LA-UR 92-23

1--2

LA-UR--92-23

DE92 007426

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

TITLE: THE ORIGINS OF LINER MATERIAL
IN A SHAPED CHARGE JET PARTICLE

AUTHOR(S) Louis ZERNOW, Zernow Technical Services, Inc.
E. J. CHAPYAK, X-3, Los Alamos National Laboratory
K. A. MEYER, X-3, retired

Richard ZERNOW, Applied Research Associates, Inc.

SUBMITTED TO The 13th International Symposium on Ballistics
to be Held in Stockholm, SWEDEN, May 30-June 3, 1992

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

THE ORIGINS OF LINER MATERIAL IN A SHAPED CHARGE JET PARTICLE

Dr. Louis Zernow (1,*), Dr. Edward J. Chapyak (2),
Dr. Ken Meyer (3), Richard H. Zernow (4)

(1) Zernow Technical Services Inc., San Dimas, California, U.S.A.,
(2) Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.
(3) Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.
(4) Applied Research Associates, Inc., Lakewood, Colorado, U.S.A.

An improved high resolution LaGrangean tracer particle technique (using 198 identified tracer particles arranged as 99 particle pairs) has been used with an Eulerian Code (MESA 2D) to determine the locations in the jet to which liner material flows from various tagged locations in the liner, during the collapse, jet formation and jet stretching process. Time dependent strain and strain rate data has been computed, using the identified particle pairs of LaGrangean tracer particles as linear strain gauges. Sharp radial gradients of strain and strain rate have been found in the jet, with the liner material flowing nearest the jet axis being subjected to the highest strains and strain rates. Liner material from many extended initial locations along the liner can be traced by this method to jet locations corresponding to individual jet particles. The new quantitative data derived is illustrated with selected examples whose interpretation is discussed.

INTRODUCTION

Prior work by Zernow (Ref. 1,2,3,4) involving optical, XRD and SEM examination of copper shaped charge jet particles, "softly recovered" by slow deceleration in low density recovery media, has indicated the possibility that previously unidentified and unquantified variations in radial strain gradients and radial strain rate gradients in the jet, may provide inputs to possible explanations for the radially concentric but cyclically inhomogeneous grain structures observed in these recovered jet particles, as shown in Fig. 1. These puzzling observations provided the motivation, in this present computational study, which applied a high resolution LaGrangean tracer particle technique, utilizing an Eulerian Code (MESA 2D). This method was previously applied at Los Alamos National Laboratory, in a simpler form, by Chapyak (Ref. 5).

In this paper we will describe the use of advanced versions of the tracer particle technique to analyse computationally, the flow of liner material into a shaped charge jet, as specific portions of the liner move from their original locations in the liner, through and past the stagnation zone, partitioning the liner mass into the jet and slug respectively. We will therefore be defining the origins of the liner material that end up as parts of specific regions in the jet and slug. In the course of this analysis, we have the opportunity to examine a number of fundamental dynamic aspects of the jet formation and elongation process, extracting quantitative information about time-dependent strains and strain rates, and their axial and radial gradients.

The picture that emerges from this analysis, indicates that the physics and dynamics of the liner collapse process and the jet and slug formation processes, are much more complex than was commonly believed, on the basis of earlier hydrodynamic models.

The initial shaped charge collapse and jet formation computations described here, were carried out at Los Alamos National Laboratory, using the MESA 2D code and a simple elastic, perfectly plastic material model for copper. The question of how variations in the material model would affect these results has not yet been addressed.

HISTORICAL BACKGROUND

When a conical copper shaped charge liner is collapsed by the very high pressure from a detonating explosive charge, the liner material, with yield strength far below the detonation pressure, first flows hydrodynamically into a convergent high pressure stagnation region around the liner's axis of symmetry. There is an initial unsteady collapse of the apex of the liner, after which the collapse process is stabilized to a quasi-steady state, with a nearly constant collapse angle β (Fig. 2a) during the early collapse process. At this early stage, the moving center of the stagnation zone attains a nearly constant velocity relative to the ground. To an observer stationed at the origin of the coordinate system fixed at the center of the stagnation zone, the incoming flow is seen to separate into two streams moving in opposite directions, designated as the "jet" and the "slug" respectively. In the original simple, steady state hydrodynamic plane strain wedge model of this flow (Ref. 6), the liner mass partition into the jet and the slug, is quantitatively defined in accordance with the requirements for conservation of linear momentum and the assumption that there is simple streamline flow into and out of the high pressure stagnation zone (sometimes called the collision region). Hence, the respective particle velocities and the outgoing mass per unit length of the jet and the slug are thereby defined. This original wedge model, while informative about some key aspects of the jet formation process, predicts a constant velocity jet of constant length, in contrast with the experimentally observed axially symmetric cone collapse process, which yields a stretching jet with an approximately linear velocity gradient along its length. In recognition of this discrepancy, this original paper included an ad hoc approach to a collapsing cone model. The hydrodynamic collapsing cone model was subsequently modified (Ref. 7a,b) to permit the natural introduction of an axial velocity gradient into the jet, by virtue of a non-steady state collapse process. In this process, there is a continuously changing collapse angle β (Fig. 2b) especially in the later stages of the collapse. The changing β arises as the mass per unit height of the cone is increasing and the corresponding mass per unit length of explosive is decreasing, while the detonation proceeds toward the base of the cone, e.g. in a cylindrical warhead of finite diameter.

The postulated process of convergent streamline flow into the stagnation zone and separation of the flow into the jet and slug, defines (e.g. for a uniform walled liner) an inner region of the cone which separates into the jet and an outer region of the cone which ends up in the slug. For the simple steady state wedge collapse with a constant collapse angle β, there is an interior surface defining this separation boundary for material partition, which is a plane wedge surface parallel to the inside and outside surfaces of the original wedge. By analogy, the corresponding separation surface defining the mass partitioning for a hypothetical steady state collapsing conical liner, would be an approximately conical surface of revolution on the interior of the liner, which partitions the cone mass appropriately. For a non-steady state collapse with a changing (increasing) collapse angle β, the defining separation surface would now be a non-linear surface of revolution. Thus, for the late stages of collapse, as β increases, a greater fraction of the cone mass enters the jet and a smaller fraction enters the slug.

