21-94850

UCRL-ID-114570

Modeling of Pulverulent Ceramic Jets with CALE

Final Report

Kris Winer and Don Maxwell

December 31, 1992

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This report has been reproduced
directly from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (615) 576-8401, FTS 626-8401

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161

Modeling of Pulverulent Ceramic Jets with CALE#

Kris Winer and Don Maxwell

B-Division, L-35
Lawrence Livermore National Laboratory
Livermore, CA 94551
(510) 422-2419

Final Report: December 31, 1992

#This work supported in part by the Joint DoD/DOE Munitions Technology Development Program.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Table of Contents

1.	Introduction	3
2.	Ceramic Equation of State	4
3.	Fracture and Dilation Modeling	5
4.	Air Diffusion	6
5.	Strength Modeling	6
6.	Comparison with Cagnoux-Glenn Model	7
7.	Shaped-Charge Design	8
8.	Pulverulent Jet Characteristics	8
9.	Summary and Conclusions	9
	Acknowledgments	10
	References	10
	Figure Captions	10

1. Introduction

The intent of this work is to provide an accurate, predictive description of the formation and evolution of pulverulent (consisting of finely divided grains) ceramic jets. The present phase of this effort is devoted to validation and optimization of the intact and powder ceramic material models by comparison of calculated model performance with experimental data. Physically reasonable parameters were chosen for the model which was then optimized by comparison of the calculational results with experimental flash X-ray density data. Optimization parameters included jet tip velocity, jet density distributions, jet radius, and penetration depth. The optimized jets were then tested in configurations similar to those of experiment and were found to reproduce the data adequately.

Jet formation from intact ceramic liners is a complicated physical process which is not yet completely understood. Models have been developed to describe this process at the level of current understanding. The models take into account such processes as fracture of the solid ceramic by the high explosive detonation shock front, the loss of yield strength as the resulting pulverized ceramic is decompressed and flows into the jet, the dilatation and expansion of the pulverized ceramic as jet formation proceeds, and the entrainment of air into the voids between the grains of the pulverized ceramic as the jet stretches and expands.

The description of the behavior of ceramics under shock loading consists of four models:

1) the *equation of state model* corresponds to a) the intact solid before fracturing has occurred and afterwards b) to a mixture of solid particles and interstitial voids containing air under pressures determined from the diffusion model;

2) the *dilatancy model* provides for the subsequent dilatation after fracture has occurred;

3) the *air diffusion model* provides for the adjustment of the air pressure in the interstitial voids of the powder due to the free air in the vicinity;

4) the *strength model* employs a constant yield strength until an effective plastic strain criterion is met. Thereafter, the ceramic is considered to be fractured and a linear yield strength vs. pressure curve is employed for the powder.

These models are incorporated into a special version of LLNL's CALE, a C-language-based, two-dimensional Arbitrary Lagrangian-Eulerian hydrocode that is portable to Unix systems.² Details of the models and their implementation are described in Sections 2-5.

Other models of brittle fracture and dilatation have been applied to describe the behavior of glasses and ceramics under shock loading conditions such as that of Glenn *et al.*³ and Cagnoux.⁴ Salient features of the Cagnoux-Glenn model are compared to the present model in Section 6.

The description presented here is based on simple physics with reasonable assumptions applied to complex mechanisms. Despite the interdependence of the model components, it is possible to determine reasonable values for the model parameters which allow quantitative agreement

with the existing experimental data. These will be briefly described and compared to the results of CALE simulations in Sections 8 and 9.

2. Ceramic Equation of State

The solid intact ceramic equation of state is chosen to be of standard 7-term polynomial form:

$$P_s = a_0 + a_1\mu + a_2\mu^2 + a_3\mu^3 + (b_0 + b_1\mu + b_2\mu^2) E_s \quad (1)$$

where μ is the solid excess compression ($V_{s0}/V_s - 1$), V_{s0} is the solid reference specific volume, V_s is the solid specific volume, E_s is the solid effective internal energy per reference cc. The coefficient a_{0-3} and b_{0-2} are determined from available Hugoniot data for solid polycrystalline Al_2O_3 (Coors AD 85) ceramic;⁵ $a_0 = 0.$, $a_1 = 0.56652$ Mbar, $a_2 = 1.34945$ Mbar, $a_3 = 2.15729$ Mbar, $b_0 = 1.3$, $b_1 = b_2 = 0.$, with $a_2 = 0.$ under tension (when μ is less than 0.). The reference density for this material is 3.42 g/cc, corresponding to an initial porosity of 0.134. No attempt has been made to take this initial porosity into account. Furthermore, the appropriateness of the equation of state parameters depends on the specific ceramic material being modelled. While some of the experiments described below were carried out with ceramic material of density 3.20 and 3.81 g/cc, the calculations were performed with the model parameters and density given above.

