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# ADVANCED WARHEADS CONCEPTS: AN ADVANCED EQUATION OF STATE FOR OVERDRIVEN DETONATION

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The Advanced Warhead Concepts ILIR FY90 effort has produced an advanced thermodynamic equation of state [Jones-Wilkens-Lee-Baker (JWLB)] for high explosive detonation products. JWLB is suitable for overdriven detonation and material acceleration applications. It has been implemented into the dynamic finite element programs SYNA2D and DYNA3D and parameterized for octol 75/25. Calculated and experimental results are compared.

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## BACKGROUND

Modern explosively formed projectile warheads, such as SADARM, produce a single robust penetrating fragment. However, greater lethality could often be achieved by either a number of smaller fragments or a deep penetrating jet depending on the target properties. Therefore, multiple mode warheads provide increased utility and overall lethality due to their applicability over a larger range of targets. The Advanced Warhead Concepts ILIR project is investigating advanced multiple mode warhead concepts based on charge designs employing explosives with different properties and initiation logic. These advanced warhead concepts are being investigated using dynamic finite element analysis and experimental verification. Current dynamic finite element programs, such as DYNA3D, do not adequately treat detonation interaction phenomena produced by explosives with different properties and multiple initiation points. Therefore, the FY90 effort was to develop and implement a significant enhancement for the treatment of detonation interactions. This has been done by producing an advanced detonation products equation of state, appropriate for overdriven detonations produced by detonation interactions. This new equation of state provides an improved high pressure description, and retains the low pressure expansion behavior required for standard material acceleration modeling.

## APPROACH

Thermochemical calculations have proven to be very useful for the prediction of explosive products properties, particularly near and above the Chapman-Jouguet state. Unfortunately, they do not reproduce the products expansion behavior accurately enough for typical warheads design. Currently, thermodynamic equations of state (JWL) used for warheads design are normally calibrated to give agreement with copper cylinder explosive expansion experiments. These equations of state have not been calibrated for high pressures above the Chapman-Jouguet state. Experimentation and comparison with thermochemical calculations (Figures 1,2, and 3) have demonstrated that a poor description of the high pressure region exists. In order to achieve a suitable equation of state, an appropriate equation of state form (JWLB) was derived. A standard explosive (octol 75/25) was used for copper cylinder expansion tests and explosive dent plate tests. The new equation of state was parameterized for octol 75/25, using both thermochemical calculations and cylinder test results in order to adequately describe both the high pressure region and lower pressure expansion behavior. After implementing the equation of state into a finite element program, dynamic finite element analysis of the experimentation using JWLB and a standard equation of state (JWL) with standard octol 75/25 parameters was completed. The experimental and computational results were reduced and compared.

## EQUATION OF STATE FORMULATION

The equation of state form was chosen so as to adequately describe the high pressure regime produced by overdriven detonation, and yet retain the low pressure expansion behavior required for standard material acceleration modeling. To this end, the derived form is based on the Jones-Wilkens-Lee (JWL) equation of state due to its asymptotic approach to an ideal gas at high expansions. Additional exponential terms and a variable Gruneisen parameter have been added to adequately describe the high pressure region above the Chapman-Jouguet state. The resulting equation of state form, named Jones-Wilkens-Lee-Baker (JWLB), is as follows:

$$P = \sum A_i\left[1 - \frac{\lambda}{R_i V}\right]e^{-R_i V} + \frac{\lambda E}{V} + C\left(1 - \frac{\lambda}{\omega}\right)V^{-(\omega+1)}$$

$$\lambda = \sum A_{\lambda i} V e^{-R_{\lambda i} V} + \omega$$

The JWLB equation of state form is based on a first order expansion around the principle isentrope:

$$Ps = \sum A_i e^{-RiV} + CV^{-(\omega+1)}.$$

Using the Gruneisen Parameter,

$$\lambda = V \frac{\partial P}{\partial E}\Big|_V ,$$

the isentropic identity,

$$P = - \frac{\partial E}{\partial V}\Big|_S ,$$

and the Chapman-Jouguet condition,

$$Ecj = Eo + \frac{1}{2}(Pcj + Po)(Vo - Vcj)$$

$$= \sum \frac{A}{Ri} e^{-RiVcj} + \frac{C}{\omega} Vcj^{-\omega} ,$$

the final form may be derived

$$P = \frac{\lambda}{V}(E - Es) + Ps \Rightarrow \text{Final Form.}$$

Some important characteristics of the equation of state are that the Gruneisen Parameter $\lambda$, is represented as an analytic function of specific volume, V. $\lambda + 1$ approaches a constant adiabatic gamma, $\frac{V}{P} \frac{\partial P}{\partial V}\Big|_S = \omega + 1$ for large V, so that ideal gas behavior is asymptotically approached.

## EXPERIMENTATION

Copper cylinder expansion tests and steel dent plate tests were done. The copper cylinder expansion tests consisted of oxygen free copper tube (10"H X 1"OD X 3/4"ID) filled with octol 75/25. Each charge was detonated from one end, and the cylinder wall movement was measured using an ultrahigh speed smear camera. The dent plate tests consisted of a 3" diameter charge placed on top of three 3" thick RHA steel plates. The charge is detonated and the resulting dent profile is measured using a sliding micrometer. The charges consisted of 1.5" and 2.5" height octol 75/25.

## PARAMETERIZATION

A generalized method of parameterization has been developed using a nonlinear optimization program (NLQPEB), thermochemical calculations (TIGER), and a mathematical cylinder test model (CYLTEST). The NLQPEB program was developed by ARDEC for the solution of generalized nonlinear optimization problems with equality and inequality constraints. The program utilizes sequential quadratic programming, with a Broyden-Fletcher-Goldfarb-Shanno (BFGS) variable metric update and a modified merit function based on the Kuhn-Tucker first order necessary conditions. NLQPEB is used to solve for a set of JWLB parameters that reproduce the predicted pressure, volume, Gruneisen parameter principle isentrope behavior in the least squares sense. Additional equality constraints are imposed so that the predicted Chapman-Jouguet state be reproduced, and that CYLTEST reproduces the experimental cylinder expansion test results at seven volume expansions. The pressure, volume, Gruneisen parameter principle isentrope behavior and the Chapman-Jouguet state are predicted using the computer program TIGER. Either the Becker-Kistiakowsky-Wilson (BKW) or the Jacobs-Cowperthwaite-Zwisler (JCZ3) thermochemical equations of state can be used for the calculations. The mathematical cylinder expansion test model, implemented into the program CYLTEST, is a modification of the model suggested by G.I. Taylor using Reynolds hydraulic treatment. The modification includes radial flow and cylinder wall thinning considerations. The parameterization method was used with BKW and the LLNL revised BKW parameters (BKWR) to produce JWLB parameters for octol 75/25. The octol 75/25 JWLB parameters are:

| $A_1$,Mbar | $A_2$,Mbar | $A_3$,Mbar | $R_1$ | $R_2$ | $R_3$ | C,Mbar | $\omega$ |
|---|---|---|---|---|---|---|---|
| 909.17 | 89.469 | .81495 | 15.941 | 5.4178 | 2.1956 | .01048 | .30731 |

| $A_{\lambda 1}$ | $A_{\lambda 2}$ | $A_{\lambda 3}$ | $A_{\lambda 4}$ | $R_{\lambda 1}$ | $R_{\lambda 2}$ | $R_{\lambda 3}$ | $R_{\lambda 4}$ |
|---|---|---|---|---|---|---|---|
| 65.093 | -179.81 | 156.04 | .78487 | 3.69061 | 4.52693 | 5.80143 | .958640 |

| $\rho o$,g/cc | Eo,Mbar | D,cm/$\mu s$ | Pcj,Mbar |
|---|---|---|---|
| 1.821 | .096034 | .85381 | .33755 |

Figures 4, 5, and 6 compare BKWR and JWLB calculations.

