LA-5001-MS

AN INFORMAL REPORT

C.3

A Parameter Study of Spall Calculations in One-Dimensional Hydrodynamics Codes

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

In the interest of prompt distribution, this LAMS report was not edited by the Technical Information staff.

Printed in the United States of America. Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy $3.00; Microfiche $0.95

LA-5001-MS
An Informal Report
UC-25
ISSUED: July 1972

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

A Parameter Study of Spall Calculations in One-Dimensional Hydrodynamics Codes

by

George N. Brotbeck

A PARAMETER STUDY OF SPALL CALCULATIONS IN ONE-DIMENSIONAL HYDRODYNAMICS CODES

by

George N. Brotbeck

ABSTRACT

Spall calculations were made using a pressure gradient spall model in the one-dimensional hydrodynamics codes CIRCE, COMBO, RICSHAW, and SIN. The system for which these calculations were carried out consisted of a 10 cm. slab of Composition B high explosive adjacent to a 2.54 cm. slab of aluminum. The results are presented in this paper, and it is shown that the calculated spall layers are not sensitive to noise in the rarefaction wave, but that variations in the spall constants can have a significant effect on the quantitative results obtained in the tension region of the aluminum.

I. INTRODUCTION

The original object of this study was a comparison of the spall calculations done by the one-dimensional Lagrangian hydrodynamics codes CIRCE and COMBO. These two codes are similar in that they both use finite difference methods to solve the flow equations, necessitating the employment of an artificial viscosity to smear shock fronts across several mass points. However, COMBO's initial shock can be propagated as a sharp, or nonsmeared shock, whereas CIRCE's initial shock is smeared. In each code, an artificial viscous pressure contribution to the total pressure is calculated for a mass point whenever compressions are indicated subsequent to the initial shock.

The use of finite difference methods in the solution of the flow equations causes a certain amount of noise to appear in the solution. The artificial viscosity has a damping effect on the noise, which is dependent on the type being used. Both codes have the QLQ form of the artificial viscosity developed by K. A. Meyer[1] available to them, although COMBO still makes frequent use of a quadratic form. However, COMBO's use of a sharp initial shock should eliminate noise to a large extent, and so the initial solutions behind this shock should appear very smooth. When the sharp shock traveling through a material encounters a vacuum, or another material with appropriate conditions, a rarefaction is reflected back through the original material. Any noise present behind the incident shock will be reflected in the rarefaction, so that reducing noise behind the incident shock should reduce the noise in the rarefaction. Hence, by reason of the previous discussion it was anticipated that COMBO would give smoother rarefaction waves than CIRCE.

To produce spall, an area of tension must be produced in a material. This involves the interaction of two rarefactions, producing the necessary tension, and spalling of layers of the material to relieve the tension. If noise is present in one or both of the rarefactions, inaccurate locations of these layers may result, accompanied by erroneous spall tensions in the material. It was felt at the start of this study, for the reasons already cited, that COMBO must give more accurate results than CIRCE in predicting spall phenomena.

To test this hypothesis, a relatively simple physical system was desired for which good experimental results were available. The system chosen was a slab geometry configuration consisting of 10 cm. of composition B high explosive adjacent to 2.54 cm. of aluminum. Air or vacuum was assumed to be on the opposite side of the aluminum from the HE.

Experimental data for this system was obtained from a report by C. L. Mader.[2]

II. BEHAVIOR OF THE SYSTEM

The burning of the high explosive is accomplished by using a Chapman-Jouguet process, with a Taylor wave following the detonation shock wave. When the detonation wave reaches the aluminum, a shock is transmitted into the aluminum, and a shock is reflected back into the HE. The reflected shock interacts with the Taylor wave, modifying both to some extent. The modified Taylor wave is transmitted into the aluminum with some reflection into the HE.