The linear thermo-elastic approximation to Eq. (1) is

$$P_s \approx a_1\mu + b_0E_s \quad (2)$$

In order to model the dilatation after fracture, "spring" forces are postulated which tend to increase the void volume between the solid grains. The corresponding linear elastic approximation of the pressure-volume relation for the interstitial voids of the fractured powder due to these spring forces is

$$P_v \approx K_v (V_{v0}/V_v - 1) \quad (3)$$

where K_v is the "spring" constant (modulus of void compression), V_{v0} is the void specific reference volume for uncompressed pores, and V_v is the void specific volume (i.e., void volume per solid mass). In the unfractured material, V_{v0} is zero and there are no dilatational forces in the ceramic. After fracturing, the void specific reference volume increases monotonically according to the dilatation model described below until it reaches some maximum D_{max} , at which point dilatation stops. In addition, the compression modulus is taken to be a function of specific volume such that the strength of the dilatation force decreases as dilatation increases. Specifically,

$$K_v = K_{v1}f + K_{v2}(1 - f) \quad (4)$$

where

$$f = \frac{1 + D_{max} - \rho_{s0}V}{D_{max}} \quad (5)$$

and $K_{v1} = 0.001$ Mbar and $K_{v2} = 0.000001$ Mbar are the dilatation force constants.

Finally, the interstitial gas that has diffused into the void volume between the solid grains of the powder is at the pressure P_{gas} , which is determined by applying the diffusion model described below.

The linear thermo-elastic response of the ceramic powder follows from local pressure equilibrium $P_s = P_v + P_{gas}$, or

$$a_1 (V_{s0}/V_s - 1) + b_0 E_s = K_v (V_{v0}/V_v - 1) + P_{gas} \quad (6)$$

where $V_v = V - V_s$ and V is the powder specific volume (total powder volume per gram of solid). Eliminating V_v from Eq. (6) gives

$$aV_s^2 + bV_s + c = 0. \quad (7)$$

where

$$a \equiv a_1 + P_{gas} - K_v - b_0 E_s \quad (8)$$

$$c \equiv a_1 V V_{s0} \quad (9)$$

$$b \equiv -aV - c/V - K_v V_{v0} \quad (10)$$

The solution for V_s is

$$V_s = V_s(V, V_{v0}, E_s, P_{gas}) = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \quad (11)$$

The basic assumption is that the volume partition V_s/V also holds in the non-linear regime of the solid equation of state. In this case, the V_s of Eq. (11) is exact and can be used to construct the $\mu = (V_{s0}/V_s - 1)$ for use in the exact P_s relation of Eq. (1). The local pressure equilibrium condition then completes the model for the powder equation of state:

$$P(V, E_s, P_{gas}) = P_s(V_s, E_s) = P_v + P_{gas} \quad (12)$$

Since P_{gas} is known from the diffusion model and V_{v0} is determined from the dilatational model described below, V_s is known from Eq. (11). Therefore, the correct powder ceramic pressure as a function of total volume, solid internal energy, and gas pressure can be determined.

3. Fracture and Dilatation Model

Fracture is assumed to occur catastrophically when the effective plastic strain in the ceramic reaches 15%. Thereafter, a tensile-failure-induced dilatation mechanism is employed to monotonically increase the value of the reference specific void volume, V_{v0} , which is stored each calculational cycle as a history variable. The dilatancy is increased whenever the solid grain pressure in a region of the powder falls below the void gas pressure in that region. The latter is determined by the air diffusion model discussed below. In this case, V_{v0} is increased to the value that results in the equalizing of the solid grain and void gas pressures in the following manner:

$$\Delta V_{v0} = \Delta P \left(\frac{dV_{v0}}{dP} \right) \quad (13)$$

where ΔP is the difference between the solid grain and void gas pressures. This corresponds to tensile failure of the powder with respect to the minimum pressure that is sensible, namely, the gas pressure. The dilatancy increases in this fashion until V_{v0} reaches the maximum dilatancy $D_{\max}$.

