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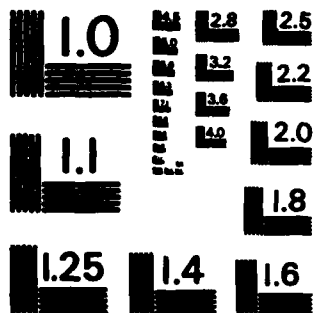
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DEVELOPMENT OF RESEARCH TOOLS TO STUDY STRUCTURE AND EVOLUTION IN THE INTERMEDIATE ALTITUDE REGIME

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Technical Report

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19. ABSTRACT (Continue on reverse if necessary and identify by block number) This report covers the initial research on alternative methods to study aspects of the nonlinear dynamics of low and intermediate altitude fireballs. The research consisted of developing a 2-D vortex-in-cell code, VINCE, and examining the flow field interaction of some simple multiple burst scenarios during the rise and torusing phase of the dynamics. This code will allow the study of a variety of potential structure mechanisms. It was determined that a 3-D version of this code was possible. A final aspect of the research reported here was a cursory study of the problem of small scale structure convection in large codes. Some speculative ideas are presented.					
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PREFACE

This is the final technical report on contract DNA 001-84-C-0018 covering the contract period 1 November 1983 through 31 October 1984. The purpose of this effort was to examine alternative methods by which the nonlinear dynamics of structure formation could be studied. In the following report the results of this preliminary study will be presented.

Acknowledgements must be made to Dr. Clifford Prettie, who worked on the structure algorithms, and Mr. John Ferrante for his programming assistance. A further acknowledgement is made to several useful discussions with Mr. Daniel Matuska.



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SECTION 1

INTRODUCTION

During the period of this contract Berkeley Research Associates (BRA) was tasked to address the problem of structure creation and convection in the intermediate and low altitude regime. More specifically the effort was directed toward finding alternative methods by which the nonlinear dynamics of structure formation and convection could be studied. If such approaches proved adequate, then the information generated could be used as models in various systems codes where the knowledge of both neutral fluid structure and plasma structure is very important to evaluation of various systems.

The effort took two directions. One was to investigate the applicability of current microstructure algorithms to the intermediate altitude structure and convection problem. The second direction was the construction and testing of a vortex-in-cell approach to investigate this technique's ability to handle vortex formation and torusing dynamics in multiburst situations. Further these techniques offered the possibility of studying the production of very small scale structure evolution.

During the course of this contract a 2-D vortex-in-cell code, VINCE, was constructed and tested. Methods by which VINCE could be generalized to 3-D were considered and found to be something we could accomplish. The high altitude microstructure algorithm was considered as a model for a possible mid-altitude structure algorithm and avenues of further research were laid out.

In the following sections a discussion of the results obtained in this third of a man year effort will be presented. In Section 2 a presentation will be made of the numerical results to date. These results include some of the possible nonlinear dynamics that might occur in the multiburst environment. In Section 3 a discussion of some concept concerning a possible structure convection model will be presented. Section 4 will contain a brief discussion of the simulations accomplished during this contract.

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SECTION 2

SIMULATION METHOD

As mentioned previously, one of the tasks was to address the problem of structure creation in the low to intermediate altitude regime. In this context intermediate means bursts of up to 90 km or so and low means, from our standpoint, altitudes above which ground effects need to be considered. One of the most obvious mechanisms by which structure is created is the torusing of the fireball which is a form of the Rayleigh-Taylor instability. Less obvious but maybe as important is the further evolution of these torused regions when they are in the flow field created by other bursts, or the convection of debris material in the flow fields of this late time fireball. Here late time implies after the original shocks have left the immediate vicinity of the problem.

A tool that might provide information of the sort just mentioned is a vortex-in-cell code. The basic algorithm was first explained and used by Meng and Thomson.¹ It makes use of the fact that physical problems such as shear flow, flow with a sharp interface separating two fluids of different densities or regions of different viscosities can be handled by noting that generation and convection of vorticity is the primary quantity of interest. For example, because of the density difference across the interface, vorticity is generated along it by the interaction of the pressure gradient and density gradient. The resulting motion consists of essentially two processes: the creation of a vortex sheet and the subsequent mutual induction of different portions of the sheet. The method treats vorticity as a basic quantity of fluid motion to be handled in a code much the same way charged particles are treated in a plasma particle simulation. The algorithm as discussed by Meng and Thomson¹ simply follows the interface between the hot fluid and the cold fluid background, computes the development and convection of the vortices which in turn delineate the dynamics of the interface. These calculations can be done in both viscid and inviscid situations.^{1,2,3} As will be shown later, the code calculates the torusing of a rising fireball

or bubble. This formulation can also address smaller scale structure such as the Kelvin-Helmholtz instability and the Saffman-Taylor^{1,3} instability, both of which may play a role in the structuring of debris material and perhaps the rising fireball.

