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SIMULATION OF THE STATE OF THE M42/M46 GRENADE DURING PRESS LOADING

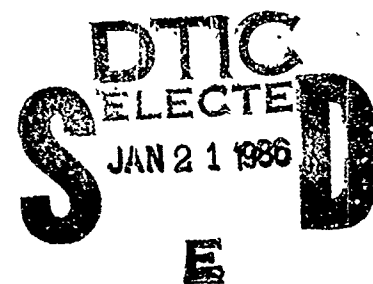
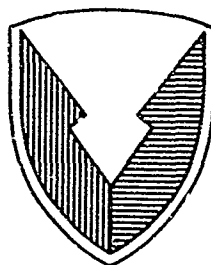
GEORGE J. SCHLENKER

DECEMBER 1985

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report is a contribution to an ongoing study of explosive incidents (blows) which occur during press loading of the M42/M46 grenade. One of the causal mechanisms posited for the blows is brittle fracture of the grenade body. The physical state of the grenade during final consolidation is of critical impor- tance for this mechanism. A detailed simulation of the compression phase of final loading helps to verify the feasibility of this causal mechanism and to suggest means of minimizing a part of the rate of incidents. This report		

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describes a continuous simulation of several, related phenomena which occur during final consolidation. These phenomena include: (a) compaction of the bulk HE, (b) production of elastic strain in the grenade body, (c) elastic compression of RDX particles in the HE, (d) kinematics of the punch, (e) heating of the HE, and (f) diffusion of heat within the grenade. A sample of simulation results is given in graphical form, with key variables displayed as functions of punch displacement and of time. Sensitivity of results to certain parameters is shown. Comparisons are made between some experimental measurements and results of the simulation. These comparisons demonstrate the validity of the simulation within the limits imposed by its scope. For the interested analyst, the implementing computer program is listed and explained. *K. J. ...*

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EXECUTIVE SUMMARY

This report is a contribution to an ongoing study of explosive incidents (blows) which occur during press loading of the M42/M46 grenade. High explosive (HE) Composition A-5 is pressed into a steel body (either M42 or M46) of the grenade in two operations: pre- and final -consolidation. The latter is nearly always where blows occur. Several causal physical mechanisms for blows have been hypothesized. One of these mechanisms involves brittle fracture of the grenade body. If a crack opens and propagates, the rapid release of elastic strain energy at the interface of the body wall and HE fill appears to be capable of igniting the HE. The physical states of the grenade body and of the HE during the compaction phase of final consolidation are critical to this mechanism. Quantification of these states helps to verify the feasibility of the brittle-fracture mechanism and to suggest means of minimizing the portion of the blow rate contributed by this mechanism. This report describes a continuous simulation of several, related physical processes which occur during the final consolidation of the HE in the M42/M46 grenade. Typical simulation results are presented in graphical form, with pertinent variables displayed as functions of both punch displacement and time. The sensitivity of these results to certain parameters is shown. For example, punch travel and work done by the punch are shown to be sensitive to the initial, preconsolidated system state. Also the maximum stress and hoop strain energy are sensitive to peak punch pressure. Where possible, comparisons are made between experimental data and results of the simulation. These comparisons demonstrate the validity of the simulation within the limits imposed by its scope. For the interested analyst, the implementing computer program is listed and explained.

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MEMORANDUM REPORT

SUBJECT: Simulation of the State of the M42/M46 Grenade During Press Loading

1. Foreword

Order of topics in this report represents increasing detail. Background information is presented first to set a context and to motivate the work presented here. The goals of the subject simulation are given next, followed by the scope of- and assumptions for -the simulation. Simulation results are given in tables and graphs, followed by comments about these results. Sections on validation and methodology complete the body of the report. A source program listing of the simulation is given in Annex A. Annex B contains a memorandum concerning a model of the bulk density of Comp A-5. The following references are cited thruout the report.

2. References

- a. MFR, AMSMC-RDA-S, 22 Oct 85, subject: Evidence for a Steel-Supplier Effect on the Rate of Press Blows in M42 and XM77 Grenades.
- b. Technical Report ARLCD-TR-79002, Collett, R.W. and England J.T., ARRADCOM, LCWSL, Dover, NJ, Jun 79, title: Press Loading Incident Investigation of M42/M46 Grenade Bodies.
- c. MFR, AMSMC-RDA-S, 9 Aug 85, subject: Some Observations About the Explosive Sensitivity of Comp A-5.
- d. MFR, AMSMC-RDA-S, 28 Aug 85 (Revised 24 Sep 85), subject: Predicted Bulk Densities of Comp A-5 and Comp A-4 as Functions of Peak Consolidation Pressure. (Given in Annex B.)
- e. Technical Report #371, 23 Aug 85, Day & Zimmerman Kansas Div., subject: Investigation of Effects of Charge Density on Penetration in M42/M46 Grenades.
- f. MFR, DRSMC-SAS (R), 4 Nov 83, subject: Particle-Size Distribution of Nominal Class 1 RDX Before Incorporation and After Extraction From Extrusions of Comp C-4.
- g. Reference Book, Kaye, S.M., US ARDC, Dover, NJ, c. 1980, title: Encyclopedia of Explosives and Related Items, Vol 9.
- h. Text Book, Timoshenko and Goodier, McGraw-Hill, NY, c. 1951, title: Theory of Elasticity.
- i. MFR, AMSMC-RDA-S, 23 Aug 85, subject: Time Series Analysis of the Peak Consolidation Load for Pressing of HE into M42/M46 Grenades.

3. Background

Previous studies of explosive incidents during press loading of M42/M46 grenades posited various physical mechanisms for initiating an explosion. Ref 2a presents arguments supporting the mechanism of brittle fracture of the grenade body. The scenario for an explosion with this mechanism is as follows: During final consolidation of the HE (Comp A-5), a latent crack suddenly opens and propagates. A rapid release of elastic strain energy in the grenade body is deposited at the surface of the HE in proximity to the crack. This energy release over a small area is regarded as sufficient to initiate an explosion of the HE *. If this mechanism is responsible for some of the incidents, one would expect to see the observed variation in blow rate between bodies by different body producers, since variation in metal parts quality between producers is quite evident. Ref 2b also presents evidence for a steel-supplier effect, which, again, is germane to the mechanism of brittle fracture. A similar phenomenon, occurring in the powder nest, is one of the mechanisms hypothesized in Ref 2b. The very limited set of experiments reported in Ref 2b failed to demonstrate a blow with either a cracked body or a cracked nest. However, these negative results are not persuasive, because only rare and special conditions--very rapid energy deposit in a small area--must exist in order to provoke a blow. Based on simulated results, brittle fracture must still be considered a credible mechanism.

4. Considering this mechanism, several actions to reduce the frequency of press blows are appropriate: (a) Improve the specified quality, including fracture toughness, of steel used in making grenade bodies. This action is suggested in Ref 2a. (b) Improve quality of grenade bodies from the "marginal" body producers. Actions started by AMCCOM Quality Assurance in 1985 address this issue. (c) Use a less sensitive HE fill, such as Comp A-4. This idea is still on the back burner. (d) Load at a lower peak consolidation pressure. This suggestion is made in Ref 2c, and justified by data which show reduced explosive sensitivity when grain breakage is minimized. Although easy to implement, the last suggestion has met resistance on the grounds that effectiveness (penetration & lethal area) would suffer. Nevertheless, some tradeoff here seems possible to reduce blow rates.

5. Because of the importance of the state of stress of the grenade body to the brittle fracture mechanism, some effort was made to take experimental measurements (for example, Ref 2b). And, because of the importance of HE density to grenade performance, various data have been gathered relating HE density to peak consolidation load (or pressure), under both quasi-static (very slow rate of loading) and transient conditions (which occur in load plants). Some of these experimental results are compared with simple mathematical models in Ref 2d. Ref 2e presents additional results for the transient loading condition, in a study designed to relate average HE density to grenade penetration performance. Notwithstanding these experiments to understand the processes occurring during press loading, to my knowledge no unified mathematical model has been developed to simulate the physical processes which interact during final consolidation. This memorandum presents such a model. The simulation is not very sophisticated, model output is in good agreement with pertinent experimental data.

* Ref 2g indicates that the threshold value of energy per unit area for shock ignition of RDX is about 10 cal/sq cm, a value which may be achieved by release of elastic strain energy in the body.

6. Goals of the Simulation

The primary goal of the simulation is to achieve better understanding of the relationship of several physical parameters pertinent to loading of the M42/M46 grenade. Understandings of this sort ultimately guide design of experiments and help to quantify improvement in rate of press blows, expected to accompany loading at lower peak pressure. A partial list of questions addressed by the simulation may clarify my intentions:

- (a) How does the HE respond to punch displacement during consolidation? For example, how does punch load vary with punch displacement and with time? (In this case, time is simply a convenient variable for use in comparison with experimental results. Since punch acceleration is quite low, inertial forces are not important. The phenomena are mostly kinematic rather than dynamic.)
- (b) How does the work done by the punch vary as a function of punch displacement and as a function of time?
- (c) What portion of the punch work is invested in elastic, i.e., recoverable, energy components? This question has a bearing on volume change in the HE following punch withdrawal. Also, these elastic strain-energy components would become sources of energy for initiating an explosion of the HE, if a metal failure occurred during compression.
- (d) Are physically significant temperature gradients developed within the RDX particles during consolidation?
- (e) Do any of the variables of interest display a large sensitivity to the initial conditions for final consolidation, i.e., does variation in preconsolidation affect final results?
- (f) How well does the model match the experimental load-versus-time data?

It is beyond the scope of this model to address issues such as:

- (a) Specifically, what happens if a brittle fracture of a grenade body occurs during consolidation?
- (b) What stress concentrations occur in various regions of the body?
- (c) Where does RDX grain fracture occur during loading, and what is its extent?
- (d) What is the nature of the flow in the HE during consolidation?

7. Scope and Assumptions

In terms of fidelity to geometric details of the grenade body, the model is quite crude. For the purpose of calculating hoop stress and hoop strain in the body, the grenade is modeled as a regular cylindrical sleeve, supported on one end by a smooth, unyielding surface. The HE configuration is assumed to have cylindrical symmetry

within the cavity. The simulation model is descriptive; it uses semiempirical results where appropriate, and does not insist on starting from first principles. In spite of evidence of RDX grain fracture, cited in Refs 2c and 2f, the model ignores this phenomenon. Further, because of its simple geometry, no attempt is made to describe the actual flow of the HE with respect to the punch and body cavity in an actual M42/M46 grenade. However, the effects of a pressure gradient within the HE are considered. Most of the mechanical and thermal material characteristics were obtained from standard references such as Ref 2g. The compaction model (avg HE density versus peak pressure) uses the functional form described in Annex B. This model assumes a constant pressure gradient within the HE. The pressure decreases linearly from a maximum value of p_{max} , at the punch face, to a minimum value of a constant, g , times p_{max} . The value of g used here (0.6) is obtained from data in Ref 2e. The assumed constant pressure gradient within the HE is also used in deriving an expression for the RDX elastic strain energy. Hoop stress in the simulated grenade body is calculated using the Lamé equation for thick-walled cylinders (Ref 2h). A formula for body strain energy is derived from the last equation, which assumes elastic behavior.

8. Results of the Simulation

The loading simulation is implemented by a computer program COMPACT. A source listing of this program, in Simscript 2.5, is located in Annex A. The logic of this program is sketched below (p. 19, Methodology). A portion of the output from COMPACT is shown in Table 1. After echoing the input parameters, the state variables, which characterize the HE and the grenade body, are printed as functions of the displacement of the punch. The initial, average density of the HE is chosen by the program user. This value suffices to initialize the simulation for the final consolidation cycle. Punch displacement and cycle time are taken as zero at this point. Time is calculated from punch displacement, since these are kinematically related by the punch cam shape and operational speed of the press. Program variables are plotted as functions of punch travel and time. These are shown in Figures 1 thru 19, on pages 7 thru 16. Results are discussed in paragraph 10, page 17.

9. Parametric Analyses

Two simulated body dimensions were treated as parameters for sensitivity analysis: (a) the thickness of the wall of the sleeve, representing the grenade body, and (b) the effective length of the sleeve which is exposed to internal pressure. The last parameter is determined by shape of the punch and by the 1-D nature of body stress calculations. Three values of wall thickness -- 0.110 inch, 0.115 inch, and 0.120 inch -- are used at a effective body length of 1.4 inch. And, two values of the body length -- 1.0 inch and 1.4 inch -- are used with a nominal wall thickness of 0.115 inch. Results are shown in Tables 2 and 3. In each case the initial punch pressure is 5.1 kpsi and the final pressure is 25 kpsi (to terminate the compression phase). The initial pressure corresponds to an average HE density of 1.44 g/cc. Since the final state is prescribed, certain variables, such as punch work and loading time, are not very sensitive to the parameters. However, variables such as hoop strain energy, are. Sensitivity to the initial state of compression is shown in Table 4. Sensitivity to the final state of compression is shown in Table 5.

TABLE 1. SAMPLE OUTPUT FROM THE COMPUTER PROGRAM: COMPACT

DIMENSIONS OF CYLINDRICAL SLEEVE SIMULATING THE GRENADE BODY

INTERNAL DIAMETER	3.2004	CM	1.2600	INCH
OUTSIDE DIAMETER	3.8100	CM	1.5000	INCH
EFFECTIVE HEIGHT	3.5560	CM	1.4000	INCH
PUNCH TRAVEL LIMIT	0.4157	CM	0.1637	INCH

PROPERTIES OF RDX , USED IN THE EXPLOSIVE FILL:

DIAMETER OF RDX PARTICLE	160.0	MICRON
RADIAL GRID ELEMENT OF RDX	8.0	MICRON
SPECIFIC SURFACE OF RDX	206.0	SQ CM/G
THEORETICAL MAX DENSITY OF RDX	1.820	G/CC
SPECIFIC HEAT OF RDX	0.300	CAL/G/DEG K
THERMAL CONDUCTIVITY OF RDX	+7.00000E-04	CAL/CM/S/DEG K
THERMAL DIFFUSIVITY OF RDX	+1.28205E-03	SQ CM/S
YOUNG'S CONSTANT FOR RDX	+1.80000E+10	PASCAL
POISSON'S RATIO FOR RDX	+2.20000E-01	
BULK MODULUS FOR RDX	+1.07143E+10	PASCAL
MASS FRACTION OF RDX IN HE	0.985	

THERMAL PROPERTIES OF GRENADE MATERIALS:

RADIAL GRID ELEMENT OF HE	+8.00100E-02	CM
TMD OF HE	+1.78917E+00	G/CC
SPECIFIC HEAT OF HE	+3.01485E-01	CAL/G/DEG K
THERMAL CONDUCTIVITY OF HE	+6.95200E-04	CAL/CM/S/DEG K
THERMAL DIFFUSIVITY OF HE	+1.28882E-03	SQ CM/S
RADIAL GRID ELEMENT OF STEEL	+7.62000E-02	CM
TMD OF STEEL	+7.87000E+00	G/CC
SPECIFIC HEAT OF STEEL	+1.25000E-01	CAL/G/DEG K
THERMAL CONDUCTIVITY OF STEEL	+1.65000E-01	CAL/CM/S/DEG K
THERMAL DIFFUSIVITY OF STEEL	+1.67726E-01	SQ CM/S

INITIAL CONDITIONS AT START OF FINAL CONSOLIDATION:

HE DENSITY	1.44000	G/CC	
PRESSURE ON HE	5.1046	KPSI	35.195 MPA
HEIGHT OF HE COLUMN	2.58468	CM	
MAX BODY HOOP STRESS	29.474	KPSI	203.21 MPA
HOOP STRAIN IN BODY	+9.82452E-04		
HOOP STRAIN ENERGY	1.1795	JOULE	0.2819 CAL
RDX ELASTIC ENERGY	0.4880	JOULE	0.1166 CAL
CUM WORK BY PUNCH	1.6675	JOULE	0.3985 CAL

SIMULATED CONDITIONS DURING HE CONSOLIDATION

PUNCH DISPL (CM)	HE DENS (G/CC)	HE PRESS (KPSI)	MAX STRESS (KPSI)	HOOP STRAIN (MU/U)	H STRN ENERGY (CAL)	PUNCH WORK (CAL)	THERM WORK (CAL)	TEMP RISE (D K)	CYCLE TIME (MS)
0.0010	1.4406	5.115	29.53	984.5	0.283	0.467	0.067	0.007	2.75

TABLE 2. SENSITIVITY OF SIMULATION OUTPUT TO BODY WALL THICKNESS

Output Variable	Body Wall Thickness (inch)		
	0.110	0.115	0.120
Loading Time (ms)	266	268	269
Punch Travel (mm)	3.976	4.031	4.087
Punch Work (cal)	57.5	57.3	57.1
Max Hoop Stress (kpsi)	159.1	151.8	144.9
Hoop Strain Energy (cal)	7.765	7.724	6.815

