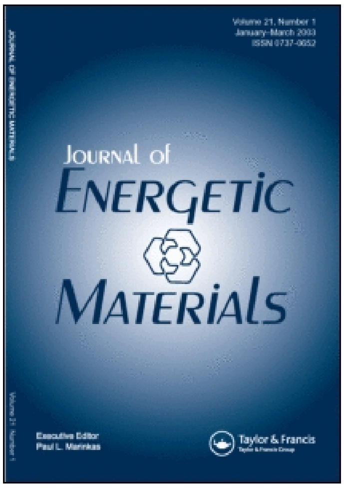

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Modelling of the underwater shock sensitivity of polyurethane FOAM / PETN explosives

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MODELLING OF THE UNDERWATER SHOCK SENSITIVITY OF POLYURETHANE FOAM / PETN EXPLOSIVES

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ABSTRACT

The underwater shock sensitivity of a Polyurethane Foam / PETN explosive system was investigated using the Forest Fire model. Pop plots for the explosive were determined by conducting calibrated gap tests. Wedge tests were used but proved extremely difficult to control due to the inhomogeneity of the explosive, its low detonation performance and its high sensitivity. Numerical modelling of calibrated gap tests and underwater gap sensitivity experiments yielded results very close to the experimental ones indicating that the technique is applicable to the low density - low impact pressure regimes.

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INTRODUCTION

Although low density explosives have been developed since the early 1950's their sensitivity is still not very well known. Yet their applicability largely depends on their sensitivity characteristics. The present study deals with the shock sensitivity underwater of a polyurethane / PETN system at a PETN concentration of 60% by weight and a density of 0.6 g/cm^3. The PETN component has a particle size between 50 and 70 μm and is dispersed evenly throughout the polyurethane foam matrix producing a low density explosive. The density of the foam is controlled by the addition of water (0 - 0.5 percent by weight)(1).

Due to the nature of the explosive, shock sensitivity models for heterogeneous explosives were examined.

The models which have been used for modelling shock sensitivity of heterogeneous explosives are the Critical Energy Criterion(2), the Forest Fire Model(3,4) and the Ignition and Growth Model(5). For computational purposes the last two are the ones commonly used. For modelling the underwater performance of the polyurethane/PETN system, it was decided to use the Forest Fire model mainly because its calibration is easier and the HOM equation of state for the system was well known from previous work(6). Thus wedge tests and calibrated gap tests to obtain the Pop Plot were performed and Forest Fire rates were calculated. The model was validated by modelling the calibrated gap tests as well as underwater gap tests using the TDL computer code[4,7].

EXPERIMENTAL DETERMINATION OF THE POP PLOTS

Wedge Shots

The initial approach to obtain the distance of run to detonation - initial pressure relationship was to use wedge tests. The experimental set up used is shown in Figure 1. The base of the wedge was 7.20cm x 7.20cm and its height was 2.6 cm. This provided a wedge angle of 20 degrees. Due to the size of the wedge a 25.4 cm diameter plane wave generator had to be developed in order to be able to use an attenuator having a thickness of about 8.8 cm. These conditions were imposed by the fact that the wedge base should have a minimum width of 7.2cm (to achieve ideal detonation) and the assumption that rarefactions destroy the planarity of the wave at a 45 degree angle.

The plane wave generator used is a binary explosive system consisting of sensitized nitromethane surrounding nitromethane absorbed by an inert material to provide the consistency of a paste and mixed with microballoons to reduce detonation velocity and provide adequate sensitivity[8]. The planarity of the wave of this plane wave generator was tested and found satisfactory (spread of the wave across the front face of less than 175 ns).

The attenuator used consisted of a combination of metallic plates, styrofoam and plexiglas, designed to reduce the pressure in the foam to about 2 kbar. The thickness of the various plates was such that the maximum total thickness of the attenuator was 8.9 cm to avoid the destruction of the planarity of the wave due to side rarefactions.

Wedge Test Results

The results of the wedge tests are presented in Table 1. The materials used to construct the attenuator are listed in order starting from the plane wave lens and progressing to the acceptor. A typical wedge test result is shown in Figure 2.

TABLE 1
Wedge Test Results

Attenuator	Shock Velocity of Explosive (m/s)	Distance of Run to Detonation (mm)	Free Surface Velocity of Attenuator (m/s)
Pl/Al/Pl/St/St	2280	2.6	1235
Pl/Al/St/Pl/St	2780	3.7	
Pl/Fe/Pl/St/St	2070	2.6	
Al/St/Al/St/St	2630	3.1	1480
Al/St/Fe/St/St	2200	3.7	790
Al/St/Fe/St/St	2130	4.0	
Fe/St/Fe/St/St	2680	2.6	
Pl/St	2460	2.6	
Al/St/Al/St/St	3300	3.2	1500

Pl - Plexiglas (12.7 mm thickness)
St - Styrofoam (25.4 mm thickness)
Al - Aluminum (12.7 mm thickness)
Fe - Steel (12.7 mm thickness)

No clear transitions to detonation were obtained by the method used. It seems that the detonation wave decelerates soon after it is generated in the explosive. This can be attributed to curvature of the wave in the last part of the wedge. Furthermore there was considerable scatter on the results. This is probably due to the large size of discontinuities and the lack of strict control of the explosive foam. The bubble size of the foam cannot be controlled even in the same batch and the distribution of the PETN explosive might not be uniform. The effect of the inhomogeneity of the foam on the detonation wave was examined in a series of experiments in which a cylinder of explosive foam was detonated and the arrival of the shock wave at the base of the cylinder opposite the point of initiation was photographed by the streak camera. The detonator and primer were centrally located and the length of the charge was sufficient for the detonation to reach steady state. A typical result is given in Figure 3.

It is obvious that the wave is not curved as might have been expected. Also it is not symmetrical indicating the effect of the heterogeneous nature of the product. Unfortunately wedge shots have the disadvantage of amplifying the effect of these inhomogeneities by multiplying their effect times $1/\sin\theta$ where θ is the wedge angle. This is probably the reason why the results from the various wedge experiments were scattered.

