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THREE-DIMENSIONAL HYDRODYNAMIC CODE STUDY
FINAL REPORT

Wallace E. Johnson

PREPARED FOR
THE BALLISTIC MISSILE DEFENSE ADVANCED TECHNOLOGY CENTER

February 20, 1980

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

A study of zone changes (thickness) indicated very small changes in peak pressure. A 2D calculation was performed for a coupling experiment. Quadrilateral zones rather than rectangular zones are required to accurately model curved surfaces. If the total impulse is the important factor to be calculated for structures, existing numerical codes and computers may be adequate to give trends, rather than absolute values.

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I SUMMARY AND CONCLUSIONS

The Ballistic Missile Defense (BMD) non-nuclear kill problem contains impact conditions involving relative velocities ranging from 40,000fps to less than 10,000 fps, many possible impact angles depending on end game geometrics and possible multiple impacts. These engagements 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.

No single numerical code exists with the capability of analyzing the complete hypervelocity impact, the penetration process and late time effects of material failure unique to BMD engagements.

This study concludes that a reasonable approach to the analytical problem may be resolved by coupling (output from one numerical technique becomes the input to another numerical technique) existing numerical techniques.

Three-dimensional Eulerian hydrodynamic codes (coupled with strength of materials) are available for the early times where extremely high pressures, non-linearities, and large deformations exist. Their shortcomings are at times where the stresses are small and where the details of material interfaces are important. On the other end of the deformation spectrum, three-dimensional finite element codes capable of including non-linear effects, detailed material interface information, and small deformation with reasonable failure models are also available.

To couple techniques such as these in a dynamic model, is a lengthy (if at all possible) task, that would require computers of the size not yet available and enormous computer times.

The possibility of coupling(static) these techniques throughout phases of the time history of the impact processes, seem reasonable and achievable in a short period of time. Some thoughts on coupling are presented in Section IV.

A re-run (Section II) of the NRL 45° oblique impact (ref 1) has been completed out to a time of $\sim$ 11.0 μ sec. where we studied the effect of zoning. Zoning apparently had little effect in changing the peak pressure for gauge number (1), the closest gauge to the front surface of the target. The area under the curve of pressure versus time appeared to remain constant.

A two-dimensional calculation of NRL #5 was performed with the SOIL code for the purpose of using output from the SOIL code as input to a structure code. This calculation and results are reported in Section III.

Some thoughts of adding techniques that may add to the accuracy of 2 and 3D calculations and allow larger grids are presented in Section V.

Some ideas as how to begin calculations in 2 and 3 dimensions and accuracy or credibility of results are presented in Section VI.

II RE-RUN OF 45° NRL TEST PROBLEM

A TRIDORF calculation of the 45° oblique NRL experiment was reported in ref (1).

To summarize briefly, the peak pressure in the gauge nearest to the front surface of the aluminum block (target) indicated ~ 52 kilobars from the experiment and ~ 32 kilobars from the code run.

We felt that there was some uncertainty in the calculation due to the coarse zones used in the 3-dimensional calculation. Due to this uncertainty and also the need for early time data for a coupling experiment, we decided to re-run the calculation with finer zoning.

Actually 3 calculations will be reported. The first one is the original calculation, the second one is where finer zoning was placed between the OTWR plate and the aluminum block and for the third calculation, we used the zoning of the second but zoned the aluminum block finer.

Figure 1 indicates the zoning in the original and re-run problems. Figure 2 shows early time comparisons.

The pressure versus time for the 3 calculations for gauge number (1) are displayed in Figure 3.

As indicated, the finer zoning between the OTWR plate and target resulted in a slight increase in peak pressure for gauge no. (1). Using the same zoning between the OTWR plate and target, but using finer zoning in the target, resulted in an additional slight increase in peak pressure for gauge no.(1).

We believe that any additional fine zoning will not result in a further increase in peak pressure in gauge number (1). These last 2 problems were only run to a time of $\sim$ 11. μ sec., due to the limitations of core size available for the ARC computer.

A zone sensitivity of the original projectile and OTWR plate was not initiated. Even though the computer run gives $\sim$ the correct degraded projectile velocity and projectile shape (Figures 2 and 3), the possible artificial diffusion of the projectile (due to zoning restrictions) just before impacting the aluminum target may be responsible for the code predicting the peak pressure for gauge number (1).

The peak pressures for gauge number (2) and (3) agree very well with experiment. Another possibility is that the experiment may have some difficulties for gauge number (1).

As indicated in Figure 3 the area under the curve ($\int$ Pdt) is fairly constant for all 3 calculations. Perhaps, for loading of inner structures, that the impulse (integral) is only important and that the magnitude of the pressure pulse is not all that important. Additional discussion of this idea is elaborated in Section VI.

The question we are addressing ourselves to whether a coarsely run 3D calculation can give reasonable and useful results to later time structural techniques.

We will continue these discussions in Section VI.

III TWO-DIMENSIONAL CALCULATION OF NRL #5 (CANDIDATE FOR COUPLING EXPERIMENT)

In Section II, we mentioned the possibility of using output from the re-run of the 3D calculation as input for a 3D finite element code. Due to the inability of acquiring 3D finite element codes and the personnel to assist in the coupling, we chose to run a 2D calculation and consider coupling these results with the EPIC family of codes (Gordon Johnson at Minneapolis Honeywell).

Figure 4 displays the experimental configuration as used in the code calculation (SOIL).

The degradation of the steel projectile passing through the heat shield material agrees very well with the experiment. The code - experimental comparison data is displayed in Figure 4. As can be seen, the calculated pressures are consistently lower (a factor of 2) than the experimental results.

This may be due to the coarse zoning used through-out the calculation. The possibility of having the wrong configuration (density and shape) due to zoning between the plate and target could also explain the differences observed.

Massless tracer particles were placed in an orthogonal grid through-out the target. The location of the tracer particles (the 2 coordinates), the pressure energy and velocities as a function of time, are available as input to a structure code.