The algorithm itself uses a very simplified version of the Navier-Stokes equation. Only enough of the nonlinearity is retained to provide the structure evolution of interest. One begins with the momentum equation for an incompressible fluid

$$\frac{d\bar{u}}{dt} = -\nabla p / \rho + \eta \nabla^2 \bar{u} + \bar{g} \quad (1)$$

where $\bar{u}$ is the velocity, p is the pressure, ρ the fluid density, η the kinematic viscosity and $\bar{g}$ is the acceleration of gravity. Vorticity is defined as

$$\bar{\xi} = \nabla \times \bar{u} \quad (2)$$

and Equation (1) becomes

$$\frac{d\bar{\xi}}{dt} = \nabla \left(\frac{1}{\rho} \right) \times \nabla p + \eta \nabla^2 \bar{\xi} . \quad (3)$$

The algorithm can be set up to do a viscous calculation or this equation can be further reduced by making the inviscid assumption. One then has the operative equation used in the simulations to be shown in this report. Equation (3) becomes

$$\frac{d\bar{\xi}}{dt} = -\nabla \left(\frac{1}{\rho} \right) \times \nabla p. \quad (4)$$

A further assumption can be made in the case of torusing bubbles that still retains the nonlinearity of the flow field. This is the assumption that the pressure can be treated to only first order then $\nabla p = \rho_0 g + O(\nabla p / \rho_0)$. Equation 4 then can be written as

$$\frac{d\bar{\xi}}{dt} = \frac{\nabla \rho}{\rho_0} \times \bar{g} = -\frac{g}{\rho_0} \frac{\partial \rho}{\partial x} \hat{n}_y . \quad (5)$$

Here we are working in the x-z grid where $\bar{g} = -g \hat{n}_z$. As expected the vorticity is directed out of the plane. From Equation (5) one sees that

the vorticity is generated only on the interface between the two fluids. The total circulation for an i th element of the fluid is given by

$$\bar{\Gamma}_i = \int \xi_i dx' dz'. \quad (6)$$

The evolution of the i th circulation element then becomes

$$\frac{d\bar{\Gamma}_i}{dt} = g \frac{(\rho_- - \rho_+)}{\rho_0} \Delta z_i \hat{n}_y \quad (7)$$

where $\rho_0 \equiv \frac{1}{2}(\rho_+ + \rho_-)$ and ρ_+ and ρ_- are the densities across the interface and Δz_i is the vertical dimension of the fluid element. This formalism leads naturally to the concept of tracking various fluid elements to get the total dynamics of the system. The standard method of tracking this element is to consider the effects of all other vortex elements on the one being considered. This is the Green's function formalism. An alternate method is to express the velocity as a stream function. Meng and Thomson¹ compared both methods and found the latter formalism much faster but not quite as accurate on very small scale phenomena. Because of our interest in a possibly large number of cases the later approach was attempted.

If one assumes that

$$\bar{u} = \nabla \times \bar{\psi} \quad (8)$$

where $\nabla \cdot \bar{\psi} = 0$ (an automatic requirement in 2 dimensions), then the stream function satisfies the Poisson equation

$$\nabla^2 \bar{\psi} = -\bar{\Omega} \quad (9)$$

where $\bar{\Omega} \equiv \sum_i \xi_i S(\bar{x}_g - \bar{x}_i)$, a summation to an Eulerian grid. The system is now closed because one knows the new stream function and hence the new velocities and positions from Equations 8 and 9. Equation 7 then advances the circulation and the process proceeds. The algorithm is written very much like an electrostatic particle code with a time-centered leap frog algorithm, particle interpolation and weighting. Similar formalisms have been developed for the viscid calculation.^{1,2,3}

At this juncture we have a vortex-in-cell formalism where we are solving an incompressible fluid problem with the assumption of a linearized pressure. What can such a simple model produce? One of the most obvious and interesting nonlinear result is the Rayleigh-Taylor instability which in the case of a buoyantly rising bubble is the torusing evolution. We have performed a variety of such simulations to test out the code and also get a glimpse of the possible applications. It should be recalled that this algorithm is not intended to replace detailed hydro codes. However, it will allow the investigation of the nonlinear interaction of flow fields such as one might expect in the late time evolution of a multiburst situation.