TABLE 3. SENSITIVITY OF SIMULATION OUTPUT TO EFFECTIVE BODY LENGTH

Output Variable	Effective Length of Body (inch)	
	1.0	1.4
Loading Time (ms)	268	268
Punch Travel (mm)	4.031	4.031
Punch Work (cal)	57.3	57.3
Max Hoop Stress (kpsi)	151.8	151.8
Hoop Strain Energy (cal)	5.196	7.274

TABLE 4. SENSITIVITY OF SIMULATION OUTPUT TO INITIAL SYSTEM STATE
Internal Diameter (cm) 3.226 Effective Length (cm) 3.556

Output Variable	Initial Punch Pressure/HE Density	
	4.75/1.42 (kpsi)/(g/cc)	5.10/1.44
Loading Time (ms)	281	268
Punch Travel (mm)	4.392	4.031
Punch Work (cal)	59.6	57.3
Max Hoop Stress (kpsi)	151.8	151.8
Hoop Strain Energy (cal)	7.27	7.27
Remain Heat Energy (cal)	49.5	47.2

TABLE 5. SENSITIVITY OF SIMULATION OUTPUT TO PEAK PUNCH PRESSURE

Output Variable	Peak Punch Pressure		Percent Decrease
	25 (kpsi)	20 (kpsi)	
Max HE Density (g/cc)	1.697	1.678	1.1 %
Final HE Density (g/cc)	1.676	1.661	0.9 %
Max Hoop Stress (kpsi)	144.8	115.8	20.0 %
Hoop Strain Energy (cal)	6.80	4.35	36.0 %

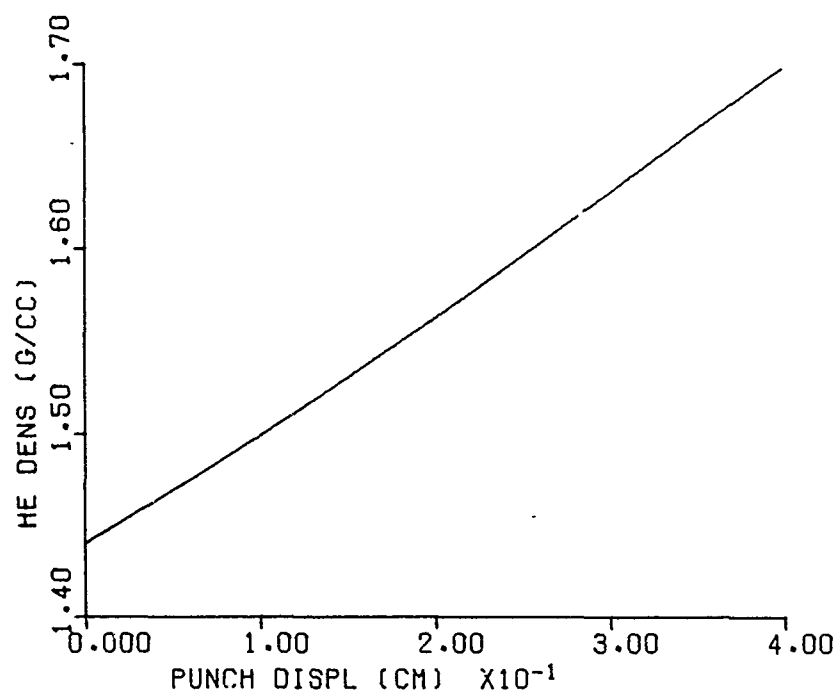


Figure 1. Avg Density of HE as a Function of Punch Displacement

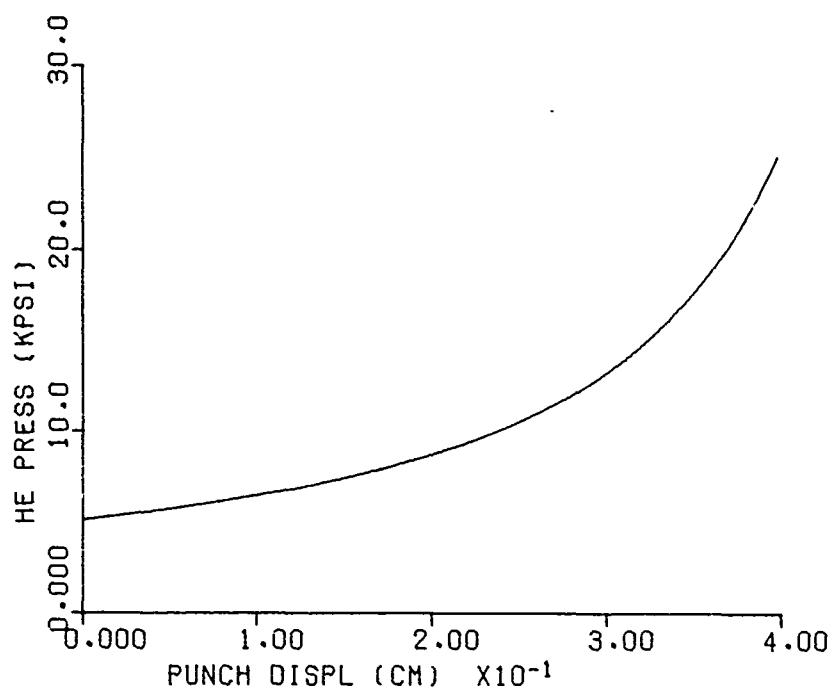


Figure 2. Max Pressure on the HE Versus Punch Displacement

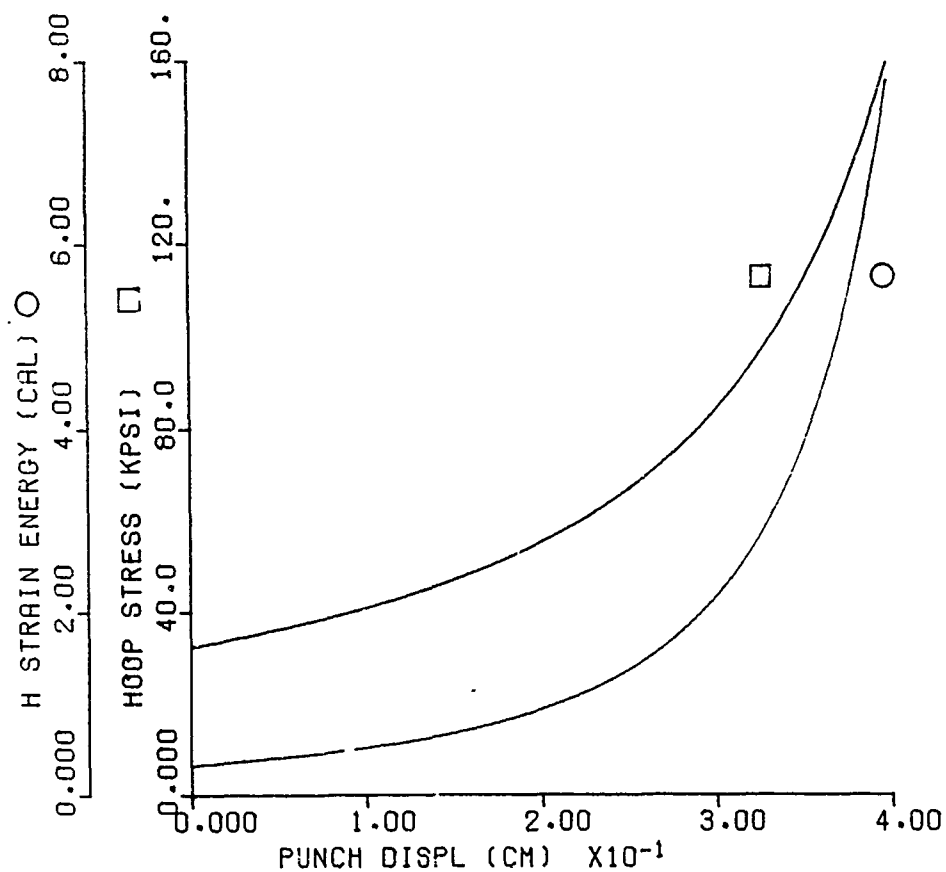


Figure 3. Hoop Strain Energy and Max Hoop Stress in the Grenade Body Versus Punch Displacement