The interaction of primary interest occurs when the shock in the aluminum reaches the air or vacuum on the other side. Now a rarefaction is reflected back into the aluminum, interacting with the incoming Taylor wave, which is itself a rarefaction. This interaction produces tension in the aluminum that eventually results in spalling, as described in the preceding section. This tension is evidenced in the calculation by the appearance of a negative pressure, and the spalling will occur when this negative pressure exceeds a limit which is calculated according to the method described in the next section. At that time, layers of the aluminum will separate, and in a nonconverging geometry remain separated. This separation can be measured experimentally by using the Phermex facility to take flash radiographs of the aluminum while spall is occurring.

III. THE CALCULATIONAL SPALL MODEL

The method used to calculate spall in COMBO and CIRCE is based on the pressure gradient spall model. When the tension in the aluminum exceeds the static tensile strength, but is less than the ultimate spall strength, the spall tension is computed using the formula[3]

$$(1) \quad \sigma_S = \sigma_0 + A \left(\frac{\Delta\sigma}{\Delta X}\right)^B$$

where σ_0 is the static tensile strength, and A, B are constants for a fixed material at a fixed temperature. This temperature dependence turns out to be important and will be examined later. For aluminum at 300° K, we have σ_0 = 0.001 mbar, A = 0.095, B = 0.65, σ_u = 0.05 mbar, where σ_u is the ultimate spall strength, in megabars (mbar).

IV. CIRCE AND COMBO RESULTS

Figure 1 shows profiles of the pressures generated by the codes CIRCE and COMBO at a time when the tension is well developed in the aluminum. The free surface locations are shown as points having zero pressure at the left side of the graph, all points to the right being in the aluminum. Both codes are using the QLQ viscosity to damp noise in the rarefaction wave, which is traveling to the right. The COMBO profile is not significantly different from CIRCE's, so that no significant differences in spalling should occur.

To facilitate comparison, the first spall layer is chosen because the experimental data for it are more reliable than that for subsequent layers. Specifically, the data for this layer indicate a thickness of 0.22 ± 0.02 cm and a spall tension of 16 ± 5 kilobars (kbars), or a pressure of -16 ± 5 kbar. The COMBO results predict a value of 0.26 ± 0.01 for the layer thickness, and a spall ten-

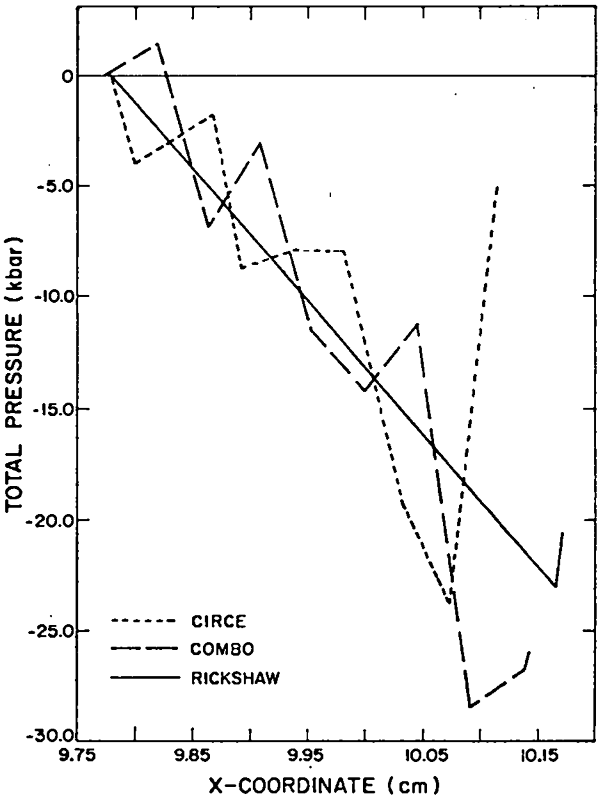

Fig. 1. Comparison of pressure profiles in the rarefaction wave.

sion of 22 ± 1 kbar, while the CIRCE calculations indicate a layer thickness of 0.23 ± 0.04 cm, and a spall tension of 21 ± 1 kbar. Variations in the calculated results are a consequence of modifying the zoning in the aluminum, which may often be used to achieve some reduction of the noise present in the calculations.