One of the first calculations that we performed with the new code called VINCE was to calculate the evolution of a bubble into a torus or vortex pair. As mentioned by Meng and Thomson¹, one can get quantitative estimates of the rise rate and separation of the pair by observing as Turner⁴ did that the circulation of each vortex approaches a constant value after vortex or torus formation. After the vortex formation the density along a path threading the center of the vortex is essentially constant and equal to the ambient value and $d\rho/dt \rightarrow 0$. For a constant Γ the rise velocity varies inversely as the separation of the vortex pair; $u \propto 1/R$. The upward momentum increases at a constant rate $d(\mu)/dt = F_B$, where F_B is the buoyant force and m , is the mass in the vortex. Since $m \propto R^2$ in two dimensions and Ru is constant, the separation, R , increases linearly with time so one has the scaling that

$$R \propto t. \quad (10)$$

Since the rise velocity of the vortex pair varies as Γ/R , the net rise distance, z , increases logarithmically (in 2-D) with time. Therefore, one can write the relation

$$z \propto \ln(t). \quad (11)$$

For three dimensions the mass varies as R^3 , the momentum equation reduces to dR^2/dt equals a constant after torus formation. Then $R \propto t^{\frac{1}{2}}$ and $dz/dt \propto t^{-\frac{1}{2}}$ and unlike Equation 10, $R \propto z$.

The two dimensional relations (10) and (11) were tested to determine if the code produced the correct behavior and time dependence. Figure 1 shows the result of the test. The time dependence of the rise rate and vortex widths were correct. Figure 2 shows the time evolution of the vortex positions as the bubble evolves into a torus. The evolution was as expected and showed the creation of the vortex pair. Figure 3 displays the corresponding flow fields, note that the vectors are renormalized with Figure 3b having maximum flow ~ 50 times larger than 3a.

At this point a variety of experiments were performed with VINCE to get some experience with the various nonlinear interactions one might expect. In the next few figures a series of time dependent snap shots are displayed for two interesting cases. In the first case two bubbles are placed on a vertical line as shown in Figure 4a. They are slightly more than one radius apart at $t = 0$. One sees that evolution has only the crudest relation to the 1 bubble situation. The bottom bubble does not expand horizontally as far but is considerably elongated. At a time slightly beyond the last time shown the lower vortex pair actually breaks off from the material rising into the upper torus. One then actually has four discrete regions, the two vortexes from the bottom bubble, the center section of the bottom bubble and the upper bubble; far different from the expected linear picture. In Figure 5 one sees the flow fields corresponding to 4a and 4d. Note there is an increase of ~ 100 in the maximum flow field. Also note that there appears only two discernable vortexes in the flow field. The remainder of the large flow is an upward column.

The next experiment was the examination of three cylindrical bubbles rising together. Each bubble was placed approximately one radii apart. As can be seen from Figure 6, the subsequent evolution deviates substantially from the one bubble case. The outer halves of the two outside bubbles evolve in what appears to be a normal fashion. However, the

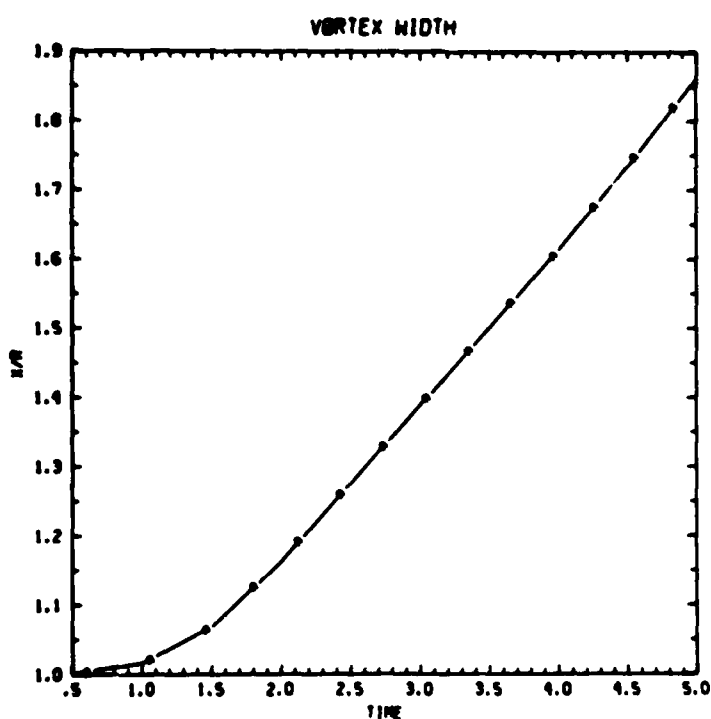
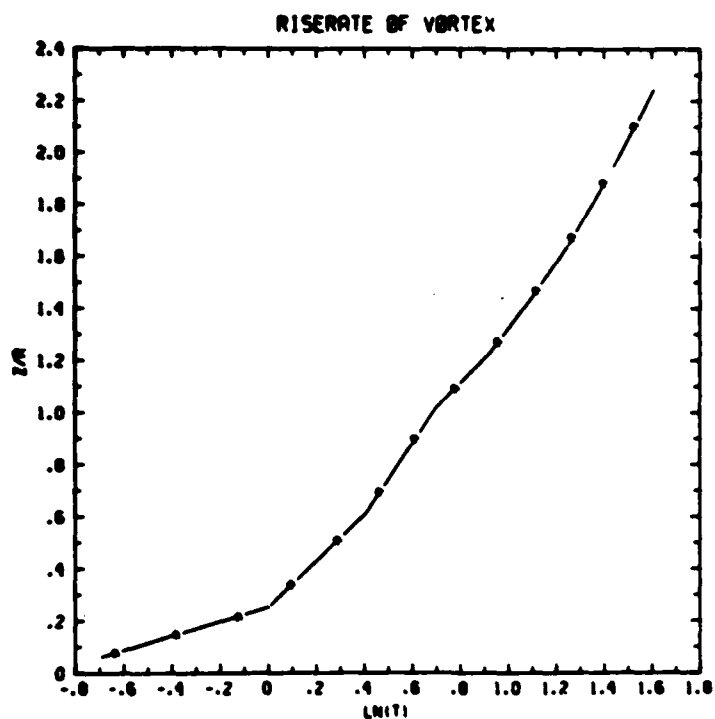


