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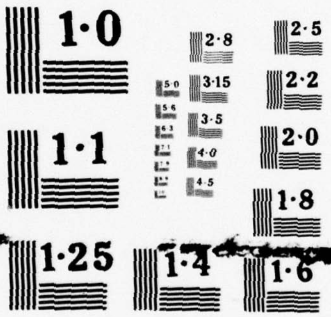

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HYDRO CODE STUDY

Final Report

Wallace E. Johnson

PREPARED FOR
THE BALLISTIC MISSILE DEFENSE ADVANCED TECHNOLOGY CENTER

December 30, 1977

DEPARTMENT OF THE ARMY
Contract DASG60-77-C-0095

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A study was performed to determine if a 3D hydrodynamic code coupled with strength of materials formulation exists which is capable of predicting failure or break-up due to the interaction of a projectile (or multiple interactions) with a reentry vehicle system.

This study investigated ten potential 3D modeling techniques, to determine if an existing three-dimensional hydrodynamic code exists which has the capability of analyzing the BMD hypervelocity impact problem. Results of this study and future recommendations (over)

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Continuation of Section 20. Abstract

are included.

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Section Page

I INTRODUCTION

The objectives of this study is to determine if a three-dimensional hydrodynamic code coupled with strength of materials formulation exists which is capable of predicting failure or break-up due to the interaction of a projectile (or multiple interactions) with a reentry vehicle system. This numerical technique must be able to accurately model high stresses, non-linear phenomena, large deformation and penetration, and stress regimes where strength of materials are important. In addition, accurate failure models such as fracture, spallation and tearing must be working features of the numerical code.

If this numerical technique or phases of it, are not available, a development plan showing a recommended schedule, development tasks, required computer times, and estimates of man-hours and costs will be undertaken for each task.

Section II presents the summary and conclusions. The background for this study is discussed in Section III. Also discussed in Section III is a brief summary of the history of the development of impact codes and descriptions of various approaches and formulations.

In Section IV, we describe the mathematics and physics that will be required to solve our problem.

In Section V, we determine the "state-of-the-art" for solving problems in hypervelocity impact. This was accomplished by visitations to ten installations that have been involved in impact phenomena. A summary of the available techniques pertinent to this objective is also presented in this section.

A possible approach of coupling existing techniques is presented in Section VI. Also included is a development plan including schedule, computer time and costs (man-hours and computer time) for each task.

II SUMMARY AND CONCLUSIONS

The Ballistic Missile Defense (BMD) non-nuclear kill problem contains impact conditions involving relative velocities ranging from 40,000 fps to less than 10,000 fps, many possible impact angles depending on end game geometrics and possible multiple impacts. These engagement conditions cannot be simulated in existing experimental facilities, therefore, a credible three dimensional (3D) analytical tool which can evaluate the impact process at every stage through its time history is essential to better understanding the impact phenomena and resolving the non-nuclear lethality problem. This study investigated ten potential 3D modeling techniques which were developed, operational, validated by test problems or experiments and have available documentation (users' manuals, code description, etc.) to determine if an existing three dimensional hydrodynamic code exists which has the capability of analyzing the BMD hypervelocity impact problem.

The study determined that there is no single existing 3D hydrodynamic code which is capable of predicting structural failure and/or breakup of a reentry vehicle system from interaction with hypervelocity projectiles. This study concludes that a logical approach to the analytical problem may be resolved by coupling existing hydrodynamic techniques.

Numerical techniques which have been validated and documented are available for coupling but material properties for RV/Weapon System materials involved in the penetration process are not readily available. Accurate modeling for such material failure modes as fracturing and spallation are essential for accuracy in the analytical outputs. A joint theoretical, experimental program to evaluate material failure is recommended. In Section VI Development Plan, a preliminary recommendation is made for the 3D coupling process with possible candidate numerical techniques suggested.

III BACKGROUND

Preliminary studies of expected engagement conditions for non-nuclear intercepts have indicated that impact conditions are likely to involve velocities above 30,000 fps low obliquity and multiple impacts on the target. Currently these engagement conditions cannot be simulated in the existing experimental facilities; therefore, it is desirable to have an analytical tool which can evaluate the impact process at every stage through its time history and to better understand the physical phenomena and effects of each parameter in the non-nuclear problem.

It seems appropriate to review the development of the analytical tools.