These earlier hydrodynamic models of the collapse process involving streamline flow, have tended to lead one to expect that relatively specific, small well defined regions on the interior of the conical liner could be associated with specific localized relatively well defined sections of the jet as shown in Fig.2c. The present study indicates quantitatively that this expectation is clearly not valid in terms of either the axial or radial locations within the liner, although there is still a defining separation surface marking the partition of liner material into the jet and slug.

The problem of identifying the locations in the shaped charge liner, from which specific portions of a jet originate, is a problem of general interest in understanding the physics of jet formation as well as of specific interest in connection with the interpretation of the structures observed in individual "softly recovered" shaped charge jet particles (Ref. 4).

Over the years, a variety of techniques have been used to try to shed light on various aspects of that question of origin. These included radioactive tracer methods (Ref. 8) and mechanical methods (Ref.9,10) both of which have provided some illuminating insights, but have not provided sharply defined answers to the detailed question of origin.

In 1987, experimental and analytical work by Walters and Golaski (Ref.11) on stratified bimetallic liners, showed what they called a "tubular layered" liner collapse, which differed from the conventional simple minded hydrodynamic concept and indicated that for jet regions away from the jet tip, any given jet region could contain material from varying locations on the liner. While the visual interpretation of the smearing of the liner material between jet and slug was evident, detailed quantitative interpretation was limited in their analysis because of the thickness of the strata on the liner, and the absence of spatial resolution along the interfaces between strata.

In 1989, Brown & Nordell (Ref. 12) discussed a computational technique using tracer particles, which again confirmed the "smearing" of the liner material between the jet and the slug, as shown earlier by Walters and Golaski (Ref. 11) and also discussed the mixing of material from various portions of the liner in the jet. The visual interpretation of the process, based on the graphic material provided in the paper, was again not straight forward and not quantified.

The original high resolution LaGrangean tracer particle technique used by Chapyak (Ref. 5)   deployed 99 tracer ✓
particles through the thickness direction of the liner at three widely separated locations along the liner height. There are 5 separate improvements in this technique introduced in the present program. These improvements include deploying 99 close pairs of tracer points at known short separation distances (e.g. 1mm and 3mm separations) at various locations along the liner height (Fig. 3a and 3b). Identifying the individual particles with numbers and with symbols (o and +) provided further unequivocal identification of their specific locations at any

time as shown in Fig. 3d. These identifiers precisely define the particular line of particles from which they originated. These corresponding pairs of identifiable points therefore served as built-in internal linear strain gauges, whose separation distance variation with time, could provide time dependent linear strain data and time dependent linear strain rate data. Since it turned out that these tracer point pairs ended up at many different radial and axial locations in the jet, they could also provide a measure of the radial gradients in the pertinent dynamic quantities, when the results of the separate computational outputs from different origination locations were combined. Corresponding pairs of tracer points were also joined by lines, on the graphical output, to avoid ambiguity, which was easily introduced by difficulties in visual tracer particle pair matching.

In the final computations, each liner location for a pair of tracer lines (each line composed of 99 tracer points) required a separate computation because the MESA 2D code was not set up to handle more than 198 tracer points in any problem. This is a memory constraint and not an inherent limitation of MESA 2D.

In order to gain additional specific supplementary information about the dynamic processes occurring in the jet itself, after it has emerged from the stagnation zone, another extension of the technique applied the La-Grangean tracer method directly to the jet. This served as a supplement to the original tracer point analysis which used tracers originating in the liner. In this extension of the tracer technique, 8 pairs of tracer particles (1mm apart axially) were inserted, perpendicular to the jet axis, into the rear of the visible jet, starting from when the jet first emerged from the stagnation zone. These insertions of tracer pairs were repeated four times and carried out approximately every five microseconds, as the jet length grew. This permitted the tracer pair's time dependent locations and separations to be tracked after the jet emerged and stretched. It also provided direct access to radial gradients in velocity, strain and strain rate, at various radial and axial locations within the stretching jet.

OUTPUT FROM THE PRIMARY LINER COLLAPSE AND JET FORMATION COMPUTATIONS

The tabulated raw data was first downloaded from Los Alamos National Laboratory to Lakewood, Colorado where it was to be analysed. For each of the 198 identified tracer points originally located in the liner, the individual spatial coordinates R (radial) and Z (axial) were printed out, as a function of time, at one microsecond intervals. For a 198 tracer point computation, lasting 50 μsec, this meant 198 x 50 data pairs (R_i, Z_i) or 9,900 data pairs per computation. Since there were 9 separate computations of this type, some with 99 tracer points and others with 198 tracer points, there were of the order of 58,000 raw data pairs which were input to the processing of the data.

PROCESSING THE RAW DATA

It was clear that the sheer volume of data posed a major problem for the required data processing. At each microsecond time interval, the distance between corresponding pairs of tracer points had to be calculated for each of the 99 individually identified point pairs, in each of the computations, involving 198 tracer points.

The simple algorithm for the distance between two Cartesian coordinate points, was generalized to handle successive corresponding point pairs e.g. points 1-100, 2-101, ...99-198, with running indices. This computation was automated to provide the time dependent values of these interparticle distances, given the time dependent coordinates of all of the tracer points. The computed time dependent interparticle distances were then analysed to extract strain and strain rate as a function of time and location within the collapsing liner, the jet and the slug. The output of each of the 99 point pair distances was tabulated in successive blocks of 1 microsecond time steps, for each computation.

The outputs from this time dependent strain and strain rate analysis were plotted as functions of time, at microsecond intervals, for each pair of the 99 pairs of tracer points. This was done separately for each computation, i.e. for each new set of tracer origination points on the original liner.

The time dependent Cartesian coordinate locations of the 99 tracer points (R_i, Z_i) at a given time were also plotted separately, for each computation and finally combined for the various computations on a single composite plot of R vs. Z at each given time, over the duration of the computation, which was 50 usec for the VIPER.

SUMMARY OF RESULTS

In the time and space available for this paper, it would be impossible and not very useful to go through all the details of the massive data processing and data reduction. It was therefore considered best to extract the most useful summary data and some specific examples which define the new quantitative information which has been generated as a result of this analysis.

FINAL PROCESSED COMPUTATIONAL OUTPUTS

The power of the high resolution tracer technique is illustrated in Fig. 4 which is an output for one of the VIPER computations. This indicates how the tracer pairs, which originally started 1mm apart within the liner wall, move into the collision zone and partition themselves between the jet and the slug. Their distribution axially and radially, at any given time (30 usec in this case) clearly illustrates some of the changes that have occurred in strain and its radial variation, as a function of location within the jet.