## DYNAMIC FINITE ELEMENT COMPUTATIONS

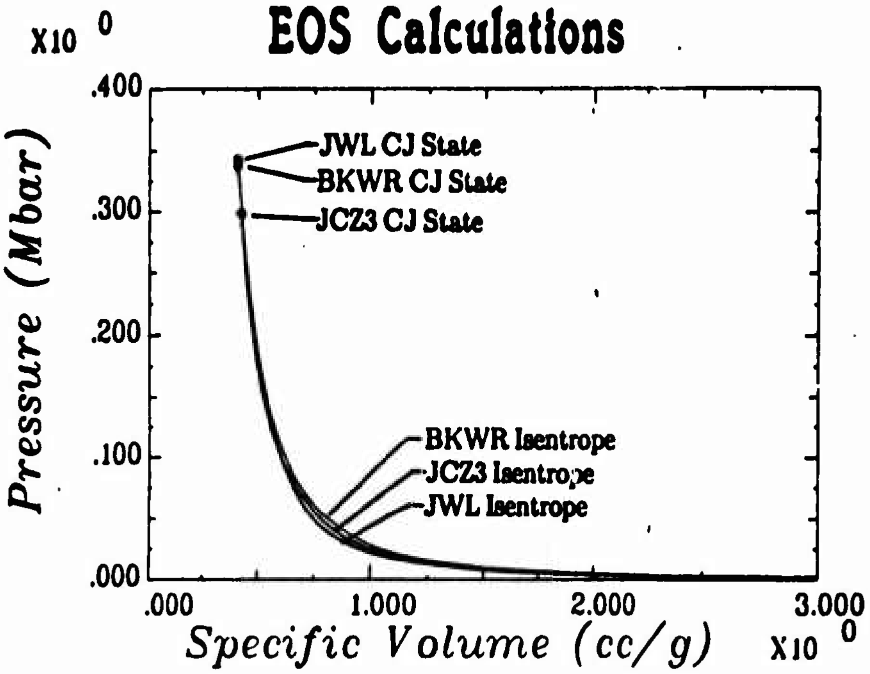
The equation of state has been implemented into the dynamic finite element program DYNA2D. The cylinder expansion and plate dent tests have been modeled using JWLB, as well as JWL with standard parameters for comparison. Figure 7 shows the cylinder test modeling at 6 microsecond intervals. Figure 8 shows the plate dent test initial and final configurations. The material boundaries and computational mesh of both computations can be clearly seen in the figures. The Johnson-Cook material model and the Mie-Gruneisen equation of state were used for both the copper and steel material descriptions. Extensive rezoning was required for the plate dent calculation.

## RESULTS COMPARISON

Figure 9 presents a comparison of the finite element and experimental cylinder expansion test results. The cylinder test dynamic finite element results agree very closely with the experimental results. The JWLB equation of state results agree slightly better than the JWL results. The dent plate computations also agree closely with the experimental results. It was found that the closest agreement was achieved using an Ignition and Growth reactive scheme rather than a standard programmed burn for the explosive detonation. Figure 10 presents a comparison of the finite element and experimental plate dent test results.