The dynamics of hypervelocity impact were first described by a theory of the penetration of a shaped-charge jet into armor by PUGH (1). His theory was based on incompressible fluid flow. EICHELBERGER (2) further generalized the theory by including an additive strength term. It may be argued that the compressibility of solid materials cannot be neglected at the pressures produced by impact, however, it has been demonstrated by numerical calculations that the incompressible model is a good approximation for most combinations of jet and target materials, even when effects of compressibility are taken into account by use of the proper equation of state(3).

While very successful in predicting a relation between the impact and penetration velocities, the penetration theory for jets was unable to provide information concerning the size of the hole produced by the jet or projectile.

With the advent of larger and faster computers, codes capable of solving the hydrodynamic equations in two-dimensions were developed in the early 1960's by groups in industry and the government laboratories. The development of realistic thermodynamic descriptions of materials (equation of state) was formulated by fitting available experimental and theoretical data.

It became apparent that in order to accurately describe and calculate hole size, that new mechanisms such as viscous effects, elastic plastic and rate-sensitive strength effects had to be incorporated into the numerical techniques.

Again, many investigators have developed two-dimensional hydrodynamics coupled with strength of materials numerical techniques that have been successful in solving certain class of impact problems for axisymmetric impact. These investigations also required additional material modelling, which has been partially successful in predicting some failure or fracturing phenomena.

Basically, there are four numerical approaches to the solution in two and three-dimensions.

1) Eulerian - a fixed grid with material moving through the grid (finite difference)
2) Lagrangian - constant mass, where the grid points move to account for deformation (finite difference)
3) Finite Element - constant mass, where the grid points move to account for deformation (finite element)
4) Method of Characteristics - Considers the flow equations in terms of characteristic variables and solves for shocks exactly.

The difference between the finite difference and finite element approach is that in the finite difference one makes assumptions concerning the derivative between spatial positions, while the finite element approach makes assumptions about the solution between spatial positions.

The method of characteristics approach is not nearly as flexible as the other three techniques, in particular when there are many discontinuties (shocks) or material interfaces present.

Recently, three-dimensional numerical techniques (Eulerian, Lagrangian and Finite element) have been developed and should be applicable for solving the real three-dimensional problem utilizing the next generation of computers (Illiac, Star and Cray).

The task, that we have addressed, of predicting break up and/or failure of a reentry vehicle system due to the interaction with a projectile, must certainly call upon all the knowledge and techniques that have been developed in the two and three-dimensional world and the impact phenomena such as non-linear flow, large and small deformation, ductile and brittle material behaviour.

In addition, certain investigators have been using approximate techniques in simulating oblique impact by two dimensional axisymmetric and two dimensional (X - Y) plane strain. These approximate techniques will require checks and balances to verify their credibility.

IV DESCRIPTION OF NUMERICAL TECHNIQUES THAT WILL BE REQUIRED

The three-dimensional hydrodynamics code must be capable of modelling the following features to fulfill the objectives of the desired code or codes.

A) Multi-material capabilities (for all times) for normal and oblique impact.

B) Large deformations(early times).

C) Complete penetration through multi-material structure.

D) Large stresses (from megabars attenuating down to fractions of a kilobar).

E) Transferring debris (from back surface) and projectile material across large distances (with no interaction), and finally for this material to interact with additional multi-material structures.

F) Projectiles of various geometric shape (chunks, sphere and long rods). Calculations (two and three-dimensional) may be required to establish extrapolation laws.

G) Strength of material formulation and correct constitutive relations to accurately determine hole size and attenuation of the stresses through out the entire system.

H) Fracturing and spallation techniques to accurately predict various forms of break-up.

I) Multi-impact phenomenas.

In addition, the Finite Element Lagrangian and Finite Difference Lagrangian techniques may require slip surface treatment during phases of the interaction.

Flexibility in selecting different forms of the equation of state and constitutive models is a desirable feature of the technique.

In order to accurately interpret the results of the calculations, graphical display is equally important as the numerical technique itself. Pressures, densities and other scalar quantities should be displayed as contours or in three-dimensional plots (two of the dimensions are coordinates, and the other dimension is the scalar desired). Options for displaying velocity and mass flux vectors in two-dimensions will be required.

Capabilities of rezoning the computational mesh during the course of the problem will be required.

