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June 1967

RESULTS OF A SHORT TERM STUDY TO INVESTIGATE
THE USE OF DIFFERENCE EQUATION CODES TO
PREDICT EXPLOSIVE DRIVEN SHOCK TUBE
RESPONSE

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ABSTRACT

A short term study in response to Sandia Contract S5611-001 (73-4026) was performed relative to the problem of using digital computer codes to predict the response of explosive driven shock tubes. The study showed that existing codes such as WONDY, written at Sandia Corp Sandia Laboratory, can be used to predict responses which are in general agreement with experimental results. It should be noted that existing codes as they stand are relatively difficult to set up properly and much care must be exercised in their use. Equations of state and data are in some cases not completely satisfactory and additional work in the area of accounting for the explosive energy is indicated.

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INTRODUCTION

Concurrent with the interest in testing various vehicle shapes in shock environments ranging from a peak shock pressure of a few atmospheres to a few tens of atmospheres, has been the interest in constructing explosive driven wells and tubes. Typically such facilities have a charge of HE located at one end of a vertical or horizontal tube with the test sample located at the other end or at some point downstream from the HE. The particular shock tube facility studied in this report is a horizontal tube six feet in diameter and either 50 or 200 feet in length. It is driven by an HE charge typically of a few hundred pounds surrounded by an expendable jacket. The tube itself is not expended in tests. The test sample is placed in the tube opposite the HE charge and the entire facility evacuated to some desired level. In the cases considered, the fluid in the tube was either air or sulphur hexafluoride (SF_6) at 1 psi. The detonating of the HE caused an overpressure wave to travel down the tube and impinge on the test sample.

The problem to be solved is the setting up of a means for predicting the general character of the fluid pressure in the tube as a function of the variables of that particular test such as the fluid pressure, the distance from the HE charge, the quantity and type of HE and any other details such as the presence or absence of backing plates on the end of the tube and the like. The study was to be short term in nature to determine the general feasibility of using existing digital computer codes.

This report deals with the results of the short term study. The duration of the study was about two months and extended through the months of May

and June, 1967. Since it was necessary to make commitments based on the results of the study, results to come from the study were to be in hand before the end of June, 1967. The rather pressing nature of this program dictated that certain ground rules needed to be observed from the very beginning in order to maximize the probability that useful results would be obtained during the period allotted. In essence these ground rules were that only those activities having a minimum risk and a maximum chance of producing useful results could be considered. This led to a formal definition of the short term problem as follows:

a. Primarily only existing computer codes would be used. These codes would have to be de-bugged and actually running, adaptable to the CDC 3400 equipment, and have definite promise of being able to solve the problem at hand.

b. Assuming that such codes defined a. could be found and be made to run on the 3400, the study would then establish the procedures for using the codes to solve the problem at hand and determine the bounds and limitations on their use.

c. Since it is natural to assume that the disposal of the energy generated by the HE is of basic importance in the solution of the problem, a study concurrent with a. and b. would be carried out to account for the HE energy.

- d. Those areas uncovered in the pursual of a, b, or c above needing additional attention would be defined.

SELECTION OF A SUITABLE COMPUTER CODE

In the initial consideration of this problem, two computer codes were considered: the Puff 66¹ code, and the WONDY² code. Both codes are similar in that the differential equation which describe the conservation of mass, momentum and energy in a Lagrangian coordinate system are solved by difference equation methods as described in the classic works by Richtmyer and others.^{3,4} Both codes being written in the FORTRAN computer language would be potentially suitable for running on the CDC 3400. Both codes have been extensively used and it is the author's opinion that the major advantages of the WONDY code over the PUFF code are its greater flexibility in allowing for new equation of state formulation, and the superiority of its existing equations of state for solids, HE and gases. It has demonstrated its ability to accurately predict low pressure phenomenon in the past. The decision was made to use WONDY.

The major disadvantage of WONDY was that whereas PUFF virtually runs on the 3400 with no difficulty, WONDY being originally written for the 3600, had to be overlayed, the size of its common block storage reduced and editing procedures changed slightly.

Obtaining the program, getting it to run on the 3400, setting up the first test cases and obtaining the initial results consumed about the first month of the allotted time.