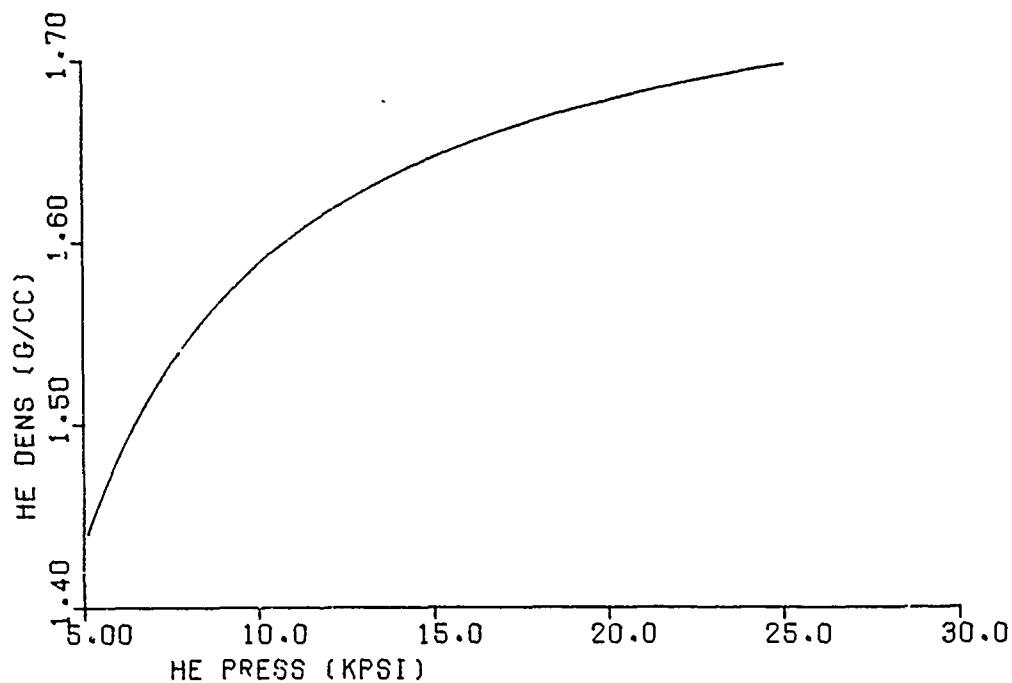


Figure 4. Avg Density of the HE Versus Max HE Pressure

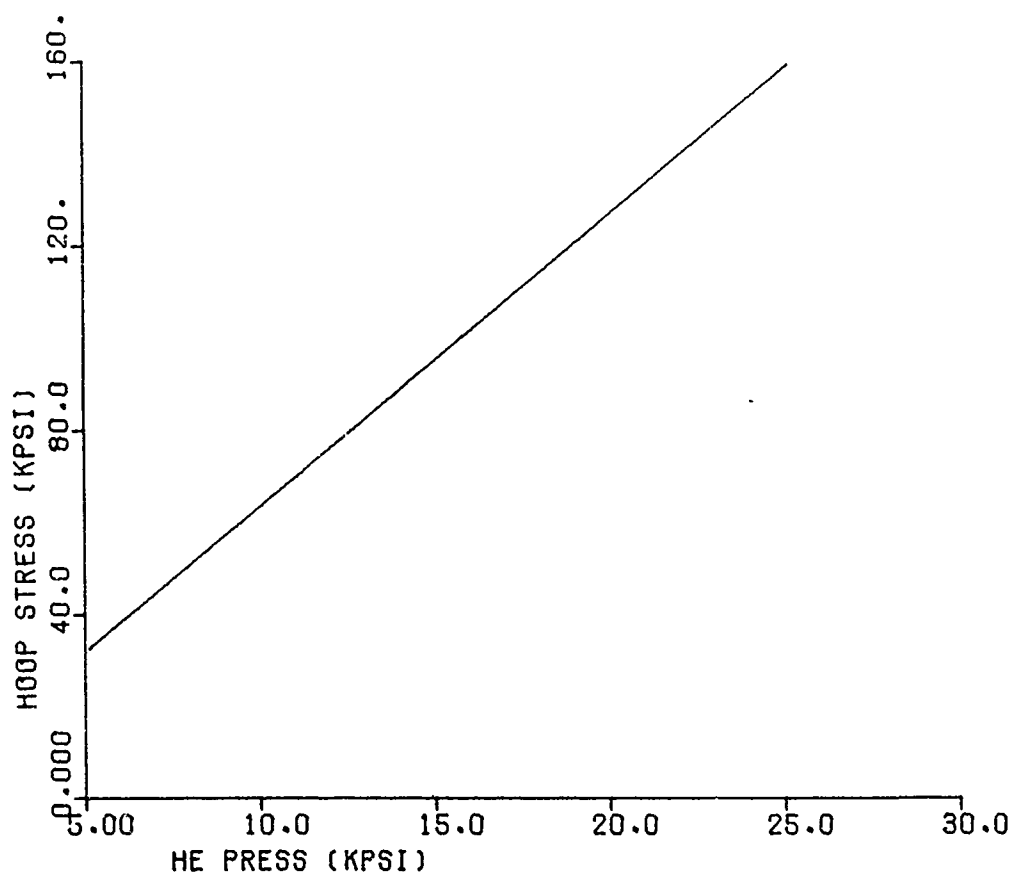


Figure 5. Max Hoop Stress in Grenade Body Versus Max HE Pressure

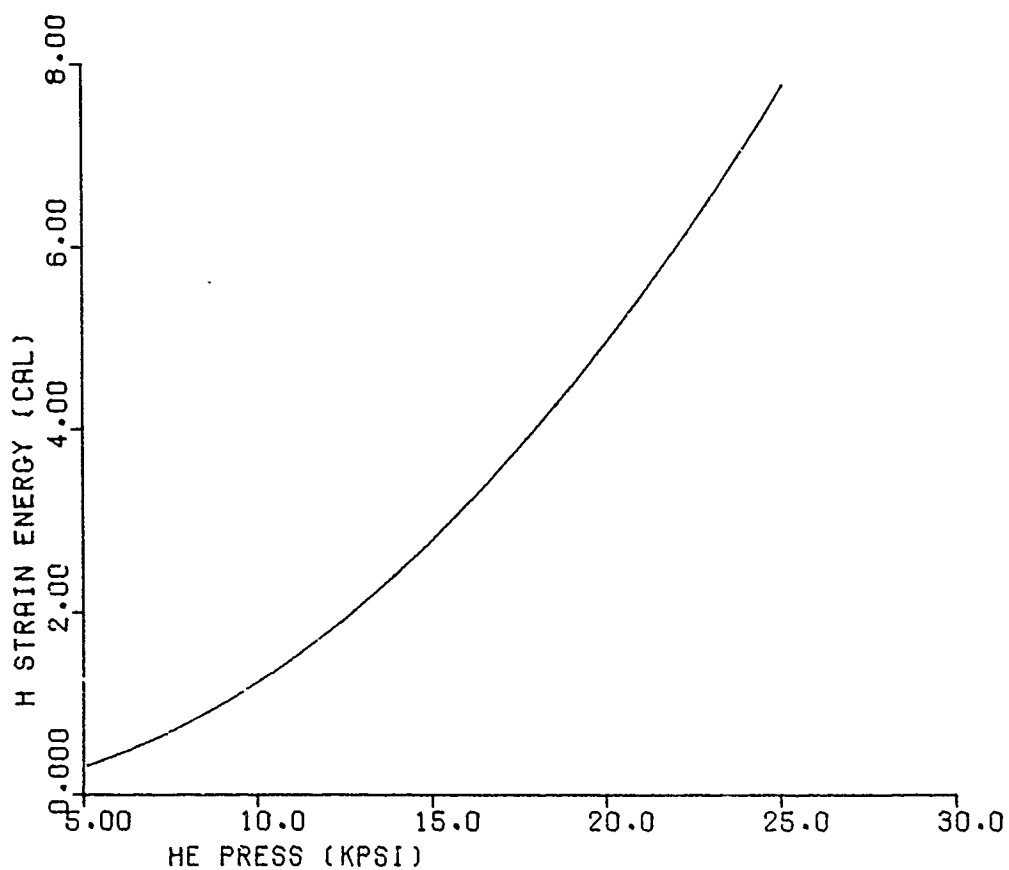


Figure 6. Hoop Strain Energy in the Grenade Body Versus Max HE Pressure

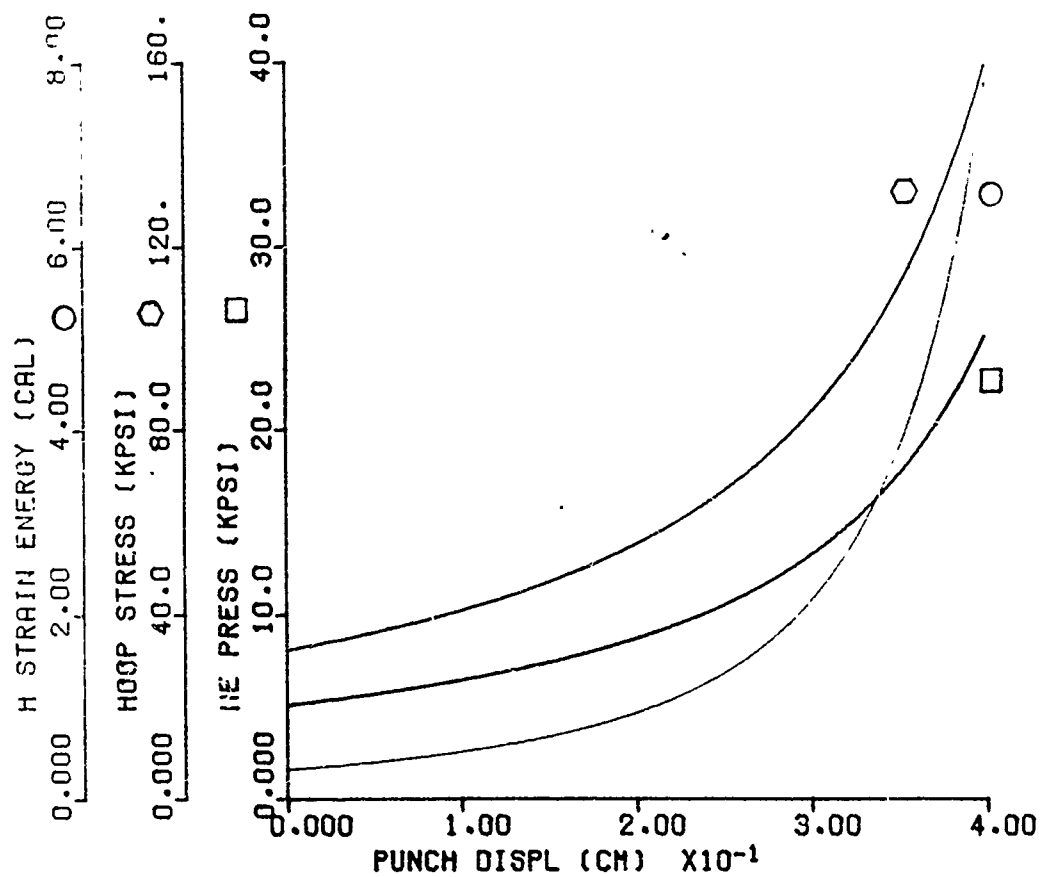


Figure 7. Comparison of Several Variables as Functions of Punch Displacement

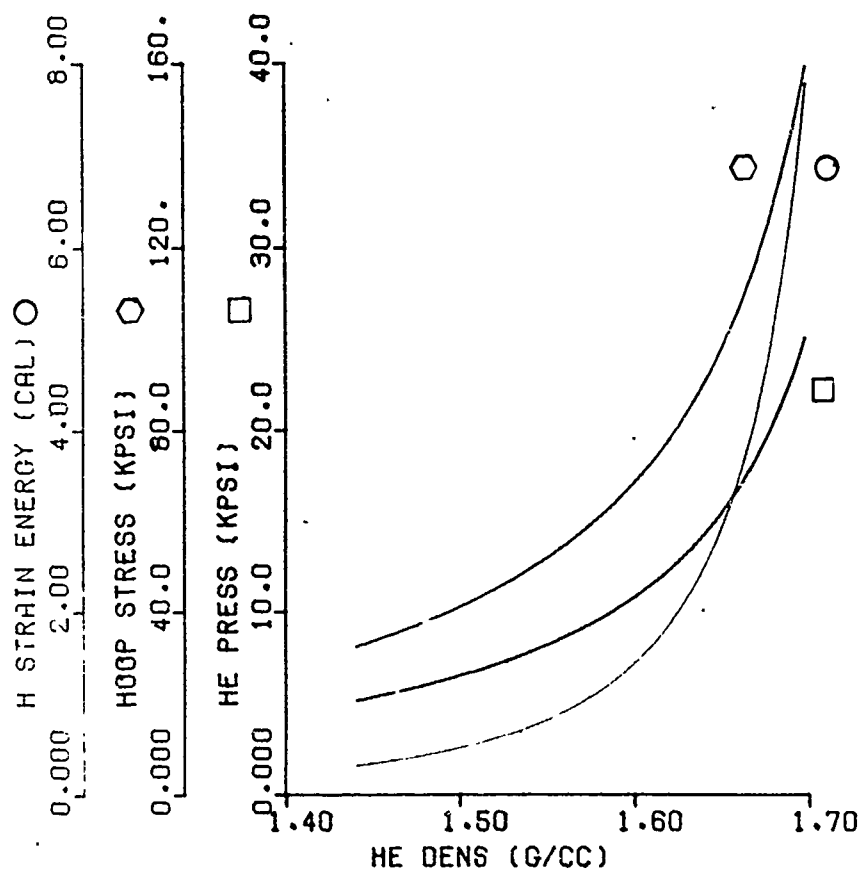


Figure 8. Comparison of Several Variables Versus Avg HE Density

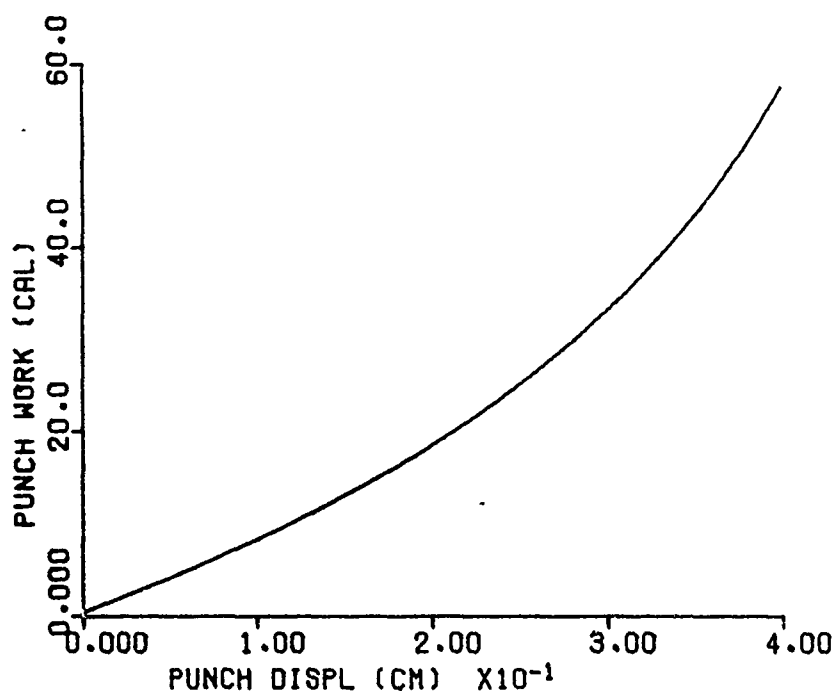


Figure 9. Work Done by the Punch as a Function of Punch Displacement

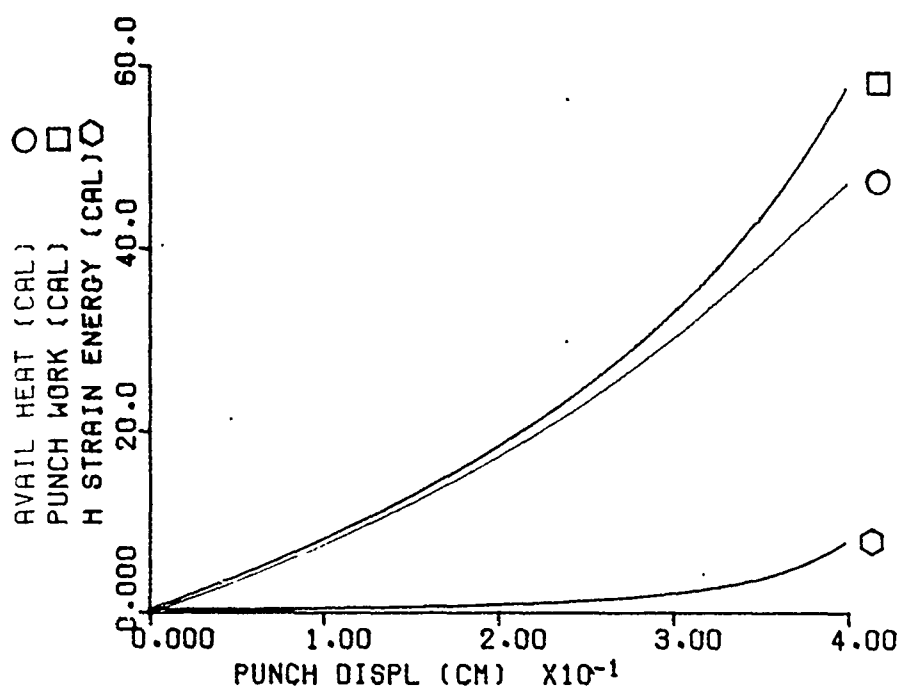


Figure 10. Comparison of Energy Components as Functions of Punch Displacement

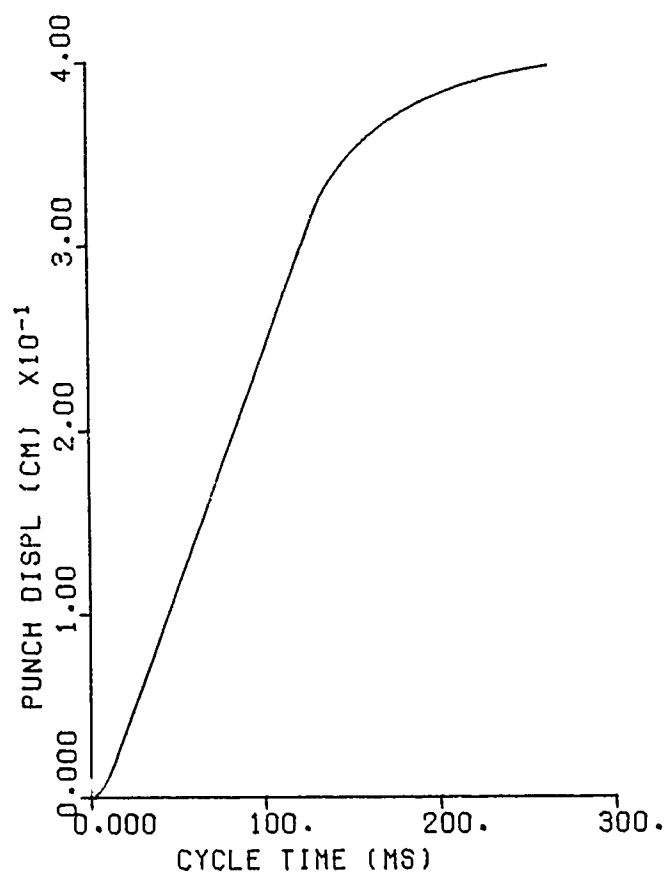


Figure 11. Punch Displacement Versus Cycle Time

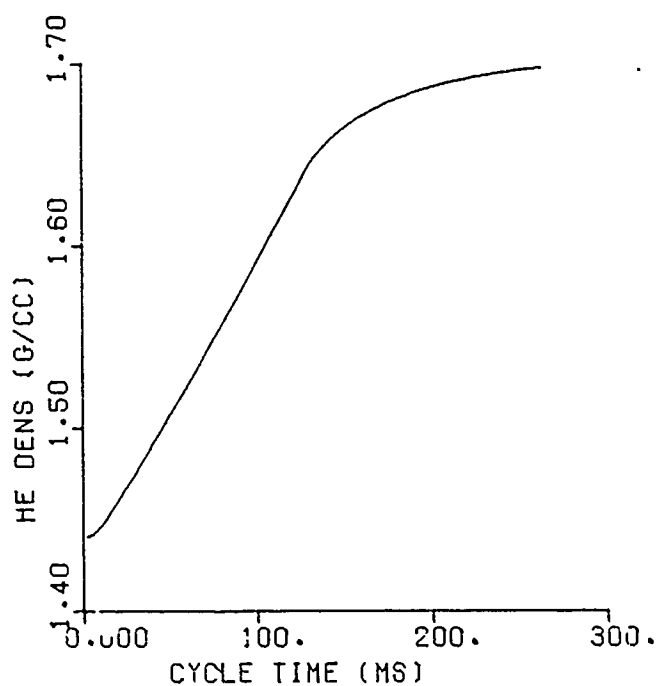


Figure 12. Avg Density of the HE Versus Cycle Time

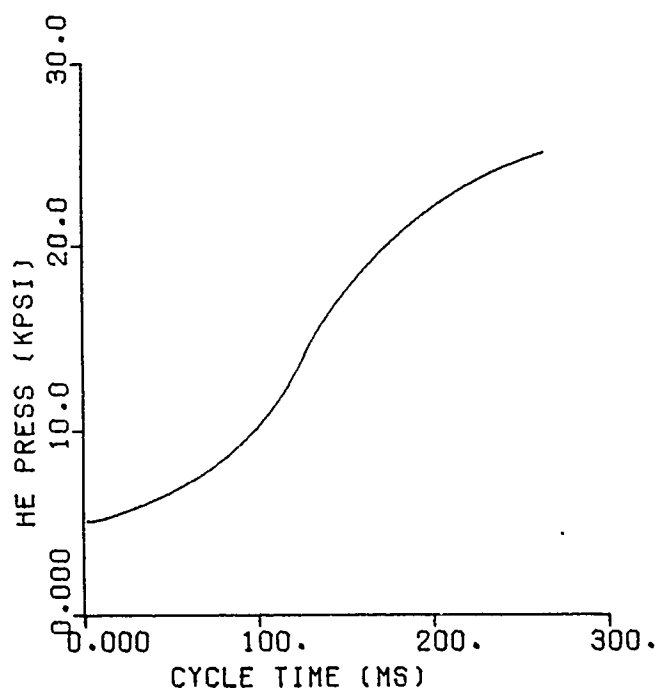


Figure 13. Max HE Pressure Versus Cycle Time

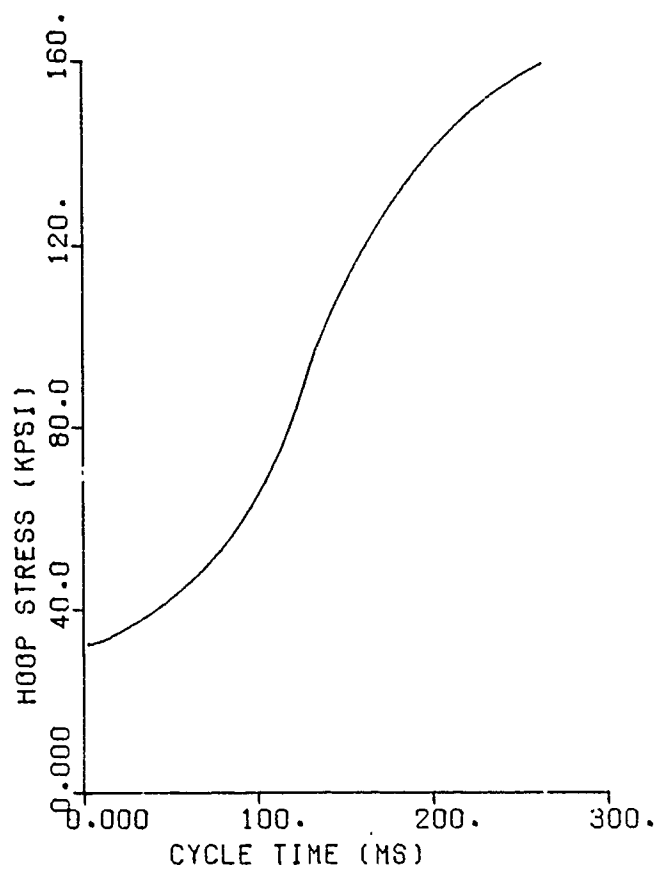


Figure 14. Max Hoop Stress Versus Cycle Time

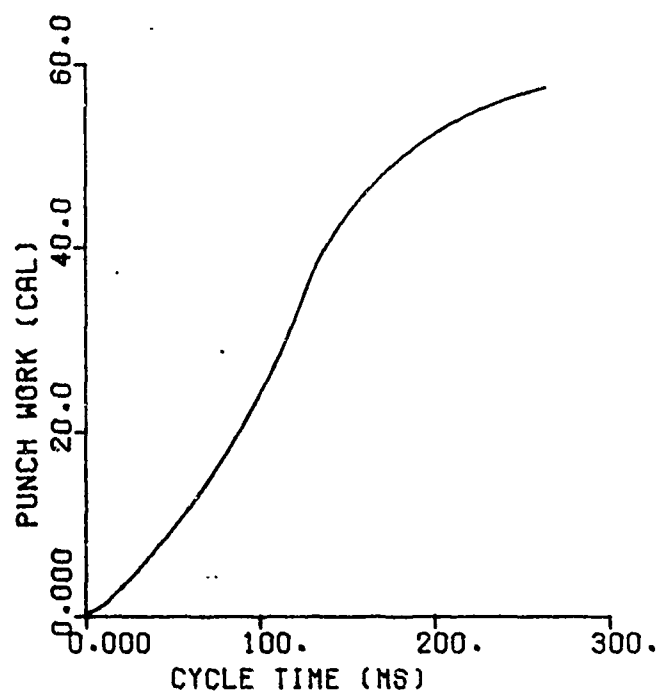


Figure 15. Punch Work Versus Cycle Time

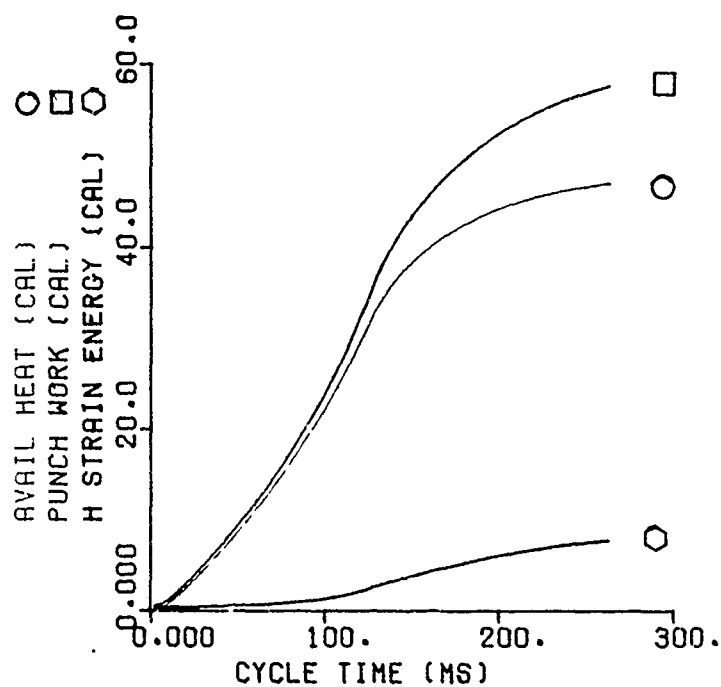


Figure 16. Comparison of Energy Components as Functions of Cycle Time

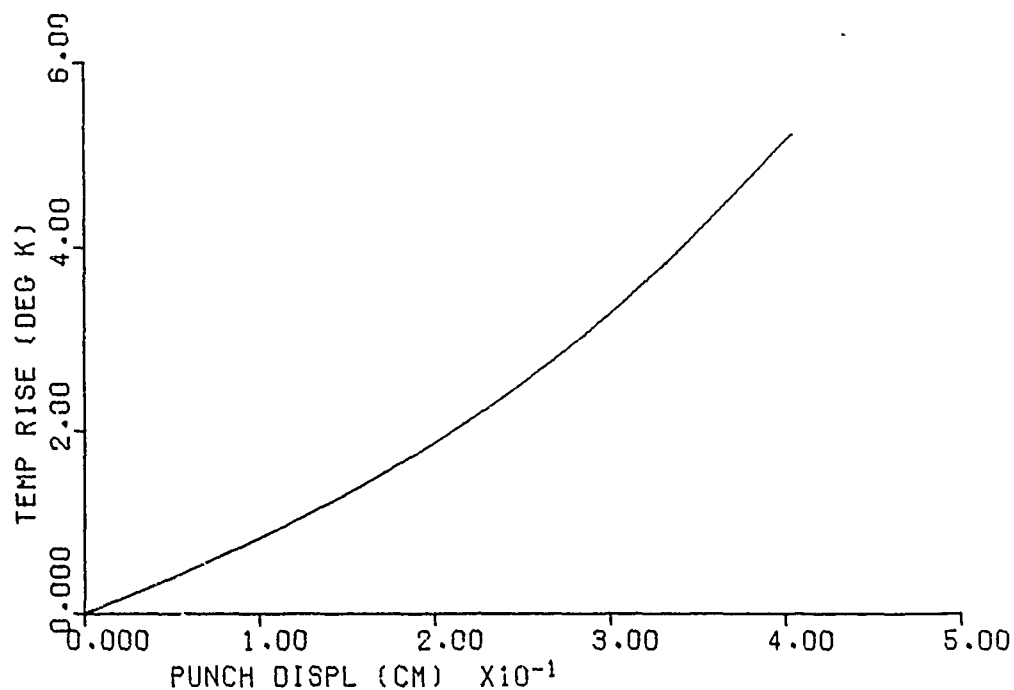


Figure 17. Avg HE Temperature Rise as a Function of Punch Displacement

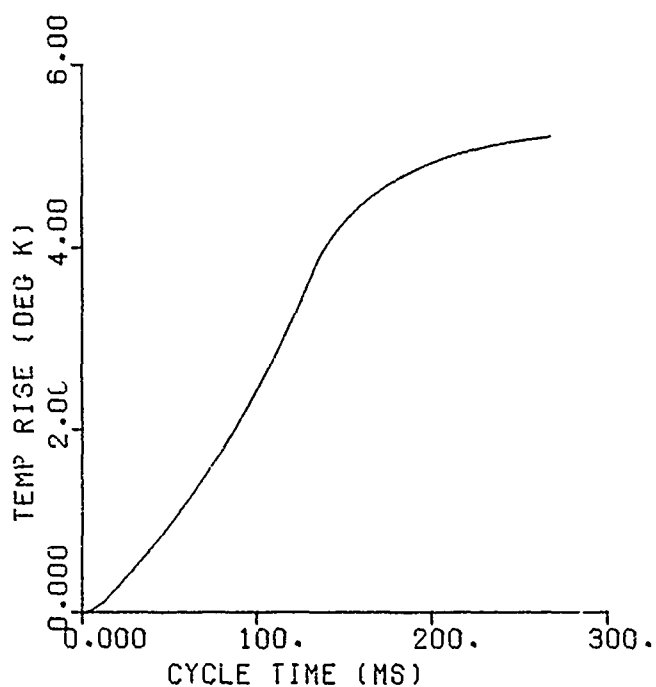


Figure 18. Avg HE Temperature Rise as a Function of Cycle Time

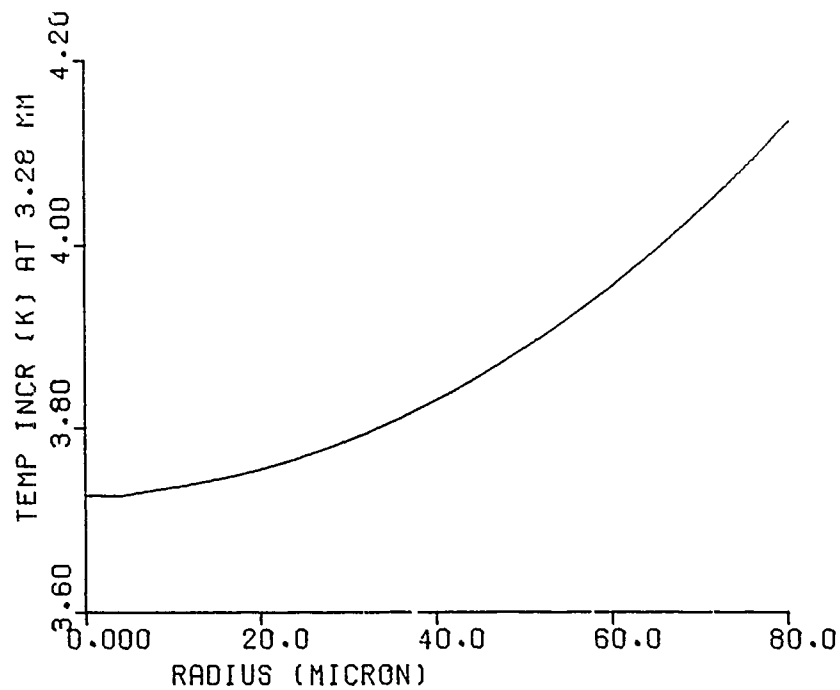


Figure 19. Radial Profile of Temperature in an RDX Particle (at 3.28mm Punch Travel)

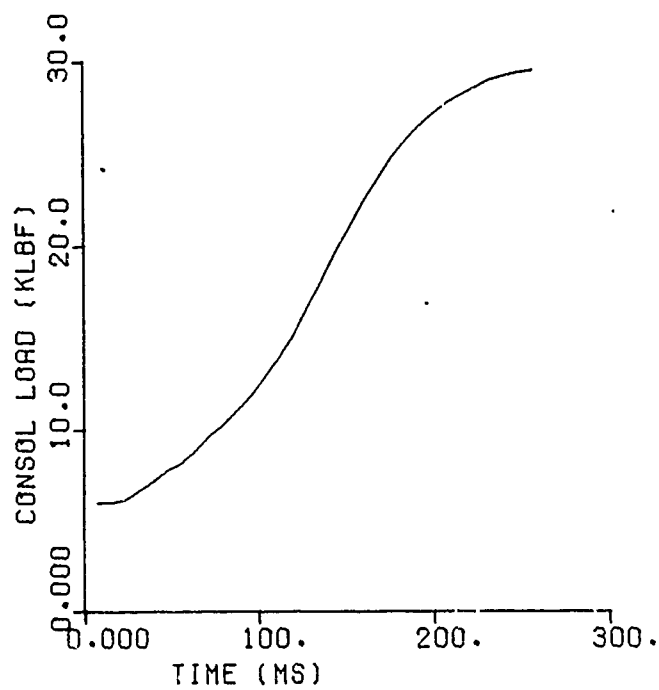


Figure 20. Experimental Consolidation Load Versus Cycle Time

10. Discussion of Results

For the most part the graphical results do not require comment. In some cases, however, my observations may help to clarify an issue or to make an interpretation. The first ten figures show important variables as functions of punch displacement (or travel), whereas the last ten are largely functions of cycle time. By "cycle time" is meant time, measured from the start of the compression phase of the final consolidation cycle. Another semantic point: Maximum pressure on the HE fill is identical to the punch pressure. These terms are used interchangeably. In Figure 1 the average density of the HE is shown plotted as a function of punch displacement. Altho this relationship appears linear, it is not quite. Departure from linearity is due to progressive hoop strain in the body wall as the punch advances. Figure 2 shows the punch pressure as a function of punch travel. It is clear that the most rapid increase in pressure happens during the final half of the forward displacement. This functional form indicates that the HE behaves compressionally as a very nonlinear spring. Hoop strain energy and maximum hoop stress in the grenade body are shown as functions of punch displacement in Figure 3. It is noted that strain energy is a quadratic function of stress. Also, observe that hoop stress builds rapidly near the end of forward travel of the punch. For these reasons the hoop strain energy in the body is strongly dependent upon punch travel during the last quarter of the forward stroke. Therefore, one expects that brittle fracture would most probably occur in the last quarter of compressional punch travel. Only in this last quarter does the body strain energy exceed about two calories. Note that the max strain energy is nearly 8 calories. Figure 4 is a cross-plot of avg HE density versus punch pressure. It is apparent that at about 15 kpsi pressure, the rate of increase of HE density diminishes rapidly. Max body hoop stress is shown as a function of punch pressure in Figure 5. Maximum hoop stress occurs at the inside surface of the body wall. As predicted by this model, max hoop stress is a linear function of punch pressure. Figure 6 shows the hoop strain energy in the grenade body as a function of punch pressure. When plotted in this manner, hoop strain energy exhibits a more uniform rate of increase than when plotted versus punch displacement, as in Figure 3. In both Figures 7 and 8, hoop strain energy, max hoop stress, and max HE pressure are compared functionally. Whether the abscissa is punch travel (Fig 7) or avg HE density (Fig 8), it is seen that strain energy shows the greatest relative variation of these variables. Hoop stress and punch pressure exhibit more uniform growth. Figure 9 shows work done by the punch as a function of punch displacement. Because of the greater stiffness of the HE fill near the end of forward travel of the punch, the rate of work done by the punch increases progressively. This work is converted into both elastic and inelastic energy components. The elastic components are: (a) hoop strain energy in the grenade body, and (b) bulk-compression strain energy of RDX crystals in the HE. Punch work, available heat, and hoop strain energy are shown as functions of punch travel in Figure 10. The work performed by the punch is the total available energy. This is divided among the components: (a) body hoop strain energy, (b) RDX strain energy, (c) thermal loss, and (d) available thermal energy. Of these components, only the largest two are shown here.