The requirements listed so far have reference to the numerical techniques. Of equal importance is the qualifications of the personnel doing the calculations. Doing a task of this magnitude will require skill and background in selecting the size of the calculational zones used, the time step for stability and accuracy, and in general, a comprehensive background and experience in developing and running large codes pertinent to the solution of impact phenomena and failure predictions.

V NUMERICAL TECHNIQUES NOW AVAILABLE

Visits to ten installations were made for the purpose of discussing numerical techniques. Many of the potential techniques exist at several installations, however, only those installations at which the numerical techniques was actually developed, were included for the visitations.

The following features of their numerical techniques were investigated.

1. Can they describe the requirements as listed in Section III?
2. Are they operational?
3. Are they documented (user's manuals - code description) - have they completed test problems to validate analytical solutions and/or experiments?
4. Are these techniques available to BMDATC contractors?
5. Are the codes written as machine (computer) independent?

For simplicity, we have selected the following acroynms (some of these are actual acroynms) for the data in tables (1) and (2).

1) CRT - CALIFORNIA RESEARCH TECHNOLOGY
2) C^3 - COMPUTER CODE CONSULTANTS
3) DELTA- DEL MAR TECHNICAL ASSOCIATES
4) EAFB - EGLIN AIR FORCE BASE
5) GAC - GRUMMAN AIRCRAFT, NEW YORK
6) LH - LOCKHEED AIRCRAFT, HUNTSVILLE
7) LLL - LAWRENCE LIVERMORE LABORATORY
8) LASL - LOS ALAMOS SCIENTIFIC LABORATORY
9) DSC - HONEYWELL INCORPORATED
10) S^3 - SYSTEMS, SCIENCE AND SOFTWARE
11) SAND - SANDIA LABORATORY, ALBUQUERQUE

Table (1) is a matrix of codes available at the various installations. By available, one refers to actual codes that these various investigators have and are knowledgeable concerning the physics, the mathematics and the correct usage. Many of these same codes may exist elsewhere, but the matrix indicates those codes that were actually developed by members of that group.

Table (2) is a matrix of groups and their codes and whether they actually have completed two-dimensional and three-dimensional calculations.

Again by definition, the solutions by finite element techniques were limited to small deformations, while the finite difference (Lagrangian and Eulerian) techniques were for larger deformations. Rezone techniques were used to continue the calculations in the case of Lagrangian calculations.

All researchers have adequate plot packages. Some of the numerical techniques are more machine (computer) dependent than others. All techniques investigated would be available to BMDATC contractors.

TABLE (1)

GROUP	3D Finite Element	3D Euler-ian	3D Lagran-gian	3D Other	2D Finite Element	2D Euler-ian	2D Lagran-gian
CRT				X	X	X	X
C^3		X				X	
DELTA	X				X		
EAFB	X	X			X	X	
GAC	X				X		
LH	X				X		
LLL	X		X				X
LASL	X				X	X	
DSC	X				X		
S^3		X				X	X
SAND	X				X	X	X

TABLE (2)

GROUP	3D CODE	2D CODE	3D RESULTS	2D RESULTS
CRT	3D FOURIER	WAVEL	X	X
C^3	TRIDORF	DORF	X	X
DELTA	SWISS	SWISS	X	X
EAFB	HULL EPIC	HULL	X	X
GAC	DYCAST	DYCAST	X	X
LH	CELFE	CELFE	X	X
LLL	HEMP	HEMP	X	X
LASL	NONSAP	NONSAP	X	X
DSC	EPIC	EPIC	X	X
S^3	METRIC	HELP	X	X
SAND	WULFF	TOODY CSQ	X	X

Three-Dimensional Eulerian Codes

1) HULL (EAFB)
    A) Multi-Material continuous
    B) 2nd order accurate for the Lagrangian phase
    C) Elastic-Plastic strength model
    D) Failure models are being investigated and incorporated
    E) Generator and plot packages
    F) Flexible equation of state library
2) Metric (S^3)
    A) Multi-Material continuous
    B) Elastic-Plastic strength model
    C) Failure models are being investigated
    D) Generator and plot packages
3) TRIDORF (C^3)
    A) Multi-Material continuous
    B) Rigid-plastic strength model. An elastic plastic model is being incorporated.
    C) Failure model is a simple density check.
    D) Generators, rezoners and a rezone routine to convert two-dimensional axis-symmetric flow to three dimensions is available.
    E) Tillotson form of the equation of state
    F) An equilibrium Radiation Diffusion routine

Three-Dimensional Finite Element Codes

An excellent overall reference to Structural Mechanics Computer Programs is reference (4).