Again, we address the question of whether impulse is sufficient or whether the magnitude of the pulse is required in order to give meaningful input data to a structure code. Again, discussion on the alternative (fine zones with an increase in computer time) is left for Section VI.

We will continue to use this 2D calculation to study the effects of zone size and material properties.

IV COUPLING IDEAS

We have chosen the two-dimensional world as a beginning for some coupling experiments. The results (Section III) from the SOIL (2Dcalculation) in the form of velocities as a function of time and 2 coordinates will be imposed as input to a finite element code. The objective will be to determine if the velocity and stress field, some distances into the target will duplicate the SOIL results given velocities as a function of time at a moving lagrangian set of points (close to the initial front surface of target). This coupling experiment is presently being worked on.

Other potential possibilities may be to apply stresses at this moving lagrangian boundary to correlate stresses and velocity fields some distance into the target.

We feel that the techniques developed for the 2D geometry will be applicable to the 3D world also.

Failure models, fracture and spall events are considerably easier to adopt to a Lagrangian or Finite element technique due to the ease of interface (free surface or material) treatment in techniques where the mass in a given zone is preserved. These models exist in rather primitive or simple formulation as of now.

V NEW CONCEPTS FOR 2D AND 3D TECHNIQUES

Most Eulerian techniques are adopted to rectangular zones rather than quadrilateral zones. As indicated in Figure 5, quadrilateral zoning of Shells in 2 dimensions or generalized zoning in 3 dimensions may be sufficiently more accurate and requiring fewer computational cells. A moderate effort has been initiated and will continue during this year. It is anticipated that one will use a well formulated Lagrangian code for the hydrodynamics and add an advection model with the appropriate geometric modifications for fluxing mass, momentum and energy across non-normal interfaces or planes.

Another approach enabling one to have a larger number of computational zones (actually, the limitation will be the computer time) to represent the problem of interest is the packaging concept. Figure 5 is a possible representation of the packaging concept (dividing a large problem into N smaller problems). These N problems would communicate across a common boundary, allowing the zoning to be different in each of the N sub-problems. This would allow one to have fine zoning only in the problem that requires it, rather than thru the entire N problems. A version of a 2D Eulerian (RADOIL) was successfully modified for the packaging concept. We would incorporate as many of those features that would be applicable into existing 2D and 3D Eulerian codes.

VI SOME IDEAS AS TO ACCURACY AND ZONING FOR 2D AND 3D PROBLEMS

As indicated in Section II (3D RE-RUN) the varying of zone sizes did not effect the peak pressure for the gauge nearest the front surface of the target.

However, in Section III (the 2D calculation), the peak pressures as calculated were consistently lower by a factor of 2 when compared to the experimental results. However, the velocity degredation and hole size in the target correlated very well with experimental results. Again, we postulated that finer zoning might bring the comparison into much better agreement. One question that we might ask is would this change the impulse delivered to the target.

Zoning, indeed is a crucial question. A-prior, do I know how to zone up a 2 or 3D problem such as to remove the possible uncertainties associated with a finely or coarsely zoned problem.

Perhaps a systematic approach to this question is possible.

1) Run, whenever possible, a one-dimensional calculation, approximating the pulse to find a consistent set of zone sizes that would produce the same pressure magnitude and pulse shape. For a one-dimensional slab geometry, the only attentuation of the pulse will result from the rarefaction from the bottom surface, however a sperical or cylindrical pulse with a shell of

approximate thickness in the 2 or 3 dimensional configuration would produce divergence such as to attentuate the pulse.

2) It has been our experience, that once the calculation (2 or 3D) has been completed, it requires an extensive period of time for the analysis of the results. It would be more practical, if one can eliminate some of the uncertainty in results due to zoning, before going ahead with the large full calculation.

3) Fine zoning may be required at spall surfaces, since spalling is a function of the peak stress, but for momentum delivered to a target, it may only require that the impulse be calculated properly.

4) Any discontinuity, free surface, material interface or shock front will require a minimum number of zones. For example, 3 zones are required to represent a shock in almost any numerical technique and approximately the same number of zones (mini-) mum) will be required to describe a shell or layer of a given material.

5) With these restrictions, it is very important to know whether the impulse is adequate or whether the pressure (shape of impulse) magnitude is necessary.

6) For a 2D calculation, requiring zoning that is a factor of 2 finer in both directions, transposes into a factor of 8 in additional computer time.

For a 3D calculation, this could result in a factor of 16 in computer time. It may be that one would calculate the same result with fewer zones, this information, at the beginning of the calculation, would be extremely useful.

7) The configuration, and the size of the computer, and time and funds available, may dictate the zoning.

An example of this approach has been reported in a three-dimensional calculation of the venting process for an - on axis explosion in the MX trench (ref 2). The comparison between the finely zoned 2D and the 3D zoned problem (using all available core of a CDC 7600) is remarkable. The one dimensional calculations would still give one some feelings to the credibility of the results. These results are shown in Figures 6,7 and 8.

8) An impact calculation (ref 3) of a cadmium plate backed up by a void and a iron plate gave excellent comparisons of pressure on the iron plate, hole size in cadmium plate with experimental results (Figures 9 and 10). The final calculation was completed only after a series of preliminary 2D calculations were completed investigating the pressure pulse in the first target, and the zoning required to adequately represent the debris cloud impacting the iron plate. The number of zones in each plate and the separation between plates were varied in addition to the material properties.