On the whole, both codes tend to give thicker layers and larger tensions than observed experimentally. This is a direct consequence of the oscillations in pressure in the rarefaction wave, as is evident from studying (1) and the profiles in Fig. 1. Consequently we concluded that COMBO did no better than CIRCE in matching the experimental results, even though it used an initial sharp shock.

Returning to the quadratic form of the artificial viscosity in COMBO did not improve the results, and, in fact, gave slightly poorer matching with the experimental data. The reason for this is evident after looking at Fig. 2, showing the COMBO profiles for both viscosities. The oscillations have become worse using the quadratic viscosity, leading through (1) to differences in the spall calculations.

Finally, a COMBO option was examined in which spall is allowed at a fixed tension, irrespective of the pressure gradient. The tension selected is supposed to be large enough so that noise is insignificant by comparison. The present value used in COMBO is 60 kbar. Figure 3 shows the CIRCE and COMBO profiles at a time when the tension has reached the 60 kbar level, and it is evident that the noise is in fact only a small percentage of that value. However, the spall thickness of the first layer is now approximately 1.2 cm, or more than four times the previously calculated thickness, and about five times the observed thickness of this layer. This option is evidently not effective as a quantitative description of spall for this problem, and considering the relative insensitivity of the calculations to the noise present in the rarefaction, is probably an unnecessary precautionary measure.

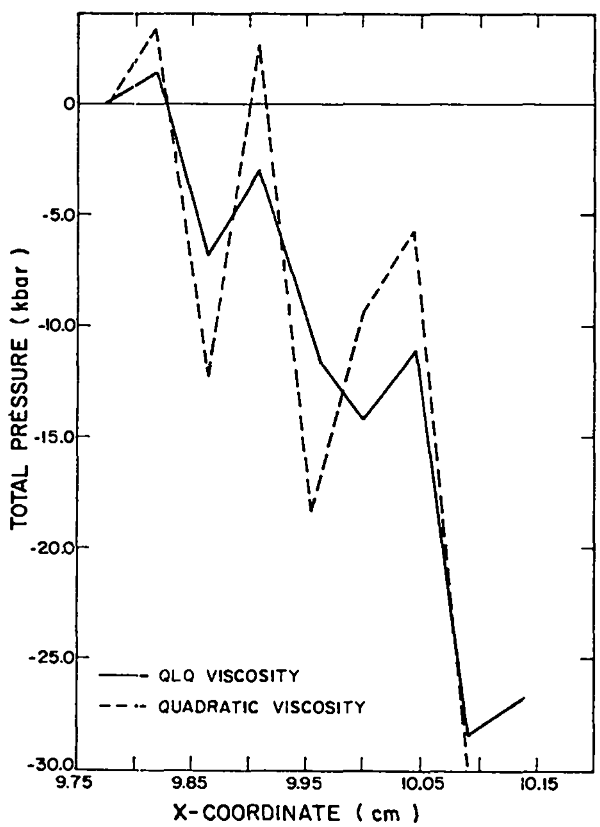

Fig. 2. Effect of viscosity on the pressure profiles.

V. RICSHAW AND SIN CALCULATIONS

The results of the preceding section were a definite surprise in view of the anticipated