All difference equation codes such as PUFF or WONDY require that the problem be suitably zoned into Lagrangian mass cells. Zoning on any such codes remains in the large an art rather than a science. Although for many problems the zoning becomes a matter of well-defined practice after a period of time; initially, much time must be expended to find a suitable zoning procedure. In essence the basic constraints on the zoning problem are that adjacent mass cells have roughly the same mass, and that the number of cells which the problem is divided into must be minimum on the one hand to minimize computations, and enough on the other hand to allow for a reasonable degree of precision. Although on some rather simple problems, the requirement to keep mass cells nearly the same mass is solved by making them all the same mass, in the shock tube problem, it was immediately noted that this was an unsatisfactory alternative because of the large density differential between the HE and the air or SF_6 requiring that the HE mass cell adjacent to the fluid be very small. Making all HE cells the same size would have made the number of HE cells number several thousand. After considerable experimentation, it was finally decided that reasonable precision could be obtained in the air or SF_6 if the shock fluid were zoned with constant mass cells having a length of about 5 to 10 cm. and the HE were zoned with a zoning constant of .975 to .98 making the zones progressively finer from left to right. A more complete discussion of zoning will be found in Appendix D.

The initial runs made with the code indicated that the constant gamma HE equation of state formulation supplied with WONDY gave an unsatisfactory prediction of the HE gas behavior, as indicated by the typical shock wave pattern of Fig. 1. It is noted that the HE gas products abruptly trail off rather than the pressure gradually trailing off as indicated by the dashed line. To improve the prediction of pressure of the HE gas products, the Blackwell⁵

formulation of gamma was incorporated in WONDY as subroutine STATE 4. A listing of this equation of state is in Appendix A. The utilization of Blackwell's equation of state improved the trail off of the shock in the HE gas products although it still leaves something to be desired. Additionally, the Blackwell energy/gram of 46.82×10^9 ergs/gm was used as the standard for full strength TNT. The equation of state for air and SF_6 and the other constants used to describe the TNT in addition to those mentioned are listed below in Table 1.

SUBSTANCE	DATA SOURCE	EQUATION OF STATE CONSTANTS
TNT	Ref. 5 (Blackwell)	$C_s = 2.88 \times 10^5$ cm/sec
	Ref. 6 (Bickel)	$D = 3.88 \times 10^5$ cm/sec
		$E_z = 46.82 \times 10^6$ ergs/gm
SF_6	Ref. 6 (Bickel)	$P_{\text{zero}} = 6.88 \times 10^4$ dynes/cm ²
		$\text{Rho}_{\text{zero}} = 4.36 \times 10^{-4}$ gm/cm ³
		$C_s = 1.365 \times 10^4$ cm/sec
		$\gamma = 1.096$
AIR	Ref. 7 (Standard Atmosphere Table)	$P_{\text{zero}} = 6.88 \times 10^4$ dynes/cm ²
		$\text{Rho}_{\text{zero}} = 81.94 \times 10^{-6}$ gm/cm ³
		$C_s = 3.403 \times 10^4$ cm/sec
		$\gamma = 1.4$

TABLE I
Equation of State Constants Used in Computer Runs

ENERGY ACCOUNTING RESULTS

Although this area is one which requires much additional attention, some results were forthcoming from this study. When the HE is detonated the energy can be accounted for in at least the following areas:

- a. Energy absorbed by the steel water jacket assembly around the HE charge.
- b. Energy transferred to the steel backing plate.
- c. Energy dissipated by the HE gases leaving the rear of the tube.
- d. Energy transferred by the HE into the shock wave.
- e. Energy transferred by the shock wave to the tube walls due to viscous effects.
- f. Energy dissipated by the HE gases leaving the front of the tube.

Since WONDY is a one-dimensional code (hence its name), the effects of the HE on the water jacket simultaneously with consideration of the shock formation was not possible. It was decided to make a hand analysis of the energy lost to the water jacket and establish at least an upper bound of the energy lost in this area. The assumptions for the water jacket study are as follows:

Ultimate stress of the welds	75 psi.
Average driver tank deformation (based on photos and measurement)	8%

A typical stress strain curve as shown below was integrated to obtain the result that the energy absorbed by the water tank was less than 1.2×10^7 ft. lbs., or less than 2.5% of the energy from 216 lbs. of TNT.