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predicted rise in HE temperature, when loading to 26.4 kpsi, is 5.2 deg K. This compares with a measured value of 3.9 deg K, when loading to the same point (max load of 33 klb) *. A max external hoop stress is reported (Ref 2b) as 105.5 kpsi for a peak punch load of 26.5 klb. Simulated external stresses were obtained for the max compression (21.2 kpsi) for two values of body ** wall thickness. For a 0.12-inch wall, the predicted peak, external hoop stress is about 102 kpsi; whereas, for a 0.11-inch wall, this value is about 107 kpsi. Agreement between the simulated and measured values of these variables is surprisingly close. With respect to the third variable used for comparison, one should note that functions, not scalars, are being compared. A single, arbitrary parameter in the simulation--max punch speed--is selected to obtain a good match of theory and experiment. This parameter adjusts the kinematics of the simulation to that of the experiment; however, this parameter does not affect the shape or the amplitude of the load function. Therefore, good agreement in the simulated and measured load functions constitutes a challenging test of the validity of the model. The experimental load-time curve, shown in Figure 1 in Ref 2i, is matched by simulated results well within experimental error (+ or - 1.6 klb) over the loading interval of about 260 ms from start of cycle. The experimental load function is shown for comparison in Figure 20, for just the compression phase of the load cycle. No systematic difference is apparent between model and measured functions.

13. Methodology

Before discussing math models for various phenomena, I will outline the procedure followed in simulating the loading process. The independent variable in the simulation is the displacement (or travel) of the punch. The kinematics of the process are obtained thru the functional relationship between punch displacement, x_p , and punch speed, sp . Only the compression-, or loading, -phase of the consolidation

* Temperature in this environment is very difficult to measure. Ref 2b states that two types of transducers were used--thermocouple and nickel-foil gage. The nickel-foil gages were too fragile; three of four were damaged. Two measurements, at different locations within the HE, were made with thermocouples. One measurement was made just above the tip of the punch, with the HE consolidated at at max load of 43 klb. The reported temperature rise in this case is 18.9 deg K. This value seems much too high; and, in any case, does not represent a volume-average temp rise. The other reported measurement was made between the axis and wall near the top or cap end of the cavity. This is the value (3.9 deg K) cited here, which was obtained at the lowest reported peak load (33 klb). Parenthetically, one observes that if the temperature variation within the HE is as great as measured, this fact would support the assertion that considerable differential flow and, possibly, grain fracture occurs within the HE.

** Recall that the grenade body is represented by a uniform cylindrical sleeve. Wall thickness of the sleeve is the parameter in this instance. The parametric variation studied (0.010 inch) is about three times the body-to-body standard deviation for a particular body producer.

cycle is simulated. After initialization of the grenade to a given HE density and corresponding punch pressure, the following steps are followed until the desired terminal state is achieved:

- (a) The punch is advanced thru a small increment. This increases the density of the HE. (One micrometer is the increment used here.)
- (b) The max pressure on the punch and the pressure gradient in the HE are calculated at the current average HE density. The incremental work performed by the punch, to advance incrementally at this pressure, is added to cumulative punch work.
- (c) The (one-dimensional) hoop strain in the cylindrical sleeve, which represents the grenade body, is calculated. Max strain is reached at the inside radius. Elastic behavior of the metal is assumed.
- (d) Since the hoop strain increases the HE cross-section, calculate the additional displacement of the punch (at this pressure) required to preserve HE density at the value calculated previously with no incremental body strain.
- (e) At each movement of the punch, by Δx_p , add the punch work to the cumulative punch work. The isobaric, incremental work is just the total force times Δx_p , where the total force is the product of the current values of HE cross-section and punch pressure. Updates of punch work are required at steps (b) and (d).
- (f) Since the RDX particles within the HE experience elastic volumetric compression, calculate the strain and the strain energy in the RDX mass.
- (g) To obtain the total available heat energy, subtract the sum of hoop-strain energy plus RDX strain energy plus thermal loss to body from the punch work. (All cumulative energy terms are calculated in joules and reported in units of J and calories.)
- (h) The total incremental punch displacement (since prior loop pass) has consumed a time increment which is the ratio of the displacement increment to the punch speed. This speed is obtained as a function of current value of x_p . Time is updated by addition of the time increment.
- (i) The time increment is also used to calculate the thermal flux to the RDX particles. Flux is the incremental heat/total particle surface/time increment. At the program user's option, the temperature distribution as a function of RDX particle radius is obtained by numerically solving the diffusion equation, using the average thermal flux as the outside boundary condition.
- (j) The heat generated incrementally during this loop pass is used to calculate the volume-average temperature rise of the HE, by dividing by the heat capacity of the HE. HE temperature is updated by this increment.