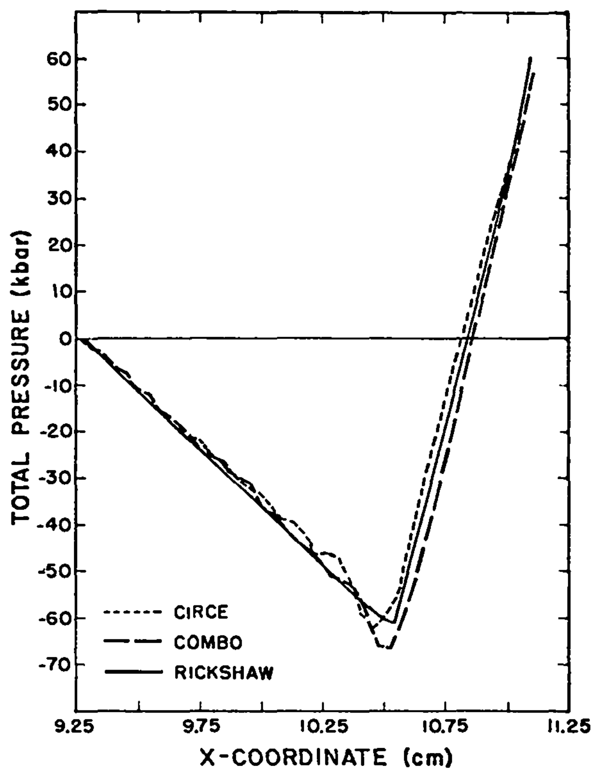

Fig. 3. Pressure profiles in the rarefaction at the 60 kbar level.

findings set forth in the first section. It does not appear possible to match the calculations to the observed data by variations in the zoning or viscosity used in CIRCE and COMBO. Therefore, the original objectives, as defined in the first section, were modified to determine what parameters could affect the calculations in a favorable manner.

To obtain smoother pressure profiles in the rarefaction, two additional codes were used, RICSHAW and SIN. RICSHAW solves the flow equations using the method of characteristics.* While it is also a one-dimensional Lagrangian code, it does not employ an artificial viscosity, treating the shocks as actual discontinuities in the flow. The equations are solved at points of a characteristics mesh, which may be thought of as a transformation of the (x,t)-plane, with the important property that initial discontinuities in the first derivatives of the solution are propagated along characteristics. In particular, characteristics define the boundaries of rarefactions, and the method of solution generates very little noise, as can be seen in Figs. 1 and 3. The two sets of characteristics carry values of u + c and u - c respectively, where u is the particle velocity and c is the local sound speed. For this reason, RICSHAW is very sensitive to the type of equation of state being used.

To check on equation of state effects, we consulted C. L. Mader of LASL Group T-4, who suggested the use of the SIN code for this purpose. SIN is a one-dimensional Lagrangian code, using a PIC type of artificial viscosity, which is quadratic in the particle velocity. SIN also uses more realistic equations of state than the previously mentioned codes, with options that give detailed descriptions of HE burning. A comparison of SIN and RICSHAW profiles is shown in Fig. 4, which also illustrates the effect of the equation of state on the RICSHAW profile. There are significant differences in the profiles generated by the two codes, even when RICSHAW uses the SIN equation of state. In our opinion, the differences are attributable to the presence of the artificial viscosity in the SIN code, although this has not been thoroughly investigated. Another possibility is that the HE burn description is inadequate in RICSHAW, although several attempts at modifying the RICSHAW burn had no significant effect on the results shown in Fig. 4.

*For more information on this technique, see Ref. 4.

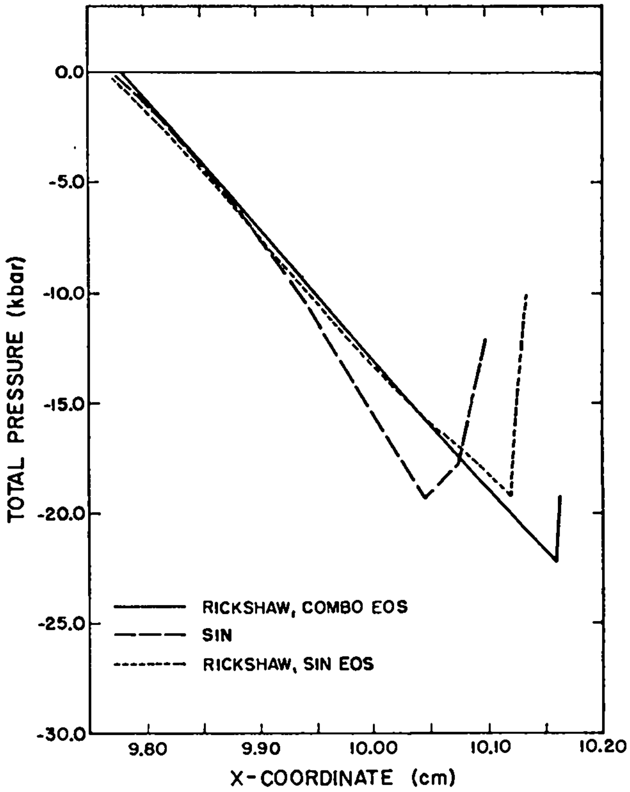

Fig. 4. SIN and RICSHAW pressure profiles.