Figure 2

Typical Stress-strain Curve for Steel

The energy transfer into the steel backing plate was analyzed by setting up a WONDY run to simulate the exploding TNT going into 1 psi air on the front, and through an epoxy layer to the 1" steel plate to the rear. The calculated value of the steel plate velocity is somewhat less than the observed value due to the fact that the observed value was averaged over approximately the first 100 feet of flight. The long computer running time for this problem (12 hrs.) prevented carrying the result beyond the first $\frac{1}{2}$ ms. and as a result shock pressure down the tube and plate velocity later in time were not obtained. Based on the calculation, approximately

FIGURE 3
ENERGY DEPOSITION

6.7% of the HE energy was transferred to the steel plate in the form of kinetic energy. Internal energy rise of the plate was not considered.

CALCULATED PLATE VELOCITY	1050 fps
EXP. PLATE VELOCITY (100' average)	775 fps
CAL. % HE ENERGY INTO PLATE	6.7%

TABLE 2

Calculated and Exp. Steel Plate Velocity and Energy

The parametric runs considered in the next section suggested that approximately 53% of the energy of the HE gave rise to the shock and gases dissipated to the front of the tube. All of these results give the approximate energy accounting shown in the circle graph in Fig. 3.

DISCUSSION OF PARAMETRIC COMPUTER RUNS

In addressing the question as to whether the one dimensional code WONDY would be capable of predicting both shock peak amplitude and arrival time, the fundamental question is which parameter of the input might be the most sensitive or have the most effect. It was postulated that, since the HE burning time is on the order of 20 microseconds compared with the shock arrival times on the order of milliseconds, perhaps the most significant parameter might simply be the total HE energy. To investigate the feasibility of this contention three computer runs were devised where the effective HE energy was varied. Plotting of these results did indicate strongly that energy might well be a very significant parameter to the exclusion of such things as HE density, burn time (providing it is small compared with shock arrival time), and other factors. Additional parametric runs were made and the results of shock peak amplitude vs. arrival time were plotted in Fig. 4-8 for air at 1 psi and Fig. 9-13 for SF_6 at 1 psi.

On the basis of the air runs, a value for HE energy was selected to represent the measured arrival time at the 31 ft. station and this run produced the results of Table 3 showing fairly good correlation with the measured values at all stations. It should be noted that the values might have been improved had the editing program used chosen the extrapolated value of the shock peak amplitude at the point of maximum artificial viscosity rather than the value simply of maximum sigma from the WONDY run.

For user convenience the parametric run results were plotted in the form of arrival time vs. HE equivalent charge in Fig. 14 for air at 1 psi, and Fig. 15 for SF_6 at 1 psi. Assuming that energy losses stay in proportion, one can

TABLE 3
A COMPARISON OF PREDICTED AND
EXPERIMENTAL SHOCK AMPLITUDE AND ARRIVAL TIME

Distance from face of HE	15.5 ft.	23.5 ft.	31.5 ft.	39.5 ft.	48.39 ft.
Predicted Time (ms)	.960	1.54	2.12	2.76	3.46
Experimental Time (ms)	1.05	1.58	2.15	2.69	3.53
Predicted Shock (psi)	190.00	169.00	149.00	139.00	138.00
Experimental Shock (psi)	242.00	204.00	195.00	136.00	144.00

predict the shock arrival time for charges different from the 216 lb. charge used previously, by suitably scaling the HE energy. Note that for different density and/or different energy/gram the new mass of HE used times its energy/unit mass compared with the energy produced by 216 lbs., $\rho = 1.0 \text{ g/cm}^3$, TNT would be necessary. Results using this procedure have not been checked and it is only offered as a possibility.

PSI x 100

8

7

6

5

4

3

2

1

0

• 3.995

• 3.508

• 3.0344

• 2.655

• 2.086

• 0.794

FIG. 9

PEAK SHOCK PRESSURE IN SF₆

vs

ARRIVAL TIME

X = 15.5 Ft.

Milliseconds

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

There are two major conclusions to come from this study.

First is that one dimensional models for the shock tube do appear to offer the possibility of accurately predicting at least the arrival time and peak shock amplitude and to a lesser extent predicting the exact nature of the shock signature. Two runs made with a free back surface on the HE rather than a fixed back surface would tentatively indicate that better shock signature prediction can be obtained if greater attention is given to the back boundary. This area is worthy of additional consideration. At the risk of repetition it must be emphasized that properly setting up the one-dimensional model is somewhat tedious and must be done correctly if good results are to be obtained. WONDY as it stands now is not particularly easy to set up particularly for one lacking experience with the code.