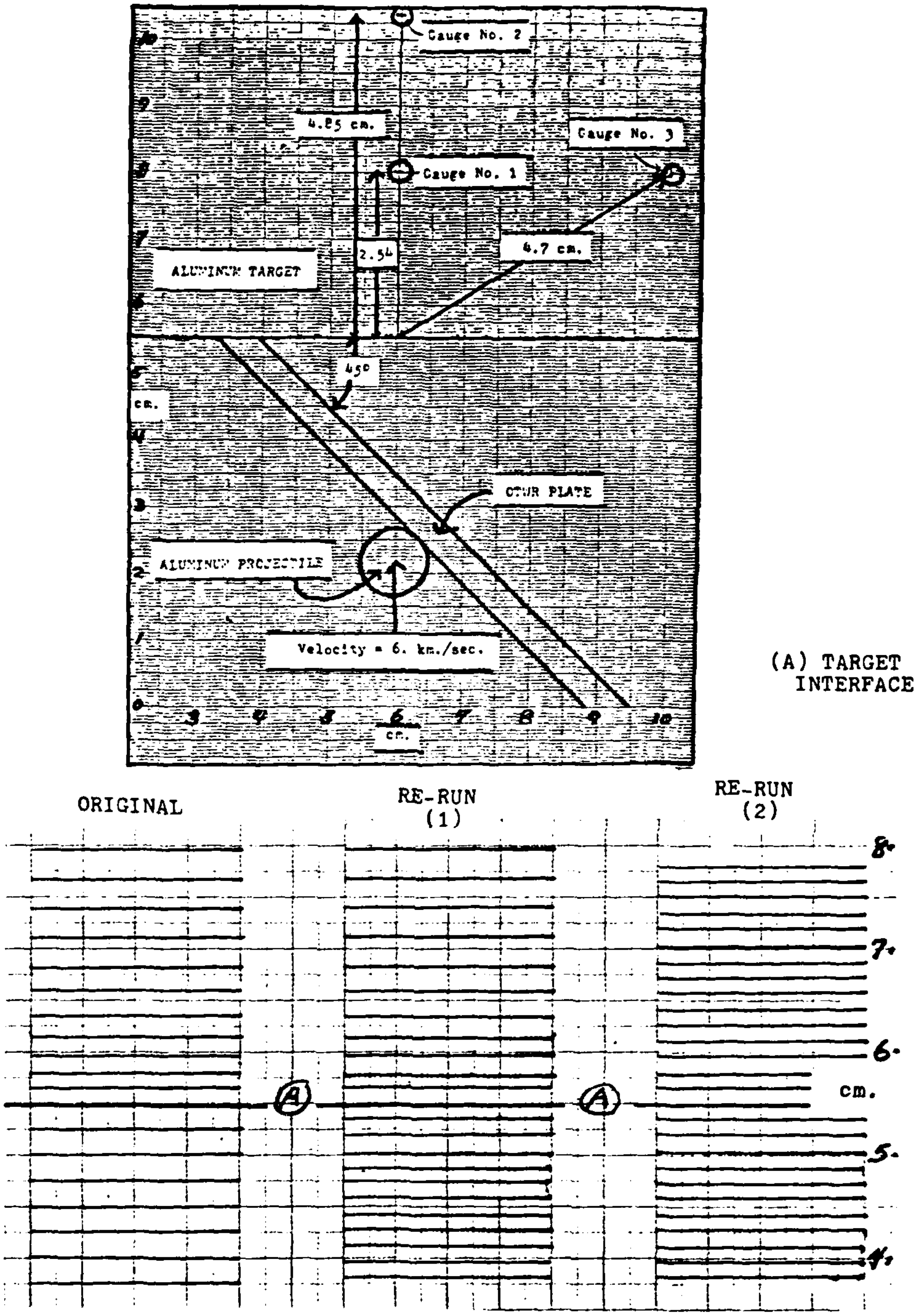
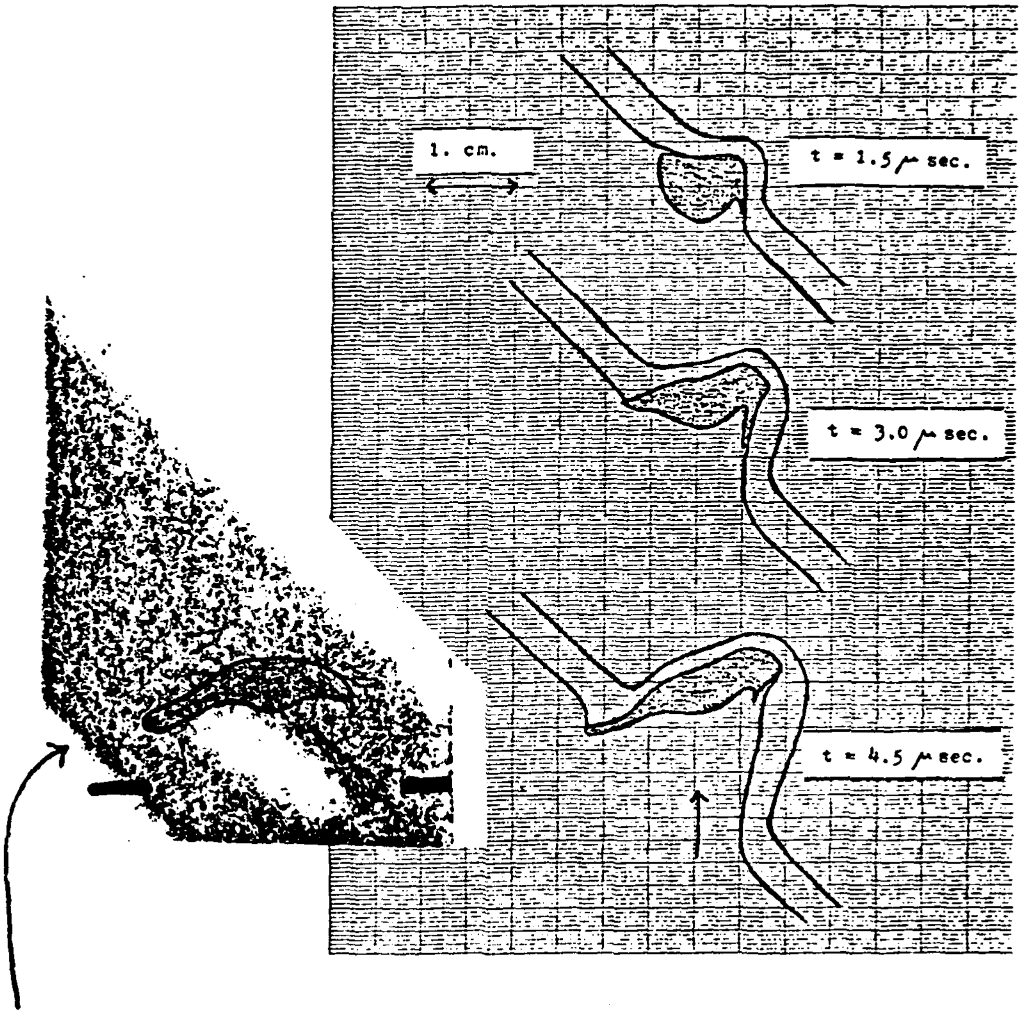


Figure 1
INITIAL CONFIGURATION and
ZONING (ΔZ) for the 3 CASES

NRL 45° OBLIQUE IMPACT



FLASH X-RAY AT T=4.5μ sec.