- (k) The incremental heat loss from the HE to steel body is calculated using current average values of HE temperature and steel temperature. Continuity of temperature and thermal flux at the HE-wall boundary are assumed. The incremental heat loss is used to update the total heat loss and the average steel temperature.
- (l) Current values of the state variables are printed optionally at multiples of the number of loops. Regardless of option, saved values--such as punch displacement and available heat--are stored.
- (m) If the required terminal state has not been reached, loop back to (a) for another pass. Otherwise, stop and print final results. Among the final results are: volumetric increase in the HE due to elastic recovery and the associated decrease in HE density. (If a portion of the mass of RDX experienced grain fracture, some of the RDX strain energy would be thermalized, and the volumetric recovery would be smaller than calculated.)

14. Model Equations

The average density of the HE is, by definition, the ratio of HE mass, M , to volume, V . But, the volume of HE depends upon the cross section and length (or height) of the HE column. Denoting cross sectional area by A , initial column length by x_0 , and punch displacement by x_p , the volume of the HE is given by

$$V = A(x_0 - x_p), \quad 0 \leq x_p \leq x_{pmax}. \quad (1)$$

Denoting the average (bulk HE) density by $E(\rho)$,

$$E(\rho) = M/(A(x_0 - x_p)). \quad (2)$$

Altho not explicitly written as a function of displacement, the area A should be considered a function of x_p , since the max hoop strain, ϵ_p , is a function of x_p , and since

$$A = A_0(1 + \epsilon_p)^2, \quad (3)$$

where A_0 is the unstrained, internal cross section of the body. A formula for $E(\rho)$ is derived in Ref 2d in terms of the theoretical maximum density of the HE, TMD, and of the punch pressure, p . This formula is repeated here:

$$E(\rho)/TMD = 1 + (0.8/c)\ln((p+0.8-c)/(p+0.8)), \quad (4)$$

where c is the difference between maximum and minimum pressure within the volume of the HE. This result assumes a constant pressure gradient within the volume. The basis of the derivation is a constitutive relationship between local HE density, ρ , and local pressure, p :

$$\rho/TMD = p/(p + 0.8), \quad (5)$$

where the constant 0.8 is given in kpsi.

Based on several experimental studies, cited in Ref 2d, the parameter c , which is a measure of the pressure gradient, is found to be directly proportional to the maximum pressure on the HE. Thus, parameter

$$c = g p , \quad (6)$$

where g is a constant. From Ref 2e, the value of g which best fits data on average bulk density is 0.6. This value is used here. (In earlier experiments at KSAAP and MAAAP, a value of 0.8 for g was indicated.)

15. Equation (4) for average density is not readily inverted in order to give punch pressure as a function of $E(\rho)$. This fact poses no problem numerically, however, since the relationship of these variables is monotonic. In a subroutine of COMPACT, punch pressure is calculated as a function of $E(\rho)$ by an iterative Newton-Raphson method. Given the punch pressure from (4), one can calculate the maximum hoop (i.e., tangential) stress within the wall of the cylindrical sleeve, representing the steel body, by Lamé's formula (Ref 2h). The hoop stress at radius r is $s(r)$:

$$s(r) = \frac{a^2 b^2 (p - p_o)}{(b^2 - a^2) r^2} + \frac{p a^2 - p_o b^2}{b^2 - a^2} , \quad (7)$$

where p is the pressure on the inside wall and p_o is the pressure on the outside of the wall. The internal radius of the sleeve is a and the outside radius b . The radius to an arbitrary point is r . In the present application, the maximum internal pressure is identified with the punch pressure, and the outside pressure is taken as atmospheric pressure, i.e., the outside of the wall is assumed unsupported. The maximum stress occurs at the inner wall, where $r = a$. The max body stress is, then,

$$s(a) = (p(a^2 + b^2) - 2 p_o b^2) / (a^2 + b^2) . \quad (8)$$

If the body remains elastic thruout, the maximum strain is simply

$$\text{eps} = s(a)/E_y , \quad (9)$$

where E_y is Young's modulus for steel.

As indicated above, the cross section of the HE is related to x_p functionally thru equations (2), (3), (4), (8), and (9).

16. The total hoop strain energy in the body is obtained by integrating the strain energy per unit volume,

$$s(r)^2 / (2 E_y) ,$$

over the volume of the cylinder wall subject to strain. Let the effective cylinder height experiencing this hoop strain be denoted by h . Then, using equation (7), the hoop strain energy is given by:

$$HSE = (\pi h/Ey)(T_1 + T_2 + T_3), \quad (10)$$

where the indexed terms are functions of the dimensions a and b and of the punch pressure p .

$$\begin{aligned} T_1 &= A (b^2 - a^2)/(2ab), \\ T_2 &= B (b^2 - a^2)/2, \\ T_3 &= 2AB \ln(b/a), \end{aligned} \quad (11a)$$

where the auxiliary factors A and B are given by

$$\begin{aligned} A &= (ab(p - p_0))/(b^2 - a^2) \\ B &= (pa^2 - p_0b^2)/(b^2 - a^2). \end{aligned} \quad (11b)$$

Energy is also stored in the RDX crystals as elastic strain. If a local hydrostatic condition is assumed for each RDX particle, an expression for the total RDX strain energy can be derived by integrating strain energy per unit volume over the total volume. Let the bulk modulus of RDX be denoted by B_m . Also, let the pressure at a normalized axial coordinate x be denoted by $p(x)$. The assumption of a constant pressure gradient in the HE means that

$$p(x) = p(1 - gx), \quad 0 \leq x \leq 1, \quad (12)$$

where, as above, p is the punch pressure and g is a constant. The RDX strain energy per unit volume, at x , is

$$p(x)^2 / B_m / 2.$$

By integrating this expression, with $p(x)$ given in (12), over the total volume of RDX, V_r , one obtains the RDX strain energy, RSE:

$$RSE = (V_r p^2 / (2 B_m))(1 - g + g^2/3). \quad (13)$$

Work performed by the punch is, of course, the source of both elastic and inelastic energy components. The punch work, W , is the integral over punch travel of

$$A p \delta(x), \quad (14)$$

where $\delta(x)$ is the incremental displacement of the punch, given the constant punch pressure p and HE cross section A . For 3-digit accuracy the value of $\delta(x)$ must be quite small--about 5 microns

or less. At any instant, the total heat residing in the HE is the work performed by the punch minus (elastic) potential energy, of body and RDX, and minus heat energy lost to the body. The heat loss is relatively small, but is included to be complete. Denoting the available thermal energy in the HE by H and the heat lost by L, an energy balance requires that

$$H = W - HSE - RSE - L . \quad (15)$$

The average temperature rise, avgUh, of the HE, with heat capacity Ch is, then,

$$\text{avgUh} = H/\text{Ch} . \quad (16)$$

Similarly, the average temperature rise of the steel body, avgUs, is obtained from L and the heat capacity of the body, Cs:

$$\text{avgUs} = L/\text{Cs} . \quad (17)$$

17. A mathematically exact calculation of the heat loss from HE to body wall requires the solution of the diffusion equations in both HE and steel wall. The diffusion equation in the HE involves a heat source term, representing the rate of energy production per unit mass. To describe this source term requires an assumption concerning HE flow within the cavity, since viscous effects produce the heat. But, details of the HE flow are not modeled here. To escape this dilemma, I have simply assumed that the source term is independent of position (but, not of time). (Actually, this isotropic assumption implies something concerning HE flow, but is not pursued.) Denoting the rate of heat released per unit mass per unit time as Q, one can write

$$Q = \Delta(H)/\Delta(t)/M , \quad (18)$$

where $\Delta(H)$ is the increment of heat added during the time increment $\Delta(t)$. Notationally, let $U(r)$ be the temperature at radial position r . When r is less than or equal to the inner radius, a , the temperature pertains to the HE. For r between a and outside radius, b , the temperature describes the steel wall. Further, let a terminal "1" indicate a property of the HE, and a terminal "2" indicate a property of the steel. Thus, α_1 denotes the thermal diffusivity of HE, C_1 denotes the specific heat of HE, and K_1 denotes the thermal conductivity of HE. (The particular HE is Comp A-5.) Partial differentiation by r and by t are denoted, respectively, by subscripts r and t . With these conventions, the temperature in the HE is given by

$$U_t = (\alpha_1/r)(r U_r) + Q/C_1 , \quad 0 < r < a . \quad (19)$$

The diffusion equation for the cylindrical wall is:

$$U_t = (\alpha_2/r)(r U_r) , \quad a < r < b . \quad (20)$$

Boundary conditions are needed at radial positions: 0, a, and b. At $r = 0$, cylindrical symmetry requires that no heat is transported across the center. Thus,

$$\lim_{r \rightarrow 0} (U(r)) = 0. \quad (21a)$$

At $r = a$, temperature is the same on each side of the boundary; and, the thermal flux out of the HE must equal flux into the steel wall.

$$U(a-) = U(a+)$$

and

$$K_1 \lim_{r \rightarrow a} (U(r)) = K_2 \lim_{r \rightarrow a} (U(r)), \quad (21b)$$

where $a-$ and $a+$ means r approaching a from below and from above, resp. Finally, the boundary at $r = b$ can be treated as thermally insulated, since still air outside the cylinder is a good insulator.

$$\lim_{r \rightarrow b} (U(r)) = 0. \quad (21c)$$

The rate of heat loss from HE is obtained from the following equation:

$$\frac{\Delta L}{\Delta t} = -K_1 A_{\text{wall}} \lim_{r \rightarrow a} (U(r)), \quad (22)$$

where A_{wall} is the area of HE contacting the wall. The cumulative heat loss, L , is obtained by numerical integration of the time derivative in (22). A numerical solution of (19) thru (22) is obtained by integrating a set of total differential equations for $U(i)$, defined on a radial grid $r(i)$, $i=1,2,\dots$. These equations are derived from (19,20,21) by a conventional forward-difference scheme. The implementing computer code is located on page A-7 of Annex A.

18. An Approximation for Heat Loss

Because the importance to this simulation of the heat loss from the HE is relatively small, the approach taken in paragraph 17 may entail too much computation. An approximation is given here which, tho not as accurate, may suffice. The approximate rate of loss makes use of the great difference in the thermal diffusivities of HE and steel. Because RDX has a very low diffusivity, heat loss is not felt very far into the HE from the cylinder wall. Therefore, a very steep temperature gradient exists in the HE near the wall. However, since heat diffuses rapidly in steel, a rather shallow radial temperature gradient exists in the wall. Thus as a first approximation, the gradient in the steel is taken as zero, which implies that the temperature at the wall is nearly $avgU_s$. Additionally, assume that the temperature in the HE drops linearly from $avgU_h$ to the value at the wall over a radial interval DEL_R . The negative gradient in the HE near the wall is approximated by

$$(avgU_h - avgU_s)/DEL_R. \quad (23)$$

The approximate rate of heat loss from the HE is, from (22), the product of the factors A_{wall} , K_1 , and the negative gradient in (23). The increment DEL_R is effectively the distance traveled internally from the wall at which the temperature rises linearly to $avgU_h$. A natural length for measuring temperature change is the diffusion length, the distance a temperature spike will propagate by diffusion in time t . The diffusion length in the HE is

$$\sqrt{\alpha_1 t} . \quad (24)$$

Empirically, a good approximation for the temperature gradient at the wall, during the compression phase of loading, is obtained when DEL_R is 4 times the diffusion length.

19. Temperature in an RDX Particle

Among the physical processes occurring during loading, thermal diffusion in RDX particles appears to be of minor importance. If the heating rate of the surface of a typical RDX particle were sufficiently great, thermally (as well as mechanically) induced stresses might play a role in grain fracture. Actually, now this does not appear to be the case; but, this idea led to a study of the temperature profile with respect to radius in an RDX particle. The mean RDX particle diameter is about 160 microns for Class 1 RDX, which is presently being used in Comp A-5. Therefore, a spherical particle of this diameter was selected for the temperature study. The RDX specific surface--area per unit mass--was calculated for a uniform granulation of this diameter. Denoting the specific surface of the RDX by spS , the heat flux directed at a particle is given by

$$q = spS Q (\text{Mass RDX} / \text{Mass HE}) , \quad (25)$$

where the generation rate per unit mass of HE, Q , is given by (18). Notationally, let the RDX particle diameter be d , and let a terminal "3" denote a material property of RDX. Thus, K_3 denotes the thermal conductivity of RDX. Additionally, denote the RDX temperature rise at particle radius r by $U(r)$. With this notation and subscript conventions, one can write the boundary condition at the surface of the typical particle as

$$q = -K_3 \left(\frac{dU}{dr} \right)_{r=d/2} , \quad (26)$$

assuming that all the flux is absorbed.

By spherical symmetry, the boundary condition at particle center is:

$$\left(\frac{dU}{dr} \right)_{r=0} = 0. \quad (27)$$

These boundary conditions are applied to the spherically symmetric form of the diffusion equation in a particle. Functional dependence of U upon r is suppressed here:

$$\frac{d^2 U}{dr^2} = \frac{1}{\alpha_3} \left(\frac{2}{r} \frac{dU}{dr} + \frac{d^2 U}{dr^2} \right) , \quad 0 < r < d/2. \quad (28)$$

Solution of the RDX diffusion equations is an option in the program COMPACT. The numerical method uses a radial grid of points at which the temperature is evaluated. The differential equations on this grid are developed from (28) using a central-difference approximation to spatial derivatives. An update is performed using two half-steps at each step in time. Equations are found on page A-8 in Annex A. Quite small time steps, Δt , are required for numerical stability of this method. To insure that stability is met, the incremental punch travel, Δx_p , is kept small (1 micron), since this and punch speed, implicitly determine Δt . Additionally, when calculating RDX particle temperature, the initial punch speed is taken to be its maximum value, (with a slight loss of fidelity to kinematics).