The shock velocities in the acceptor as obtained by the wedge tests seem to be very high. This can be attributed either to immediate reaction of the acceptor or to non planar shock wave in the wedge. Immediate reaction is rather difficult to accept in view of the findings of the calibrated gap tests (discussed in the following) which showed definite distances of run and reaction starting well inside the acceptor. Moreover the pressures in the explosive foam, estimated by measuring the free surface velocity at the surface of the attenuator (styrofoam) were below 2 kbar which should be low enough to eliminate the possibility of an over driven detonation in the acceptor charge. To estimate those pressures the Hugoniot of styrofoam was assumed to be $U_s = 0.0 + 1.5U_p$, the density of styrofoam was 0.03 g/cm^3, the Hugoniot of the acceptor charge was assumed to be $U_s = 0.015 + 1.5U_p$ and the density of the acceptor charge was 0.6 g/cm^3. In the previous Hugoniots both U_s and U_p are in cm/μs.

Calibrated Gap Tests

Since the wedge tests resulted in inconclusive results, a calibrated gap test was designed to obtain data for the Pop Plot of the polyurethane - foam explosive. The experimental set up is shown in Figure 4. The test consists of a donor charge, an attenuator plate an acceptor charge and an argon filled light bomb. The donor is made of three disks of pressed waxed RDX (91% RDX, 9% wax by weight). Each disk has a diameter of 7.62 cm and a height of 2.54 cm. The density of the charge is 1.50 g/cc. The attenuator is made of square plates of plexiglas with dimensions of 7.62 cm x 7.62 cm.

The block of plexiglas is normally polished so that it is transparent. The acceptor has the same diameter as the donor and a height of 7.62 cm and is placed in such a way that they have a common axis of symmetry. The various parts of the experiment are glued carefully with plexiglas glue so that no air bubbles are included in the mass of the donor and attenuator or at the interfaces.

The donor is initiated by 5g of Detasheet and the event is recorded by using a streak camera the slit of which is at the centre of the charge and parallel to its axis. The camera records the shock wave in the attenuator and the shock to detonation transition in the acceptor as it appears on the surface of the charge. In most of the cases the transition point is clear from the hook produced in the record by the simultaneous detonation and retonation of the charge. Typical results are shown in Figure 5.

The results of the calibrated gap tests are reported as pressure in the acceptor and distance of run to detonation. The pressure in the acceptor is found by locating the intersection of the reflected Hugoniot of the attenuator at the point determined by the measured shock wave velocity at the interface (plexiglas attenuator - explosive foam) and the direct Hugoniot of the acceptor. The Hugoniot of plexiglas was expressed by(4):

$$U_s=0.2430+1.5785U_p \qquad (1)$$

while the Hugoniot of the explosive foam was estimated by:

$$U_s = 0.0150 + 1.5U_p \qquad (2)$$

where U_s is the shock velocity (cm/μs) and U_p is the particle velocity (cm/μs). The distance of run to detonation was read from the streak camera record. Due to the irregularity of the wave no correction for the curvature of the wave was applied to the measurement. Nevertheless, from the records of the shots examining the shape of the wave across the diameter of a cylindrical charge (a typical example is shown in Figure 3) it was estimated that the maximum error would be less than 0.25 cm.

The results of the gap tests are presented in Table 2. The

TABLE 2
Results of Gap Tests

Plexiglas Thickness (cm)	Pressure (Mbar)	Distance of Run to Detonation (cm)
6.3	0.0124	0.45
6.8	0.0111	0.58
7.6	0.0091	0.90
8.2	0.0077	0.97
9.1	0.0055	1.11
9.6	0.0046	1.18
9.8	0.0039	1.48
10.2	0.0031	failed
10.3	0.0031	failed

resulting Pop Plot can be expressed as:

$$\ln(x^*) = -4.4344 - 0.87326 \ln(P) \qquad (3)$$

where x^* is the distance of run to detonation (cm) and

P is the initial pressure in the foam (Mbar).

The coefficient of determination for the above expression was 0.88 which is considered sufficient given the nature of the explosive and the nature of the test.

FOREST FIRE COEFFICIENTS - MODEL VERIFICATION

The Pop Plot obtained previously was used to determine Forest Fire Coefficients for the Polyurethane foam - PETN explosive.
The Forest Fire coefficients were calculated by using the FFIRE computer code(3). Input data are the HOM parameters for the solid explosive, the HOM parameters for the detonation products, the reactive Hugoniot and the Pop Plot. Output is the decomposition rate as a function of pressure in a table form which can be fitted to equation(3,4)

$$\ln(rate) = A_0 + A_1 P + A_2 P^2 + \ldots + A_n P^n \qquad (4)$$

by a least squares fit.

The HOM parameters have been determined and reported previously(5). The reactive Hugoniot was estimated using the same estimated sound speed of the unreacted explosive and its calculated C-J state parameters (detonation velocity of 0.377cm/μs and detonation pressure of 26.2 kbar) which are close to the experimental values(9) and assuming that the shock velocity - particle velocity relationship is linear.

The input data are presented in Table 3. The Forest Fire coefficients are shown in Table 4.

VERIFICATION

The verification of the calculated Forest Fire coefficients was performed in two stages. The first stage involved the modelling of the calibrated gap experiments while the second involved the performance and modelling of underwater gap experiments. Modelling was performed by the TDL (Two Dimensional Lagrangian) hydrocode(4,7).

Modelling of the Gap Experiments

For the modelling of the gap experiments, HOM data for the donor (waxed RDX), attenuator (plexiglas) and acceptor (polyurethane foam - PETN) are required. The HOM parameters for the donor are shown in Table 5. The solid HOM parameters were assumed to be the same as for PBX 9407 with a low density of 1.5 g/cm^3 while the

TABLE 3
Input Data for the Forest Fire Model

REACTIVE HUGONIOT

Parameter	Value
C	0.0150 cm/μs
S	3.1250

POP PLOT

$$\ln(x^*) = -4.4344 - 0.87326 \ln(P)$$

(x^* in cm and P in Mbar)