Figure 2
PROJECTILE CONFIGURATION as a FUNCTION of TIME
and an EXPERIMENTAL COMPARISON at t=4.5 sec.

NRL 45° OBLIQUE IMPACT

	Experiment	Code (theory)
Peak pressure at gauge (1) and arrival time	52 kilobars (t = 6. μsec.)	32 kilobars (t = 9.5 μsec.)
Peak pressure at gauge (2) and arrival time	12.7 kilobars (t = 10.5 μ sec.)	13. kilobars (t = 14 μ sec.)
Peak pressure at gauge (3) and arrival time	8.3 kilobars (t = 16.5 μ sec.)	9.0 kilobars (t = 12.5 μsec.)
Velocity of projectile before striking aluminum target	4.5 km./sec.	4.52 - 4.58 km./sec.
Hole size in OTWR target (t = 4.5 sec.)	2.34 cm.	2.2 cm.
Crater dimensions in aluminum target	.79 cm. depth 2.70 cm. min. diameter 3.41 cm. max. diameter	.7cm. depth 2.7 cm. min. diamter 3.6 cm. max. diameter

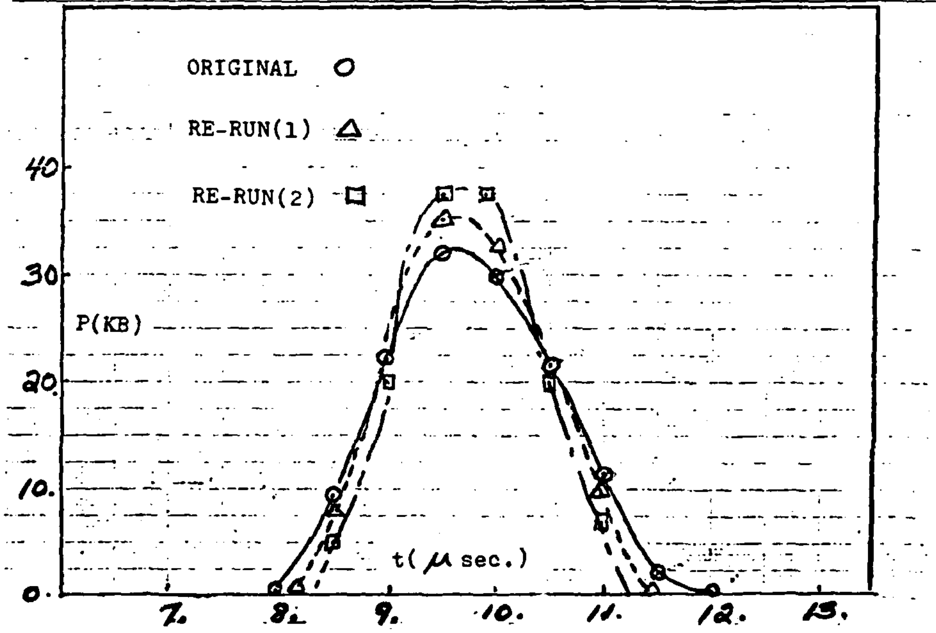


Figure 3
PRESSURE at GAUGE #1 as a
FUNCTION of TIME for 3 CASES

	EXP.	CODE
V/Vo PROJECTILE	.92	.90
HOLE SIZE DEPTH/DIAMETER	.554	.529
P (GAUGE1) KB	72	32
P (GAUGE2) KB	31.5	15.5
P (GAUGE3) KB	14.5	6.8