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ANNEX A

SOURCE PROGRAM FOR SIMULATING THE STATE OF AN M42/M46 GRENADE DURING PRESS LOADING

```

1  PREAMBLE ''COMPACT
2  NORMALLY MODE IS REAL
3  DEFINE PRESS AS A REAL FUNCTION GIVEN 2 ARGUMENTS
4  DEFINE RHOTRANS AS A REAL FUNCTION GIVEN 2 ARGUMENTS
5  DEFINE STRN.ENER AS A REAL FUNCTION GIVEN 2 ARGUMENTS
6  DEFINE ESTRN.RDX AS A REAL FUNCTION GIVEN 1 ARGUMENT
7  DEFINE RPSPEED AS A REAL FUNCTION GIVEN 1 ARGUMENT
8  DEFINE FLAGU AS AN INTEGER VARIABLE
9  DEFINE EYOUNG,LBODY,RINT,ROUT,GRAD.PRS,XPMAX AS REAL VARIABLES
10 DEFINE BM.RDX,EY.RDX,PR.RDX,VOL.RDX AS REAL VARIABLES
11 END ''PREAMBLE

1  MAIN ''COMPACT
2  ''
3  ''PROGRAM SIMULATES THE COMPACTION OF THE HE AND THE STRAINING OF THE
4  ''GRENADE BODY DURING PRESS LOADING OF AN M42 GRENADE.  A BODY IS REP-
5  ''RESENTED AS A CYLINDRICAL SLEEVE OF CONSTANT HEIGHT.
6  ''
7  ''PARAMETERS:
8  ''MASSHE _____ MASS OF THE HE (G).
9  ''AXHE _____ CROSS-SECTIONAL AREA (SQ CM) OF THE HE DURING PRESSING.
10 ''AXHEO _____ INITIAL CROSS-SECTION OF THE HE (SQ CM)
11 ''RINT _____ INITIAL INTERNAL RADIUS OF THE GRENADE (CM).
12 ''ROUT _____ INITIAL OUTSIDE RADIUS OF THE GRENADE (CM).
13 ''LBODY _____ EFFECTIVE LENGTH OF THE BODY SUBJECT TO HOOP STRAIN (CM).
14 ''XO _____ INITIAL EFFECTIVE HEIGHT OF THE HE CYLINDER (CM).
15 ''XP _____ DISPLACEMENT OF THE PUNCH (CM).
16 ''XPMAX _____ MAX DISPLACEMENT OF THE PUNCH (CM).
17 ''DELXP _____ INCREMENT IN DISPLACEMENT OF THE PUNCH (CM).
18 ''RHOHEO _____ DENSITY OF THE HE PRIOR TO FINAL CONSOLIDATION (G/CC).
19 ''RHOHE _____ AVG DENSITY OF THE HE DURING CONSOLIDATION (G/CC).
20 ''TMDHE _____ THEORETICAL MAX DENSITY OF THE HE (G/CC).
21 ''PHE _____ PRESSURE ON THE HE (KPSI) DURING CONSOLIDATION.
22 ''PINT _____ INTERNAL PRESSURE ON THE HE BODY (PASCAL).
23 ''POUT _____ OUTSIDE PRESSURE ON THE BODY (PA).
24 ''MAXKPSI _____ MAX PRESSURE (KPSI) TO STOP THE SIMULATION.
25 ''EYOUNG _____ YOUNG'S MODULUS OF THE BODY STEEL (PA).
26 ''DENS.STEEL _____ DENSITY OF STEEL IN BODY (G/CC).
27 ''SPHT.STEEL _____ SPECIFIC HEAT OF STEEL (CAL/G/DEG K).
28 ''TCOND.STEEL _____ THERMAL CONDUCTIVITY OF STEEL (CAL/CM/S/DEG K).
29 ''DIFUZ.STEEL _____ THERMAL DIFFUSIVITY OF STEEL (SQ CM/S).
30 ''SIGPA _____ BODY HOOP STRESS (PA).
31 ''SIGKPSI _____ BODY HOOP STRESS (KPSI).
32 ''HSTRAIN _____ BODY HOOP STRAIN.
33 ''GRAD.PRS _____ COEFFICIENT FOR THE PRESSURE GRADIENT WITHIN THE HE.
34 ''MASS.RDX _____ MASS OF RDX IN HE (G).
35 ''FRACT.RDX _____ MASS FRACTION OF RDX IN HE.
36 ''VOL.RDX _____ VOLUME OF RDX CRYSTALLS (CC).
37 ''BM.RDX _____ BULK MODULUS OF RDX (PA).
38 ''EY.RDX _____ YOUNG'S MODULUS FOR RDX (PA).
39 ''PR.RDX _____ POISSON'S RATIO FOR RDX.
40 ''SPS.RDX _____ SPECIFIC SURFACE FOR RDX (SQ CM/G).

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41  'TMD.RDX  ___ THEOPETICAL MAX DENSITY OF RDX (G/CC).
42  'SPHT.RDX  ___ SPECIFIC HEAT OF RDX (CAL/G/DEG K).
43  'TCOND.RDX  ___ THERMAL CONDUCTIVITY OF RDX (CAL/CM/S/DEG K).
44  'DIFUZ.RDX  ___ THERMAL DIFFUSIVITY OF RDX (SQ CM/S)
45  'MASS.STER  ___ MASS STERIC ACID (G).
46  'DENS.STER  ___ DENSITY OF STERIC ACID (G).
47  'SPHT.STER  ___ SPECIFIC HEAT OF STERIC ACID (CAL/G/DEG K).
48  'HSE  ___ BODY (ELASTIC) HOOP-STRAIN ENERGY (JOULE).
49  'EE.RDX  ___ ELASTIC ENERGY IN THE RDX CRYSTALS (JOULE)
50  'HENERGY  ___ (THERMAL) ENERGY AVAILABLE FOR HEATING THE RDX.
51  'DELTAR  ___ SPACE INTERVAL IN RDX-PARTICLE RADIAL GRID (CM).
52  'DELTAT  ___ TIME STEP IN INTEGRATING THE HEAT TRANSFER DIFF EQNS.
53  ''
54  DEFINE FLAGUHE,I,J,K,KPRINT,KUPRINT,L,M,N,NGRID,NHE,NST AS INTEGER
    VARIABLES
55  DEFINE ANSWER AS A TEXT VARIABLE
56  DEFINE UV,UOV,U1V AS REAL, 1-DIMENSIONAL ARRAYS 'RDX PARTICLE TEMP
57  DEFINE UHEV,UHEOV,USTV,USTOV AS REAL, 1-DIMENSIONAL ARRAYS 'HE TEMP
58  ''
59  'ASSIGN CONSTANTS.
60  ''
61      LET FLAGUHE=0 'IS 1 TO FLAG CALC OF RADIAL DIST OF UHE
62      LET NGRID=11
63      LET NHE=21
64      LET NST=5
65      LET DELTAR=0.0008 'CM STEP IN RDX XTAL (8 MICRON)
66      RESERVE UV(*),UOV(*),U1V(*) AS NGRID
67      RESERVE UHEV(*),UHEOV(*) AS NHE
68      RESERVE USTV(*),USTOV(*) AS NST
69      FOR I=1 TO NHE, LET UHEOV(I)=0.0
70      FOR I=1 TO NST, LET USTOV(I)=0.0
71      FOR I=1 TO NGRID DO
72          LET UV(I)=0.0
73          LET UOV(I)=0.0
74          LET U1V(I)=0.0
75      LOOP 'TO INITIALIZE THE RDX TEMPERATURE PROFILE
76      LET HTLOSS=0.0
77      LET KPRINT=10
78      LET KUPRINT=100
79      LET DELXP=0.0001
80      LET GRAD.PRS=0.6
81      LET PA.KPSI=6.89474*10**6 'PASCALS PER KPSI CONVERSION
82      LET CALPJ=0.239 'CALORIES PER JOULE CONVERSION
83      LET EYOUNG =2.06843*10**11 'PA. YOUNG'S MODULUS FOR STEEL
84      LET DENS.STEEL=7.87 'G/CC
85      LET SPHT.STEEL=0.125 'CAL/G/DEG K
86      LET TCOND.STEEL=0.165 'CAL/CM/S/DEG K
87      LET DIFUZ.STEEL=TCOND.STEEL/DENS.STEEL/SPHT.STEEL
88      LET LBODY=3.556
89      LET RINT=1.6256 'FOR 110 MIL WALL THICKNESS
90  '' LET RINT=1.6002 FOR 120 MIL WALL THICKNESS
91  '' LET RINT=1.6130
92      PRINT 2 LINES WITH RINT
93      THUS
CURRENT VALUE OF INTERNAL RADIUS IS *.***** CM, FOR A 110 MIL WALL THICKNESS.
INPUT THE VALUE OF RINT WANTED. NOTE: 1.6002 (120 MIL WALL THICKNESS).
96      READ RINT
97      LET ROUT=1.9050 'CM

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98     LET DRHE=RINT/(NHE-1)
99     LET DRST=(ROUT-RINT)/(NST-1)
100    LET POUT=1.01353*10**5 'PA (14.7 PSI)
101    PRINT 1 LINE THUS
      INPUT THE MAX PUNCH PRESSURE, IN KPSI, TO STOP SIMULATION.
103    READ MAXKPSI
104    LET AXHEO=PI.C*RINT**2
105    LET AXHE=AXHEO 'INITIALLY
106    LET MASSHE=30.0 'G
107    LET FRACT.RDX=0.985 'FRACTION OF RDX IN HE
108    LET MASS.RDX=MASSHE*FRACT.RDX
109    LET MASS.STER=MASSHE-MASS.RDX
110    LET SPHT.STER=0.399
111    LET DENS.STER=0.847
112    LET TCOND.STER=3.8/10**4
113    LET HTCAP.STER=MASS.STER*SPHT.STER 'CAL/DEG K
114    LET TMD.RDX=1.82 'G/CC
115    LET TMDHE=1.78 'G/CC FOR COMP A-5
116    LET VOL.RDX=MASS.RDX/TMD.RDX 'VOLUME (CC) OF RDX CRYSTALS
117    LET RAD.RDX=(NGRID-1)*DELTAR
118    LET NPARTICLES=VOL.RDX/PI.C/4.0*3.0/RAD.RDX**3
119    LET SPS.RDX=NPARTICLES*4.0*PI.C*RAD.RDX**2/MASS.RDX
120    LET SPHT.RDX=0.300 'CAL/G/DEG K
121    LET HTCAP.RDX=MASS.RDX*SPHT.RDX
122    LET TCOND.RDX=0.0007 'CAL/CM/S/DEG K
123    LET DIFUZ.RDX=TCOND.RDX/TMD.RDX/SPHT.RDX
124    LET FRACT.STER=1.0-FRACT.RDX
125    LET SPHT.HE=FRACT.RDX*SPHT.RDX+FRACT.STER*SPHT.STER
126    LET TCOND.HE=FRACT.RDX*TCOND.RDX+FRACT.STER*TCOND.STER
127    LET DENS.HE=1.0/(FRACT.RDX/TMD.RDX+FRACT.STER/DENS.STER)
128    LET DIFUZ.HE=TCOND.HE/DENS.HE/SPHT.HE
129    LET UCON.HE=DIFUZ.HE/DRHE/DRHE
130    LET UCON.ST=DIFUZ.STEEL/DRST/DRST
131    LET DTIME=0.27 '(S) TIME FOR TEMP DIFFUSION
132    LET DL.HE=SQRT.F(DIFUZ.HE*DTIME) '(CM) DIFFUSION LENGTH IN HE
133    LET DELR.HE=4.0*DL.HE '(CM) FOR APPROX THERM GRAD IN HE AT WALL
134    LET BETA=TCOND.HE*DRST/TCOND.STEEL/DRHE
135    LET B=1.0/(1.0+BETA)
136    LET UCON=DIFUZ.RDX/DELTAR**2
137    LET UOCON=DELTAR/TCOND.RDX
138    LET U1CON=DIFUZ.RDX/DELTAR
139    LET EY.RDX=1.8*10**10 'YOUNG'S CONSTANT FOR RDX (PA)
140    LET PR.RDX=0.22 'POISSON'S RATIO FOR RDX
141    LET BM.RDX=EY.RDX/3.0/(1.0-2.0*PR.RDX) 'BULK MODULUS FOR RDX
142    ''
143    ''GET INITIAL HE DENSITY FROM THE TERMINAL.
144    ''
145    PRINT 1 LINE THUS
      INPUT THE INITIAL DENSITY OF THE HE. SUGGEST 1.440 G/CC.
147    READ RHOHEO
148    PRINT 1 LINE THUS
      DO YOU WANT THE TEMPERATURE PROFILE IN AN RDX PARTICLE? (Y OR N).
150    READ ANSWER
151    IF SUBSTR.F(ANSWER,1,1) = "Y"
152      LET FLAGU=1
153    OTHERWISE
154      LET FLAGU=0

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155     ALWAYS
156     ''
157     ''GET INITIAL HEIGHT OF HE CYLINDER.
158     ''
159     LET VOL.HEO=MASSHE/RHOHEO
160     LET XO=VOL.HEO/AXHEO
161     ''
162     ''CALCULATE INITIAL BODY STRAIN DUE TO PRECONSOLIDATION.
163     ''
164     LET PHE=PRESS(TMDHE,RHOHEO)
165     LET PINT=PA.KPSI*PHE
166     LET PINTO=PINT
167     LET EE.RDX=ESTRN.RDX(PINTO) ''RDX STRAIN ENERGY FOR PRECONSOL COND
168     CALL STRS.STRAIN (PINT,POUT) YIELDING SIGPA, HSTRAIN
169     LET SIGKPSI=SIGPA/PA.KPSI
170     LET HSTRESS=SIGPA/10**6
171     ''
172     ''GET CROSS-SECTION OF HE, ACCOUNTING FOR BODY STRAIN.
173     ''
174     LET AXHE=AXHEO*(1.0+ABS.F(HSTRAIN))**2
175     ''
176     ''REEVALUATE HEIGHT OF HE COLUMN TO GIVE DESIRED DENSITY.
177     ''
178     LET XO=MASSHE/RHOHEO/AXHE
179     ''
180     ''GET MAX HOOP STRAIN AND MAX DENSITY.
181     ''
182     CALL STRS.STRAIN (MAXKPSI*PA.KPSI,POUT) YIELDING MAXSIGPA,MAXSTRAIN
183     LET MAXRHO=RHOTRANS(TMDHE,MAXKPSI) + 0.0001
184     LET XPMAX=XO-MASSHE/MAXRHO/AXHEO/(1.0+ABS.F(MAXSTRAIN))**2 + 0.007
185     LET AWALL=2.0*PI.C*(RINT*XO+RINT**2) ''WALL AREA FOR HEAT LOSS
186     LET HVOL.STEEL=AWALL*(ROUT-RINT) ''VOL OF STEEL HEATED BY HE LOSS
187     LET HTCAP.STEEL=HVOL.STEEL*DENS.STEEL*SPHT.STEEL
188     LET USTEEL=0.0 ''INITIALIZATION OF TEMPERATURE OF STEEL BODY
189     LET HSE=STRN.ENER (PINT,POUT)
190     LET PWORK=HSE+EE.RDX
191     LET HENERGY=0.0 ''INITIAL HEAT ENERGY DEFINED AS ZERO (REFERENCE)
192     LET TIME=0.0
193     LET XP=0.0
194     LET XP0=XP
195     LET HOLDXP=0.0
196     SKIP 2 LINES
197     PRINT 5 LINES WITH 2*RINT,2*RINT/2.54,2*ROUT,2*ROUT/2.54,LBODY,
198     LBODY/2.54,XPMAX,XPMAX/2.54
199     THUS
DIMENSIONS OF CYLINDRICAL SLEEVE SIMULATING THE GRENADE BODY
INTERNAL DIAMETER  _____ *.***** CM _____ *.***** INCH
OUTSIDE DIAMETER  _____ *.***** CM _____ *.***** INCH
EFFECTIVE HEIGHT  _____ *.***** CM _____ *.***** INCH
PUNCH TRAVEL LIMIT _____ *.***** CM _____ *.***** INCH
205     SKIP 2 LINES
206     PRINT 15 LINES WITH 20000*RAD.RDX,10000*DELTAR,SPS.RDX,TMD.RDX,
207     SPHT.RDX,TCOND.RDX,DIFUZ.RDX,EY.RDX,PR.RDX,BM.RDX,FRACT.RDX
208     THUS
PROPERTIES OF RDX , USED IN THE EXPLOSIVE FILL:

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DIAMETER OF RDX PARTICLE _____	****.	MICRON
RADIAL GRID ELEMENT OF RDX _____	****.	MICRON
SPECIFIC SURFACE OF RDX _____	****.	SQ CM/G
THEORETICAL MAX DENSITY OF RDX _____	*.***	G/CC
SPECIFIC HEAT OF RDX _____	*.***	CAL/G/DEG K
THERMAL CONDUCTIVITY OF RDX _____	.....	CAL/CM/S/DEG K
THERMAL DIFFUSIVITY OF RDX _____	.....	SQ CM/S
YOUNG'S CONSTANT FOR RDX _____	.....	PASCAL
POISSON'S RATIO FOR RDX _____	.....	
BULK MODULUS FOR RDX _____	.....	PASCAL
MASS FRACTION OF RDX IN HE _____	*.***	

224 PRINT 15 LINES WITH DRHE,DENS.HE,SPHT.HE,TCOND.HE,DIFUZ.HE,DRST,
 225 DENS.STEEL,SPHT.STEEL,TCOND.STEEL,DIFUZ.STEEL
 226 THUS

THERMAL PROPERTIES OF GRENADE MATERIALS:

RADIAL GRID ELEMENT OF HE _____	.....	CM
TMD OF HE _____	.....	G/CC
SPECIFIC HEAT OF HE _____	.....	CAL/G/DEG K
THERMAL CONDUCTIVITY OF HE _____	.....	CAL/CM/S/DEG K
THERMAL DIFFUSIVITY OF HE _____	.....	SQ CM/S
RADIAL GRID ELEMENT OF STEEL _____	.....	CM
TMD OF STEEL _____	.....	G/CC
SPECIFIC HEAT OF STEEL _____	.....	CAL/G/DEG K
THERMAL CONDUCTIVITY OF STEEL _____	.....	CAL/CM/S/DEG K
THERMAL DIFFUSIVITY OF STEEL _____	.....	SQ CM/S

242 PRINT 9 LINES WITH RHOHEO,PHE,PINT/1000000,XO,SIGKPSI,HSTRESS,
 243 HSTRAIN,HSE,HSE*CALPJ,EE.RDX,EE.RDX*CALPJ,PWORK,PWORK*CALPJ
 244 THUS

INITIAL CONDITIONS AT START OF FINAL CONSOLIDATION:

HE DENSITY _____	*.*****	G/CC	
PRESSURE ON HE _____	**.*	KPSI	***.*** MPA
HEIGHT OF HE COLUMN _____	*.*****	CM	
MAX BODY HOOP STRESS _____	***.***	KPSI	***.*** MPA
HOOP STRAIN IN BODY _____	.....		
HOOP STRAIN ENERGY _____	**.*	JOULE	**.* CAL
RDX ELASTIC ENERGY _____	**.*	JOULE	**.* CAL
CUM WORK BY PUNCH _____	**.*	JOULE	**.* CAL

254 SKIP 2 LINES

255 PRINT 7 LINES THUS

SIMULATED CONDITIONS DURING HE CONSOLIDATION

PUNCH	HE	HE	MAX	HOOP	H STRN	PUNCH	THERM	TEMP	CYCLE
DISPL	DENS	PRESS	STRESS	STRAIN	ENERGY	WORK	WORK	RISE	TIME
(CM)	(G/CC)	(KPSI)	(KPSI)	(MU/U)	(CAL)	(CAL)	(CAL)	(D K)	(MS)

263 WHILE XP < XPMAX, DO

264 ''

265 ''INCREMENT DISPLACEMENT OF THE PUNCH.

266 ''

267 ADD DELXP TO XP