Fig. 4 also illustrates the results of the original negative velocity gradient at the tip of the jet which accounts for the increased diameter of the front of the jet, which is now moving at a constant velocity, with no axial velocity gradient along its length. It also illustrates the very high strain that is undergone by particles which end up near the jet's geometric axis, particularly where the two tracer points in a pair move apart in opposite directions, with one going into the slug and the other one going into the jet. This figure also qualitatively illustrates the radial strain and strain rate gradients, with the strain and strain rate both increasing dramatically as the particle pair approaches the axis of the jet. Quantitative data is shown in Fig. 5a, b, c and d.

TIME DEPENDENT AND RADIAL VARIATIONS IN STRAIN AND STRAIN RATE

The computed strain and strain rate history as a function of time, for selected tracer points in this same VIPER computation, is shown in Fig. 5a and b. In order to illustrate the extremely high radial gradients in strain and strain rate within the jet itself, these calculated parameters were also plotted in Fig. 5c and d as a function of the initial location of the tracer point pairs in the liner. For 99 point pairs, adjacent point pairs represent initial tracer pair separation distances in the thickness direction of the liner, of the order of 30 μmeters in the VIPER liner. The quantitative data obtained in this analysis indicates that order of magnitude changes can occur in the strain and strain rate over radial distances in the jet, as short as 60-120 μmeters.

COMPOSITE PLOT OF ALL COMPUTATIONS ON A GIVEN LINER

Fig. 6 illustrates a composite plot of the R_i, Z_i coordinates of all tracer particle pairs at a late time in the jet stretching process. In this particular case, the initial locations of the identified tracer particles cover the full range of liner positions shown in the inset. Clearly, a jet particle coming from the region between Z= -.3 and Z= -1.6 would contain material coming from all four of the initial locations on the liner. This material would be distributed at various radial locations within the jet particle.

DATA OBTAINED FROM THE JET INSERTION COMPUTATIONS

Fig. 7 illustrates the early data obtained from the insertion of two pairs of 8 tracer particles (separated by 1mm axially) into the jet at successive time intervals 5 microseconds apart. Clear evidence of radially varying coaxial shear and axial stretching can be seen for regions of the jet away from the front lead particle.

CONCLUSIONS

The improved high resolution LaGrangean tracer particle technique used in this study with an Eulerian Code (MESA 2D) provides a detailed estimate of time dependent linear strains, strain rates and strain and strain rate gradients in quantitative terms. The sharpness of the radial strain and strain rate gradients found in this study, indicates the inhomogeneity of the material processing going on in various radial portions of the jet. Clearly the region near the jet axis is subjected to the highest strains and strain rates. To the extent that strain and strain rate dependent processes play a role in determining the radial inhomogeneity in the grain structure of "softly recovered" shaped charge jet particles (see Fig. 1), the quantitative information provided by this study provides an initial basis for checking some of the theoretical models.

The quantitative information obtained about the initial large range of locations of the origins of the liner material that can become part of an individual jet particle, indicates one of the reasons why previous experimental studies (Ref. 8-10) could not find simple and clean correlations.

There are some interesting questions remaining that warrant further study. One of these is the effect of changes in the material model. Another concerns the possible extension of this method of analysis from linear tracer particle pairs to planar quadrilateral cells and ultimately to three dimensional parallelopiped cells. There are also some presently unanswered questions regarding the apparently anomalous behavior of some of the tracer particles and the clearly observed rotation of the axes of the tracer particle pairs.

ACKNOWLEDGMENT

The primary liner collapse computations which included the LaGrangean tracers were supported at the Los Alamos National Laboratory by the joint DoD/DOE Munitions Technology Development Program. The analysis and interpretation by Zernow Technical Services Inc. was supported jointly by the U.S.Navy (NSWC (WOL)), U.S.Army (BRL) and DARPA under Navy Contract N60921-89-C-0172.

The subsequent detailed data reduction of the raw data and the graphics for the time dependent arrays of LaGrangean tracer pairs was carried out by Richard H. Zernow of Applied Research Associates, Inc., on his own time and at no cost to the contract. Assistance from Peter Dzwilewski of Applied Research Associates, Inc., in expediting the downloading of the raw data from Los Alamos National Laboratory to Lakewood, Colorado, is gratefully acknowledged.

BIBLIOGRAPHY

1. L. Zernow, "Recovery of Shaped Charge Jet Samples for X-Ray Diffraction Studies", 10th International Symposium on Ballistics, San Diego, CA (1987).
2. L. Zernow, "Metallurgical, X-Ray Diffraction and SEM Studies of Individual Shaped Charge Jet Particles Captured by Soft Recovery-II", International Conference on Ballistics, Nanjing, PRC (1988).
3. L. Zernow, "New Results From the Examination of Jet Particles Captured by Soft Recovery", 11th International Symposium on Ballistics, Brussels, Belgium (1989).
4. L. Zernow, L. E. Lowry, "High Strain Rate Deformation of Copper in Shaped Charge Jets", International Conference on High Strain-Rate Phenomena in Materials (Explomet '90), San Diego, CA, Aug.1990.
5. E. J. Chapyak, Los Alamos National Laboratory, Private Communication, June 1990.
6. G. Birkhoff, D. P. MacDougall, E. M. Pugh and Sir G. Taylor, "Explosives with Lined Cavities", Journal of Applied Physics, Volume 19, June 1948, Page 563.
7. E. M. Pugh, R. J. Eichelberger and N. Rostoker, "Theory of Jet Formation by Charges with Lined Conical Cavities", Journal of Applied Physics, Volume 23, May 1952, Page 532.
8. G. M. Bryan, R. J. Eichelberger, D. MacDonald, F. E. Zigman, "Application of Radioactive Tracers to the Study of Shaped Charge Phenomena", Journal of Applied Physics, October 1957.
9. R. DiPersio, J. Simon, T. H. Martin, "A Possible Method of Identifying the Origin of Shaped Charge Jet Particles", BRL Technical Note 1571, July 1965.
10. E. Perez, C. Fauquignon, P. Chanteret, "Fundamental Studies of Shaped Charge Mechanisms", ISL, French-German Institute, St.Louis, 3rd International Symposium on Ballistics, Karlsruhe, Germany, March 1977.
11. W. F. Walters, S. K. Golaski, "Hemispherical and Conical Shaped Charge Liner Collapse and Jet Formation", BRL TR2781, February 1987.
12. R. E. Brown, A. Nordell, "Kinematics of Shaped Charge Liner Collapse and Jet Formation", 11th International Symposium on Ballistics, Brussels, Belgium, May 1989.