4. Air Diffusion

The diffusion model provides the value of P_{gas} in each zone of the CALE calculation. The complete model is based on D'Arcy's law and is employed in a fashion that is stable for any time step. Thus the CALE mechanical time step can be used without subcycling.

A driver model was employed to exercise the model under a variety of conditions. It was determined that most applications do not require the complete model. These correspond to cases where the diffusion time constant is small with respect to the mechanical time step. In this case, the average air pressure at all interior points is estimated from the average air pressure of the surrounding neighboring points, corresponding to an infinitely fast diffusion constant. Some of the interior points will have boundary points as neighbors. In this case, the slowly changing free air pressure at the region boundary controls the slowly changing interior pressures.

In fact, it is probably possible to dispense with the air diffusion model completely and simply treat the interstitial regions of the solid as true voids. This possibility has yet to be explored.

5. Strength Modeling

The ceramic liner initially is characterized by constant yield ($Y = 0.040$ Mbar) and shear ($C = 0.880$ Mbar) strengths corresponding to properties of Coors AD 85 Al_2O_3 ceramic.⁵ The ceramic is considered to fracture catastrophically above an effective plastic strain of 15%. After fracture, the yield and shear strengths depend linearly on pressure with a slope of one and maximum values arbitrarily set to one-quarter of those of the unfractured material. The strength is zero at zero pressure and under tension.

The drop in strength upon fracture and the dependence of strength on compressive pressure are reasonable assumptions that qualitatively describe the expected behavior of this material. The arbitrariness of the choices for slope and maximum pressure-dependent strengths results from a lack of detailed knowledge of the behavior of fractured ceramics under pressure. Fortunately, the characteristics of the resulting jets and their performance against both monolithic and reactive composite targets do not depend sensitively on these assumptions. In fact, behavior similar to that reported below can also be obtained by assuming that the ceramic liner is always fractured with a constant shear strength and a pressure-dependent yield strength initially set to zero. The physically more realistic treatment of fracture described in the preceding paragraph allows both ceramic jet formation and metal jet interaction with ceramic targets to be treated reasonably accurately with one and the same calculational model.

The yield and shear strengths of the fractured ceramic are further multiplied by the same factor f described in Eq. (5). This degradation of the material strength with dilatation is similar to the Cagnoux-Glenn treatment of the metamorphosis of glass from the virgin to the pulverized state. In

the latter case, an empirical damage parameter depending on the tensile stress plays a similar role as the parameter f in the present model.

6. Comparison with the Cagnoux-Glenn Model

The Cagnoux-Glenn model^{2,3} has been applied to the fracture of glass. This model is appropriate for comparison here because it has also been incorporated into CALE. The basic model consists of three components. The scalar component of the stress tensor is given by the Mie-Gruneisen equation of state

$$p\delta_{ij} = p(v, e) = P(v) + \Gamma e/v_0 \quad (14)$$

where v is the specific volume, e is the specific internal energy, Γ is the Gruneisen parameter, and the subscript 0 refers to the initial unfractured state. Also,

$$dP = -K_0(v) \frac{dv}{v} \quad (15)$$

where K is the bulk modulus. The deviatoric stress tensor components are given by the usual elastic-plastic formulation, with the yield stress $Y_0 = Y_0(P)$.

The most important component of the model is its description of tensile failure. The initiation criterion is based on limiting the most tensile principal stress component, *i.e.*, failure initiates whenever

$$\tau = \min(\sigma_1, \sigma_2, \sigma_3) < \tau_0 \quad (16)$$

where τ_0 is the measured spall strength. Upon initiation, a scalar damage parameter D is calculated according to the empirical relation:

$$\frac{dD}{d\tau} = \frac{\tau}{B(1-D)^{b\tau}} \quad (17)$$

where B and b are constants, $D(0) = 0$, and $0 < D < 1$. The damage is assumed to affect a metamorphosis of the glass from the virgin (0) state to the pulverized (1) state according to the simple linear transformations:

$$K(v, D) = K_0(v)(1-D) + K_1(v)D \quad (18)$$

$$G(v, D) = G_0(v)(1-D) + G_1(v)D \quad (19)$$

$$Y(v, D) = Y_0(v)(1-D) + Y_1(v)D \quad (20)$$

where G is the shear modulus.