The second conclusion stated in all its simplicity is that approximately half of the energy from the exploding HE can ultimately be expected to be dissipated down the front of the tube and half down the rear of the tube. In the case where the back steel plate is employed, it would be expected that a significant variation in the steel plate energy would occur when the HE charge was made sufficiently large to drive the plate to Mach 1 velocity.

There are several specific areas where additional work is recommended. These are summarized below and in greater detail in Appendix E.

1. Better definition of the HE equation of state.
2. Work to obtain a clearer understanding of the tube

performance particularly when the HE charge is substantially increased over the present values. This would specifically include looking at possible 2D effects, and a further investigation into energy effects.

3. With regard to computer codes much needs to be done in making any existing code easy to use from the standpoint of collecting equation of state data on a library tape, automatic zoning and possible alternation of the physical relations used in the code to account for effects heretofore neglected.

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4. Von Neumann and Richtmyer, "A Method for the Numerical Calculation of Hydrodynamic Shocks", Applied Physics, Vol. 21, P. 232, 1950.
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6. L. Bickel to G. R. Case - Private Communication.
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APPENDIX A
LISTING OF STATE 4

```

SOURCE LANGUAGE STATEMENT
SUBROUTINE STATE4
C PROGRAM WONDY
C
C      INSERT COMMON CARDS HERE
C
C      HIGH EXPLOSIVE EQUATION OF STATE USING THE BLACKWELL GAMMA
C      FORMULATION.
5002 F=CES(4,PLATE)*(T-P(J))/(CES(6,PLATE)*DELTAX(PLATE))
      IF(P(J).GE.T)F=0.0
      IF(F.GT.1.0)F=1.0
C
C      CES(1,PLATE) IS MULTIPLICATIVE FACTOR TO CONVERT RHO1 TO GM/CM**3
      RH02=RHO1*CES(1,PLATE)
      IF(RH02.GT..66653)5006,5007
5006 GM1=1.439-.655/RH02
      GO TO 5008
5007 GM1=.20+RH02/(5.6-4.5*RH02)
5008 E1=(E(J)+(SIGMA(J)+Q1+Q(J))*DELRHO)/(1.0-F*RHO1*DELRHO*GM1)
      SIGMA(J)=F*RHO1*E1*GM1
      C(J)=CES(3,PLATE)*SIGMA(J)/RHO1
      IF(C(J).LT.CES(8,PLATE))5003,5004
5003 C(J)=CES(2,PLATE)
      GO TO 5005
5004 C(J)=SQRTF(C(J))
5005 E(J)=E1
      GO TO 5999
      ENTRY STIN4
      PRINT 5201,PLATE
      IF(W4020)WRITE(21,5201)PLATE
      CES(8,PLATE)=CES(2,PLATE)**2
      IF(CES(1,PLATE).EQ.0.)CES(1,PLATE)=1.
      LOM=LOL+1
      DO 5001 LF=LOM,LOR
      JF=(LF-1)*NVAR+1
5001 P(JF)=ABSF(0.5*(X(JF)+X(JF-NVAR))-CES(5,PLATE))/CES(4,PLATE)
5201 FORMAT(#0 THE BLACKWELL HE EQUATION OF STATE WILL BE USED FOR PLAT
      1E  *,I5)
5999 RETURN
      END

```


APPENDIX B
LISTING OF WODEDIT

SOURCE LANGUAGE STATEMENT

PROGRAM WODEDIT

THIS PROGRAM EDITS WONDY BINARY TAPES UP TO 5 SELECTED POSITION
POINTS OF INTEREST. UP TO 4 WONDY 20 TAPES MAY BE EDITED

COMMON/1/STORE(16000)

DIMENSION ITABLE(50),TABLE(2,50),MARKP(5),SIGMAD(500
1,5),UD(500,5),TIME(500),DELT(4),C(1),E(1),M(1),P(1),PHI(1),Q(1),
2RH0(1),SIGMA(1),U(1),X(1),NTAP(4),XPOS(5),NDPS(4)
EQUIVALENCE(STORE(10),X(10),U(9),SIGMA(8),RH0(7),Q(6),PHI(5),P(4),
1 M(3),E(2),C(1))

100 FORMAT(15I5)

101 FORMAT(7E10.3)

103 FORMAT(*1NOMINAL X POS *,E12.5,4X,

//,6X,*U*,

112X,*SIGMA*,12X,*T*,//)