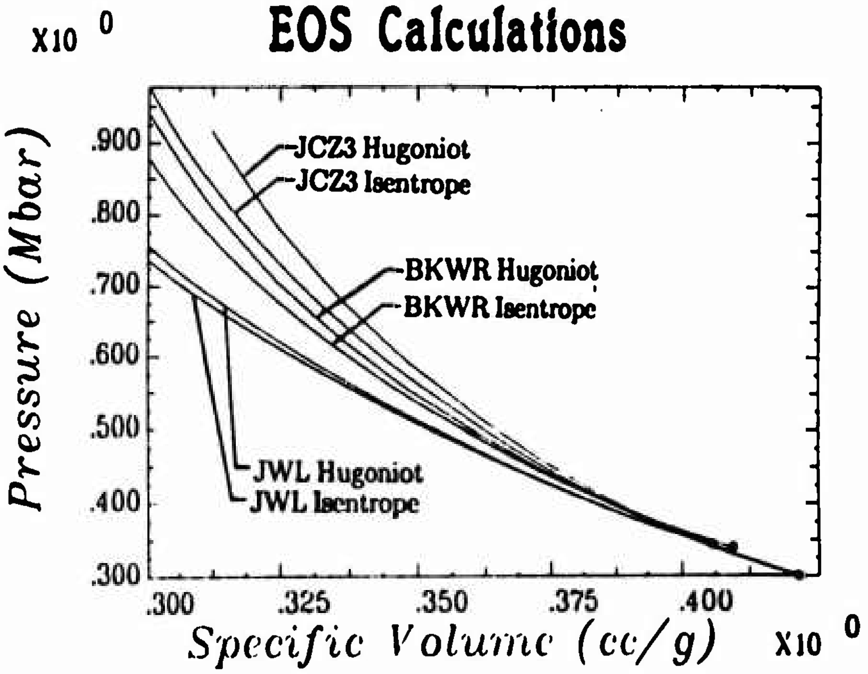
## CONCLUSION

An advanced thermodynamic equation of state applicable to problems involving overdriven detonation has been developed. The equation of state has been parameterized for octol 75/25 and a comparison of experimental results to computational results has been completed. The new equation of state maintains required low pressure expansion behavior while providing a better high pressure description applicable to overdriven detonation. The new equation of state will be used for evaluating advanced multiple mode warheads concepts based on charge designs employing explosives with different properties and initiation logic. Finally, the new equation of state will be used for warheads development and analysis on several other programs including Insensitive Munitions, More Powerful Explosives and Target Defeat. Typical applications include shaped charge wave shaping, peripheral initiated explosively formed projectiles, and Mach stem detonations.



Low Pressure Behavior (Below CJ)

Figure 1. Pressure versus relative specific volume for the principle isentrope of octol 75/25 below the Chapman-Jouguet state. The thermochemical calculations (BKWR and JCZ3) agree fairly well with the standard JWL.



High Pressure Behavior (Above CJ)

Figure 2. Pressure versus relative specific volume for the principle isentrope and reactive Hugoniot of octol 75/25 above the Chapman-Jouguet state. The standard JWL underpredicts the high pressure region.

