UCID- 19737

ON THE FRAGMENTATION OF CONDENSED MATERIAL
BY ISOCHORIC HEATING AND RELEASE

L. A. Glenn

March 1, 1983

MASTER

Lawrence
Livermore
Laboratory

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 Laboratory under Contract W-7405-Eng-48.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

UCID--19737

DE83 008597

ON THE FRAGMENTATION OF CONDENSED MATERIAL
BY ISOCHORIC HEATING AND RELEASE

L. A. Glenn

University of California, Lawrence Livermore National Laboratory
Livermore, California 94550

Abstract

A model is suggested to describe the mechanics of fragmentation when a liquid or solid body disassembles under intense isochoric heating. The model is based on the concept that surface area created in the fragmentation process is governed by an equilibrium balance of the surface energy and a local inertial or kinetic energy. An expression is derived for the resulting fragment size as a function of the initial size, the specific energy deposited, and thermomechanical properties of the material. The theory is applied to calculate the blanket break-up due to neutron heating in the HYLIPE and Cascade Chamber inertial confinement fusion reactors.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, 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 any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

169

1.0 Introduction

In inertial confinement fusion (ICF) reactors a blanket material containing lithium will surround the fuel pellet. The main function of the blanket is to breed tritium for fuel resupply by interacting with the neutrons released when the pellet explodes. The blanket also serves to protect the structural walls from excessive blast or radiation damage and, at least in power reactors, may act as a heat exchange medium with an external power loop. The neutron penetration of the blanket occurs in a time period small in comparison with the time for release waves to move in any significant distance from available free surfaces. The material is therefore heated at constant volume, which can result in large internal pressures being generated. The subsequent pressure release will cause the blanket to disassemble unless its tensile strength is sufficient to hold it together.* The effects of the disassembly have been discussed at length in connection with blanket designs consisting of cylindrically-concentric liquid sheets^{1,2} or close-packed arrays of liquid lithium jets.³⁻⁵ In the previous work, details of the fragmentation process itself were omitted; it was merely assumed that the liquid would break up into particles of a given size, and the results were expressed in terms of this parameter. A significant conclusion was that both the wall loading and the time for x-ray and debris-induced plasma cooling could be markedly reduced if the fragmentation process was efficient and the particle size was sufficiently small.

On the other hand, liquid lithium is pyrophoric and highly toxic so that its employment in large quantity, as required in an ICF reactor, would preferably be avoided. An alternate design has recently been proposed⁶ that uses, instead of the liquid, a lithium oxide pebble blanket. The reactor is football-shaped and is rotated about its major axis. The pebbles are injected at the ends and cascade towards the center, where they are eventually removed in collectors located around the periphery of the minor axis. To facilitate

*In what follows, we assume that the energy density in the blanket is large compared with the tensile strength; this is virtually always the case with a liquid blanket. For a solid, the assumption is consistent, with neglecting elastic strain energy in comparison with the center-of-mass kinetic energy.

handling and processing, in this case, it is preferable that the pellets not be comminuted.

It is clear that a theory of the fragmentation mechanics is needed. Such a theory has recently been formulated in connection with the dynamic fragmentation of solids subjected to intense impulsive loading. It is our purpose here to discuss the foundations of this theory and to show how it can be applied to the isochoric heating problem.

2.0 Theory of Dynamic Fragmentation

The main idea--similar to that employed in classical fracture mechanics--was proposed by Dennis Grady⁷ and is based on a description of the energies governing the fragmentation process. These consist of surface energy, which is created during the formation of new fragment surface area, and a local kinetic energy, which measures the intensity of expansion of the body and is responsible for driving the fragmentation process. The crucial point is the recognition that the total kinetic energy of the body is not available for fragmentation. Only that fraction is available for breakage that is relative to the center of mass--which is regarded as a local kinetic energy--while the remainder must continue to reside in the rigid body flight of fragments.

Consider an incompressible fluid medium of density ρ , undergoing rapid expansion at a rate $\dot{\rho}$, and focus on a small spherical element within the fluid of radius a . The kinetic energy of a spherical shell of mass dm within the sphere is

$$dT' = (1/2)\dot{r}^2 dm \quad (1)$$

where the radius r is measured not from the center-of-mass of the fluid medium at large, but from the center of the small element in question. The mass increment is then

$$dm = 4\pi\rho r^2 dr \quad (2)$$

so that

$$\dot{T}' = \int_0^a \dot{\rho} dr = 2\pi \rho \int_0^a (ur)^2 dr \quad (3)$$

where the particle velocity $u \equiv \dot{r}$.