Figure 1. Plots of the rise rate of a single bubble. Note the linear rise with $\ln(t)$ after torus formation $\ln(t) \sim 0$, in 1a. The width exhibits the linear increase with time as expected.

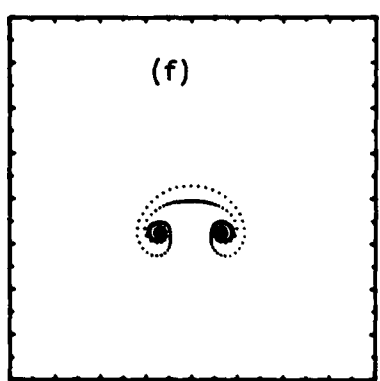
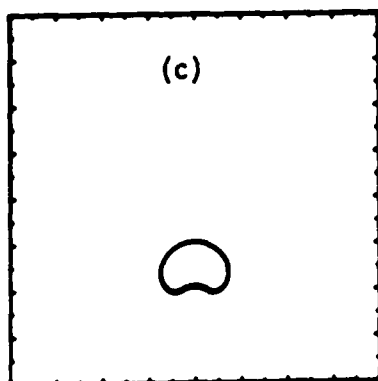
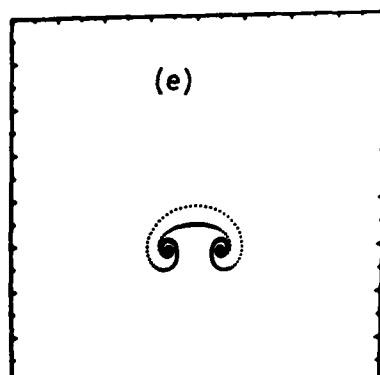
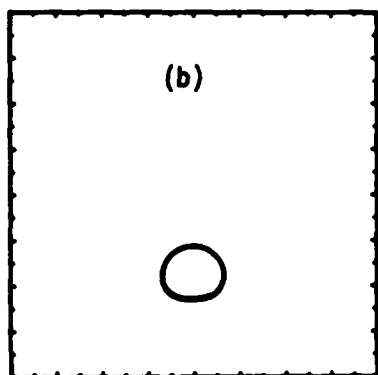
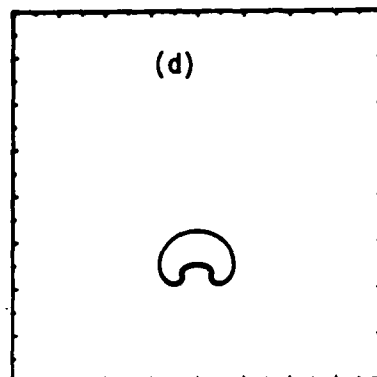
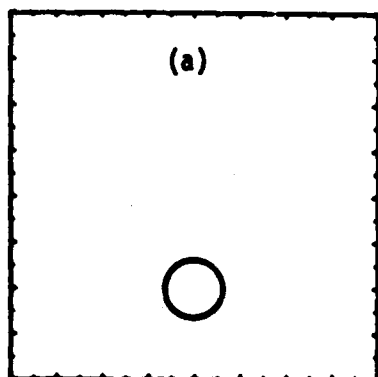