HOM PARAMETERS

SOLID		GASEOUS	
Parameter	Value	Parameter	Value
C	0.1500000000E-01	A	-0.348488795700E+01
S	0.1500000000E+01	B	-0.214968235620E+01
F	0.7028132000E+01	C	0.201946522059E+00
G	-0.2169825000E+01	D	-0.155694314760E-01
H	0.1050892000E+02	E	0.332200669700E-03
I	0.6761549000E+02	K	-0.139413906130E+01
J	0.9900002000E+02	L	0.368105328620E+00
V_0	0.1666666667E+01	M	0.476178105180E-01
C_v	0.3500000000E+00	N	0.306922137860E-02
γ	0.1500000000E+01	O	0.750069583600E-04
		Q	0.776378454960E+01
		R	-0.452785271170E+00
		S	0.107815496290E+00
		T	-0.143297558500E-01
		U	0.689396034930E-03
		C_v	0.900000000000E+00
		Z	0.100000000000E+00

gaseous parameters were calculated by fitting the expansion isentrope predicted by TIGER to the gaseous HOM equations. Data for the Plexiglas were found in the literature[4] and presented in Table 6 while the acceptor was modelled by using the same data used in the Forest Fire model (Table 3). The donor was burned by using the sharp shock model while the acceptor was burned according to the

TABLE 4
Forest Fire Coefficients for Polyurethane Foam - PETN

Coefficient	Value
A_0	-0.927671909413 E+01
A_1	0.251968171872 E+04
A_2	-0.398164004252 E+06
A_3	0.352665935709 E+08
A_4	-0.151226379675 E+10
A_5	0.250546214292 E+11

TABLE 5
HOM Parameters for the Waxed RDX Donor

SOLID		GASEOUS	
Parameter	Value	Parameter	Value
C	0.1328000000E+00	A	-0.362081869972E+01
S	0.1993000000E+01	B	-0.227785354690E+01
F	0.1487924490E+02	C	0.223118556376E+00
G	0.2942381533E+02	D	-0.181095930794E-01
H	0.5140788160E+02	E	0.559530466360E-03
I	0.3666680381E+02	K	-0.153439161906E+01
J	0.1077530936E+02	L	0.481624308042E+00
V_0	0.6666666667E+00	M	0.672740592823E-01
C_V	0.2930000000E+00	N	0.482242728914E-02
γ	0.1730000000E+01	O	0.138126837430E-03
		Q	0.749095589915E+01
		R	-0.422147183265E+00
		S	0.416848511825E-01
		T	0.205833985706E-01
		U	-0.568458461297E-02
		C_V	0.565000000000E+00
		Z	0.100000000000E+00

Forest Fire model. The cell size for the finite difference grid was 0.4cm x 0.4cm and the geometry selected was the same as in the experiment. The results of the runs are shown in Table 7. Figure 6 shows the pressure and the undecomposed mass fraction along the axis of the acceptor charge for the case for which the attenuator thickness was 9.6 cm while Figure 7 shows the undecomposed mass fraction contours at various times for the same experiment. The interval of the contours is 0.1 and the time of each graph is expressed in microseconds. It is obvious that the acceptor detonated. It can be observed that the distance of run to high order detonation is about 2 cm which is acceptable compared to the experimental measurement of 1.2 cm, the value of 1.3 cm produced by the fit of the Pop Plot (equation 3) and the low impact pressures

TABLE 6
HOM Equation of State Parameters for Plexiglas

Parameter	Value
C	0.24320000000E+00
S	0.15785000000E+01
F	0.52938024351E+01
G	-0.42495037137E+01
H	-0.15505557633E+02
I	-0.30863807557E+02
J	-0.14670819374E+02
V_0	0.84745762700E+00
C_v	0.35000000000E+00
γ	0.10000000000E+01

involved. Figures 8 and 9 present the same properties for the 10.8 cm gap case in which the acceptor failed to detonate.

TABLE 7
TDL Results for Calibrated Gap Shots

Plexiglas Thickness (mm)	Result	Distance of Run to Detonation (cm)
92	Detonation	1.6
96	Detonation	2.0
100	Detonation	3.2
104	Failure	-
108	Failure	-

Modelling of the Underwater Experiments.

In order to examine the model in predicting the sensitivity of the polyurethane foam - PETN explosive underwater, underwater experiments were conducted and modelled.

TABLE 8
Results of the Underwater Gap Tests

Gap Distance (mm)	Result
55	Detonation
60	Detonation
63.5	Detonation
70	Failure
70	Detonation
72	Failure
75	Failure

The experimental arrangement is shown in Figure 10 while a typical streak camera record appears in Figure 11. The donor and acceptor charges consist of 7.2cm diameter, 7.6cm long cylinders of the foam explosive placed in 0.4 cm thick plexiglas tubes. The results of the tests are presented in Table 8.

For the pupose of modelling, HOM parameters for the polyurethane - PETN explosive, water and plexiglas are necessary. The HOM parameters for the explosive and plexiglas have been presented previously; the parameters for water are presented in Table 9.

TABLE 9
HOM Equation of State Parameters for Water(4)

Parameter	Value
C	0.14830000000E+00
S	0.20000000000E+01
F	0.57205950000E+01
G	0.69263060000E+00
H	0.88139450000E+01
I	0.36011980000E+02
J	0.60133030000E+02
V_0	0.10000000000E+01
C_v	0.10000000000E+01
γ	0.10000000000E+01

For the calculations the cell size used was 0.2 cm x 0.2 cm. The geometry used was axisymmetric and the finite difference grid represented the geometry of the experiment (radius of 12.7 cm, height 24 cm).

The results of the modelling of the underwater gap tests are

TABLE 10
TDL Results for Underwater Gap Shots

Gap Thickness	Result	
(mm)	Low density fit[9]	RDX fit of BKW
60	Detonation	Detonation
64	Detonation	Detonation
68	Marginal	Detonation
70	Failure	Detonation
72	Failure	Detonation
74	-	Marginal
78	-	Failure

summarized in Table 10. As can be seen by comparing Table 10 to Table 8 the agreement between predicted and measured results is good. This suggests that the shock sensitivity of the PETN - polyurethane foam explosive is well modelled by the Forest Fire model and the derived coefficients. The difference in the results of the two types of fit (low density, RDX) for the BKW equation of state stems from the fact that the low density fit resulted in slightly lower performance parameters for the explosive foam[9], thus reducing the shock wave amplitude in the water attenuator. It is worth noting that the low density fit resulted in performance parameters very close to the experimental ones (detonation velocity of 0.36 cm/μs, detonation pressure 25 kbar)[9].