1) DYCAST (GAC)
   - A) Stringer, beam and thin skin elements
   - B) Material nonlinearities (plasticity)

     Three types of stress-strain curves:

     Elastic-linearly hardening plastic

     Elastic-nonlinearly hardening plastic

     Elastic-perfectly plastic
   - C) Geometric-nonlinearities (large displacement)
   - D) Structural inertia internally distributed
   - E) Delete "failed" members at any time
   - F) The choice of internally - varied or fixed time step.

2) EPIC (DSC)
   - A) Lagrangian finite element formulation where the equations of motion are integrated directly rather than the stiffness matrix approach.
   - B) Non-linear material strength and compressibility effects are included to account for elastic-plastic flow and wave propagation.

     Strain hardening

     Strain rate effects

Thermal softening

Fracture

C) Tetrahedrons used to represent the elements

D) Multiple sliding surfaces

3) CEL-FE (LH)

A) A coupled Eulerian - Lagrangian Finite Element Program

B) Structure divided into two zones.

<u>Impact</u> - large deformation, material failure, propagation of shocks and failure zones, hydroelastic-viscoplastic model, arbitrary moving coordinate system, multi-step finite element algorithm based on theorem of weak solutions, material failure based on Chamis' failure criterion.

<u>Lagrangian</u> - small deformation, classical structural analysis, lagrangian coordinate system.

C) Finite element program used is NASTRAN.

4) SWISS (DELTA)

A) Treats linear and nonlinear response of continua and structures.

B) Both dynamic (explicit or implicit) and static problem may be considered without loss in efficiency.

C) Governing equations are formulated in a completely Lagrangian manner.

D) Facilitates analysis of irregular geometries through the use of tetrahedrons as well as simpler elements.

E) The time step is allowed to vary within the computational mesh for explicit dynamic calculations.

5) WULFF (SAND)

A) Patterned after the two-dimensional code HONDO.

B) Material models

Elastic-plastic
Strain hardening
Strain rate behaviour
Crushable foam and soil
Viscoelastic elasticity

C) Simultaneous equations of motion are integrated by a central difference expression for velocity and acceleration. Artificial viscosity is used to smooth shock fronts.

D) Spatial discretization is accomplished by the use of 8-node tri-linear isoparametric elements.

Three-Dimensional Finite Difference Codes

1) HEMP (LAGRANGIAN) (LLL)

   A) The three-dimensional difference operator is the analogue of the two-dimensional operator used in the two-dimensional HEMP code.

   B) Slip surfaces are presently being incorporated into the code.

   C) Strength models, fracture models, high explosive burn and many of the features of the two-dimensional code are incorporated into this version.

Other Three-Dimensional Code

1) WAVE-L FOURIER (CRT)

   A) Lagrangian and Ale techniques

   B) Multiple computing planes spaced in θ - direction.

   C) θ - gradients approximated by Fourier series.

   D) Best suited to perturbed axially-symmetric problems, such as oblique incidence impacts on simple targets.

Two-Dimensional Codes

1) CSQ - (EULERIAN) (SAND)

   A) Finite difference analogs of the Lagrangian equations of motion with material strength and energy transport are employed with continuous rezoning.

   B) Material descriptions with phase transition are available.

   C) Heat conduction

   D) Radiation diffusion

   E) Plasma conduction

   F) Elastic-plastic strength model

   G) Fracture model treated by retention of void volumes.

- H) Geometry is rectangular or cylindrical coordinates.
- I) Multi-material capability
- J) Source routines and high explosive burn options

2) WAVE-L (LAGRANGIAN) (CRT)

- A) Plane or axisymmetric geometry
- B) Material models
  - Cap model
  - Associated or non-associated flow rules
  - Hysteresis
  - Strain hardening
- C) Failure models
  - Generalized Plastic Strain
  - Oriented tensile fracture, multiple crack modes
  - Dynamic degradation of properties as material fails
  - Principal stress tensile limit model
- D) Sliding interfaces
  - Jetting and sliding along material interfaces
  - Collisions
  - Coupled, decoupled, dynamic decoupling
  - Void opening and closing
- E) Rezoning

Automatic redistribution of cell variables

Dezoning (merging of columns or rows)

3) DORF (EULERIAN) (C^3)
    - A) Plane or axisymmetric geometry
    - B) A version will handle up to 4 different materials in a cell.
    - C) Elastic-plastic strength model
    - D) A equilibrium Radiation Diffusion routine
    - E) General generators and rezoners
    - F) Operator splitting

4) HELP (EULERIAN) (S^3)
    - A. Multi-Material
    - B. Elastic-plastic strength model
    - C. Uses tracer particles for free surfaces and to Describe material interfaces.