104 FORMAT(1X,3(E12.5,3X))

READ IN NUMBER OF TAPES AND LOGICAL UNIT NO S IN ORDER (UP TO 4)
NOTE THAT UNIT 20 IS EXCLUDED

160 CONTINUE

READ 100,NOTAPES,(NTAP(J),J=1,NOTAPES)

READ IN NUMBER OF XPOSITIONS (UP TO 5), THEY NEED NOT BE IN ORDER

READ 105,NX,(XPOS(I),I=1,NX)

PRINT105,NX,(XPOS(I),I=1,NX)

105 FORMAT(15,5E10.3)

READ IN THE NUMBER OF DUMPS ON EACH TAPE (OBTAIN FROM WONDY LIST)

READ 100,(NDPS(I),I=1,NOTAPES)

PRINT100,(NDPS(I),I=1,NOTAPES)

READ JTAPE AND NVAR FROM WONDY PROBLEM

READ 100,JTAPE,NVAR ,NWRITE

L=JTAPE/NVAR

IX=0

DO 12 KKK=1,NOTAPES

NUP=NDPS(KKK) \$ NTX=NTAP(KKK)

DO 1 I=1,NUP

IX=IX+1

READ(NTX)N,T,DELT(1),DELT(4),(ITABLE(K),TABLE(1,K),TABLE(2,K),

1K=1,50),(STORE(K),K=1,JTAPE) \$ TIME(IX)=T

IF(EOF,NTX)3634,3635

3635 CONTINUE

IF(IOCHECK,NTX)3434,3435

3434 PRINT 3466,NTX,N,T

3466 FORMAT(* PARITY ERROR SENSED ON UNIT*,15,* CYCLE NO*,15 ,
1* TIME *,E12.5)

3435 CONTINUE

IF(NWRITE)4370,4370,4369

4369 WRITE(20)N,T,DELT(1),DELT(4),(ITABLE(K),TABLE(1,K),TABLE(2,K),

1K=1,50),(STORE(K),K=1,JTAPE)

4370 CONTINUE

DO 2 J=1,NX

MARK=0

XRUN=50.E100

DO 3 K=2,L

```

        SOURCE LANGUAGE STATEMENT
        IDX=(K-1)*NVAR+1
        AUX=(X(IDX)+X(IDX-NVAR))/2.
        XDIFF=ABS(XPOS(J)-AUX)
        IF(XDIFF.LT.XRUN)6,3
6      MARK=K
        XRUN=XDIFF
3      CONTINUE
        IDX=(L-1)*NVAR+1
        IF(XPOS(J).GT.X(IDX.))MARK=0
        IF(MARK.EQ.0)GO TO 1
        IF(MARK.EQ.L)MARK=MARK-1
        IDX=(MARK-1)*NVAR+1
        X1=(X(IDX-NVAR)+X(IDX))/2.
        X2=(X(IDX)+X(IDX+NVAR))/2.
        SIG1=SIGMA(IDX)
        SIG2=SIGMA(IDX+NVAR)
        U1=U(IDX)
        U2=U(IDX+NVAR)
        SIGMAD(J,X)=SIG1+(SIG2-SIG1)*(XPOS(J)-X1)/(X2-X1)
        UD(J,X)=U1+(U2-U1)*(XPOS(J)-X1)/(X2-X1)
2      CONTINUE
1      CONTINUE
12     CONTINUE
3634   CONTINUE
        DO 8 I=1,NX
        PRINT 103,XPOS(I)
        DO 8 J=1,IX
        TEMPFAF=SIGMAD(J,I)*14.5E-06
8      PRINT 104,TEMPFAF,SIGMAD(J,I),TIME(J)
        GO TO 160
        END

```

Appendix C
Summary of Computer Runs Made

Typical Entry:

Date Time Code mm dd hh mm
(leading zero suppressed)

Data Tape Designation

L&G Tape Used

Equivalent grams of HE

$$= \frac{\text{thickness} \times \text{density} \times \text{energy/gm.}}{\text{standard energy/gm.}}$$

Shock Fluid

Time from HE initiation computed

Computer Running Time hh mm ss
(leading zero suppressed)

Remarks:

1. 6060217
TEST TNT AIR,4
WONDY,1
.91021
Air 1 psi
9.12 ms.
Est 10 hrs.