Figure 12 shows the pressure distance and the undecomposed explosive mass distance profiles along the axis of a gap experiment with a 6.4 cm gap in which detonation occurred. Figure 13 shows the undecomposed explosive mass fraction contours for the same experiment. The contour increment for the undecomposed mass fraction is 0.1. The HOM parameters for the donor were calculated on the basis of the low density fit of the BKW equation of state. Results using the RDX fit$^{(9)}$ for the donor were very similar. It is apparent that the reaction originates close to the periphery of the acceptor. This is due to the fact that the shock wave travels faster in water than in the unreacted explosive foam. As a result there is a convergence of shock waves inside the acceptor producing high pressure spots at which decomposition is more intense.

Figures 14 and 15 show the pressure and mass fraction profiles along the axis of the experiment as well as the undecomposed mass fraction contours for the case of a 7.0 cm gap in which the acceptor failed to detonate. It is apparent that no significant decomposition occurs in the acceptor charge.

CONCLUSIONS

The Forest Fire shock initiation model was implemented to predict the underwater shock sensitivity of the low density polyurethane - PETN explosive foam (60% PETN - 40% Polyurethane by mass at a density of 0.6 g/cm^3).

The Pop Plot for the explosive foam was obtained by conducting calibrated gap tests. Wedge tests were also conducted. However, due to the inhomogeneity of the explosive foam, its high impact sensitivity and its low detonation performance, the wedge tests proved extremely difficult to control.

The derived Forest Fire parameters were used in the hydrodynamic code TDL to predict the underwater shock sensitivity of the explosive foam and the results were compared to experimental data obtained from underwater gap experiments. The agreement between calculated and experimental results was good.

The modelling of the experiments showed that the underwater sensitivity of the explosive depends on its geometric characteristics which can enhance the convergence of the shock waves resulting in high pressure spots inside the explosive.

The success of the modelling in predicting gap sensitivity with a plexiglas attenuator and underwater suggests that the obtained Pop plot and the Forest Fire coefficients are accurate and could be used to predict the underwater shock sensitivity of the explosive solid foam.

The applicability of the Forest Fire model was extended by the present work to the modelling of the shock sensitivity of low density explosives indicating that the technique can be used in the low density and low pressure regimes.

Furthermore the technique for obtaining distances of run to detonation and the methodology used offer an alternative to the use of wedge shots to obtain Pop Plots. It is worth noting that wedge shots are difficult to perform and can result in inconclusive results in the cases of explosives with relatively large particle sizes, commercial explosives or explosives with a slightly non uniform distribution of their ingredients.

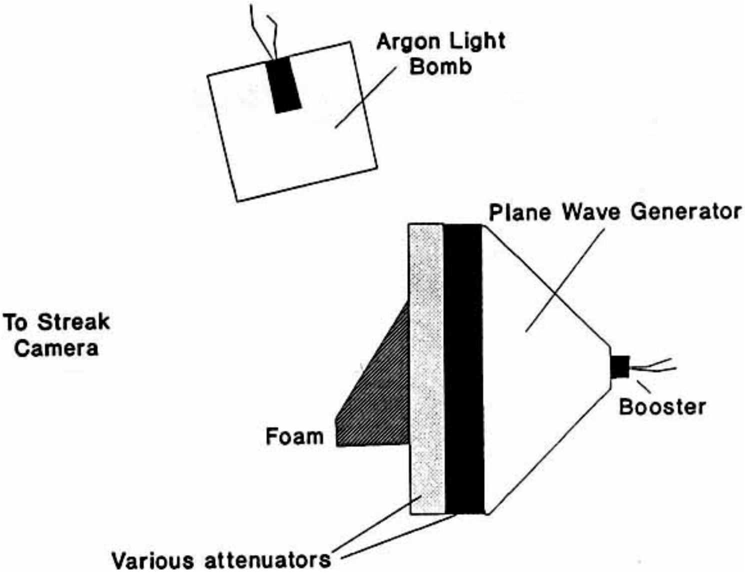


FIGURE 1

Wedge Shot Arrangement

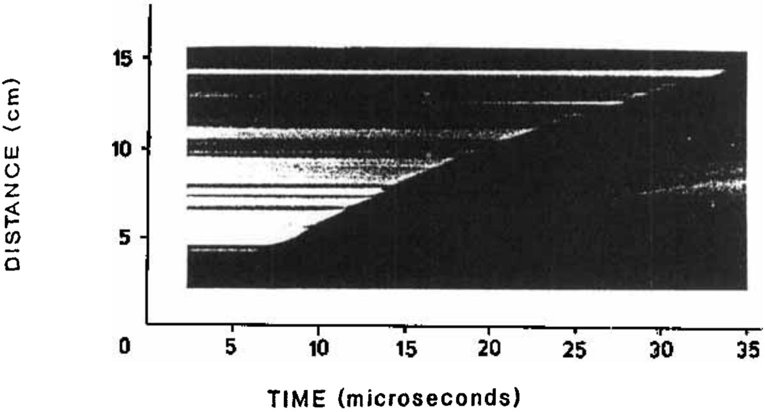


FIGURE 2

Streak Camera Record from a Wedge Shot

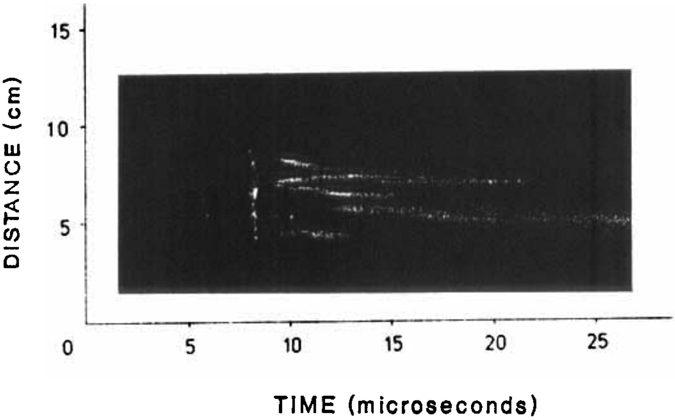


FIGURE 3

Streak Camera Record of the Detonation Wave Emerging from a Cylindrical PETN / Polyurethane Foam Charge.