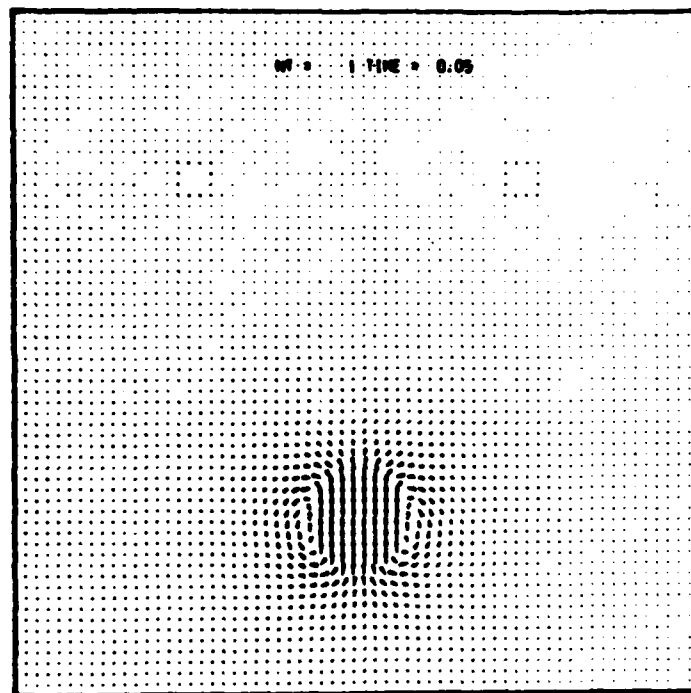
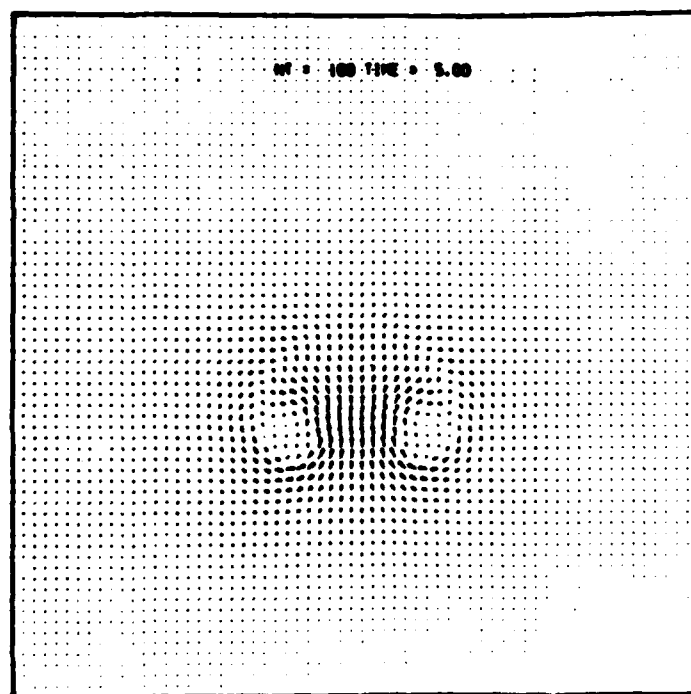


Figure 2. Shown here is the time evolution of the vortex particles location as the bubble rises. There is no symmetry plane, the calculation demonstrates symmetries evolution as expected.



(a)



(b)

Figure 3. Shown here are the flow fields corresponding to Figures 1a and 1f. Maximum velocity vector is ~ 50 times larger in (b) than in (a).