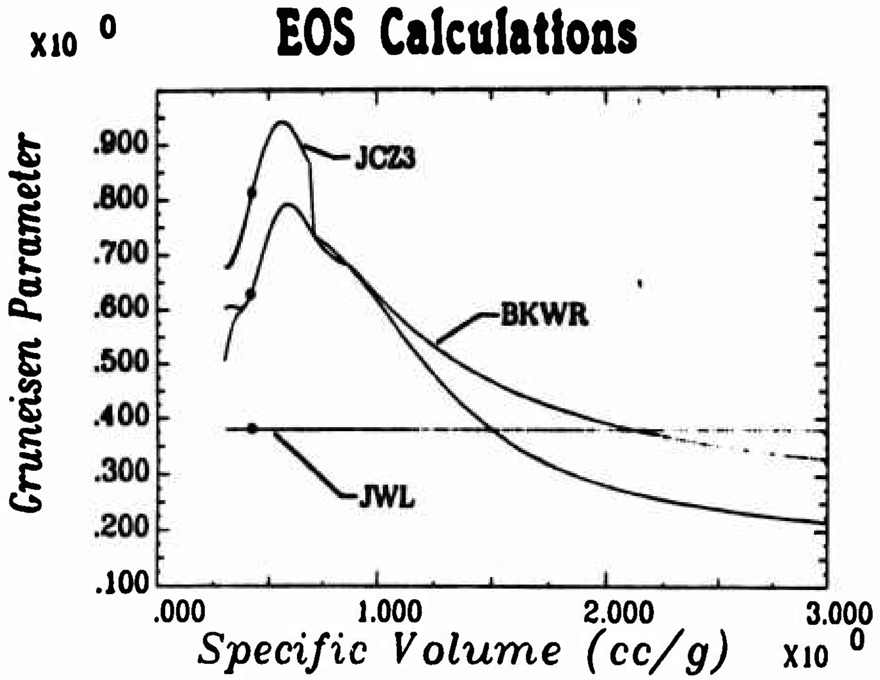
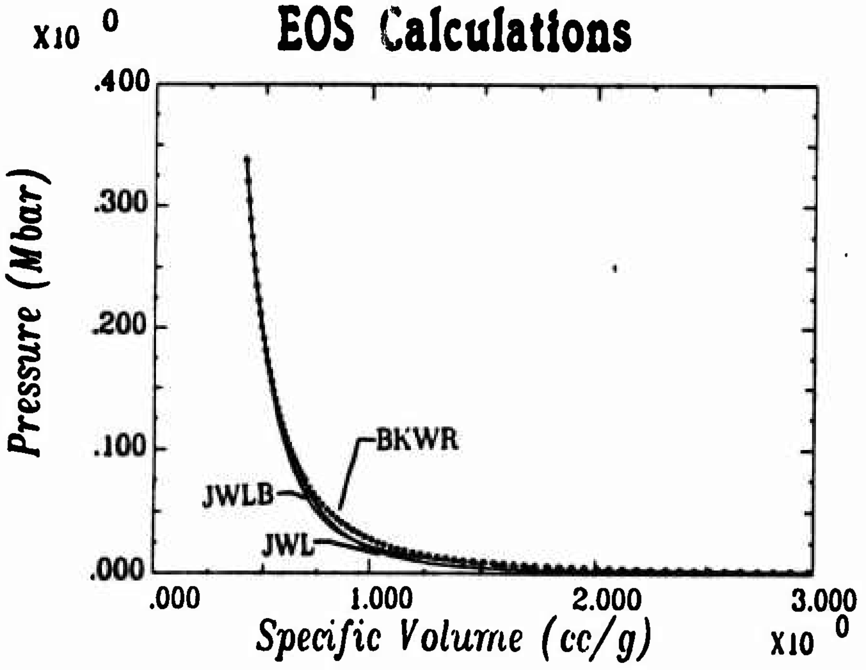


Figure 3. The Gruneisen parameter versus relative specific volume for the principle isentrope and reactive Hugoniot.



Low Pressure Behavior (Below CJ)

Figure 4. Pressure versus relative specific volume for the principle isentrope of octol 75/25 below the Chapman-Jouguet state. The BKWR and JWLB calculations agree fairly well.