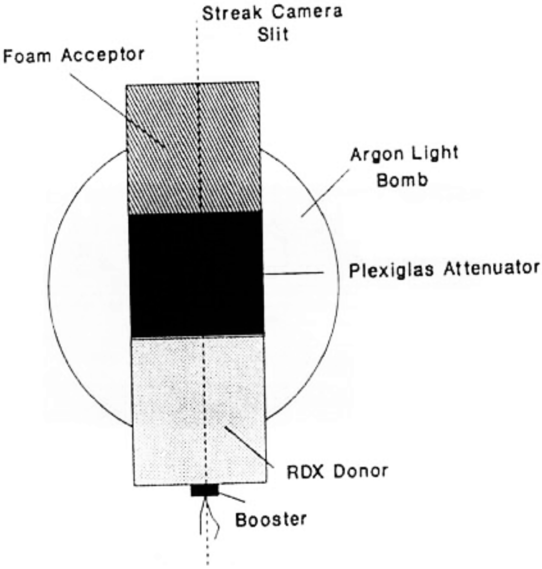
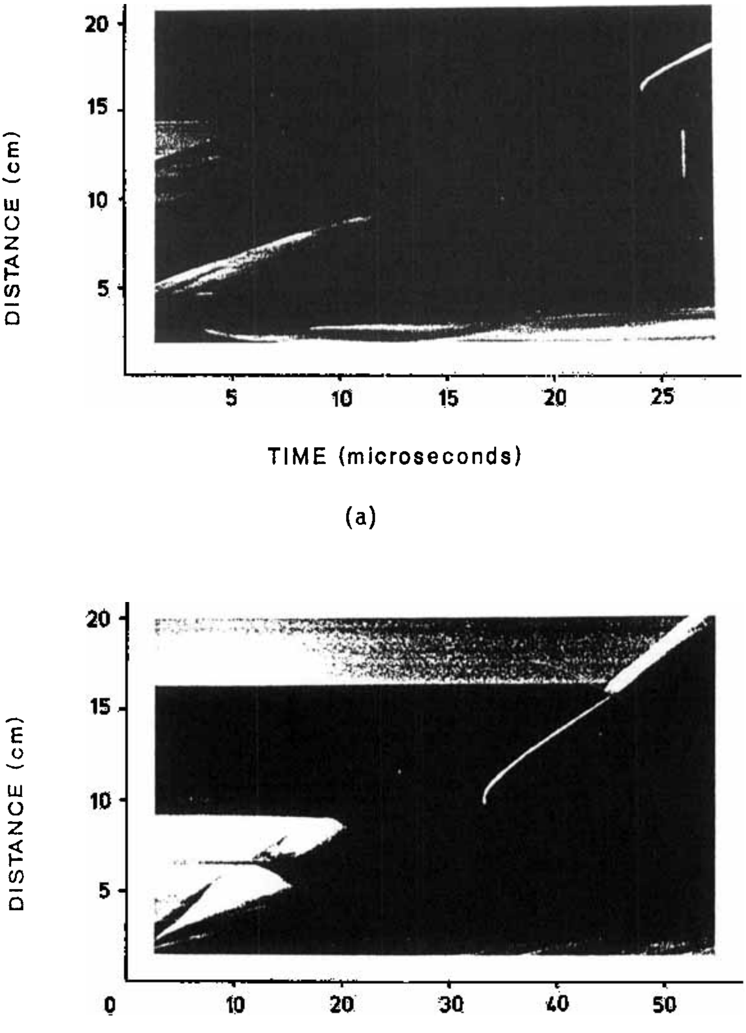


FIGURE 4

Experimental Set up for the Calibrated Gap Test.



(a)

(b)

FIGURE 5

Typical Streak Camera Records from Calibrated Gap Tests.
(Gap a: 98mm, b: 82mm)

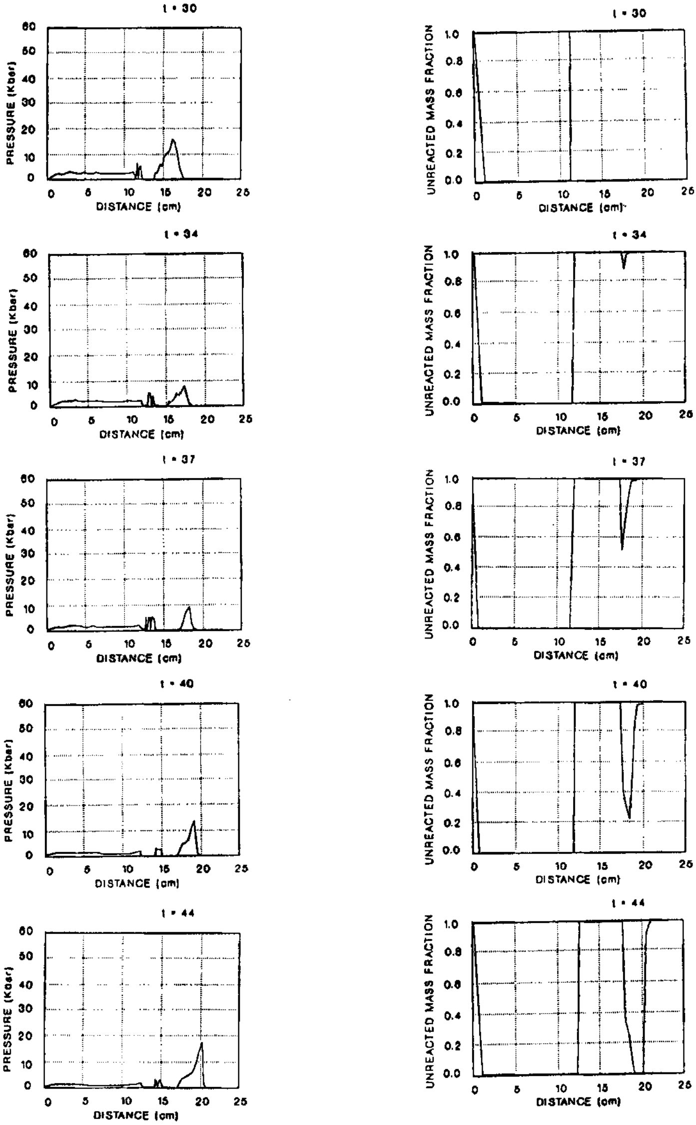


FIGURE 6

Calculated Pressure and Unreacted Mass Fraction Profiles on Axis for the Calibrated Gap Test (Attenuator Thickness : 96 mm)