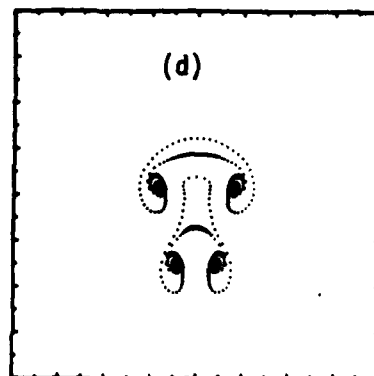
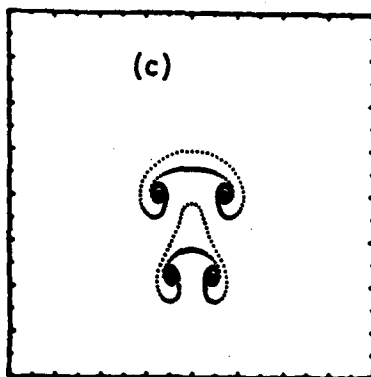
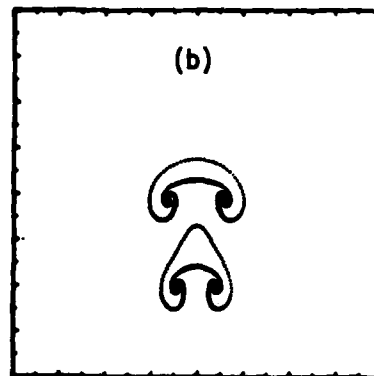
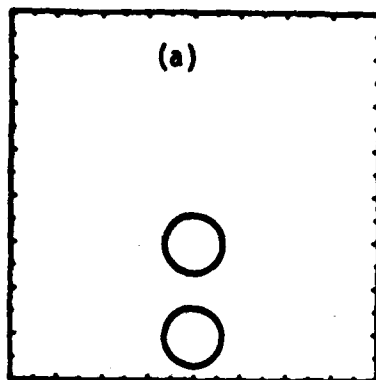
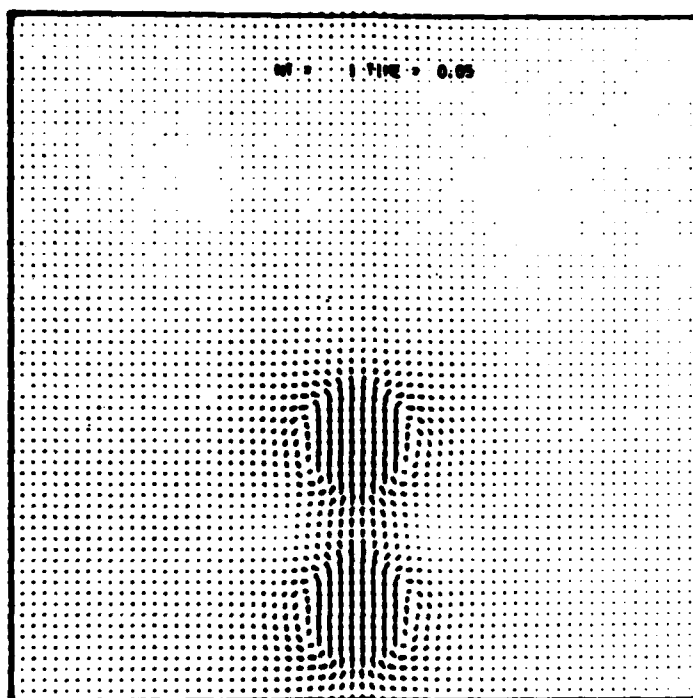
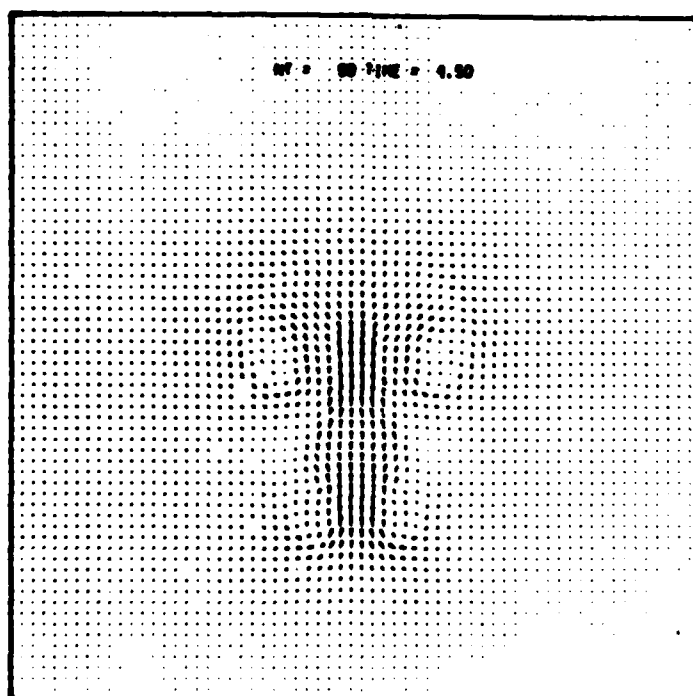


Figure 4. The two bubble case is plotted here. Note the considerable distortion of the lower bubble as the two interact. The bottom vortex rings have essentially separated as vortex particles of opposite sign are almost superimposed. At a later time the two bottom regions do separate.



(a)



(b)

Figure 5. Flow fields associated with Figures 4a and 4d. Note that only one clear set of vortices is shown in the flow field, 4d. Maximum velocity vector is ~ 100 times greater in (b) than (a).