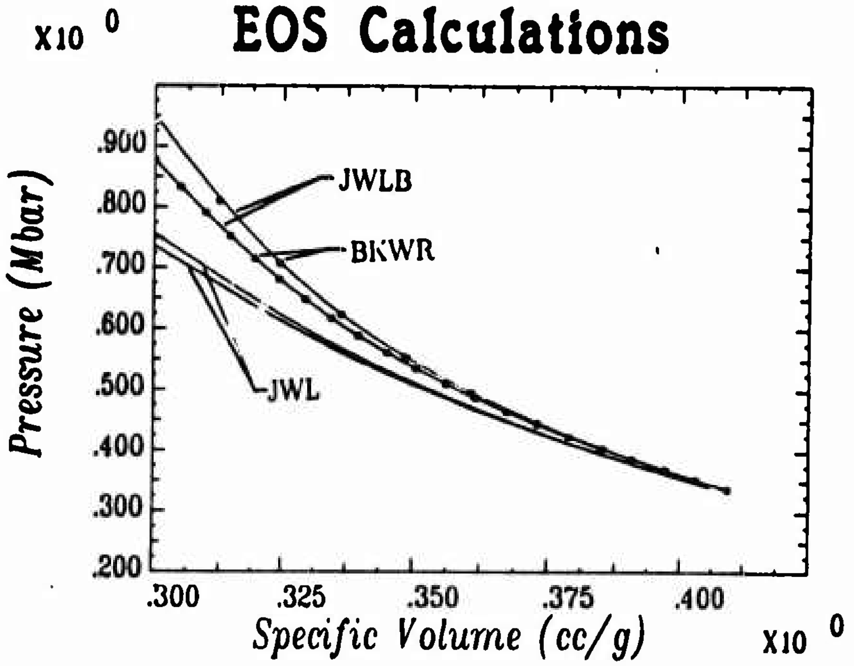


Figure 5. Plots of pressure versus relative specific volume for the principle isentrope and reactive Hugoniot of octol 75/25 above the Chapman-Jouguet state. The BKWR and JWLB calculations agree very closely.

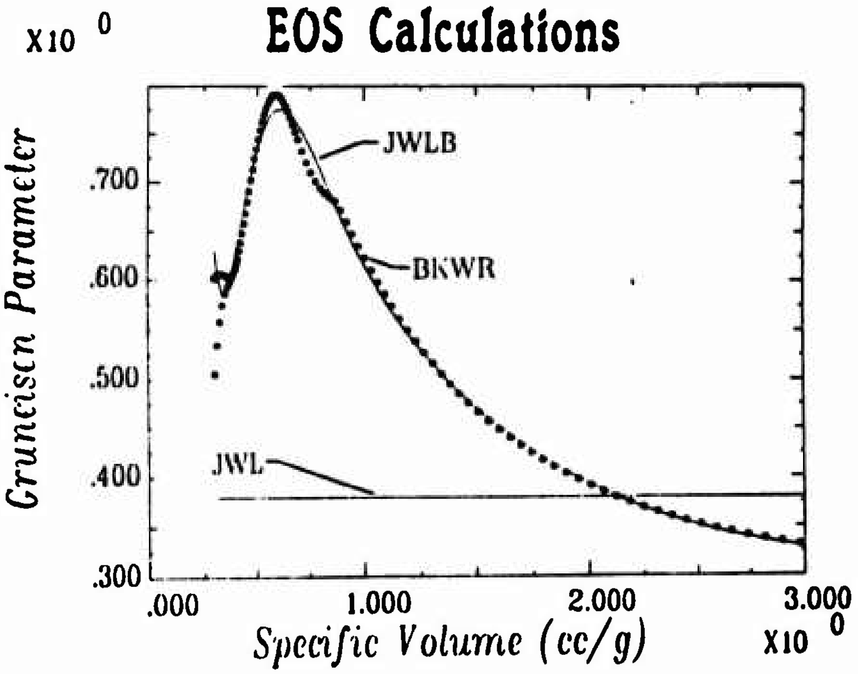


Figure 6. Plot of the Gruneisen parameter versus specific volume for the principle isentrope and reactive Hugoniot. The BKWR and JWLB calculations agree very closely.