3. 6111411
HE TO AIRCSE,01,01,999
WONDY,2
.199
Air 1 psi
6.48 ms.
9 57 49

5. 6130011
HE TO AIRCSE,01,04,999
WONDY,2
AIR 1 psi
2 ms.
1 16 51

7. 6142344
HE ENRED BLK,01,01,999
WONDY,3
2.942
Air 1 psi
6.8 ms.
2 19 03
Ez = 42.13

9. 6161447
34-00101,01,01,999
WONDY,3
2.269
1 psi air
8.0 ms.
2 37 09

2. 6111249
HE216TOSF6,01,01,999
HE216TOSF6,01,02,999
HE216TOSF6,01,03,999
WONDY,2
.7943
SF6
5.69 ms.
Est 10 hrs.

4. 6111622
TNTAIR63C,01,01,999
WONDY,2
Air 1 psi
7.8 ms.
3 29 36
60 Air cells

6. 6140240
BLKENTAIR,01,01,999
WONDY,3
3.995
Air 1 psi
10 ms.
2 38 42

8. 6161055
34-00100,01,01,999
WONDY,3
2.594
Air 1 psi
8 ms.
2 29 21

10. 6170046
34-00108,01,01,999
WONDY,3
.32726
1 psi air
6.14 ms.
3 52 56

11.	6170125 34-00104,01,01,999 WONDY,3 .972 1 psi air 6.676 ms. 3 53 35	12.	6170439 34-00103,01,01,999 WONDY,3 .648 1 psi air 6.64 ms. 4 51 35
13.	6170618 34-00105,01,01,999 WONDY,3 1.297 1 psi air 4.375 ms. 2 49 26	14.	6170844 34-00106,01,01,999 WONDY,3 1.620 1 psi air 2 24 54
15.	6171109 34-00107,01,01,999 WONDY,3 1.944 Air 1 psi 5.26 ms. 2 29 05	16.	6171640 HE216TOSF6,01,01,999 WONDY,3 3.995 SF6 10 ms. 3 48 34
17.	6172037 34-00120 WONDY,3 3.508 SF6 at 1 psi 10 ms. 2 44 22	18.	6172328 34-00110 WONDY,3 3.995 Air 1 psi .560 11 37 02 Steel plate run
19.	6172332 34-00101,01,01,999 WONDY,3 3.0344 SF6 at 1 psi 10 ms. 03 07 19	20.	6172639 34-00100 WONDY,3 3.0344 SF6 at 1 psi 10 ms. 3 10 31

21. 6180847
34-00101,01,01,999
WONDY,3
2.655
SF6
6.149 ms.
2 20 57

23. 6181210
34-00100
WONDY,3
2.086
SF6
7.085 ms.
2 44 26

25. 6181459
34-00130
WONDY,3
1.747
Air 1 psi
5 ms.
3 00 04

22. 6181129
34-00104,01,01,999
WONDY,3
3.27
1 psi air
10 ms.
2 13 36
Free back surface.

24. 6181345
34-00107
WONDY,3
4.439
SF6
10 ms.
2 06 55
Free back surface.

APPENDIX D

COMMENTS ON ZONING OF WONDY PROBLEMS

The results of the zoning philosophy established in this study are the following:

1. The air or other fluid cell length should be maintained in the order of 5 to 20 cm. to provide a reasonable precision in the air shock pressure.
2. The HE-air interface should maintain the same mass.
3. The HE should be zoned with a zoning constant not less than 0.98.
4. Normally the air should be zoned with a unity (1.0) zoning constant.

As an exercise let the following problem be zoned using the principles set forth above.

HE weight	=	216 lbs.
HE density	=	$\rho_{he} = 0.79$
Air pressure	=	1 psi

Step 1: Determine the effective HE thickness. The tube diameter of A=72" will be used for setting up the problem rather than the HE actual diameter since it is assumed that the HE gases rapidly expand to the tube diameter shortly after initiation.

$$M_{he} = HE \text{ mass} = 216. \times 453.59 = 9.7975 \times 10^4 \text{ grams.}$$

$$M_{he} = \rho_{he} \cdot A \cdot X \qquad X = \frac{M_{he}}{\rho_{he} \cdot A}$$

$$X = \frac{9.7975 \times 10^4 \times 4}{.79 \times \pi (72. \times 2.54)^2} = 4.721 \text{ cm}$$

Step 2: Determine the final HE cell thickness.

From Rule 1, we shall make the air cell thickness 8.0 cm.

From Rule 2, we wish to maintain constant mass across the HE-air interface.