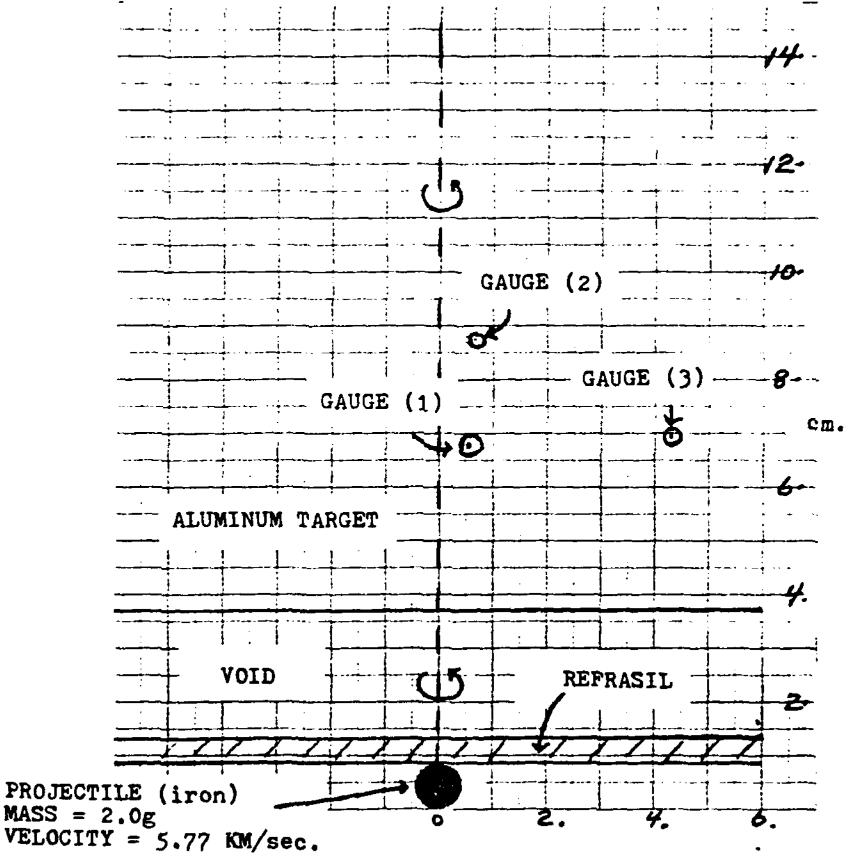
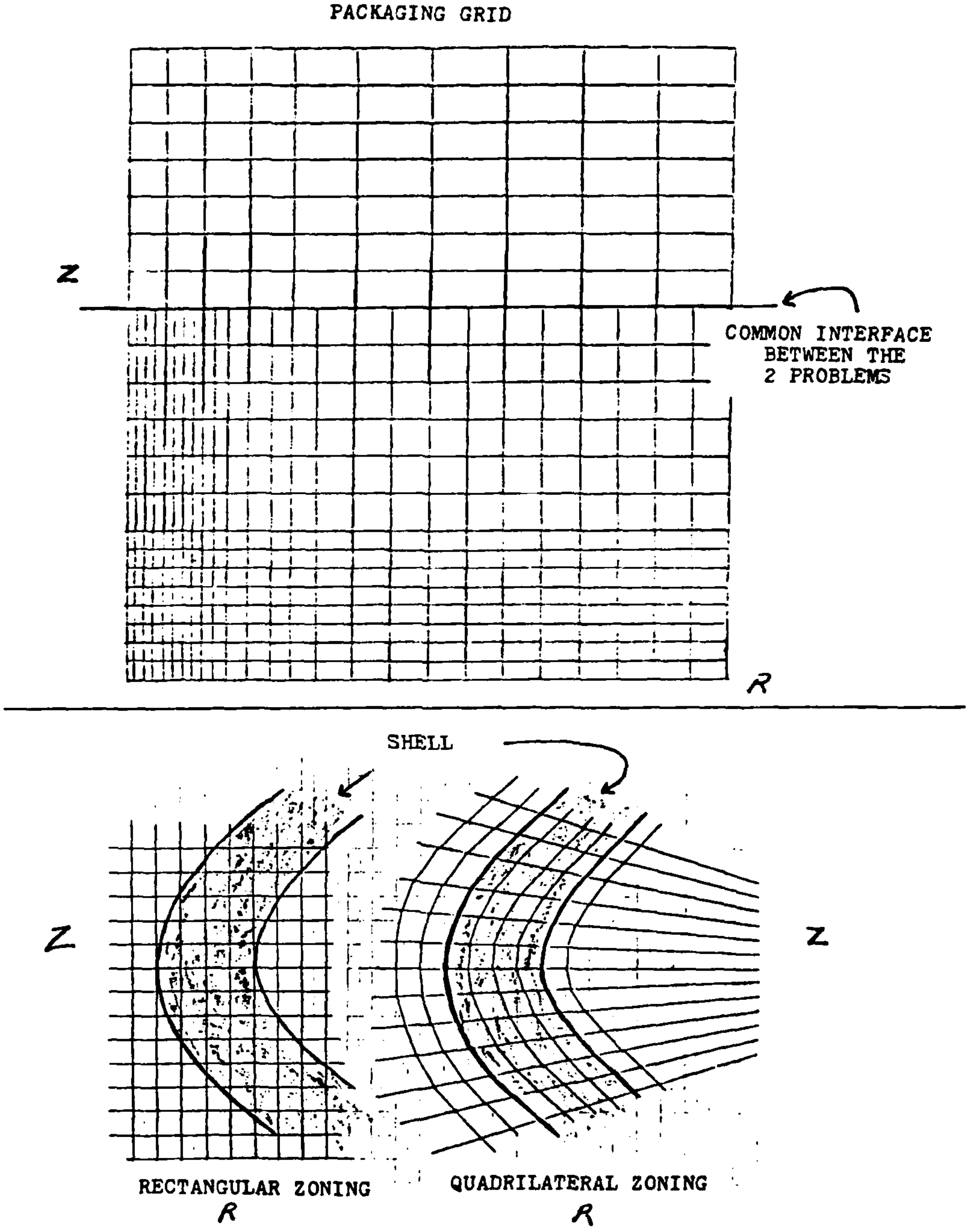


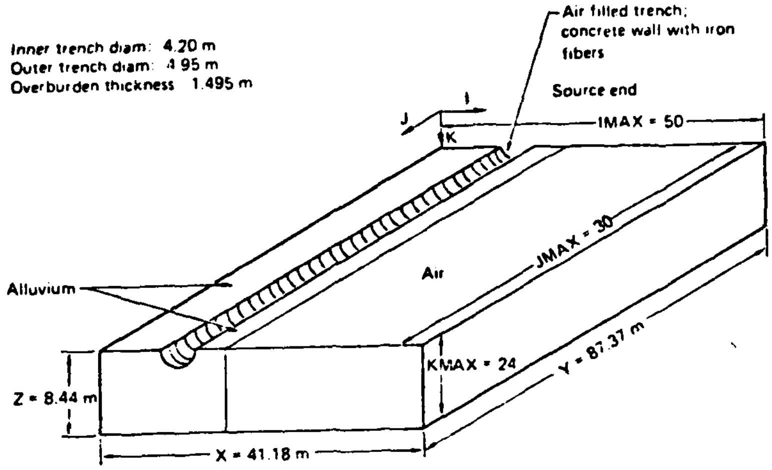
Figure 4
2D CALCULATION COMPARISONS WITH EXPERIMENT