5) HEMP (LAGRANGIAN) (LLL)
    - A) Elastic-plastic strength model
    - B) High-explosive burn routines
    - C) Sliding interfaces
    - D) Many existing Lagrangian codes are formulated from this general Lagrangian code HEMP
    - E) Flexible forms for the equation of state
    - F) Models for brittle and ductile fracture

G) Presently used to correlate computer simulations with a series of experiments.

6) TOODY (LAGRANGIAN) (SAND)
   - A) Plane or cylindrical geometry
   - B) Similar in many respects to HEMP
   - C) Slip lines
   - D) Porous modelling
   - E) Elastic-plastic strength formulation with fracture criteria
   - F) Several failure models (biaxial)

An overall reference to nonlinear continua is ref. (5), (6), and (7).

VI DEVELOPMENT PLAN

The results of the study program up to this date, indicate that a logical approach to the three-dimensional Hydrodynamic problem will be to couple existing hydrodynamic (coupled with elastic-plastic strength models) codes.

We have concluded, from our analysis of existing reports, that the numerical techniques for coupling of codes are now available, however, the material properties (in particular - accurate models for failures such as fracturing and spallation) are not readily available.

A joint theoretical, experimental program to evaluate material failure should be initiated. In addition, discussions between experimentalists and numerical (code) personnel concerning what experimental data is required for the numerical codes should be initiated.

Calculations (three-dimensional and simulated two-dimensional) should be undertaken to reproduce experimental results of oblique and normal impacts into flat plates presently being performed by Naval Research Laboratory.

In addition, the analysis of existing impact calculations (CRT's normal (R - Z) impact, Sandia's oblique (X - Y plane strain) impacts) may prove to be extremely useful. The credibility of using two-dimensional modelling for the real three-dimensional world needs investigation.

A survey of scaling laws, late - stage equivalence for impacts will be extremely useful.

In Section A, preliminary ideas and sketches for a coupling calculation are indicated. By coupling, we mean that one technique is run to a certain time t, and then information (function of space and time) from the first calculation is input into the second calculation.

True coupling (where one code, feeling the effects of the other code, - in turn - feeding effects back to the other) may be extremely time consuming because of the iterative process of maintaining continuity across the common boundary.

Section B contains table (3) describing the specific tasks required, estimates of computer time and man-hours and cost estimate for each task.

Section C is an attempt to schedule the tasks assuming a one year program.

SECTION A

PHASE (1)

The early time interaction - extremely high pressures - highly non-linear - large deformations.

Best candidate - 3D multi-material eulerian Hydrodynamic - coupled with strength of material code.

Calculate to times where the stresses have attenuated down to 1-5 Kilobars, or until projectile break through the back surface - and follow the eroded projectile up to the front surface of the second target. Place orthogonal arrays of massless tracer particles in the first target, and edit positions, velocities and pressures as a function of time.

PHASE (2)

Couple the results of Phase (1) - pressure and velocities at positions where the deformations are small (select from the array of massless tracer particles) into a three-dimensional Lagrangian finite difference or a three-dimensional Lagrangian finite element code.

Best candidate - 3D finite element - Lagrangian.

Calculate to completion - assuming no coupling with the second target. Before starting the large calculation, we should back up in time for the results of Phase (1) and check to see if we can duplicate a portion of the Eulerian calculation.