It is clear that the void specific reference volume V_{v0} in the ceramic dilatation model, or more accurately the parameter f defined by Eq. (5), plays a similar role in the accumulation of dilatancy as the damage parameter D in the Cagnoux-Glenn model. In fact, the linear transformation of the void compression modulus is carried out exactly as in Eq. (18) in the ceramic dilatation model with D simply replaced by $1 - f$. Also, the strength parameters in the ceramic model are modified

in a similar manner. One important difference between the models is that the porosity can decrease or increase according to the conditions of loading or unloading while the damage parameter D can only increase. Both models can successfully, although qualitatively, describe the behavior of shaped-charge jet penetration into brittle materials subject to dilatation. Because neither model has been completely optimized and experimental data is not plentiful, it is too early to tell which model might provide the best description of glass and ceramic failure-induced dilatation.

7. Shaped-Charge Design

A series of experiments were carried out with three shaped-charge designs (40° , 60° , and 80° conical liners). The experiments were designed to understand jet formation and development, and jet penetration into monolithic targets. Experimental diagnostics included pin switches for jet tip velocity measurements and X-ray radiographs for jet density distribution and jet shape. The penetration of the pulverulent ceramic jets into stacked, 3-inch thick, 4340 steel plates was manually measured after each experiment in the series.

The specifications for the shaped-charge designs used in the calculations were taken from the engineering drawings prepared for the experiments. The designs were simple cones of uniform thickness of 0.541 cm and three cone angles: 40° , 60° , and 80° . The charge diameters were a constant 6 cm and the axial thickness of the LX-14 explosive between the case and the liner apex was fixed at 3 cm. The explosive was point-initiated at the axis of the case resulting in an approximately planar detonation wave at the liner apex. Further specifications of the designs used in the calculations are contained in the CALE plots of material boundaries and zoning in Figs. 1a-e.

The zoning was chosen to give a reasonably accurate description of jet development while keeping the run time small enough to allow many iterations for parameter optimization. Typically 40 radial zones and 215 axial zones were included in the calculation. Full use was made of the ALE-mode capability for dynamic rezoning to increase resolution in important areas such as the liner convergence zone and the jet radius. Typical zoning during jet formation is shown in Figs. 1b-e. The calculations were run on a Cray Ymp four-processor supercomputer, where a calculation of jet development out to 2 charge diameters ($\sim 40 \mu\text{s}$ after high explosive initiation) required about 900 seconds of cpu time running at ~ 60 Mflops.

8. Pulverulent Jet Characterization

After the equation of state and strength properties, which are for the most part determined from fitting to experimental shock Hugoniot data, the most important parameter for optimization is the maximum dilatancy. The effect of this parameter on the jet density distribution is shown in Figs. 2 and 3. The need for a dilatation mechanism is made clear in Fig. 2, where the axial jet density from optical densitometer measurements of experimental radiographs is compared to that calculated for various maximum dilatancies. The experimental time of $40 \mu\text{s}$ corresponds approximately to a standoff of two charge diameters.

The axial jet density is highly non-uniform with a steep drop in density occurring near the jet

tip. The calculated axial density with zero dilatancy at 2 charge diameters standoff is nearly uniform with only a slight drop in density near the tip, which does not agree with the measured density distribution. As the maximum allowed dilatancy is increased, the axial density distribution becomes more non-uniform with a steep drop in density occurring near the jet tip as observed experimentally.

All calculated jets are characterized by a small high density region at the jet tip which is not present in the experimental radiographs. This phenomenon results from the relatively large pressure in the air shock just at the jet tip which reduces the dilatation. The peak density in the tip region decreases with increasing standoff.

The details of the axial density distribution depend strongly on the maximum dilatancy as shown in Fig. 3, where the pseudo X-ray density plots of jets produced from 80° conical liners are compared. The diameter of the jets and radial uniformity of the jet density are similarly dependent on the maximum dilatancy. It appears that a maximum dilatancy between 0.2 and 0.4 should give the best agreement with the shape of the axial jet density distribution. A value of 0.2 was arbitrarily chosen as the optimal value for the maximum dilatancy for jet penetration and jet interaction calculations described below.

Further comparisons of the calculated jets with experimental data are made in Fig. 4. As expected, the jet tip velocity increases with decreasing cone angle. This trend is captured by the calculated jet tip velocities, which agree well with the measured data. The calculation shows that the jet velocity depends linearly on axial position, which is typical for jets produced from conical liners.