```

268         LET HOLDXP=XP
269     ''
270     ''CALC VOLUME AND DENSITY OF HE W/O ACCOUNTING FOR ADD'NL BODY STRAIN.
271     ''
272         LET RHOHE=MASSHE/AXHE/(XO-XP)
273         LET PHE=PRESS(TMDHE,RHOHE)
274         LET PINT=PA.KPSI*PHE
275     ''
276     ''CALCULATE INCREMENT OF WORK DONE BY PUNCH AT THIS PRESSURE.
277     ''
278         LET DELPWORK=0.000001*AXHE*PINT*DELXP
279         ADD DELPWORK TO PWORK
280     ''
281     ''CALCULATE BODY STRAIN AT THIS PRESSURE.
282     ''
283         CALL STRS.STRAIN (PINT,POUT) YIELDING SIGPA,HSTRAIN
284         LET SIGKPSI=SIGPA/PA.KPSI
285     ''
286     ''OBTAIN NEW CROSS SECTION, ACCOUNTING FOR CURRENT STRAIN.
287     ''
288         LET AXHE=AXHEO*(1.0+HSTRAIN)**2
289     ''
290     ''FIND THE ADDITIONAL PUNCH DISPLACEMENT WHICH PRESERVES HE DENSITY.
291     ''
292         LET XP=XO-MASSHE/AXHE/RHOHE
293     ''
294     ''ADD THE ADDITIONAL PUNCH WORK FOR THE ADDITIONAL DISPLACEMENT.
295     ''
296         DELPWORK=0.000001*AXHE*PINT*(XP-HOLDXP)
297         ADD DELPWORK TO PWORK
298     ''
299     ''UPDATE TIME.
300     ''
301         LET DELTAT=(XP-XPO)*RPSPEED(XP)
302         LET DELT2=0.5*DELTAT
303         ADD DELTAT TO TIME
304     ''
305     ''CALCULATE THE HOOP STRAIN ENERGY.
306     ''
307         LET HSE=STRN.ENER (PINT,POUT)
308     ''
309     ''CALCULATE THE ELASTIC STRAIN ENERGY IN THE RDX.
310     ''
311         LET EE.RDX=ESTRN.RDX(PINT)
312     ''
313     ''CALCULATE THE THERMAL ENERGY BALANCE.
314     ''
315         LET HENERGY=MAX.F(0.0,PWORK-HSE-EE.RDX-HTLOSS)
316     ''
317     ''CALCULATE THE THERMAL FLUX TO THE RDX.
318     ''
319         LET QDOT=CALPJ*(HENERGY-HENERGYO)/(MASS.RDX*SPS.RDX)/DELTAT
320     ''
321     ''CALCULATE AVG TEMP RISE IN HEATED HE.
322     ''
323         LET UHE=HENERGY*CALPJ/(HTCAP.RDX+HTCAP.STER)
324     ''

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325  ''CALCULATE HEAT LOSS TO WALL.
326  ''
327      IF FLAGUHE NE 1
328          GO TO L3
329      OTHERWISE ''GET RADIAL DIST OF TEMP IN HE AND IN STEEL WALL
330      IF UCON.HE*DELTAT > 0.25
331          GO TO L3 ''TO AVOID NUMERICAL INSTABILITY
332      OTHERWISE
333      IF UCON.ST*DELTAT > 0.25
334          GO TO L3 ''TO AVOID NUMERICAL INSTABILITY
335      OTHERWISE
336      LET TIMEU=TIME
337      LET OMEGA=QDOT*MASS.RDX*SPS.RDX/MASSHE ''HEAT GEN RATE/MASSHE
338      FOR I=2 TO NHE-1 DO
339          LET RIA=DRHE*I
340          LET RI=RIA-DRHE
341          LET UHEV(I)=UHEOV(I)+DELTAT*UCON.HE/RI*(RIA*(UHEOV(I+1)
342              -UHEOV(I))-RI*(UHEOV(I)-UHEOV(I-1)))+DELTAT*OMEGA/SPHT.HE
343          LET UHEV(I)=MAX.F(0.0,UHEV(I))
344      LOOP ''OVER HE GRID
345      LET UHEV(1)=UHEV(2) ''AT CENTER OF HE
346      FOR I=2 TO NST-1 DO
347          LET RIA=RINT+DRST*I
348          LET RI=RIA-DRST
349          LET USTV(I)=USTOV(I)+DELTAT*UCON.ST/RI*(RIA*(USTOV(I+1)
350              -USTOV(I))-RI*(USTOV(I)-USTOV(I-1)))
351          LET USTV(I)=MAX.F(0.0,USTV(I))
352      LOOP ''OVER STEEL GRID
353      LET USTV(NST)=USTV(NST-1) ''FOR INSULATED OUTER BOUNDARY
354  ''
355  ''AT HE-STEEL BOUNDARY, CONSERVE FLUX AND TEMPERATURE.
356  ''
357      LET UHEV(NHE)=(BETA*UHEV(NHE-1)+USTV(2))*ROPB
358      LET USTV(1)=UHEV(NHE)
359      LET DELHTLOSS=AWALL*TCOND.HE*(UHEV(NHE-1)-UHEV(NHE))/DRHE*
360      DELTAT/CALPJ
361  ''
362  ''UPDATE INITIAL CONDITIONS.
363  ''
364      FOR I=1 TO NHE, LET UHEOV(I)=UHEV(I)
365      FOR I=1 TO NST, LET USTOV(I)=USTV(I)
366      GO TO L4
367  'L3' LET DELHTLOSS=AWALL*TCOND.HE*(UHE-USTEEL)/DEL.R.HE*DELTAT/CALPJ
368  'L4' ADD DELHTLOSS TO HTLOSS
369      LET USTEEL=HTLOSS/HTCAP.STEEL*CALPJ
370      ADD 1 TO K
371      IF FLAGUHE NE 1
372          GO TO L6
373      OTHERWISE
374      IF MOD.F(K,KUPRINT) NE 0
375          GO TO L6
376      OTHERWISE
377      SKIP 1 LINE
378      PRINT 5 LINES WITH 1000*TIMEU
379      THUS
TEMP DIST IN GRENADE AT TIME ***,*** MS

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HE RADIAL LOC (CM)	TEMP INCR (DEG K)	LOCATION INDEX
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385	FOR I=1 TO NHE DO	
386	LET J=I-1	
387	LET R=DRHE*J	
388	PRINT 1 LINE WITH R,UHEV(I),I	
389	THUS	
** . ****	*** . ****	**
391	LOOP ''OVER HE GRID	
392	PRINT 4 LINES THUS	

WALL RADIAL LOC (CM)	TEMP INCR (DEG K)	LOCATION INDEX
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397	FOR I=1 TO NST DO	
398	LET J=I-1	
399	LET R=DRST*J+RINT	
400	PRINT 1 LINE WITH R,USTV(I),J+NHE	
401	THUS	
** . ****	*** . ****	**
403	LOOP ''OVER ST GRID	
404	PRINT 2 LINES THUS	

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407 'L6' IF FLAGU=0
408      GO TO L5
409      OTHERWISE ''GET TEMP PROFILE IN RDX PARTICLE
410      IF UCON*DELT2 > 0.25
411      GO TO L5 ''TO AVOID NUMERICAL INSTABILITY
412      OTHERWISE
413      LET U1V(2)=UOV(2)+DELT2*UCON*(UOV(3)-UOV(2))
414      LET U1V(1)=U1V(2) ''FOR ZERO COND AT CENTER OF PARTICLE
415      FOR I=3 TO NGRID-1 DO
416      LET RI=(I-1)*DELTAR
417      LET U1V(I)=UOV(I)+DELT2*U1CON*((UOV(I+1)-UOV(I-1))/RI +
418      (UOV(I+1)-2.0*UOV(I)+UOV(I-1))/DELTAR)
419      LOOP ''OVER GRID
420      LET U1V(NGRID)=U1V(NGRID-1)+UOCON*QDOT
421      ''
422      ''MOVE NEXT HALF-TIME STEP.
423      ''
424      LET UV(2)=U1V(2)+DELT2*UCON*(U1V(3)-U1V(2))
425      LET UV(1)=UV(2) ''AT CENTER
426      FOR I=3 TO NGRID-1 DO
427      LET RI=(I-1)*DELTAR
428      LET UV(I)=U1V(I)+DELT2*U1CON*((U1V(I+1)-U1V(I-1))/RI +
429      (U1V(I+1)-2.0*U1V(I)+U1V(I-1))/DELTAR)
430      LOOP ''OVER GRID
431      LET UV(NGRID)=UV(NGRID-1)+UOCON*QDOT
432      ''
433      ''UPDATE INITIAL TEMPERATURE DISTRIBUTION.
434      ''
435      FOR I=1 TO NGRID, LET UOV(I)=UV(I)
436      ''
437      ''PRINT TEMPERATURES AS REQUIRED.
438      ''

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439      IF MOD.F(K,KUPRINT) NE 0
440          GO TO L5
441      OTHERWISE
442          SKIP 1 LINE
443          PRINT 5 LINES WITH 1000*TIME
444          THUS
TEMP DISTRIBUTION IN RDX AT TIME ***,*** MS

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RDY RADIAL LOC (MICRON)	TEMP INCR (DEG K)	LOCATION INDEX
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450      FOR I=1 TO NGRID DO
451          LET J=I-1
452          LET R=10000.0*DELTAR*J
453          PRINT 1 LINE WITH R,UV(I),J
454          THUS
****,****      ***,***      **
456      LOOP ''OVER GRID
457      PRINT 2 LINES THUS

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460      'L5'      IF PHE GE MAXKPSI
461          GO TO L2
462      OTHERWISE
463          IF MOD.F(K,KPRINT) NE 0
464              GO TO L1
465      OTHERWISE
466          PRINT 1 LINE WITH XP,RHOHE,PHE,SIGKPSI,10**6*HSTRAIN,CALPJ*
467          HSE,CALPJ*PWORK,CALPJ*HENERGY,UHE,1000*TIME
468          THUS

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*.**** *.**** ***,*** ***,** ***,* ***,*** ***,*** ***,*** ***,*** ***,**

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470      'L1'      LET XPO=XP
471          LET HENERGYO=HENERGY
472      LOOP ''OVER DISPLACEMENT
473      'L2'      PRINT 1 LINE WITH XP,RHOHE,PHE,SIGKPSI,10**6*HSTRAIN,CALPJ*
474          HSE,CALPJ*PWORK,CALPJ*HENERGY,UHE,1000*TIME
475          THUS

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*.**** *.**** ***,*** ***,** ***,* ***,*** ***,*** ***,*** ***,**

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477      PRINT 2 LINES THUS

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480      ''
481      ''FOR THE RDX IN THE HE, GET THE STRAIN, STRAIN ENERGY, VOL RECOVERY,
482      ''AND THE FINAL DENSITY OF THE HE.
483      ''
484          LET EPS.RDX=PINT/EY.RDX
485          LET EE.RDX=ESTRN.RDX(PINT) ''JOULE
486          LET DVOL.RDX=VOL.RDX*PINT/BM.RDX
487          LET DVOL.HE=VOL.RDX*EPS.RDX*(1.0+2.0*PR.RDX) ''UNI-AXIAL RELEASE
488          LET VOL.HE=MASSHE/RHOHE
489          LET RHOHE=RHOHE*VOL.HE/(VOL.HE+DVOL.HE) ''DENS AFTER RECOVERY
490      ''
491      ''HOOP STRESS ON THE OUTSIDE OF THE BODY AT AN INT PRESS OF PINT.
492      ''
493          LET A=0.01*RINT
494          LET B=0.01*ROUT
495          LET DENOM=B**2-A**2

```

```

496     LET SIGOUT=(A**2*(PINT-POUT)+PINT*A**2-POUT*B**2)/DENOM
497     LET MAXLOAD=PI.C*(RINT/2.54)**2*PHE
498     PRINT 3 LINES WITH PINT/PA.KPSI,MAXLOAD,SIGOUT/PA.KPSI
499     THUS
MAX CONSOLIDATION PRESSURE _____ ***.*** KPSI
MAX CONSOLIDATION LOAD _____ ***.*** KLB
HOOP STRESS ON BODY OUTSIDE _____ ***.*** KPSI
503     PRINT 10 LINES WITH 10**6*EPS.RDX,VOL.RDX,DVOL.RDX,100*DVOL.RDX/
504     VOL.RDX,DVOL.HE,100*DVOL.HE/VOL.HE,RHOHE,EE.RDX,CALPJ*EE.RDX,
505     HTLOSS,CALPJ*HTLOSS,USTEEL,1000*TIME,QDOT
506     THUS
STRAIN IN BULK RDX _____ ***** MU/U
VOLUME OF RDX SOLID _____ ***.*** CC
RDX VOLUME INCREASE _____ ***.*** CC (**.***%)
1-AX HE VOL INCREASE _____ ***.*** CC (**.***%)
FINAL DENSITY OF HE _____ *.*** G/CC
RDX STRAIN ENERGY _____ ***.*** JOULES _____ ***.*** CAL
CUM HEAT LOSS BY HE _____ ***.*** JOULES _____ ***.*** CAL
TEMP RISE IN STEEL _____ ***.*** DEG K
THERMAL FLUX INTO RDX AT TIME ***.*** MS _____ ..... CAL/SQ CM/S

517     SKIP 1 LINE
518     IF FLAGUHE=1
519         PRINT 5 LINES WITH 1000*TIMEU
520     THUS
TEMP DIST IN GRENADE AT TIME ***.*** MS

HE RADIAL      TEMP INCR      LOCATION
LOC (CM)      (DEG K)      INDEX
-----
526           FOR I=1 TO NHE DO
527               LET J=I-1
528               LET R=DRHE*J
529               PRINT 1 LINE WITH R,UHEV(I),I
530               THUS
***.***      ***.***      **
532           LOOP 'OVER HE GRID
533           PRINT 4 LINES THUS

WALL RADIAL      TEMP INCR      LOCATION
LOC (CM)      (DEG K)      INDEX
-----
538           FOR I=1 TO NST DO
539               LET J=I-1
540               LET R=DRST*J+RINT
541               PRINT 1 LINE WITH R,USTV(I),J+NHE
542               THUS
***.***      ***.***      **
544           LOOP 'OVER ST GRID
545           PRINT 2 LINES THUS

548     ALWAYS
549     STOP
550     END 'COMPACT

```

```

1 FUNCTION PRESS (TMD, RHO)
2 ''
3 ''FUNCTION CALCULATES THE TRANSIENT PRESSURE (KPSI) REQUIRED TO YIELD
4 ''HE DENSITY OF RHO (G/CC), WITH A THEORETICAL MAX HE DENSITY OF TMD.
5 ''TRANSIENT PRESS IS THAT APPLIED DURING LOADING OP'NS OF THE M42/M46
6 ''GRENADE. TMD OF THE HE IS ALSO GIVEN IN G/CC. THIS FUNCTION IS THE
7 ''INVERSE OF RHOTRANS. CALCULATION OF THE PRESSURE FROM RHOTRANS IS
8 ''OBTAINED ITERATIVELY VIA A NEWTON-RAPHSON METHOD.
9 ''
10     LET ERR=0.0001 ''KPSI TOLERABLE ERROR
11     LET PS= 0.8*RHO/(TMD-RHO) ''QUASI-STATIC PRESSURE FOR DENSITY RHO
12     LET P1=1.52*PS
13     LET P2=1.53*PS
14     LET RHO1=RHOTRANS(TMD,P1)
15 'L1'LET RHO2=RHOTRANS(TMD,P2)
16     IF ABS.F(P1-P2) LE ERR
17         GO TO L3
18     OTHERWISE
19         LET P3=P2+(P2-P1)/(RHO2-RHO1)*(RHO-RHO2)
20         LET P1=P2
21         LET P2=P3
22         LET RHO1=RHO2
23         GO TO L1
24 'L3'RETURN WITH P2
25 END ''FUNCTION PRESS

1 FUNCTION RHOTRANS (TMD,PRESS)
2 ''
3 ''FUNCTION CALCULATES AVERAGE DENSITY OF THE HE WITHIN A GRENADE BODY
4 ''FOR TRANSIENT LOADING CONDITIONS. ARGS: TMD IS THE THEORETICAL
5 ''MAX DENSITY OF HE IN G/CC, AND PRESS IS THE PEAK PRESSURE IN KPSI.
6 ''PRESSURE GRADIENT WITHIN THE HE IS GIVEN BY THE COEF GRAD.PRS.
7 ''
8     LET B=GRAD.PRS*PRESS
9     LET ARG=(PRESS+0.8-B)/(PRESS+0.8)
10    LET NORMRHO=1.0+0.8/B*LOG.E.F(ARG)
11    RETURN WITH TMD*NORMRHO
12 END ''FUNCTION RHOTRANS

```