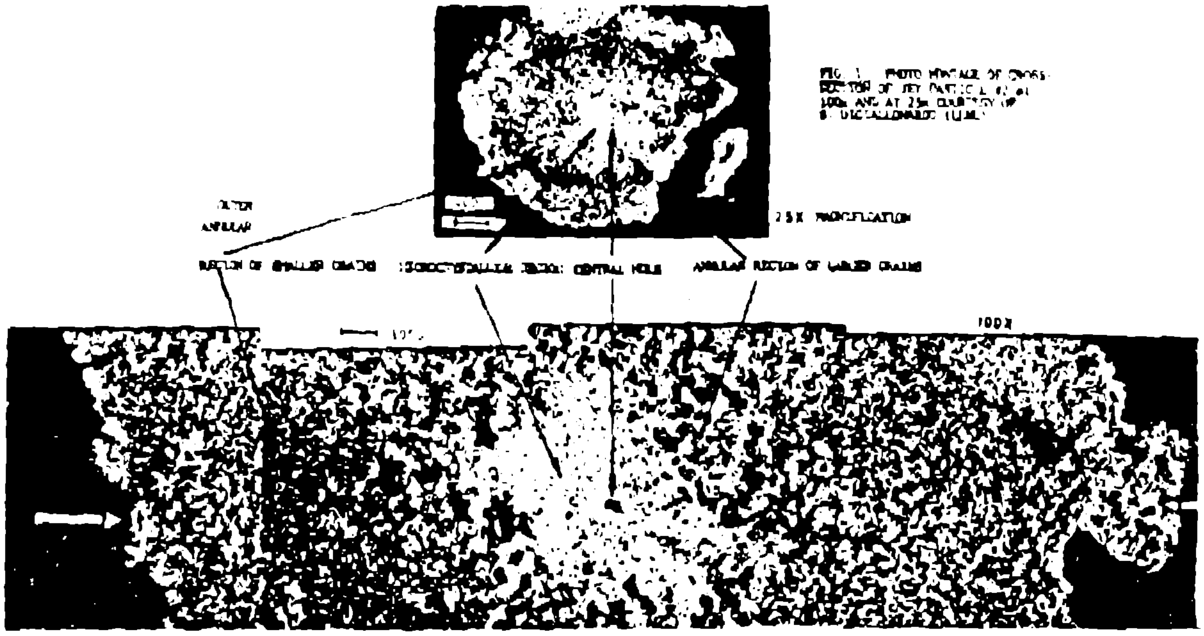


FIG. 1 TRANSVERSE SECTION OF RECOVERED JET PARTICLE SHOWING RADIAL CYCLICAL VARIATIONS IN ANNULAR GRAIN STRUCTURE.