PHASE (3)

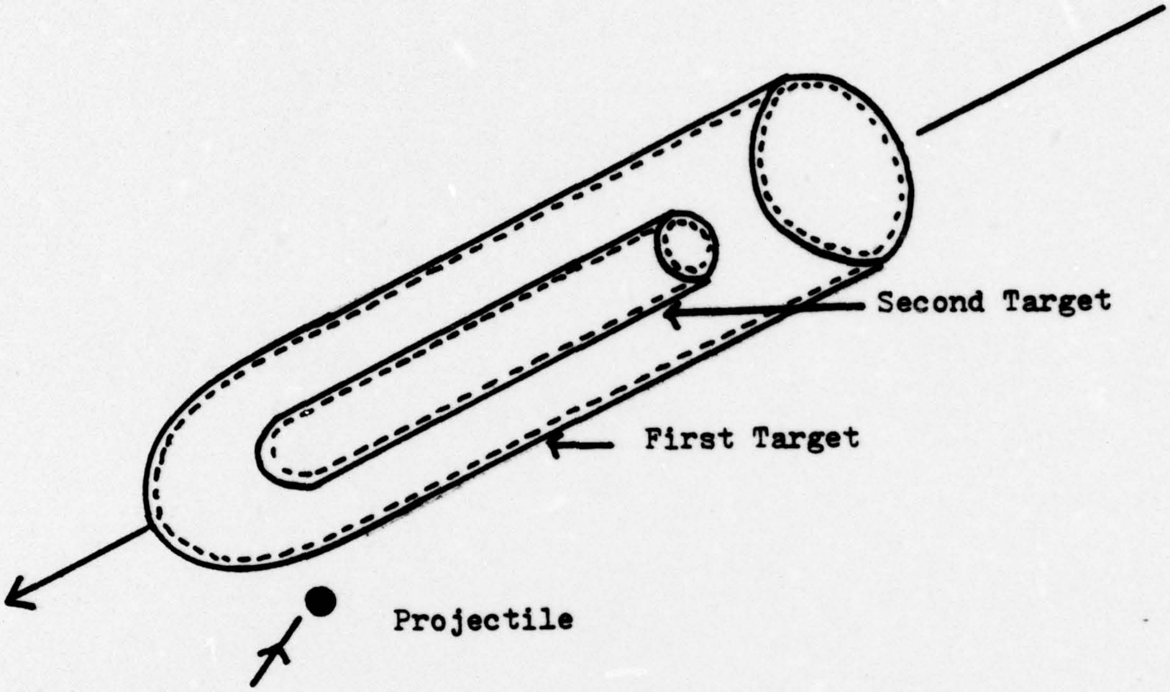
Select the results of Phase (1), with the addition of a certain portion of the second target in our grid - and perphaps taking out - or rezoning a portion of the first target. Best candidate - same as code used in Phase (1).

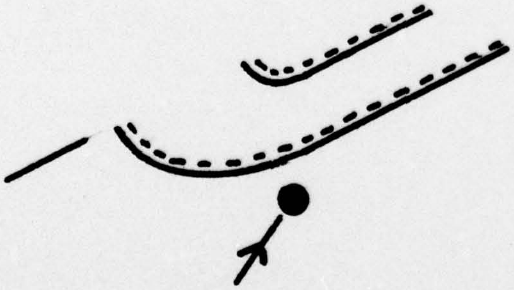
Again - run to late times - with the conversion of the kinetic energy of the debris and eroded projectile to internal energy and high stresses in the second target. Again - place arrays of massless tracer particles (following the curvature of the second target) in the calculation and edit the positions, pressures and velocities as a function of time.

PHASE (4)

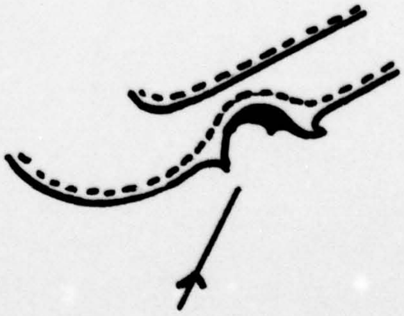
Similar to Phase (2). Select positions, where the deformations are small (arrive at this by looking at the tracer particle deformations) and apply the pressures and velocities from Phase (3).

Again - this approach implies that the outer structure (first target) is completely un-coupled from the second target.