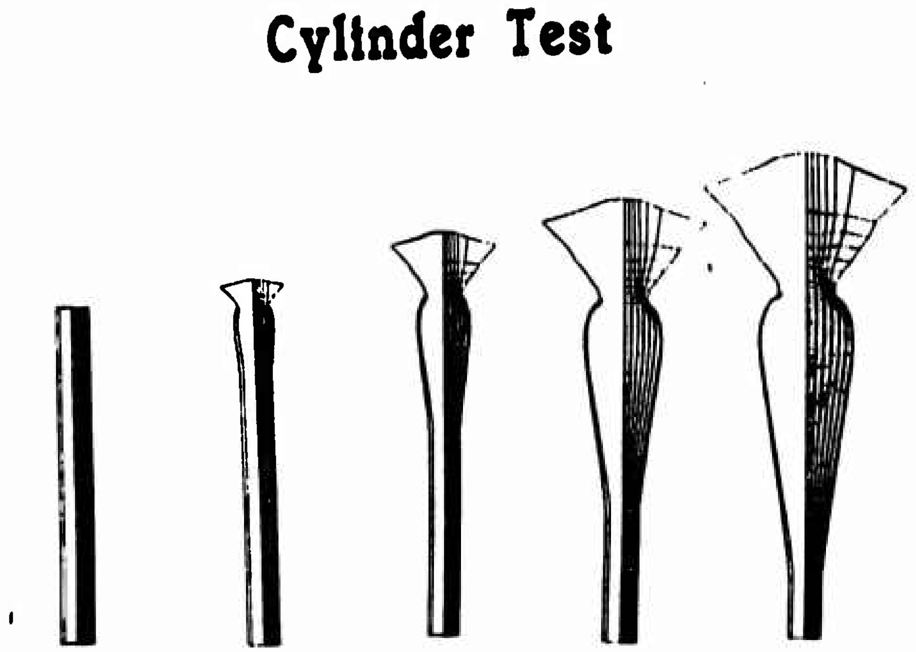
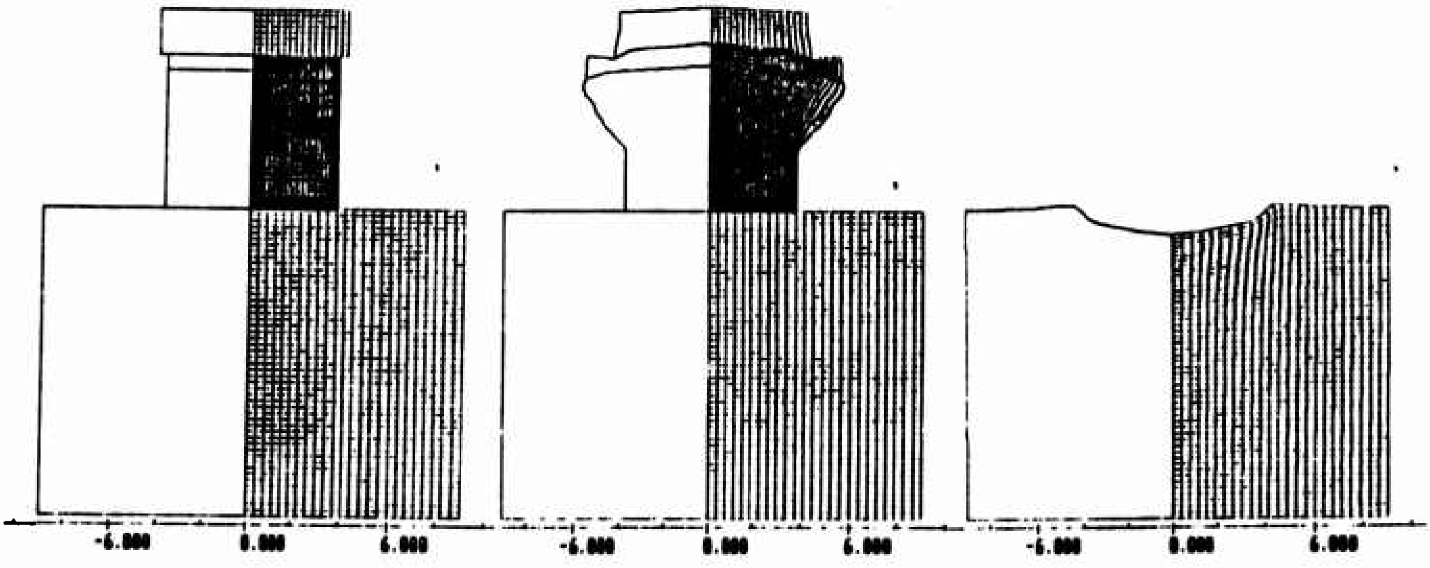


Figure 7. Cylinder expansion test finite element computation at 6 microsecond intervals.



2.5" H X 3" D Octol Charge

Figure 8. Plate dent test finite element computation initial and final configurations.