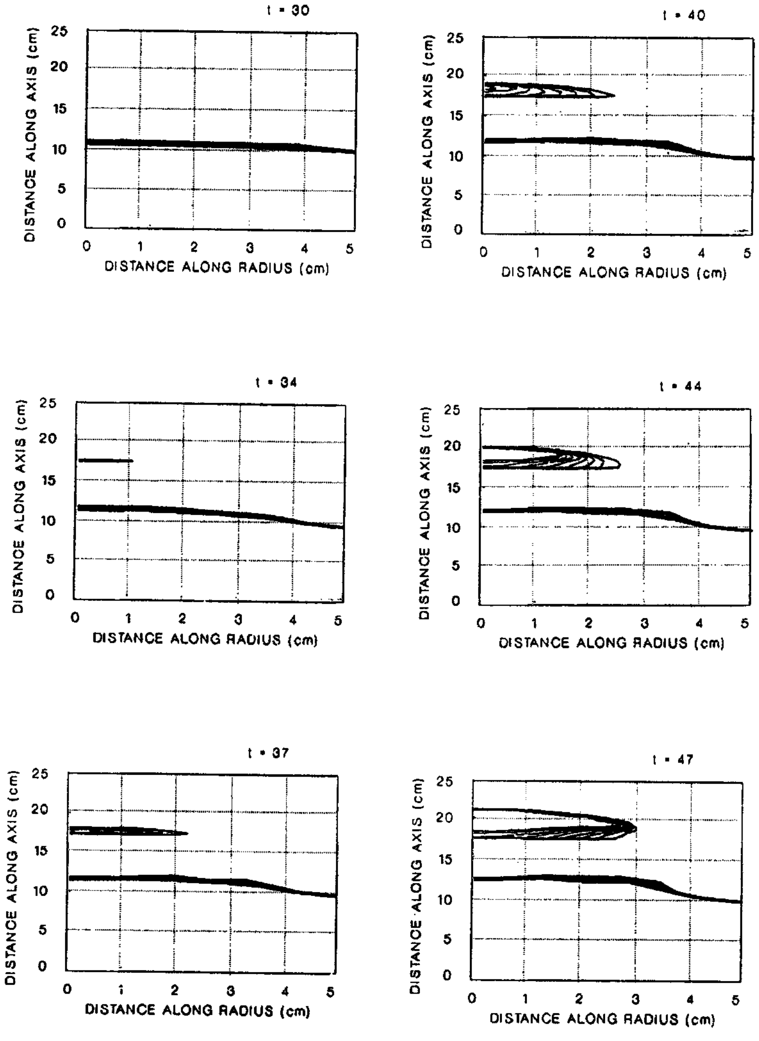


FIGURE 7

Calculated Undecomposed Mass Fraction Contours for the Calibrated Gap Test (Attenuator Thickness : 96 mm)

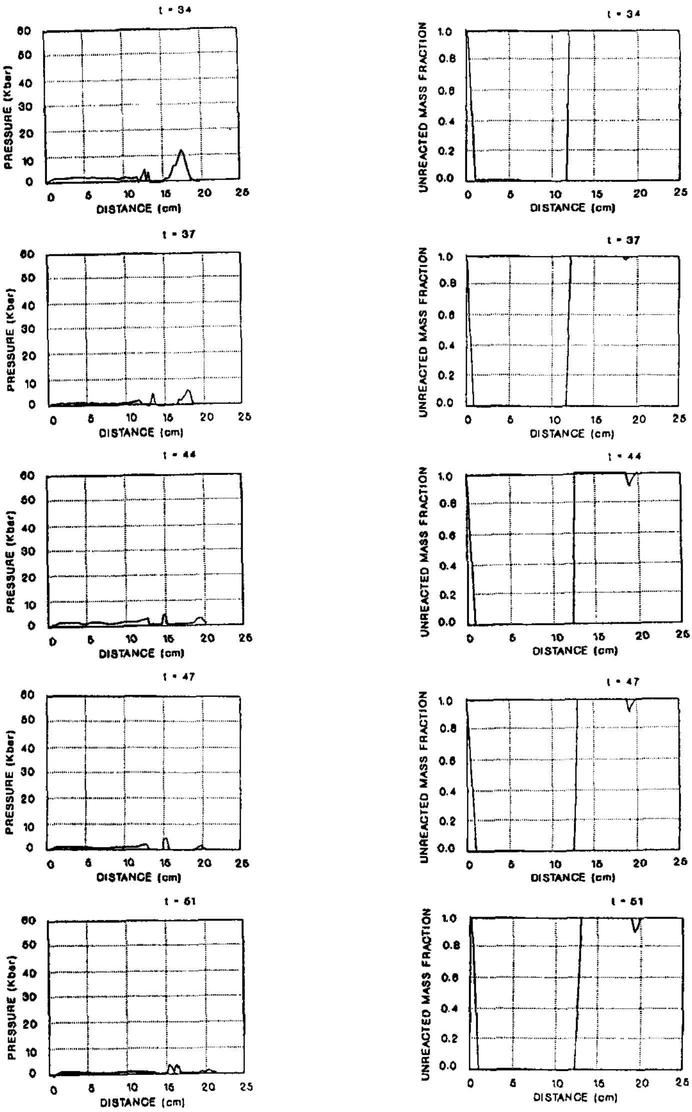


FIGURE 8

Calculated Pressure and Unreacted Mass Fraction Profiles for the Calibrated Gap Test (Attenuator Thickness : 108 mm)

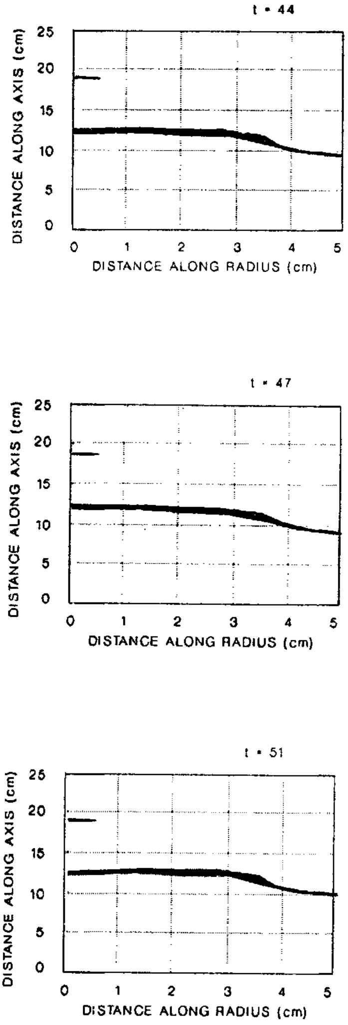


FIGURE 9

Calculated Undecomposed Mass Fraction Contours for the Calibrated Gap Test (Attenuator Thickness : 108 mm).