Now continuity demands that

$$-\dot{\rho}/\rho = (1/r^2) \frac{\partial}{\partial r} (r^2 u) \quad (4)$$

and if we assume the existence of at least local homogeneity, implying uniform velocity divergence, we must then have

$$u = Ur/a \quad (5)$$

where U is constant. Substituting (5) into (3) and performing the integration results in

$$T' = 2\pi \rho [(1/3) \dot{\rho}/\rho]^2 a^{5/5} \quad (6)$$

The local kinetic energy density is then

$$T = T' / (\frac{4}{3}) \pi a^3 = (\dot{\rho} a / \rho)^2 (\rho / 30) \quad (7)$$

The fragment surface to volume ratio is

$$A = 4\pi a^2 / (\frac{4}{3}) \pi a^3 = 3/a \quad (8)$$

and, in terms of this quantity

$$T = (3/10) (\dot{\rho}/\rho A)^2 \rho \quad (9)$$

If the surface energy of the body is σ , the new fragment surface energy density is simply σA , and the total energy density associated with the fragmentation process is given by

$$E(A) = (3/10) (\dot{\rho}/\rho A)^2 \rho + \sigma A \quad (10)$$

The kinetic energy term results in forces which tend to increase the fracture surface area, while the surface energy provides the balancing force which resists the production of new surface. The fundamental assumption is then made that the fragmentation occurs in such a way as to minimize the free energy of the system, i.e.,

$$dB/dA = 0 \quad (11)$$

This results in

$$A = [(3/5) (\dot{\rho}/\rho)^2 \rho/\sigma]^{1/3} \quad (12)$$

or, in terms of the fragment radius:

$$a = [(135/3) \sigma/\rho (\dot{\rho}/\rho)^2]^{1/3} \quad (13)$$

which is Grady's main result and provides a quantitative measure of the particle size created in fragmentation, in terms of fundamental material and thermomechanical properties. We note that Eq. (12) or (13) agreed well with diverse, but limited, data for the dynamic break-up of oil shale (rock) and explosively fragmented steel cylinders.⁷

3.0 Application to the Isochoric Heating Problem

In order to apply the theory to the isochoric heating problem it is first necessary to estimate the velocity divergence, which is plainly inhomogeneous in this case. We can illustrate the situation fairly simply by recalling that in the slightly expanded liquid phase (characteristic of the isochoric heating and release in the HYLIFE ICF reactor²) a linear Grüneisen model is a good approximation to the equation of state, i.e.,

$$P = \text{Max} \begin{cases} \rho_0 C_0^2 (\eta - 1) + \gamma_0 \rho_0 e \\ P_c \exp (1 - e/e) \end{cases} \quad (14)$$

where ρ_0 is the reference liquid density, γ_0 is the Grüneisen parameter, C_0 is the sound speed at ρ_0 , e_c is the cohesive specific energy, and P_c is a vapor-pressure constant. P , ρ , and e are respectively the pressure, density,

and specific internal energy, and $\eta = \rho/\rho_0$. For $\eta < 1 - \gamma_0 e/C_0^2$, the lower (Clapeyron) expression in Eq. (14) dominates. Physically, whenever this occurs the fluid "comes apart" and the pressure (at equilibrium) is the vapor pressure--which for our purposes is small in comparison with the initial pressure $P_0 = \gamma_0 \rho_0 e_0$.

Now consider a spherical body of fluid of initial radius R' , satisfying Eq. (14), and suddenly heated to $e = e_0$ at $\eta = 1$. A rarefaction will move in from the boundary at R' and the free surface will move outward with a particle velocity of

$$U = P_0/\rho_0 C_0 = \gamma_0 e_0/C_0 \quad (15)$$

For $U/C_0 = \gamma_0 e_0/C_0^2 \equiv M_0 \ll 1$, the rarefaction fan will appear as a discontinuity traveling radially inward at speed C_0 , behind which the pressure will have dropped to the vapor pressure, $P_0 \exp(1 - e_0/e_0)$. At $t_* \equiv R'/C_0$ the outer radius will have moved to a position $R'(1 + M_0) \equiv R$. The velocity distribution in $[0, R]$ at t_* is a function of the Mach number, M_0 , and is depicted in Fig. 1 by the solid curves, for $M_0 = 0.01$ and 0.1 . The calculations were made with the AFTON code.⁸ The dashed curves in the figure are analytic approximations to the numerical solutions of the form:

$$u/U = 1 - \exp(-\alpha r/R) \quad (16)$$

The velocity divergence may then easily be found by applying Eq. (4) to Eq. (16)

$$-\dot{\rho}/\rho = U/R \{ \alpha \exp(-\alpha r/R) + 2(R/r) [1 - \exp(-\alpha r/R)] \} \quad (17)$$