Jet diameters are non-uniform and were measured at 1/4 the length of the jet back from the jet tip from the experimental radiographs. The measured diameters tend to be smaller than the calculated minimum jet diameters. This is likely due to the simplified assumptions in the dilatation model which tend to overestimate the radial expansion of the jet (see Fig. 3). The calculated minimum diameter of the jet decreases as the jet stretches out at larger standoffs. The more important basis for comparison between the calculated and measured jets is the density distribution, which agrees reasonably well.

Finally, ceramic jet penetration into monolithic 4340 steel targets increases as the conical angle decreases and, consequently, the jet tip velocity increases, as expected. The calculations agree with the measured jet penetration behavior. There is a slight overestimation of penetration at 40° cone angle which can be attributed to the overestimated jet tip velocity. With all of the simplifying assumptions that go into the various modelling components, the degree of quantitative agreement between the calculated and measured jet characteristics is quite satisfactory.

10. Summary and Conclusions

A calculational model was developed to describe ceramic jet formation and performance, especially the process of dilatation. The model was incorporated into a two-dimensional arbitrary Lagrangian-Eulerian hydrocode (CALE), optimized by comparison with the available radiographic and timing data, and applied to describe ceramic jet interaction with steel targets. The

model was found to qualitatively reproduce the interaction behavior and holds the promise of affording an accurate, predictive capability with further improvements.

Recommended improvements include: the ability to accurately model target obliquities, increased zoning in the calculations of jet formation and jet-target interaction to improve resolution, and, finally, additional experimental data to improve the optimization of model parameters.

Acknowledgements

We thank Dennis Baum, Rod Abbot, Chuck Honodel, Don Breithaupt, and Al Brooks for their expertise in planning and carrying out the experiments, and for making their data available to us. One of us (K.W.) thanks Chris Simonson and Bob Tipton for sharing their expertise in using CALE, Dan Steinberg for sharing his expertise in the behavior of ceramics, and Don Maxwell for making such excellent progress in modelling ceramic behavior.

References

1. M. Held, *Explosivstoffe* **5** (1968) 98-113.
2. R. Tipton, *CALE User's Manual*, University of California, LLNL (1990).
3. L.A. Glenn, B. Moran, and A.S. Kusubov, *Modelling Jet Penetration in Glass*, UCRL JC-103512 (1990).
4. J. Cagnoux, *Modele phenomenologique d'ecaillage d'un verre pyrex*, J. de Phys., **C5(8)** 1985 (46) 343-350.
5. W.H. Gust and E.B. Royce, J. Appl. Phys. **42** (1971) 276.

Figure Captions

1. Calculational grid showing set-up and zoning, and development of jet formed from 80° conical ceramic liner a) 0., b) 3., c) 12., d) 20., and e) 34. microseconds after explosive detonation. Note the development of the high pressure convergence region upon liner collapse and the collection of zones there in response to the dynamic ALE zoning capability. Maximum allowed dilatation is 20%.
2. Comparison of measured axial jet density at ~2 charge diameters standoff with that calculated as a function of maximum dilatancy.
3. Calculated density distribution of pulverulent ceramic jets as a function of maximum dilatancy.
4. Comparison of measured and calculated ceramic jet characteristics. Maximum allowed dilatation is 20%.
5. Axial jet density distribution of a pulverulent ceramic jet formed from an 80° conical liner at 3, 4, and 5 charge diameters standoff. Maximum allowed dilatation is 20%.

Fig. 1a

Fig. 1b

Fig. 1c

Fig. 1d

winer
Cycle = 1780

Time = 3.40037e+01
Dtc(170,12) = 1.51409e-02

Winp 7 19 -6 6 E1max = 215 lmax = 40
plb
pli den

Fig. 1e

Fig. 2

Fig. 3

Jet Characteristics at 3CD (180 mm) Standoff

	VTIP (mm/ μ s)		Minimum Jet Diameter (mm)		Penetration into 4340 (mm)	
Cone Angle	Exp.	Calc.	Exp.	Calc.	Exp.	Calc.
40°	8.4	8.85	3.	5.	130	≥ 146
60°	6.9	6.86	4.	5.	105	
80°	5.5	5.60	5.	5.	72	≥ 70

Fig. 5

DATE

FILMED

2 / 18 / 94

END