not only on foam density but also on foam structure. The low expansion foam has a much smaller characteristic bubble size and so a much larger specific surface area than the high expansion foam. Therefore, it should cause a more rapid attenuation of the weak wave by reflections in the intact foam. This is observed in Fig. 5 where the attenuation rate above a dimensionless foam depth of 2.5 is much more rapid in the low expansion foam.

The duration changes measured for both foams also support our proposed two mechanism model. For the high expansion foams the positive duration was reduced by about 5% and the total duration by about 20%. The total reduction becomes smaller with increasing foam depths. For the low expansion foam, the positive duration was reduced by 20%, and the total duration reduced by 30%. Again, the total duration change becomes smaller with increasing depth. The large scatter in this data prevents a detailed analysis of these changes, but a consistent explanation can be given.

To understand the reductions in wave duration, we must address three influences: the duration of the wave delivered by the explosive, broadening of the wave as it travels through the foam (if present), and broadening as it propagates through the surrounding air to the microphones. For farfield measurements the last of these—growth of the positive-phase duration as the wave travels through the air—is dominant, provided that the peak pressure at the foam/air interface is not small.[11] Most of the positive duration is accrued in the air, so that even if the foam significantly altered the duration at the location of the interface, this would have only a small effect on the values measured at a large distance from the charge. The small reductions noted in the positive-phase duration are, therefore, probably due only to the lower peak pressures (when foam is used) and the consequent reduction in rate of growth of the pulse width in the air. As more foam is used, the wave broadening due to the dispersion inside the foam becomes significant enough to partially offset the diminishment due to reduced peak pressures, leading to an overall smaller reduction in the positive-phase duration.

Since the reductions in total duration are more pronounced than those for the positive phase, it is apparent that the foam must have a strong influence on the negative-phase duration. Because the negative duration is nearly independent of the length of travel of the wave and of the host material, this reduction (unlike that of the positive phase) must originate in a reduced total duration delivered by the explosive. This is attributable to the (visible) absence of afterburn observed for charges fired in the foam. Afterburn occurs when the detonation products are oxygen deficient. These products react with the surrounding air to produce about 20% of the total explosive energy of C-4. Afterburning is a relatively slow process and suppressing this reaction would substantially reduce the total duration. Although this mechanism reduces the total duration significantly, the overall energy reduction is small compared to the reduction produced by the other two mechanisms discussed above. A 20%

direct reduction in explosive energy corresponds to less than 1.0-dB reduction in the SEL and peak levels.

VI. CONCLUSION

Two densities of aqueous foam have been tested for use in reducing blast noise from a wide range of explosive masses. The low density 250:1 expansion-ratio foam gives an initial rate of reduction of 5.8, 6.6, and 6.3 dB per scaled meter of foam depth in the CSEL, FSEL, and peak level measurements, respectively. In each sound metric, a break occurs in the reductions at about 10 dB; this takes place at a scaled foam depth of 1.5 $m/kg^{1/3}$ and additional foam beyond this point gives a much smaller rate of noise reduction.

The high density 30:1 expansion-ratio foam produces initial rates of reduction of 14.0, 15.1, and 10.9 dB per scaled meter of foam depth in the CSEL, FSEL, and peak sound levels. As with the low density foam a break occurs in the rate of reduction of the FSEL and CSEL at a 10-dB total reduction. In the high density case, however, the break takes place at a smaller scaled depth of about 0.9 $m/kg^{1/3}$. No clear break in the rate of reduction of the peak level was found for the high density foam.

When all the test data are scaled by the foam density as well as the explosive mass, the reduction results for both the high and low density foams fall on a single curve for each sound metric—up to a dimensionless foam depth of 2.5. Below this dimensionless foam depth, our proposed mechanism of noise reduction is the strong-wave decay due to irreversible intercomponent heat and momentum transfer between the air and water in the foam. This mechanism depends only on the density and not details of the foam structure.

Above a dimensionless foam depth of 2.5 the high density foam gives a larger rate of reduction than the low density foam. In this regime, the apparent mechanism of mitigation is the reflection of the waves within the intact foam. The high density foam gives a larger rate of reduction here only because of its smaller cells and larger internal surface area. The rates of reduction in the sound metrics is much smaller in both foams above a foam depth of 2.5, indicating that the strong-wave mechanism is significantly more important than the nonacoustic decay mechanism for noise reduction.

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