From Eq. (17) it is clear that

$$\lim_{r \rightarrow 0} (\dot{\rho}/\rho) = -3U\alpha/R \quad (18)$$

and that

Fig. 1 Velocity distribution within spherical fluid body after pressure release. Solid curves are numerical solutions and dashed curves represent analytic approximations (Eq. 16). Initial conditions: $e(r,0) = M_0 c_0^2 / \gamma_0$, $\rho(r,0) = \rho_0$.

$$(\dot{\rho}/\rho)_{r/R=1} = -U/R[2 + (\alpha - 2) \exp(-\alpha)] \quad (19)$$

Also, for $\alpha \gg 1$ (as will generally be the case for $M_0 \ll 1$),

$$(\dot{\rho}/\rho)_{r/R=1} \approx -2U/R \quad (20)$$

Equations (18) and (20) are useful for determining a self-consistent value of α from the numerical solutions, to wit:

$$\alpha = (2/3) [(\dot{\rho}/\rho)_{r/R=0} / (\dot{\rho}/\rho)_{r/R=1}] \quad (21)$$

Figure 2 exemplifies the procedure. The solid curves depict the numerical solutions for the normalized velocity divergence for $M_0 = 0.01$ and 0.1 . The parameter α , in each case, is computed by inserting the boundary values at $r/R = 0$ and $r/R = 1$ into Eq. (21). The values of α thus computed were 10.4 (for $M_0 = 0.01$) and 7.9 (for $M_0 = 0.1$). These values were then used in Eqs. (16) and (17) to construct the dashed curves in both Figs. 1 and 2.

While the velocity divergence is seen to vary considerably in $[0, R]$, over most of the radius there is relatively little variation. This suggests that given a large enough initial mass, smaller particles or fragments may be created near the center, but the mass-averaged fragment size will more or less be determined by conditions nearer the periphery. In particular, we may seek the mass-averaged value of the velocity divergence:

$$\begin{aligned} - \frac{\dot{\rho}}{\rho} \frac{R}{U} &= (3/4\pi R^3) \int_0^R \{ \alpha \exp(-\alpha r/R) + 2(R/r) [1 - \exp(-\alpha r/R)] \} \cdot 4\pi r^2 dr \\ &= 3[1 - \exp(-\alpha)] \approx 3 \end{aligned} \quad (22)$$

which is precisely half again the value at the radial periphery (cf. Eq. (20)). Moreover, we note that the mass-averaged result equals the value that would be obtained everywhere within the body if the expansion was truly homogeneous.

Fig. 2 Normalized velocity divergence within spherical fluid body after pressure release. Solid curves are numerical solutions and dashed curves represent analytic approximations (Eq. 17). Initial conditions are as in Fig. 1.

Finally, it is interesting to determine the fraction of the total center-of-mass kinetic energy that is available to the fragmentation process. The center-of-mass kinetic energy density is:

$$E_k = (3/4\pi R^3) \int_0^R \frac{1}{2} \rho U^2 [1 - \exp(-\alpha r/R)]^2 \cdot 4\pi r^2 dr$$

$$= (1/2)\rho U^2 \{1 + (3/\alpha^3)[\alpha^2 \exp(-\alpha) - 2(1 - [1+\alpha] \exp(-\alpha))]\}$$
(23)

The second term inside the curly bracket has the value -1.2×10^{-2} for $\alpha = 7.9$ ($M_0 = 0.1$) and -5.3×10^{-3} for $\alpha = 10.4$ ($M_0 = 0.01$), so that, to first order, $E_k \sim (1/2)\rho U^2$. Combining this result with Eqs. (7) and (22) we find that

$$T/E_k = (3/5)/(R/a)^2$$
(24)

i.e., the fraction of the total center-of-mass kinetic energy that is available for fragmentation varies inversely as the square of the initial-to-final particle size. For $(R/a) \gg 1$, the fragmentation process will therefore have little effect on the velocity of disassembly. The final particle size is given simply by the expression

$$a = \left[\left(\frac{135}{27} \right) \frac{\sigma}{\rho} \left(\frac{RC_0}{Y_0 a_0} \right)^2 \right]^{1/3}$$
(25)