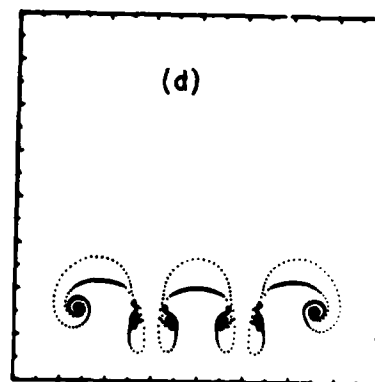
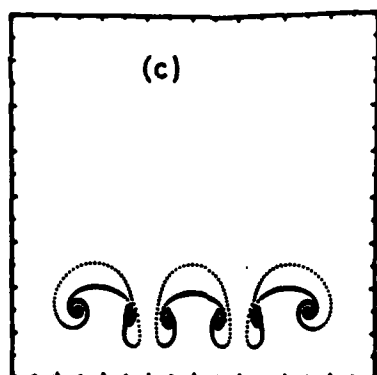
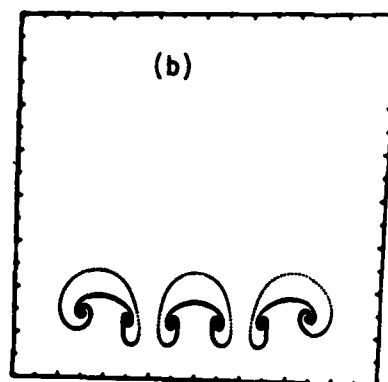
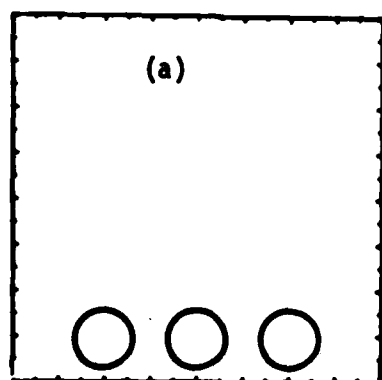
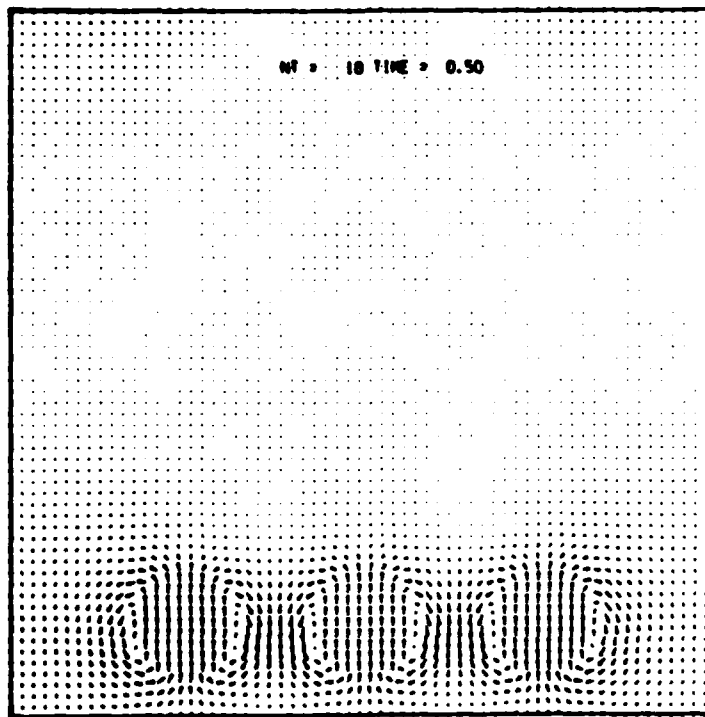
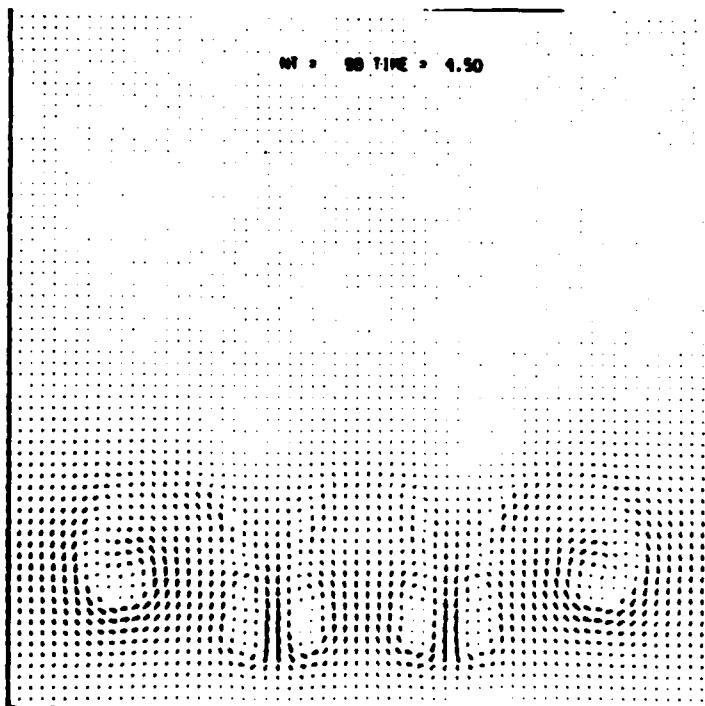


Figure 6. The vortex positions for the 3 bubble case. Note the overlapping of the vortex particles in plot d. This indicates a separation of this region from the rising region as vortex particles have opposite signs.