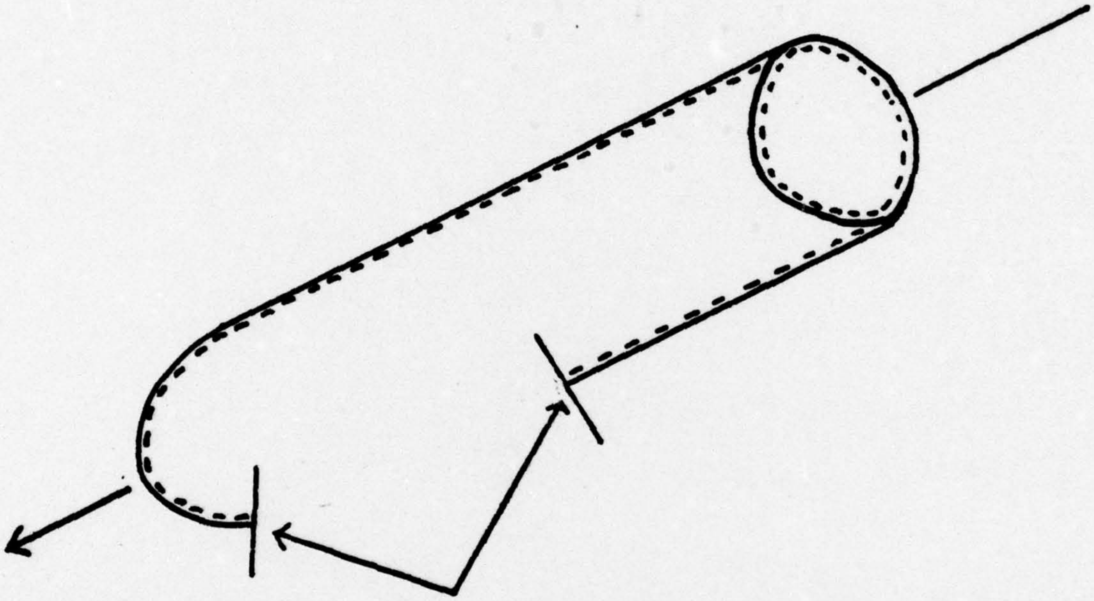




Phase 1 (t=o)



Phase 1 (t=t_1)

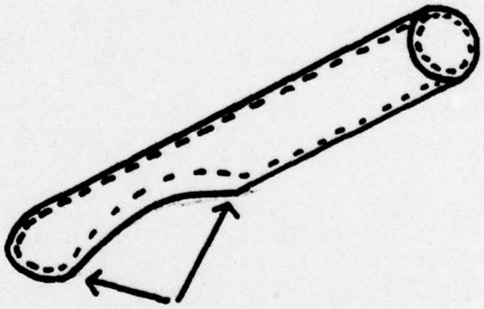


Pressure and the three velocity components applied
here as a function of time and space (Phase 1 results)

Phase 2

A continuation of the results of Phase 1

Phase 3



Pressure and the three velocity components applied here as a function of time and space (Phase 3 results)

Phase 4

SECTION B

TABLE (3)

TASK	Man years	Computer time*	Approximate total cost
1. Couple the Three-dimensional codes as described in Section A	.5	1.5 hrs.	35K PERSONNEL 1K COMPUTER
2. Couple the Three-dimensional codes in a dynamic fashion	1.0	3 hrs.	70K PERSONNEL 2K COMPUTER
3. Material properties	.04/ material	**.2 hrs. /material	2.8K PERSONNEL .13K COMPUTER***
4. Failure models - will also involve literature survey	.5	5 hrs.	35K PERSONNEL 3K COMPUTER
5. Calculations to reproduce flat plate normal and oblique impact experiments by Naval Research Laboratory	.5	20 hrs.	35K PERSONNEL 12K COMPUTER

* equivalent CDC 7600 time

** (provided Hugoniot data is available)

*** for each material

SECTION C (Scheduling)

It is anticipated that task number (5) should be initiated immediately. If any modifications are required in the numerical techniques as a result of the comparison with the NRL experiments, they can be incorporated into the couple codes.

The material modelling and the calculation of material properties should start immediately. Investigations to determine the type of coupling required should be undertaken immediately.

An approximate time schedule of one year would involve $\sim$ 1.5 to 2. man-year effort with $\sim$ 30 hours of CDC 7600 time.

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5) Lawrence Livermore Laboratory (LLL)
6) Lockheed Aircraft, Huntsville
7) Los Alamos Scientific Laboratory (LASL)
8) Honeywell Incorporated
9) Systems, Science and Software (S^3)
10) Sandia Laboratories

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