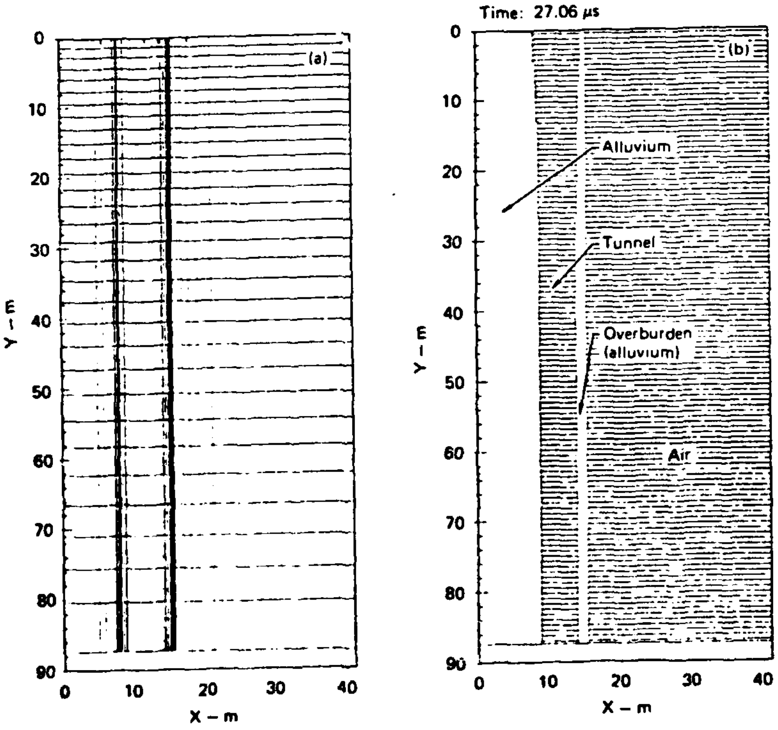
RECTANGULAR ZONING

QUADRILATERAL ZONING

Figure 5
A PACKAGED GRID, and the ZONING of a SHELL in a RECTANGULAR GRID VERSUS a QUADRILATERAL GRID

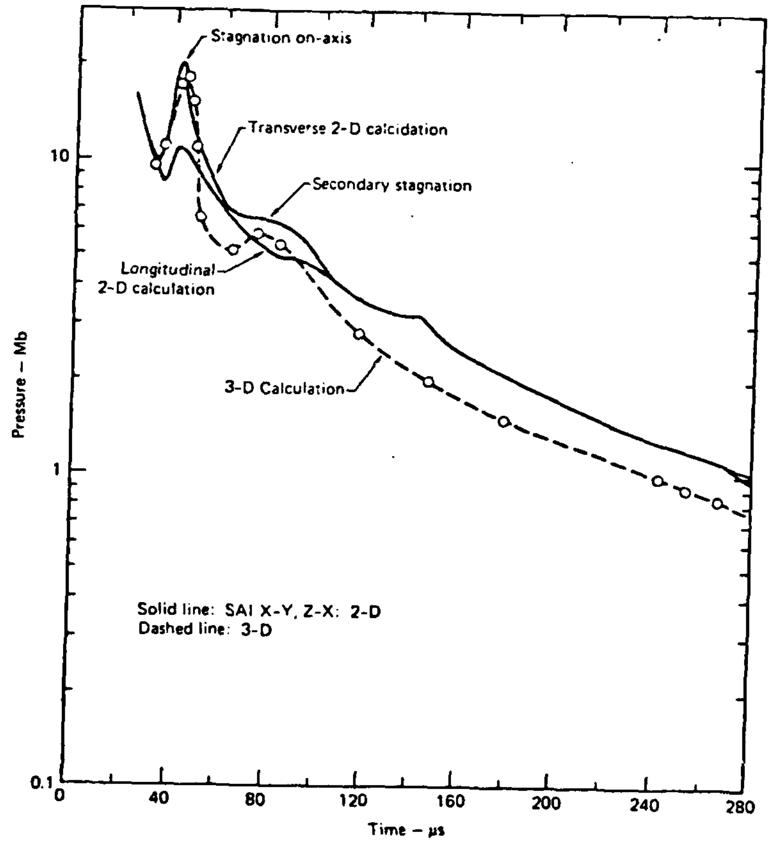


MX CONFIGURATION AT
3-DIMENSIONAL LINK TIME (27 μ sec.)



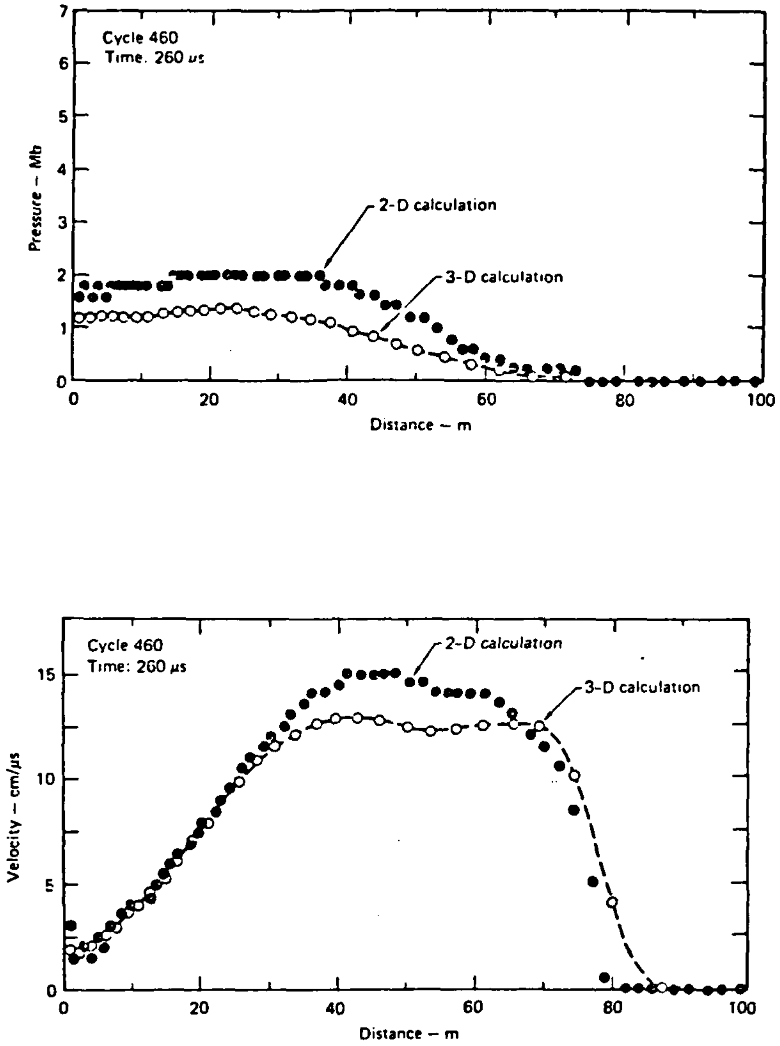
SYMMETRY PLANE: (a) X-X zoning
(b) material map