4.0 Numerical Results

4.1 HYLIFE Reactor

The HYLIFE reactor was designed for a pellet yield of 2700 MJ, about 3/4 of which was in the form of high energy neutrons; the pulse repetition rate was 1 Hz. The neutron energy deposition in the liquid lithium jets surrounding the pellet was calculated by Meier.⁹ The specific energy due to neutrons varied from a maximum of 2 kJ/g, in the liquid nearest the pellet, to perhaps 0.02 kJ/g at the outermost position. The relevant parameters in Eq. (25) are:

$$\sigma = 0.4 \text{ J/m}^2$$

$$\rho = 0.518 \text{ g/cm}^3$$

$$C_0 = 4.5 \text{ km/s}$$

$$\gamma_0 = 1.0$$

Table 1 gives the fragment size and kinetic energy fraction available for fragmentation as a function of the specific energy of deposition and the initial fragment size. The lithium is injected into the reaction chamber in the form of a close-packed array of cylindrical jets of uniform diameter. A 200 mm D was originally chosen on the basis of a jet stability criterion. The calculations in Table 1 are for initially spherical fragments of radius 100- and 10-mm; the transformation from cylinders to spheres has not been explicitly accounted for, however this can be expected to have only minor influence on the results.

We see that for the inner row of jets, fragments with initial radii of 100 mm are exploded into tiny drops with a radius equal to 0.62 mm. For the jets in the outer row, where the specific energy is 2 orders of magnitude lower, the final radius is 12.5 mm. In previous calculations, we have shown that the wall loading can be very much reduced if the inner rows of jets fragment into 2 mm D particles.^{4,5} Furthermore, as long as the average jet fragment size is less than ~25 mm, the x-ray/debris-induced plasma will cool and condense to the (laser) beam propagation pressure limit in sufficient time for the envisioned pulse repetition rate of 1 Hz.⁴ The present theory then appears to predict satisfactory reactor performance, at least in this regard.

4.1 Cascade Chamber

The Cascade chamber was designed for a pellet yield of only 600 MJ, with about 80% of the net energy deposition in the Li_2O pellets due to neutrons. The pulse repetition rate in this case is to be 5 Hz and a single Li_2O pebble will be subjected to several hundred pulses in the time it takes to make its way from the injection ports to the pebble catcher at the exit. However, with 200 ms between each laser pulse, there is adequate time for mechanical relaxation in the pebbles so that, except for inelastic structural changes, property changes due to increasing temperature, or fatigue considerations, the fragmentation should be governed by the energy deposition in a single pulse. The maximum single-pulse, neutron-related specific energy--

Table 1. Fragment Size and Kinetic Energy Fraction Available for
Fragmentation/HYLIFE Reactor

R_{mm}^*	e_0 (KJ/g)	M_0	a (mm)	R/a	T/E_k
100	2	9.88×10^{-2}	0.62	162	2.29×10^{-5}
100	0.02	9.88×10^{-4}	12.5	7.99	9.39×10^{-3}
10	2	9.88×10^{-2}	0.13	75.1	1.06×10^{-4}
10	0.02	9.88×10^{-4}	2.70	3.71	4.36×10^{-2}

Table 2. Fragment Size and Kinetic Energy Fraction Available for
Fragmentation/Cascade Chamber

R_{mm}^*	e_0 (J/g)	M_0	a (mm)	R/a	T/E_k
1	7.6	4.75×10^{-4}	(2.55)	--	--
10	7.6	4.75×10^{-4}	(11.8)	--	--
16.6	7.6	4.75×10^{-4}	16.6	1	--
100	7.6	4.75×10^{-4}	55.0	1.82	0.181

at a radius of about 4 m from the fuel pellet--was calculated to be 7.6 J/g.⁶
The relevant data for Eq. (25) are:

$$\sigma = 24 \text{ J/m}^2*$$

$$\rho = 2 \text{ g/cm}^3$$

$$C_0 = 4.0 \text{ km/s}$$

$$\gamma_0 = 1.0$$

Table 2 gives the fragment size results. Unless the initial "pebble" radius substantially exceeds 16.6 mm, the theory predicts no fragmentation will occur. We note however that in this case there are important disclaimers. First, a specific energy deposition of 7.6 J/g will generate an internal pressure of only 15.2 MPa. With stresses this low in the solid, the elastic strain energy can no longer be safely ignored. Nor can we ignore the presence of incipient microcracks which might be activated by the release wave from the surface. And finally, the thermal ratcheting may cause significant lowering of the effective surface energy or fracture toughness. Insofar as the fragment size theory developed here is concerned, however, the fragment size varies only as the cube-root of the surface energy, so that a reduction by more than 2 orders of magnitude only translates to a fragment radius decrease by a factor of 5.

5.0 Summary and Concluding Remarks

Grady's theory of dynamic fragmentation due to impulsive loading has been applied to the problem of blanket disassembly via neutron heating in an inertial confinement fusion reactor. The fragmentation process is governed by an equilibrium balance of the surface energy and a local inertial or kinetic energy. The latter results in forces which tend to increase the fracture

*Reliable data for the surface energy of polycrystalline lithium oxide were not available; we use the measured value for a fine-grained (Solenhofen) limestone, which we judge to be only a crude estimate for the actual value.

surface area while the former provides the balancing force which resists the production of new surface. The fundamental assumption is made that the fragmentation occurs in such a way as to minimize the free energy of the system. Crucial to the theory is the recognition that the total kinetic energy of the body in question is not available for fragmentation. Only that fraction can be used that is relative to the center of mass--which may be regarded as a local kinetic energy--while the remainder must continue to reside in the rigid body flight of fragments.

An expression was derived for the resulting fragment size, in terms of the initial size, the specific energy deposited, and relevant thermomechanical properties. Application of this expression to the HYLIFE reactor design (liquid lithium jets serving as the blanket) gave particle sizes consistent with earlier assumptions of efficient blanket break-up. Experimental confirmation of this result has not yet been obtained, but experiments are currently being planned under the auspices of the Electric Power Research Institute. The theory presented here should be useful in selecting the appropriate experiment and diagnostics, in scaling the apparatus, and in the choice of fluids to be evaluated.

In the case of the Cascade Chamber design, in which solid lithium oxide pebbles are used for the blanket, the calculated result was that no undesirable pebble break up would occur. The reliability of these latter calculations is questionable, however, in view of the fact that thermal ratcheting, and possible inelastic structural changes in the pebbles resulting therefrom, may be important and were not accounted for. Moreover, there is considerable uncertainty as to the value of the surface energy of polycrystalline lithium oxide--even in the virgin (unloaded) state.

References

1. L. A. Glenn and D. A. Young, "Dynamic Loading of the Structural Wall in a Lithium Fall Fusion Reactor", Int. J. Nucl. Engr. and Des. 54 (1979) 1-16.
2. L. A. Glenn, "On the Motion Following Isochoric Heating of Concentric Liquid Annuli", Int. J. Nucl. Eng. and Des. 60 (1980) 327-337.
3. L. A. Glenn, "Divergent Impulsive Crossflow over Packed Columnar Arrays", Int. J. Nucl. Eng. and Des. 56 (1980) 429-437.
4. L. A. Glenn, "Transport Processes in an Inertial Confinement Fusion Reactor", Int. J. Nucl. Eng. and Des. 64 (1981) 375-387.
5. L. A. Glenn, "A 2-D Model of Plasma-Jet Interaction in the HY LIFE Inertial Confinement Fusion Reactor", Int. J. Nucl. Eng. and Des. 69 (1982) 75-86.
6. J. H. Pitts, "Stress in the Cascade Chamber Wall due to Deposition of X-rays, Debris and Neutrons", LLNL Internal Memorandum CLY 83-5, February 8, 1983.
7. L. E. Gracy, "Local Inertial Effects in Dynamic Fragmentation", J. Appl. Phys. 53 (1982) 322-325.
8. L. A. Glenn, "AFTON Revisited: An Improved Algorithm for Numerical Solution of Initial Value Problems in Continuum Mechanics--Part 1: The One-Dimensional Equations", LLNL Report UCRL-52512, July 20, 1978.
9. W. E. Meier, "Neutron-Induced Specific Energy Deposition at the Chamber Midplane", in Laser Program Annual Report for 1979, LLNL Report UCRL-50021-79, v. 3, pp. 8-34 - 8-36.

0566c/ks