```

1  FUNCTION STRN.ENER (PINT,POUT)
2  ''
3  ''FUNCTION CALCULATES THE HOOP STRAIN ENERGY IN A CYLINDRICAL SLEEVE,
4  ''GIVEN INTERNAL PRESSURE PINT AND OUTSIDE PRESSURE POUT. SLEEVE
5  ''HEIGHT, INTERNAL RADIUS, EXTERNAL RADIUS, AND YOUNG'S MODULUS FOR
6  ''THE SLEEVE MATERIAL ARE TRANSMITTED AS GLOBAL VARIABLES. INPUT
7  ''ARGS ARE GIVEN IN PASCALS. HOOP-STRAIN ENERGY IS GIVEN IN JOULES.
8  ''RESULT IS BASED ON THE LAME EQ'N FOR THICK-WALLED CYLINDERS.
9  ''
10     LET A=0.01*RINT
11     LET B=0.01*ROUT
12     LET L=0.01*LBODY
13     LET DENOM=B**2-A**2
14     LET T1=A**2*B**2*(PINT-POUT)**2/2.0/DENOM
15     LET T2=(PINT*A**2-POUT*B**2)**2/DENOM
16     LET T3=2.0*A**2*B**2*(PINT-POUT)*(PINT*A**2-POUT*B**2)*LOG.E.F(B/A)
17     /DENOM/DENOM
18     RETURN WITH PI.C*L*(T1+T2+T3)/EYOUNG
19 END ''STRN.ENER

1  ROUTINE STRS.STRAIN GIVEN PINT,PCUT YIELDING SIGPA,HSTRAIN
2  ''
3  ''CALCULATES MAX HOOP STRESS AND HOOP STRAIN IN A CYLINDRICAL SLEEVE,
4  ''GIVEN INTERNAL PRESSURE PINT AND OUTSIDE PRESSURE POUT. THE SLEEVE
5  ''INTERNAL RADIUS, EXTERNAL RADIUS, AND YOUNG'S MODULUS FOR SLEEVE
6  ''MATERIAL ARE TRANSMITTED AS GLOBAL VARIABLES. THE LAME EQUATION FOR
7  ''THICK-WALLED CYLINDERS IS EVALUATED AT THE INT RADIUS. DIMENSIONS
8  ''ARE GIVEN IN CM. THEY ARE CONVERTED TO METERS. MAX STRESS (SIGPA)
9  ''IS GIVEN IN PASCALS. REF: TIMOSHENKO AND GOODIER, THEORY OF
10 ''ELASTICITY, C. 1951.
11 ''
12     LET A=0.01*RINT
13     LET B=0.01*ROUT
14     LET DENOM=B**2-A**2
15     LET SIGPA=(PINT*(A**2+B**2)-2.0*B**2*POUT)/DENOM
16     LET HSTRAIN=SIGPA/EYOUNG
17     RETURN
18 END ''STRS.STRAIN

1  FUNCTION ESTRN.RDX (PINT)
2  ''
3  ''CALCULATES THE ELASTIC STRAIN ENERGY (JOULES) AS A FUNCTION OF PINT,
4  ''THE PRESSURE (PA) ON THE HE . A LOCAL HYDROSTATIC STATE IS
5  ''ASSUMED. VOLUME OF RDX CRYSTALS (VOL.RDX), AND VALUES OF YOUNG'S
6  ''MODULUS (EY.RDX) AND BULK MODULUS (BM.RDX) FOR RDX ARE GLOBAL
7  ''INPUT ARGUMENTS. RDX VOLUME IS TREATED AS A CONSTANT. A CONSTANT
8  ''PRESSURE GRADIENT IS ASSUMED WITHIN THE HE VOLUME. PRESSURE VARIES
9  ''LINEARLY FROM A MAX OF PINT TO A MIN OF (PINT - GRAD.PRS*PINT). THE
10 ''VALUE OF GRAD.PRS IS ASSIGNED IN THE MAIN PROGRAM AND TRANSMITTED
11 ''GLOBALLY.
12 '' LET EPS.RDX=PINT/EY.RDX
13     LET COEF=1.0-GRAD.PRS+GRAD.PRS**2/3.0
14     LET EE.RDX=0.000005*VOL.RDX/BM.RDX*PINT**2*COEF
15     RETURN WITH EE.RDX
16 END ''FUNCTION ESTRN.RDX

```

```

1 FUNCTION RPSPEED (XP)
2 ''
3 ''CALCULATES THE RECIPROCAL PUNCH SPEED IN S/CM AS A FUNCTION OF
4 ''PUNCH DISPLACEMENT XP, IN CM. INITIAL, CONSTANT ACCELERATION OVER
5 ''TRAVEL XCEL IS ASSUMED. A FINAL, CONSTANT DECELERATION IS ASSUMED
6 ''OVER TRAVEL: XPMAX - DCEL TO XPMAX. SPEED IS CONSTANT WITHIN THE
7 ''RANGE: XCEL TO XPMAX - DCEL. XPMAX IS A GLOBAL VARIABLE.
8 ''
9     LET MAXSPEED=2.6 ''CM/S
10    LET XCEL=0.02 ''CM
11    LET DCEL=0.08 ''CM
12    IF XP LE 0.0
13        GO TO L1
14    OTHERWISE
15        IF FLAGU=1
16            RETURN WITH 1.0/MAXSPEED
17    OTHERWISE
18        IF XP < XCEL
19            LET SPEED=MAXSPEED*SQRT.F(XP/XCEL)
20            RETURN WITH 1.0/SPEED
21    OTHERWISE
22        IF XP > XPMAX-DCEL
23            LET SPEED=MAXSPEED*(1.0-SQRT.F((XP-XPMAX+DCEL)/DCEL))
24            RETURN WITH 1.0/MAX.F(SPEED,0.1)
25    OTHERWISE
26        RETURN WITH 1.0/MAXSPEED
27 'L1'PRINT 1 LINE WITH XP THUS
28     ERROR. PUNCH DISPLACEMENT IS OUT OF RANGE: XP = .....
29     STOP
30 END ''FUNCTION RPSPEED

```

ANNEX B

AMSMC-RDA-S

28 Aug 1985
Revised 24 Sep 85

MEMORANDUM FOR RECORD

SUBJECT: Predicted Bulk Densities of Comp A-5 and Comp A-4 As
Functions of Peak Consolidation Pressure

1. Reference:

-
- a. Information Paper, SMCAR-ESM-M, 25 Ap 85, subject: Follow-up Questions on Comp A-5 Density.
 - b. Ltr, SMCHO-QA, 2 July 85, subject: Density Measurements.
 - c. Information Paper, SMCAR-ESM-M, 6 Aug 85, subject: Results from Comp A-5 Density Experiment.
 - d. MFR, AMSMC-RDA-S, 9 Aug 85, subject: Some Observations About the Explosive Sensitivity of Comp A-5.
 - e. MFR, DRSMC-SAS (R), 4 Nov 83, subject: Particle-Size Distribution of Nominal Class 1 RDX Before Incorporation and After Extraction From Extrusions of Comp C-4.

2. Background

In the Ref 1a paper SMCAR-ESM-M referenced some experimental results of consolidation of explosive Comp A-5 under quasi-static conditions. The applied pressure was permitted to remain at max value for several minutes in this quasi-static test, so that the explosive might be expected to exhibit hydrostatic behavior. The bulk density is given at several values of the peak consolidation pressure. The source of these data is indicated as George Ziegler, SMCAR-LCE. At the time these experiments were run the RDX granulation used in Comp A-5 was much coarser than it currently is. Consequently, there was some concern that the relationship between peak pressure and bulk density might be somewhat different now, using nominal Class 1 RDX, than it was then. Bill Fortune (SMCAR-ESM-M) directed Holston AAP to perform another set of quasi-static experiments on Comp A-5, having the current (nominal Class 1) granulation of RDX and, incidentally, reduced residual solvent level. I suggested a set of pressures at which these experiments were to be run. The range of pressure--7 to 60 kpsi--was greater than the range of Ziegler's data, with some matching pressure values. The results of the tests at Holston were transmitted in Ref 1b. These results are in good agreement with Ziegler's, as shown in Table 1. The average intra-batch standard deviation in the HSAAP data is 0.005 g/ml. An analytic model of the quasi-static, pressure-density relationship is also shown, for comparison.

TABLE 1

COMPARISON OF COMP A-5 BULK DENSITY VERSUS PEAK QUASI-STATIC
CONSOLIDATION PRESSURE

Entries are average density in g/ml.

Pressure (kpsi)	Data Source		
	ARDC Ziegler	Holston AAP 7/2/85 *	Calculated **
7	1.61	1.599	1.597
10	1.65	1.633	1.648
15	1.69	1.686	1.690
17	1.70	1.692	1.700
24	1.72	1.725	1.722

* Average of 3 batches of 5 samples per batch.

** density/TMD = $p/(p + 0.8)$, where the theoretical max density (TMD) is 1.78 g/ml.

3. Effect of RDX Particle Size

The tabulated results support the assertion that the initial size of the RDX grains in Comp A-5 (within limits) does not have a measurable effect on the bulk density, obtained under quasi-static conditions. Ref 1c also compares these experiments, but draws a stronger conclusion from them than the conclusion which I have made. In pgf 4 of Ref 1c one finds: "The conclusion then is that there appears to be no physical change to the explosive from the process changes." In view of the fact that bulk density is the only (!) physical quantity being measured here, it may be premature to make this assertion. In fact, evidence cited in Ref 1d indicates that grain size does affect explosive sensitivity in pressed, granular explosives. Further, at the range of density to which Comp A-5 is pressed in the M42/M46 grenade, there is indirect evidence (from tests on similar explosives) that grain fracture occurs during consolidation of these grenades. There is evidence (Ref 1e) of RDX grain fracture when Comp C-4 is extruded at pressures much lower than the 25 kpsi used on Comp A-5. Whether the change in explosive sensitivity due to different initial grain size is important is another issue. The fact is that the results in Table 1 do not address that issue.

4. Average Bulk Density of Comp A-5 After Transient Pressurization

As indicated in Ref 1c, the average bulk density of Comp A-5 under the transient conditions of loading in the M42/M46 grenade is less than the quasi-static value, given the same peak pressure. This fact is conjectured to result from a non-hydrostatic behavior of the explosive during the brief (120 millisecc) time the pressure is at or near peak value. A gradient in pressure within the explosive would cause a corresponding gradient in density, yielding a smaller mean value. The compressibility of the explosive (locally) is given to a very good approximation by the quasi-static result:

$$\rho/\text{TMD} = p/(p + 0.8), \quad (1)$$

where the bulk density, ρ , and TMD are given in, say, g/ml and where the peak consolidation pressure, p , is given in kpsi. For Comp A-5 the TMD is, practically, 1.78 g/ml. Now suppose that the max pressure reached in the explosive was not the same everywhere within the explosive volume. Specifically, as an approximation, assume a constant gradient of pressure with respect to volume, plotted from the max value on the punch face, where the hydrostatic value, p_{max} , should occur. Thus, the local pressure-volume relationship would have the form:

$$p = p_{\text{max}} - b x, \quad (2)$$

with

$$b = p_{\text{max}} - p_{\text{min}},$$

and where x is the non-dimensional volume coordinate, which varies from 0 to 1 over the volume. To find the average bulk density (over the grenade internal volume), one must integrate the local density--a function of local pressure--over this volume. This corresponds to substituting equation (2) into (1), and integrating over the non-dimensional volume coordinate x . Formally, let the volume-average bulk density be denoted by $E(\rho)$. Then,

$$E(\rho)/\text{TMD} = x\text{-integral over } (0,1) \text{ of :} \\ (p_{\text{max}} - b x)/(p_{\text{max}} + 0.8 - b x) dx. \quad (3)$$

The result of this operation is a function with one arbitrary constant, b :

$$E(\rho)/\text{TMD} = 1 + (0.8/b)\ln((p_{\text{max}}+0.8-b)/(p_{\text{max}}+0.8)). \quad (4)$$

In the limit when b approaches zero, equation (1) is produced, as expected. By examining the (Ref 1c) KSAAP experiments, it is found that a good fit to all results obtains when

$$b = 0.8 p_{\text{max}}, \quad (5)$$

for values of p_{max} from 18 to 29 kpsi. With the above value of b substituted in equation (4), one has the following equation for average bulk density versus peak consolidation pressure.

$$E(\rho)/\text{TMD} = 1 + (1/p_{\text{max}})\ln((0.2p_{\text{max}}+0.8)/(p_{\text{max}}+0.8)) . \quad (6)$$

5. Comparison of Experimental and Calculated Avg Bulk Density

Experimental (transient) average bulk density values, obtained in the KSAAP M42/M46 transient loading tests, were read from a graph provided in Ref 1c. A limited number of transient data points from MAAAP is also shown in Ref 1c. These data are compared (Table 2) with the calculated values of equation (6). The fit over the range appears to be within experimental error. Further, no trend in the residuals is apparent. On this basis one can assert that Comp A-5 falls far short of being an ideal fluid

during transient consolidation. A portion of the explosive volume may experience an effective pressure which is only 20 % of p_{max} in terms of its compressible response.

TABLE 2

COMPARISON OF EXPERIMENTAL AND THEORETICAL AVERAGE BULK DENSITIES OF COMP A-5 AFTER M42/M46 GRENADE LOADING

Peak Pressure (kpsi)	Average Density (g/ml)			
	Exp (KSAAP) VE 81/82	Exp (MAAAP) July 1985	Calculated Transient	Calculated Quasi-static *
8		1.500	1.491	1.618
12		1.550	1.574	1.669
14		1.600	1.600	1.684
18	1.640		1.636	1.704
19	1.645		1.643	1.708
20	1.642		1.649	1.712
21	1.657		1.655	1.715
22	1.666		1.660	1.718
23	1.667	1.650	1.665	1.720
24	1.675		1.670	1.722
25	1.676		1.674	1.725
26	1.679		1.678	1.727
27	1.682		1.681	1.729
28	1.685		1.684	1.730
29	1.694		1.687	1.732
30			1.690	1.734

* The quasi-static value, $1.78p/(p + 0.8)$, is offered for comparison.

6. Quasi-static Bulk Density of Comp A-4

It is noted that equation (1), which is used to calculate the quasi-static density of Comp A-5, is written in a non-dimensional form. Both sides of this equation are ratios of dimensional quantities. The only dimensional parameter which relates to compressibility of the explosive is the constant 0.8 kpsi. If this constant is essentially the same for Comp A-5 and Comp A-4, the quasi-static bulk density of Comp A-4 can be calculated from (1) using the TMD = 1.76 g/ml. This density is based on a formulation of Comp A-4 that has an addition of 3.0 % wax to RDX. The assumed density of wax is 0.91 to 0.92 g/ml. Since the formulation of Comp A-4 may vary slightly in percent wax, one should recalculate the TMD if the actual formulation is much different from that assumed. Variation in the TMD of A-4 is also contributed by different waxes. The bulk density values for Comp A-4 shown in Table 3. Comparable values of Comp A-5 are shown for comparison.

TABLE 3

COMPARISON OF BULK DENSITIES OF COMP A-5 AND COMP A-4
VERSUS PEAK QUASI-STATIC CONSOLIDATION PRESSURE

Entries are calculated bulk densities in g/ml.

Pressure (kpsi)	Explosive Composition		
	A-5	A-4 with TMD of:	
		1.760	1.770
7	1.597	1.578	1.588
8	1.618	1.599	1.609
9	1.635	1.616	1.626
10	1.648	1.628	1.639
15	1.690	1.670	1.680
17	1.700	1.680	1.690
20	1.712	1.692	1.702
24	1.722	1.702	1.713
40	1.745	1.724	1.735
60	1.757	1.736	1.747

7. Conclusions and Recommendations

Mathematical models for the bulk density of Comp A-5 and Comp A-4 have been presented here. Under quasi-static pressurization the equation which relates bulk density to peak pressure has a very simple form. However, this result is shown to match experimental values of bulk density for Comp A-5 over the range of pressure from 7 kpsi to 60 kpsi. When the loading condition on the explosive is rather transient, with near-peak load persisting for only 120 milliseconds, the explosive does not have time to react in a hydrostatic manner. It has been shown that the average bulk density of the explosive in M42/M46 grenades is significantly lower than the quasi-static value obtained for a given pressure. A formula for the average bulk density, after transient loading, is derived here. This formula fits experimental results over the entire experimental pressure range for Comp A-5. A similar formula may be derived for Comp A-4, given some information about the nature of the pressure gradient which exists within the explosive during pressurization. Of course, the same assumption could be made for Comp A-4 as was made for Comp A-5. I have been reluctant to do this, since there is a large disparity in the portion binder in these two explosives. Comp A-5 has about half as much binder as Comp A-4. In the quasi-static case, the compressible behavior of these explosives is predicted to be much the same, relative to their respective TMDs. In the interest of expanding engineering knowledge, it is recommended that: (a) the bulk density predictions of Table 3 for Comp A-4 be verified empirically (as was done for Comp A-5), after quasi-static loading, and (b) the average density of explosive in M42 grenades be measured after transient loading using Comp A-4. Resources permitting, it would also be desirable to measure the local bulk density within the HE in M42 grenades at several locations. These data would support the assumption that the

TABLE 3

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effective pressure exhibits a constant gradient within the HE volume. Local densities should be measured at three locations on the grenade axis, from the cone to the inside of the cap (dome). Also, at a midaxial station, three local radial positions should be sampled for bulk density at different polar angles.



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