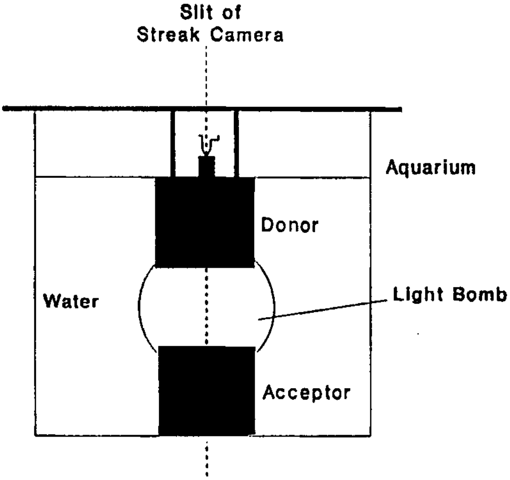


FIGURE 10

Experimental Set up for the Underwater Gap Test.

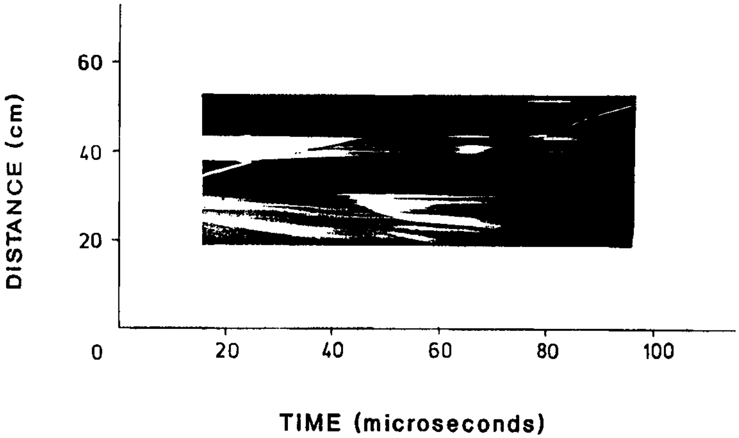


FIGURE 11

Typical Streak Camera Record from the Underwater Gap Tests.

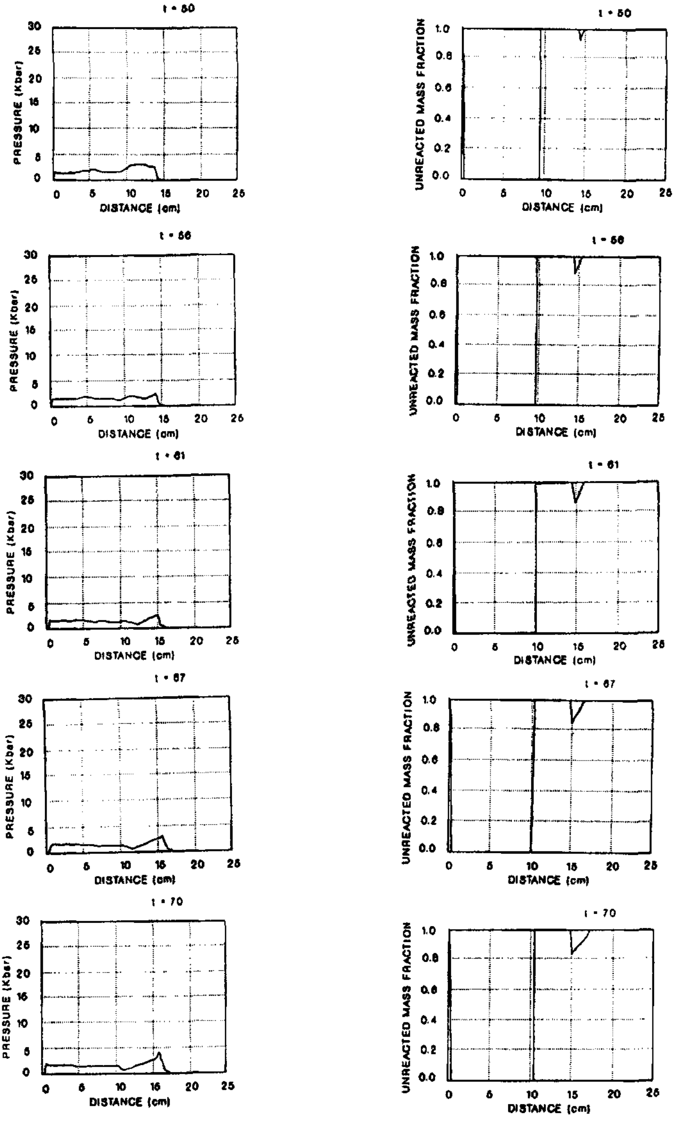


FIGURE 12

Calculated Pressure and Unreacted Mass Fraction Profiles on Axis for the Underwater Gap Test (Gap : 64mm)