Figure 6
ZONING of 3D MX - TRENCH



PEAK PRESSURE ON TUNNEL AXIS AS A FUNCTION OF TIME COMPARING RESULTS OF 3-DIMENSIONAL CALCULATIONS WITH THOSE OF TRANSVERSE AND LONGITUDINAL TWO-DIMENSIONAL CALCULATIONS

Figure 7
3D and 2D CALCULATIONS of PEAK PRESSURE ALONG TUNNEL AXIS



COMPARISON OF 3-DIMENSIONAL
AND LONGITUDINAL 2-DIMENSIONAL
CALCULATION

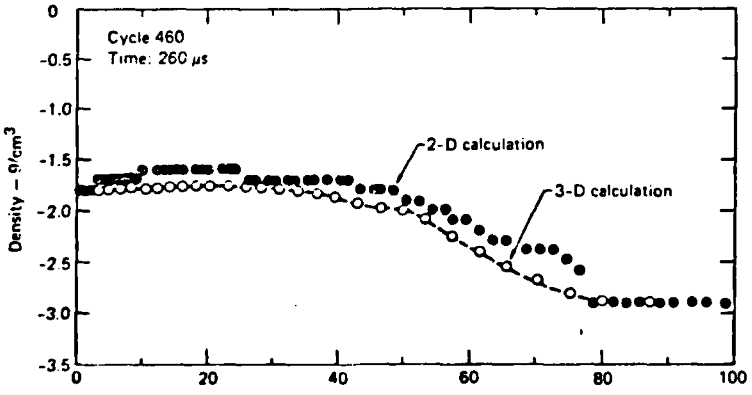


Figure 8
2D and 3D COMPARISON of PRESSURE, VELOCITY
and DENSITY ALONG CENTER LINE