Using the COMBO equation of state, RICSHAW gave a spall thickness of 0.27 cm for the first layer, and a spall tension of 16.5 kbar. With the SIN equation of state, the thickness of the first layer increased to 0.29 cm with no significant change in the spall tension. SIN indicates a thickness of 0.25 cm, which is not surprising considering the positions of the two profiles in Fig. 4.

We concluded that modification of the equation of state would not give the desired effect on the spall calculations.

VI. THE TEMPERATURE DEPENDENCE OF THE SPALL CONSTANTS

The report by Thurston and Mudd (cited as Ref. 3 in Section III) indicated that the spall constants σ_0, σ_u, A and B of (1), Section III, are sensitive to changes in temperature. The spall constants presently being used in CIRCE and COMBO are for aluminum at 300^{o} K. The constants all decrease with increasing temperature, although no analytical description of this behavior appears to be known at this time.

In studying the behavior of the rarefaction wave, we noticed that the minimum pressure point exhibited a time-dependent growth, and since its location remained near the tail of the rarefaction wave, the location could also be described as a function of time. Therefore, by a crude interpolation using the available data we could determine at what time the minimum pressure, or maximum tension point would be at a distance from the free surface corresponding to the desired spall layer thickness, and the value of the spall tension at that time. Using formula (1) we could then determine any single spall constant if the others remained fixed. Since σ_0 is very small compared to σ_S, and decreasing with increasing temperature, we decided to ignore its contribution to the spall tension, σ_S. Furthermore, the best available data indicated that the calculated spall tension did not exceed the decreased value of σ_u, so that (1) was indeed applicable. Finally for a fixed change in temperature, the constant A appeared to change more than the constant B, so that A was considered to have the largest contribution to changes in σ_S. Therefore, all constants but A were fixed, and A was then determined so that (1) gave the desired spall pressure. This value of A was 0.078 (compared to 0.095 originally).

Using this value of A, RICSHAW gave a spall layer thickness of 0.23 cm and a spall tension of 13.5 kbar. Both of these numbers are within the range of experimental error given for this system.

We concluded that while this method was the most promising in achieving the desired quantitative improvements in calculating spall, much more work should be done to bring the temperature dependence of the spall constants out of the realm of guesswork onto more solid theoretical grounds.

VII. SUMMARY OF CONCLUSIONS

We summarize the major conclusions of our work as

(1) The presence of noise in the rarefaction wave has no appreciable effect on the spall calculations.

(2) As a direct consequence of (1), the default spall option allowing spall at a preassigned fixed tension is not necessary.

(3) Changing the equation of state will not necessarily improve the quantitative results of the spall calculation.

(4) While changing the spall constants to allow for their temperature variation produces satisfactory agreement between calculation and experiment, the theoretical basis for such a modification is not complete enough to allow for generalization of the results obtained in this study.

ACKNOWLEDGMENTS

The author wishes to thank Charles L. Mader of LASL Group T-4 for his assistance in providing and interpreting the experimental data used in this report, and for giving his time to set up and run the necessary problems using the SIN code.

REFERENCES

1. K. A. Meyer, "Artificial Viscosities Considered For Use in the CIRCE Lagrangian Hydrocode (U)," Los Alamos Scientific Laboratory report LA-4383-MS (Conf. RD) (February 1970).

2. Charles L. Mader, "GMX-2 Spalling Calculations," Internal Los Alamos Scientific Laboratory Document (October 1965).

3. R. S. Thurston and W. L. Mudd, "Spallation Criteria for Numerical Computations," Los Alamos Scientific Laboratory report LA-4013 (September 1968).

4. R. Courant and K. O. Friedrichs, Supersonic Flow and Shock Waves, Vol. I (Interscience Publishers, Inc., New York, 1948), pp. 37-172.

EE/wb:325(100)