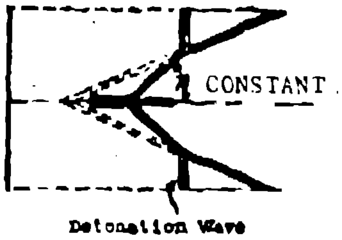


FIG. 2a STEADY STATE

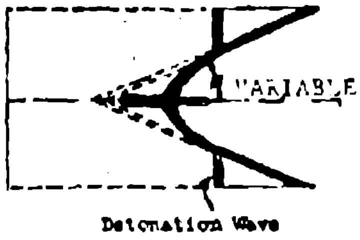


FIG. 2b VARIABLE β

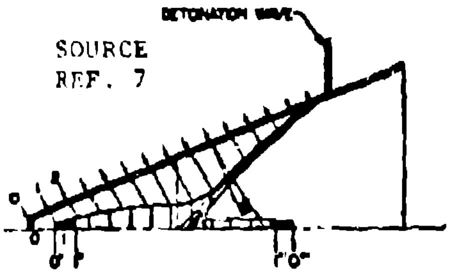


FIG. 2c MATERIAL FLOW

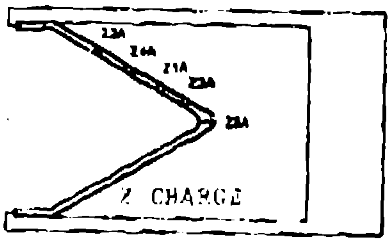


FIG. 3a INITIAL COMPUTATIONS

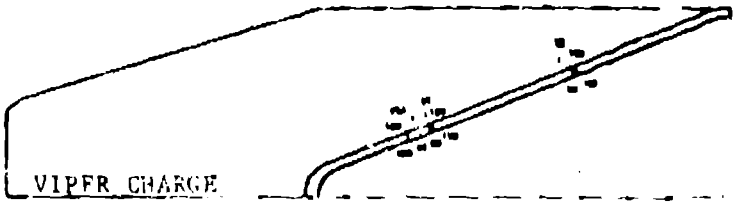


FIG. 3c VIPER COMPUTATIONS-TRACER POINT LOCATIONS

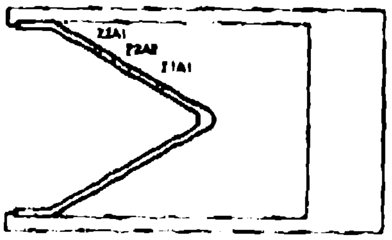


FIG. 3b ADDITIONAL COMPUTATIONS

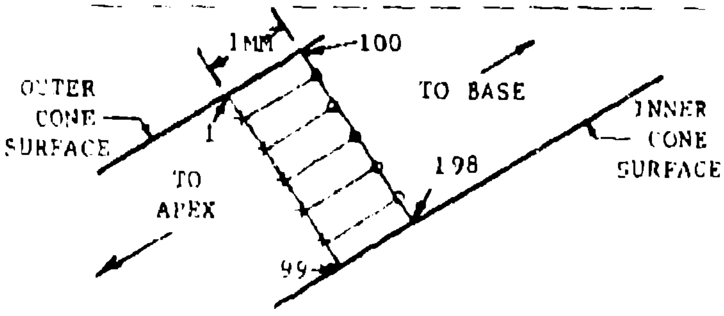
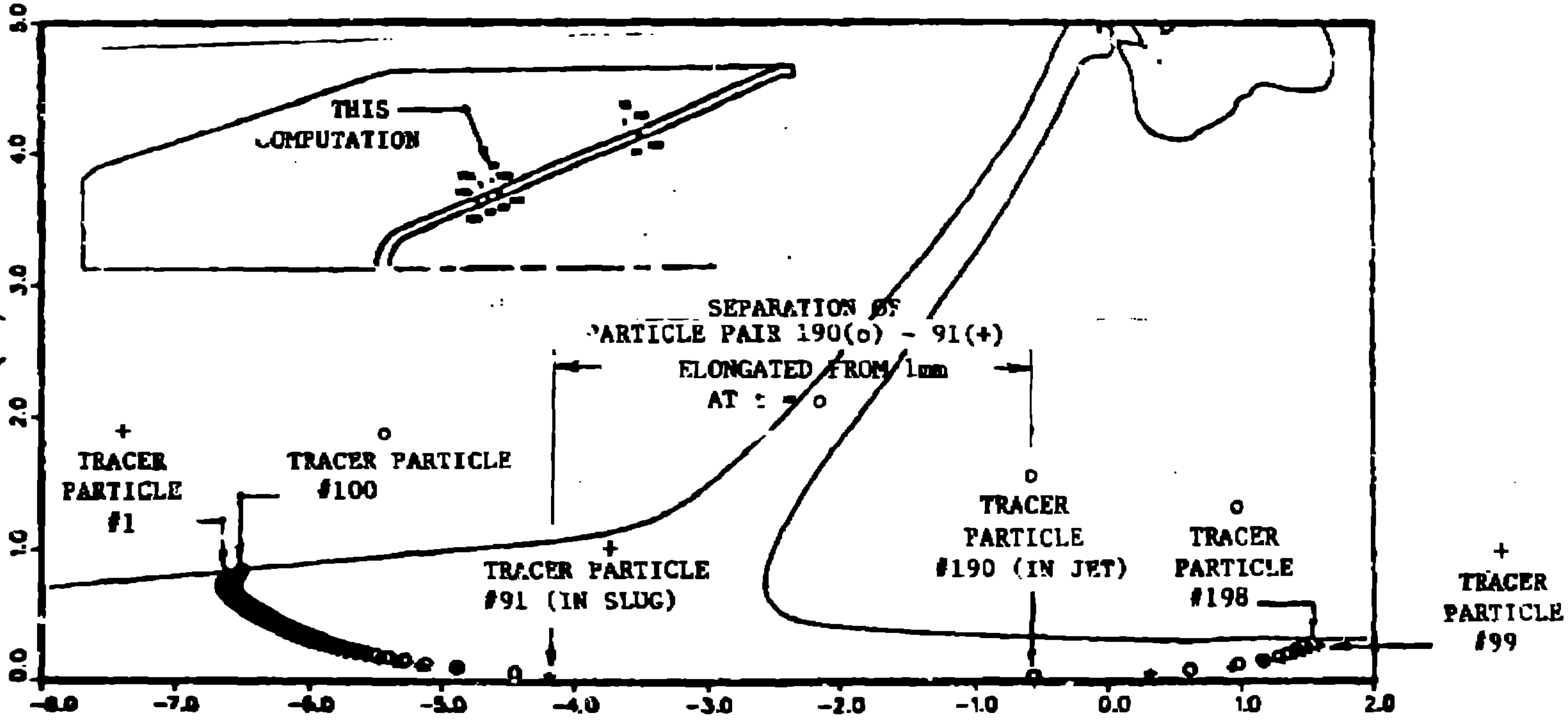


FIG. 3d ENLARGED VIEW OF NUMBERED TRACER POINT PAIR LOCATIONS WITH IDENTIFYING SYMBOLS (o, +) - PROBLEM VI

TRACER PARTICLES time 30.0726

zrvp1 – viper prob #1

FIG. 4 COLLAPSING VIPER LINER, FORMING SLUG AND JET, SHOWING TRACER PARTICLE DISTRIBUTION, FOR COMPUTATION V1. INSET SHOWS IDENTIFIED INITIAL LOCATION OF TRACER END POINTS. END POINTS ON THE SLUG AND JET ARE LABELLED WITH SYMBOLS (o OR +) AND POINT NUMBERS. THE TRACER POINT PAIR 190(o) - 91(+) SEPARATES, WITH 190(o) ENTERING THE SLUG AND 91 (+) ENTERING THE JET.