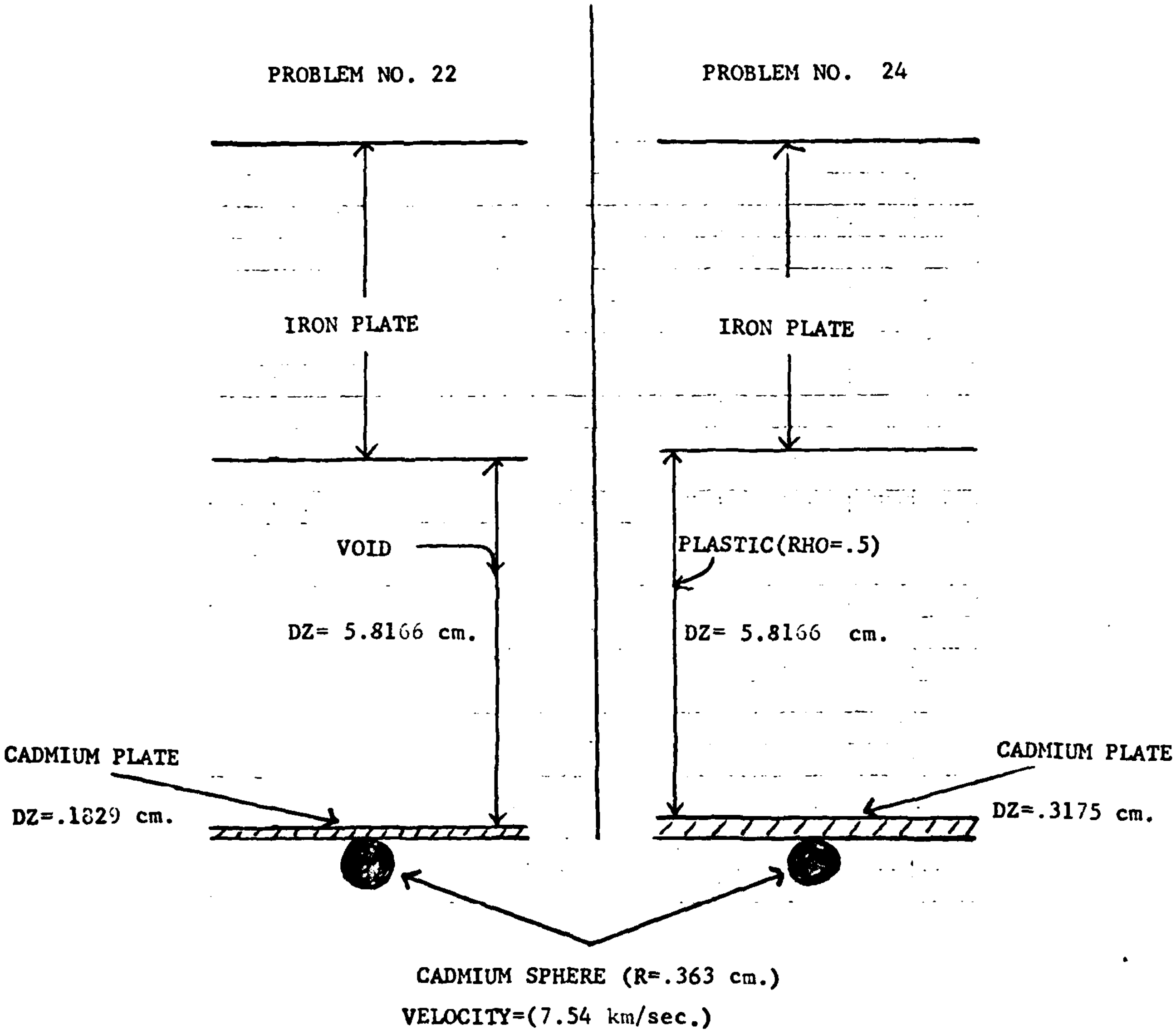
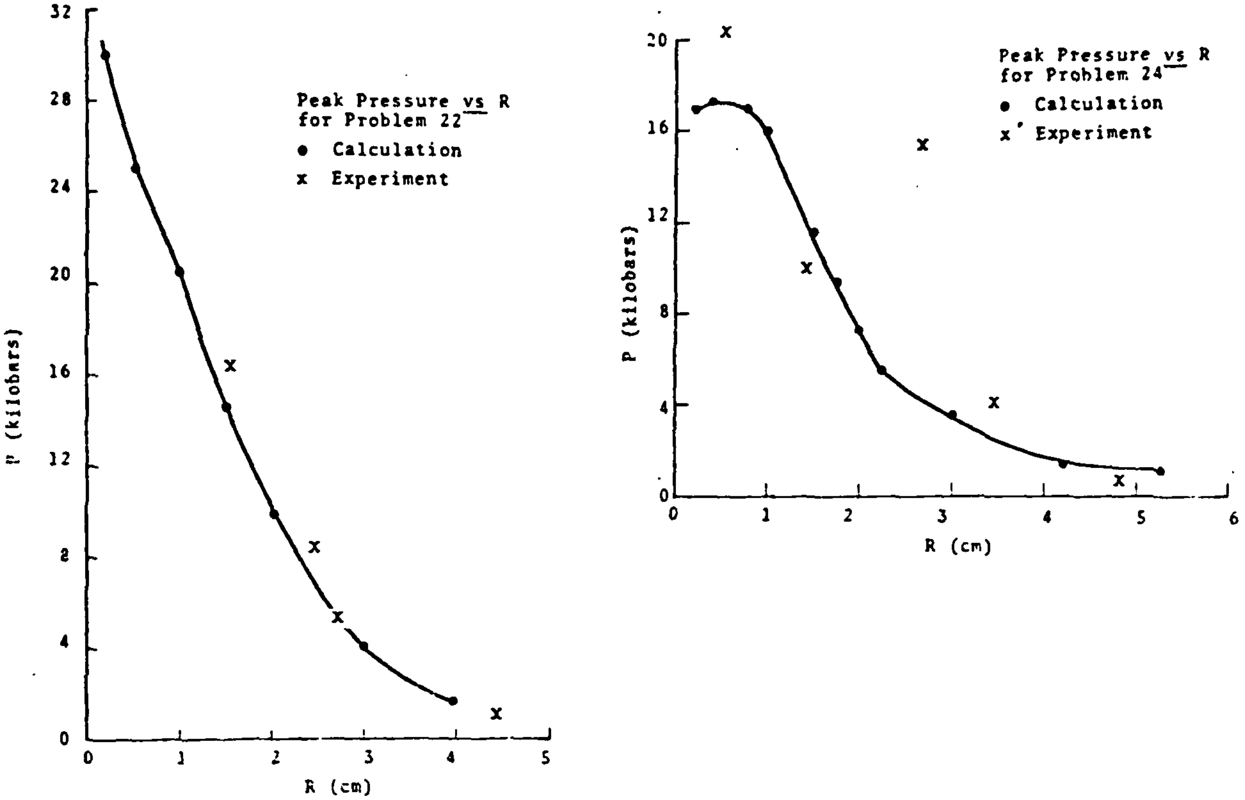
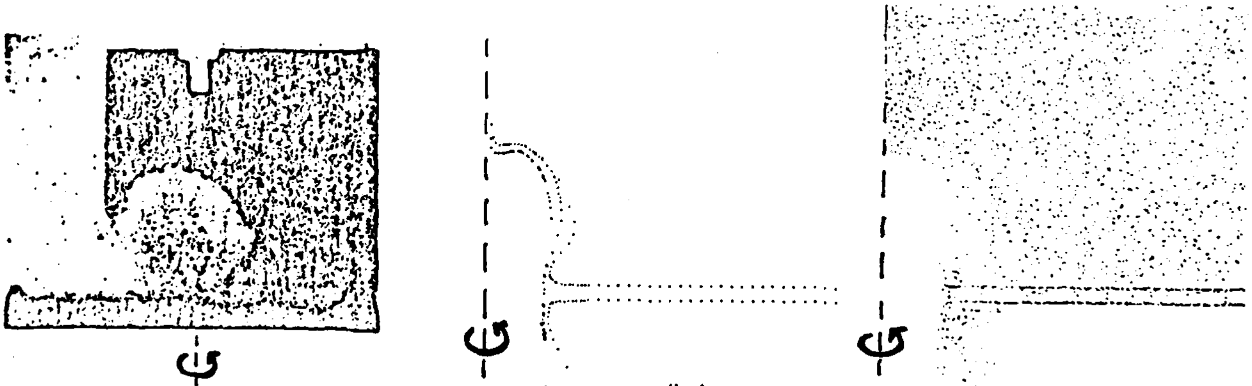


Figure 9
CODE CONFIGURATIONS for the 2 CALCULATIONS



A COMPARISON BETWEEN CODE
AND EXPERIMENT FOR PRESSURES AND
MASS DISTRIBUTION FOR PROBLEMS
22 AND 24.



FLASH X-RAY

PARTICLE PLOT (interface)

DENSITY PLOT

PROBLEM #24

Figure 10

PRESSURE COMPARISON with EXPERIMENT for the 2 CALCULATIONS:
MATERIAL CONFIGURATION COMPARISON with EXPERIMENT for #24

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