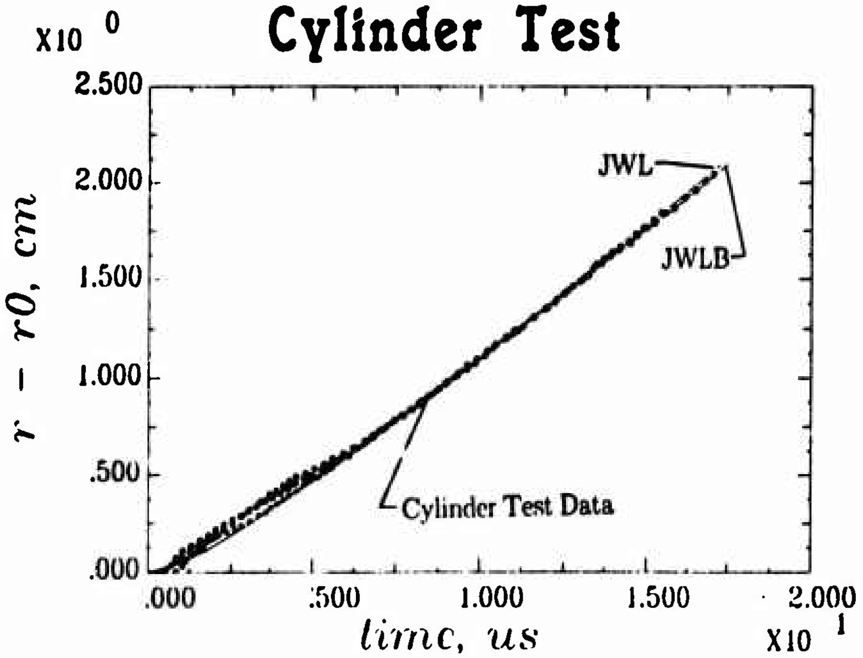


Figure 9. Dynamic finite element and experimental displacement versus time for the cylinder expansion test.

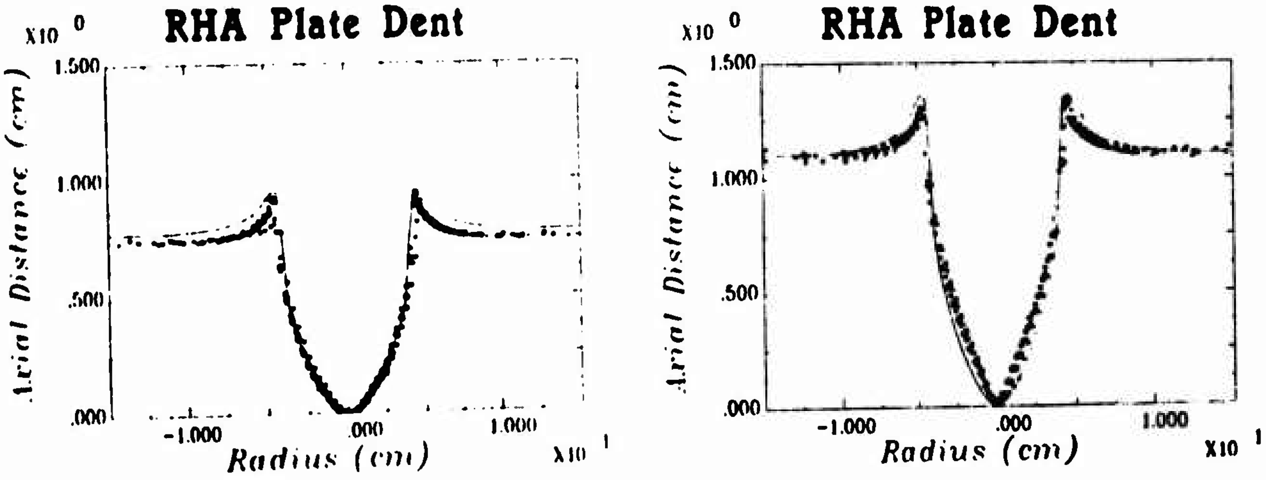


Figure 10. Dynamic finite element and experimental dent plate profile comparison.

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