MESA2D Version m4.3 91/08/21 00:39:24

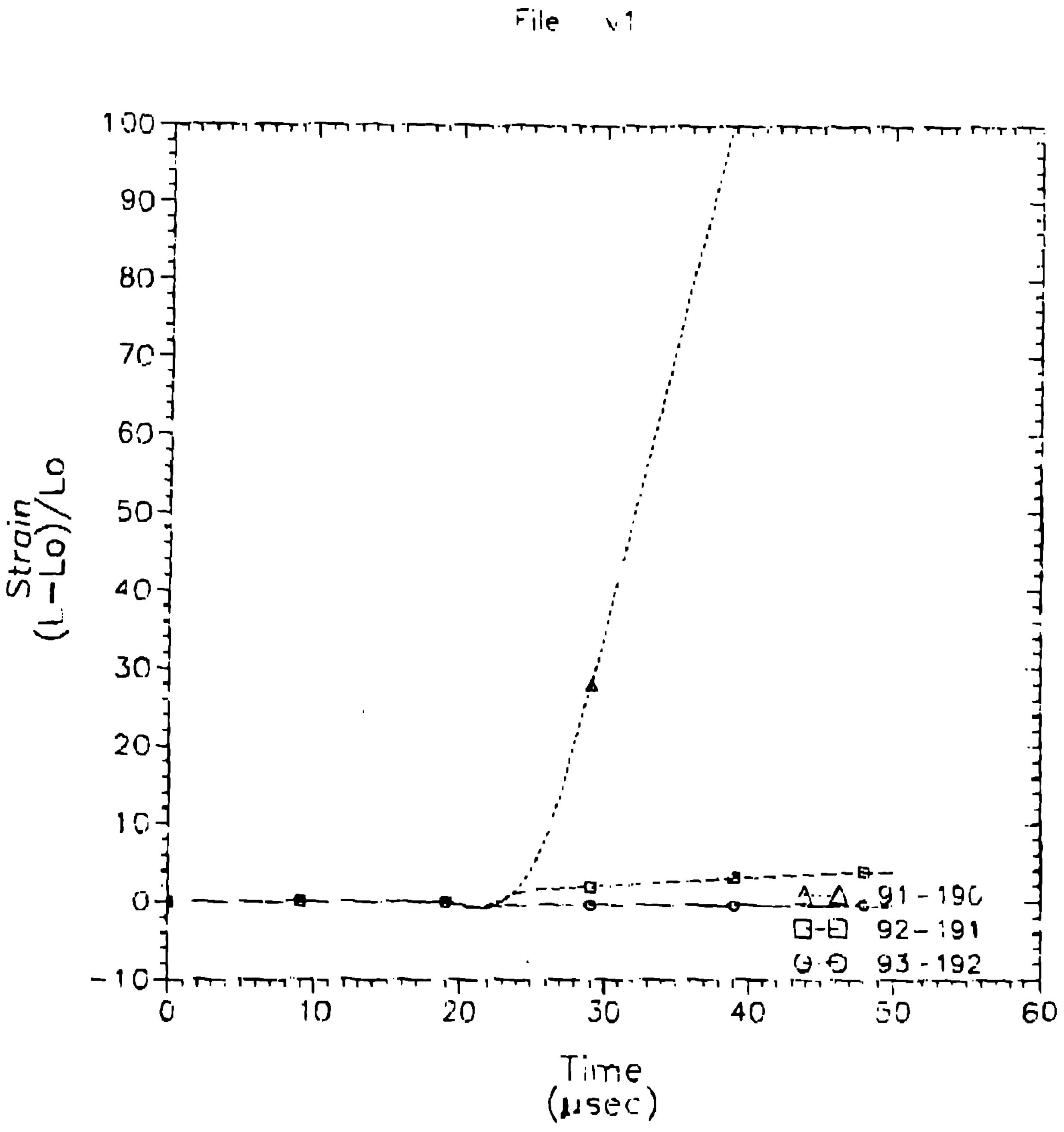


FIG. 5a STRAIN AS A FUNCTION OF TIME FOR ADJACENT THREE PARTICLE PAIRS BEING UTILIZED AS LINEAR STRAIN GAGES. PARTICLE PAIR 91(+) - 190(o) SPLITS BETWEEN THE JET AND THE SLUG.

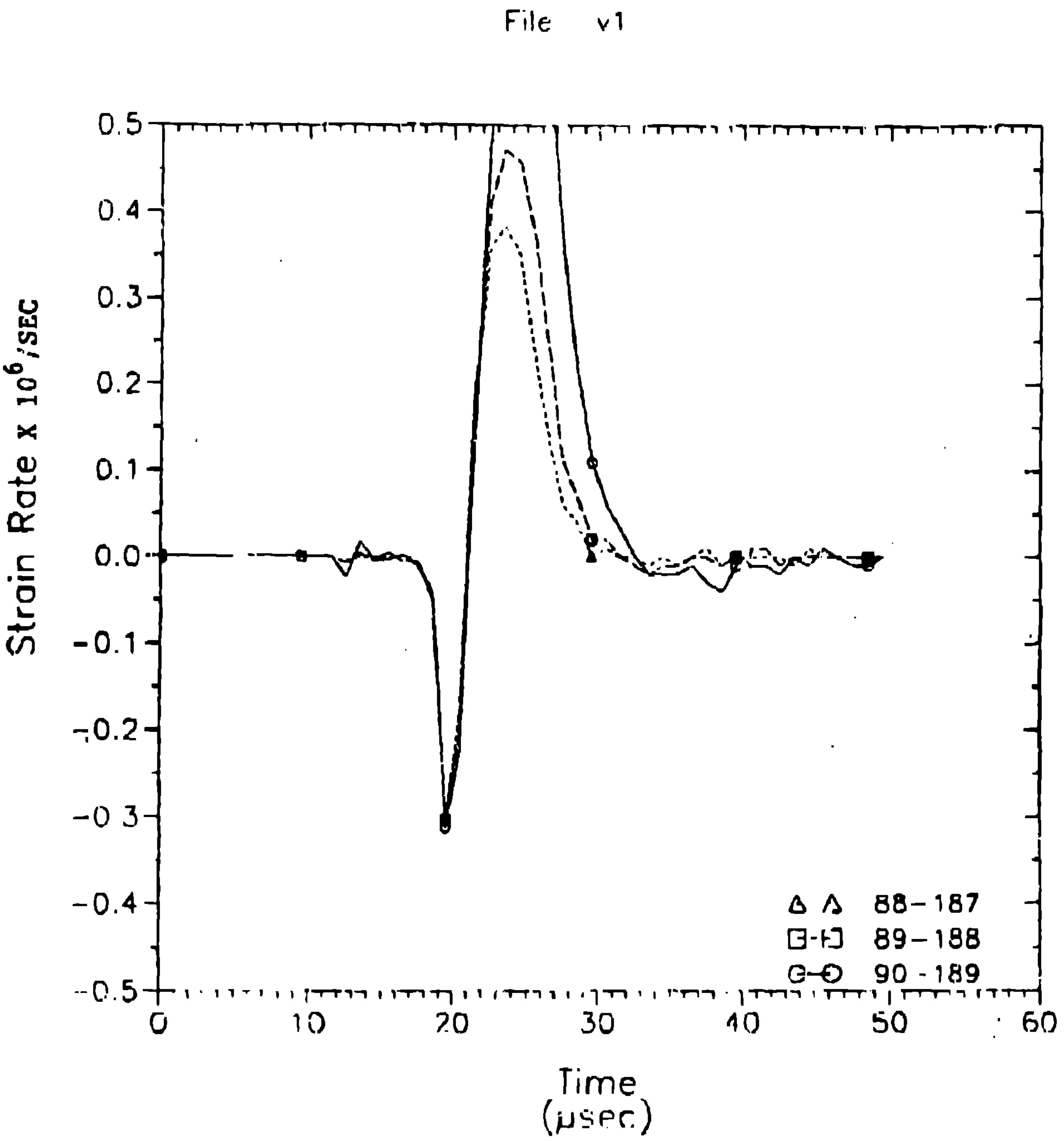


FIG. 5b STRAIN RATES AS A FUNCTION OF TIME FOR THREE PARTICLE PAIRS ADJACENT TO 91(+) - 190(o).