We determine the density of the air at 1 psi and 25°C (room temp. so to speak) as $\rho_{air} = 81.94 \times 10^{-6} \text{ g/cm}^3$

$$\text{Thus we require } \rho_{air} \cdot \Delta x_{air} = \rho_{he} \cdot \Delta x_{he}$$

$$\text{And solving for } \Delta x_{he} = \frac{\rho_{air}}{\rho_{he}} \Delta x_{air} = \frac{81.94 \times 10^{-6}}{.79} \times 80.0 = 8.2977 \times 10^{-4}$$

Step 3: Determine the Initial HE Cell Size and Zoning Constant.

It should be noted that many ways may be employed to determine the required constants. The method used here is a popular method in that it converges rapidly and lends itself to use of a desk calculator. It requires a table of zoning constants such as Ref. 7.

Turning in the "Table of Zoning Constants for Hydro Codes" (Hereafter called the "Zoning Book") we shall use a zoning

constant of .98.

The procedure goes as follows:

3a. First guess at the number of cells or meshes. Guess $NM=50$. Opposite 50 in the Zoning Book we read a thickness in the first column of 31.79 or $SF = 4.721/31.79 \times .1485$.

3b. Next divide the desired final cell thickness by the result of 3a, $IR = \Delta x_{he} / SF = 8.2977 \times 10^{-4} / .1485 = 55.87 \times 10^{-4}$

3c. Search the Δx column (the second column) to find an entry nearest the result of 3b. We find that for $NM = 257$ that $Thn = 49.72$.

We now iterate to find the solution.

3a. $Thn = 49.72$

$$SF = 4.721 / 49.72 = .0949$$

3b. $IR = 8.2977 \times 10^{-4} / .0949 = 87.39 \times 10^{-4}$

3c. $NM = 236$

3a. $Thn = 49.575$ $SF = 4.721 = .095229$

3b. $IR = 8.2977 \times 10^{-4} / .095229 = 87.133 \times 10^{-4}$

3c. $NM = 236$ the process has converged. Note rapidity of convergence. For the HE we now have $NM = 236$ $SF = DELTAX =$

.95229 and Final HE cell size (from Zoning Book) =
 $86.721 \times 10^{-4} \times .95229 = 8.2583 \times 10^{-4}$

Step 4. Determine the Exact Air Cell Thickness and Zone the Air.

From the result of Step 3 we now determine the exact air cell thickness.

$$\Delta x_{\text{air}} = \frac{\rho_{\text{he}}}{\rho_{\text{air}}} \Delta x_{\text{he}} = \frac{.79}{81.94 \times 10^{-6}} \times 8.2583 \times 10^{-4} = 7.961 \text{ cm}$$

For an air column length of about 60 feet and using a unity zoning constant, we determine the air DELTAX

$$\Delta x_{\text{air}} = \frac{60. \times 30.48}{7.961} = 230$$

To summarize the results:

	HE	AIR
NOMESHES	236.	230.
DELTAX	.095229	7.961
XRATIO	.98	1.0

APPENDIX E

OUTLINE OF SANDIA PROPOSAL

1. 3 Professional Man Months

Investigations into existing and possible new formulation of equations of state to describe HE phenomena relative to shock tubes. The origins of Blackwell's work (SCLL), the work of Hermann (SCSL), and others will be carefully examined.

2. 4 Professional Man Months, 2.5 Sub. Professional Man Months

a. A survey of existing HE data from commercial manufacturers and AEC laboratories to collect and catalog HE information in a form suitable for computer code input.

b. A survey of existing models and data for fluids such as air, SF₆ and other possible shock tube fluids to reduce and modify such data into a form suitable for computer code input.

3. 12 Professional Man Months, 2 Sub. Professional Man Months

An exhaustive study into the physics of the analysis of explosive driven shock tubes from the computer code viewpoint. A precise determination of difference equation stability limits, optimization of code running time from the theoretical viewpoint, a study of 2D effects, and energy distributions will be made.

4. 12 Professional Man Months, 2 Sub. Professional Man Months

Formulation of a shock tube computerized analysis procedure with four major objectives kept in mind.

a. The formulation of a completely general analysis procedure having minimum restrictions.

b. Existing codes will be utilized wherever possible, modified as indicated by paragraph 3.

c. Data will be collected on library tapes and much effort will be directed toward making the procedures easy to use.

d. Output data will be processed under user control for a variety of output media.

Summary

31 Professional Man Months	88K
6 1/2 Sub. Professional Man Months	10K
Computer Time and Some Travel Expense	<u>32K</u>
	130K