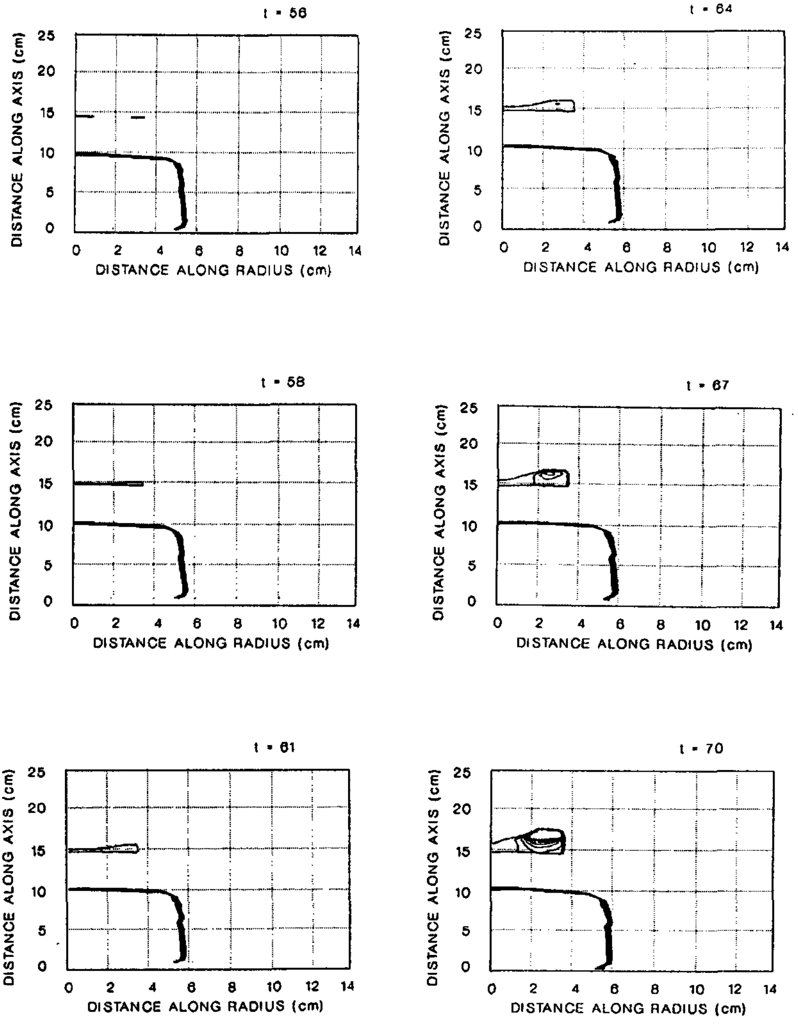


FIGURE 13

Calculated Undecomposed Mass Fraction Contours for the Underwater Gap Test (Gap : 64 mm)

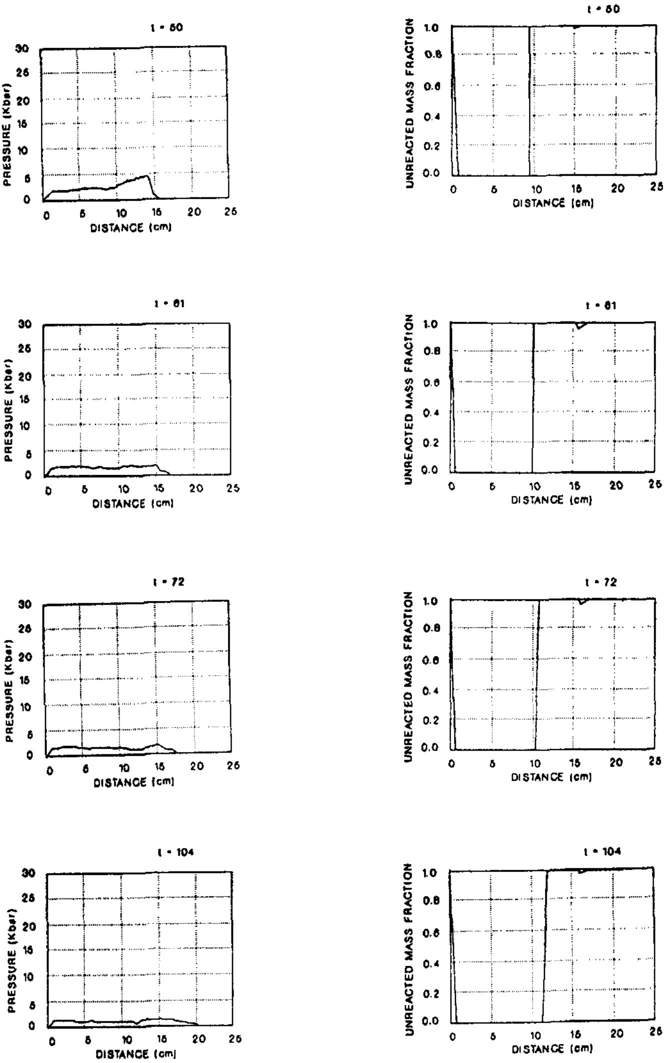


FIGURE 14

Calculated Pressure and Unreacted Mass Fraction Profiles for the Underwater Gap Test (Gap : 70 mm)

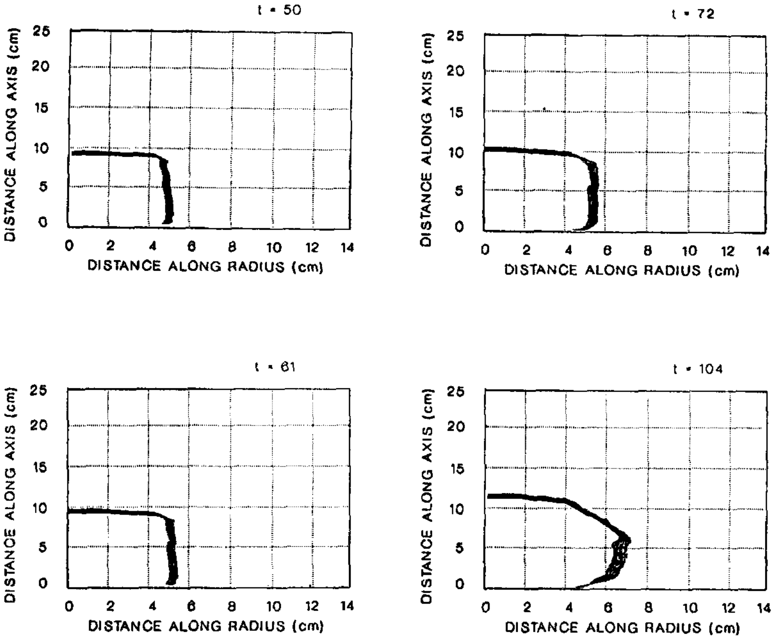


FIGURE 15

Calculated Undecomposed Mass Fraction Contours for the Underwater Gap Test (Gap : 70 mm).

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