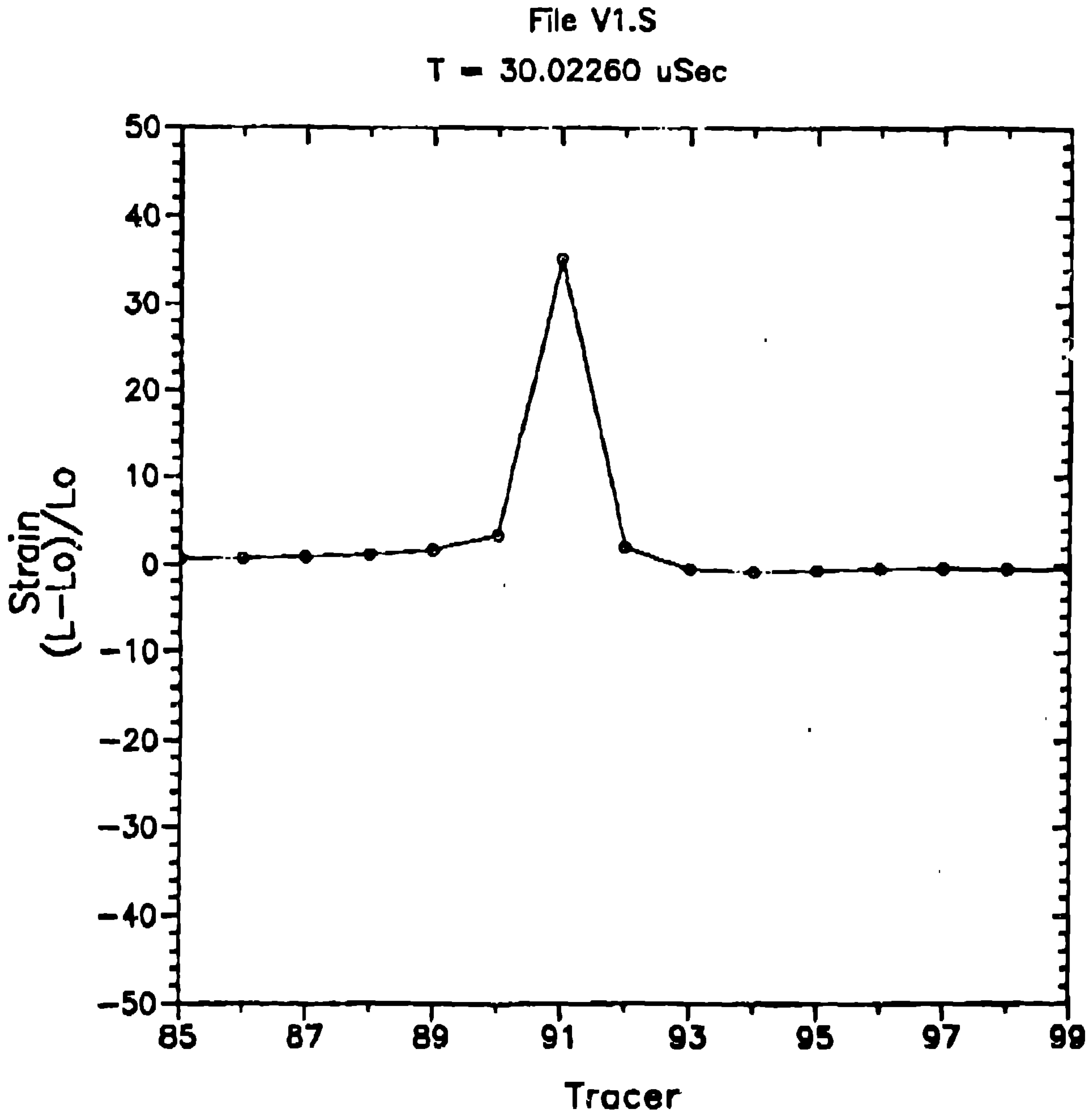


FIG. 5c STRAIN SHOWN AT t = 30 μsec AS A FUNCTION OF PARTICLE PAIR NUMBERS, IDENTIFIED BY THE LOWER NUMBER IN THE PAIR. THUS, 91 MEANS THE PARTICLE PAIR 91(+) - 190 (o).

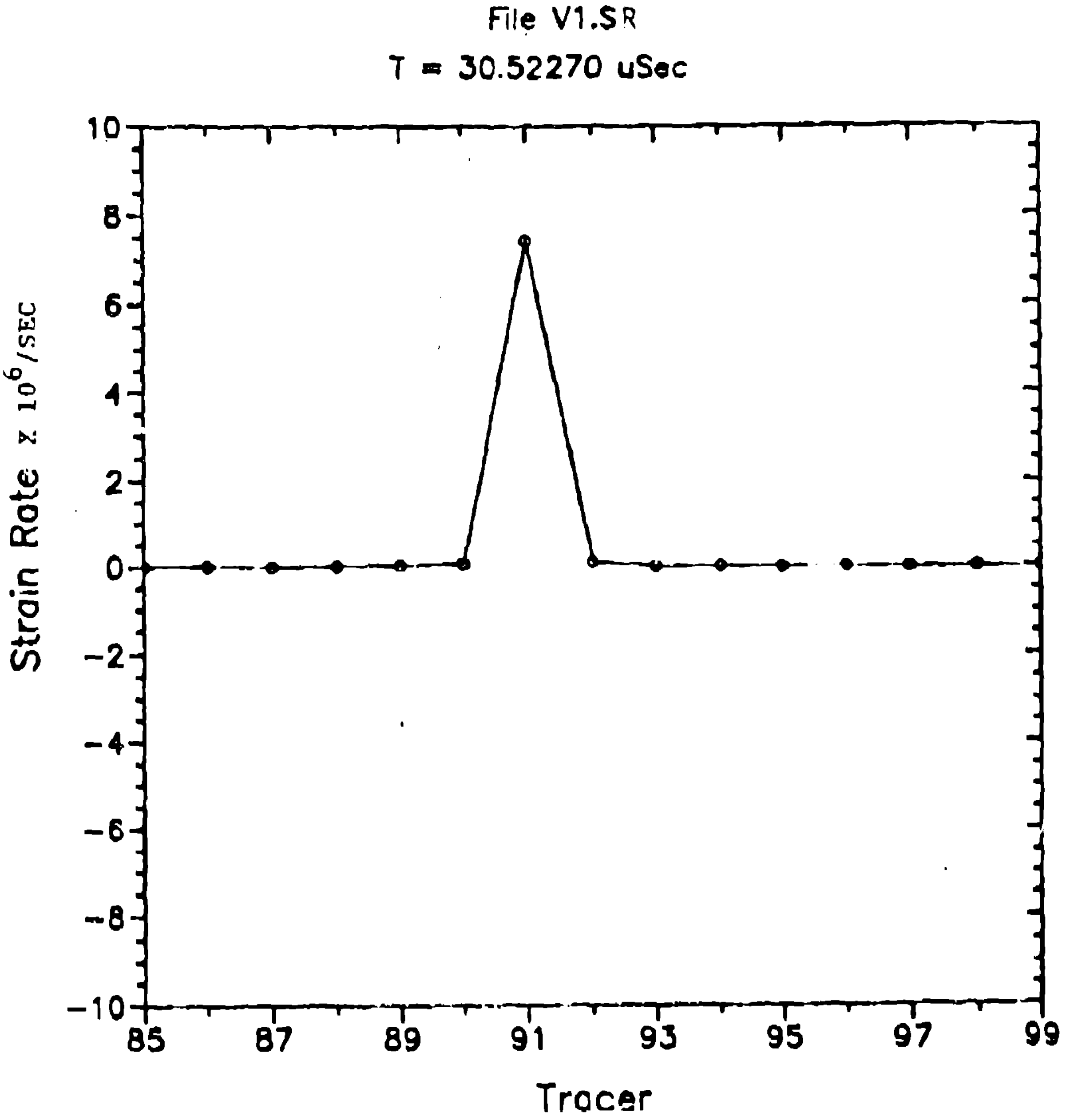
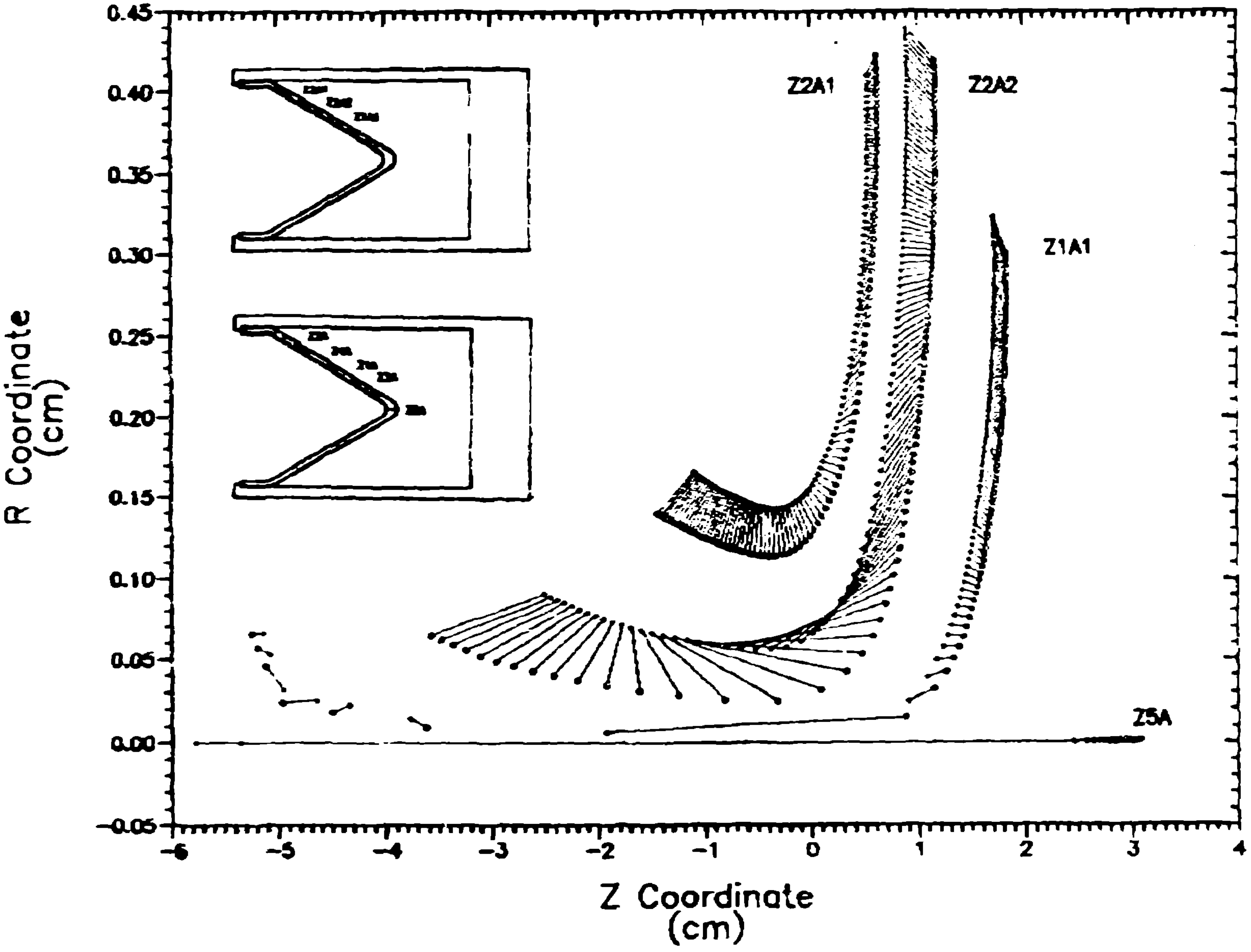


FIG. 5d STRAIN RATES SHOWN AT 30.5 μsec AS A FUNCTION OF PARTICLE PAIR NUMBERS IDENTIFIED BY THE LOWER NUMBER IN THE PAIR. THUS 91 MEANS THE PARTICLE PAIR 91(+) - 190(o).

FIG. 6 COMPOSITE OF ALL Tracer Point Locations FROM THE APEX TO Z2A1

Time = 20.01890 uSec



TRACER PARTICLES

time 24.0420

zern2a2-zernow s c,e-p,y=.0030, dr=dx=.05, lag part 2x99

FIG. 7 TWO VERTICAL ROWS OF 8 TRACER PARTICLE PAIRS, 1mm APART, INSERTED INTO REAR OF JET PERPENDICULAR TO JET AXIS AT 5 μsecond INTERVALS, DURING JET FORMATION AND ELONGATION. NOTE COMPRESSION IN LEAD PARTICLE AND RADIAL VELOCITY GRADIENT RESULTING IN CONCENTRIC AXIAL SHEAR. INSET SHOWS ENLARGED VIEW OF TRACER POINT PAIRS FROM SECOND INSERTION.