(a)



(b)

Figure 7. Velocity flow fields corresponding to Figures 6a and 6b. The maximum velocity vector has increased about 70 from plot (a) to (b). Note the oppositely directed pairs that have been created in the center region of the bubbles, (b).

center region does not. In fact, by the last time step shown, the vortex regions of all three bubbles have not only broken off from the main body of the buoyant regions but they have failed to rise substantially. Actually, as the vortex pair expanded, the inside pair condensed and created pairs with a flow pattern of opposite sizes from a rising vortex pair. In Figure 7 one sees this reversal of flow pattern which then works against the buoyant force and thus retards the rise rate.

Because of the expected need for higher dimensionality, another portion of the simulation effort was the consideration of generalizing the vortex-in-cell algorithm to three dimensions. After some analysis and experimentation we have decided that such a generalization is possible but complicated. The main thrust of course is recognition that vortex rings may be three dimensional, but vortex particles must still be two dimensional objects that are generated on the surface discontinuity with a directional vector tangent to the surface. This will require some complicated interpolation onto the eularian grid but we feel it can be done.

The reason for wanting a 3-D version of VINCE is to further investigate the level of nonlinear interaction in cases like the 3 bubble example shown earlier. Further, as one goes higher up in altitude one would like to be able to consider the effects of an anisotropic pressure tensor. At altitudes where the magnetic field may play a noticeable role, one of the first effects might be the creation of an anisotropic pressure tensor which leads to terms in the pressure equation called magnetic viscosity terms.⁵ To date, the effects of such off-diagonal terms has never been explored in any hydro or MHD code in the H.A.N.E. community.

To summarize our progress in the simulation area. The algorithm appears to have considerable potential. In the coming years it will be expanded into a 3-D code. It will be used to test such models as the linear superpositon algorithm now in place in C/LAMP. This algorithm uses a Hills spherical vortex formation to superimpose flow fields from other bursts onto the burst region being considered. The code will also be used to investigate various structuring mechanisms and perhaps to get

some handle on the structure level and convection of debris. In the next section some of our concepts of a convection algorithm will be presented as well as some additional uses for the vortex-in-cell algorithm.

SECTION 3

CONVECTION CONCEPTS

The other major task during the contract period was to consider the applicability of microstructure techniques to the mid and low altitude regimes. This formalism essentially provides a method of identifying fine scale structure intensity and location in nuclear burst flow simulations. The microstructure technique was first applied to the high altitude structure problem by Dr. Joseph B. Workman and Dr. Frank Chu of BRA⁷⁻⁹ and has since been successfully implemented by BRA in the SCENARIO code.¹⁰

Microstructure theory is basically the application of stochastic process techniques to flow problems that are typically solved numerically in order to predict the location of structure.¹¹ The theory has been used in the past to develop algorithms for predictions regarding plasma structure in the late-time high altitude multiburst environment.¹⁰ The theory develops the algorithms which produce estimates of structure parameters at the modest expense of additional complexity and storage. The theory itself is flexible. The methodology of its application to arbitrary flow problems is fairly well formulated. The success of the resulting algorithms, however, is a function of the necessary underlying assumptions regarding the statistics of the structure and is not guaranteed. In each particular application the validity of the statistical assumptions and the resulting algorithms must be tested.

To date, our understanding of the information necessary to use the microstructure approach at low and mid altitude is not complete. However, some observations of the likely phenomenon of importance has provided direction. In the high altitude algorithm, n_e and n_e^2 were found to be statistically conserved quantities. The question is what would correspond to such quantities in lower altitudes, where charge density does not provide the structure but rather radiating material. First, we noted that at late times after the shocks were out of the system, the flow was very likely to be incompressible as is assumed at high altitude. Second, once it is observed that even torus formation is a form of Rayleigh-Taylor and that

most of the structuring instabilities, i.e.: Rayleigh-Taylor, Kelvin-Helmholtz, Saffman-Taylor and such, are represented by the creation and convection of vorticity and the vorticity once created is then a dynamical fluid element until a diffusion mechanism is provided, one might reasonably consider vorticity as the quantity to consider when the role of n_e or n_e^2 is explored. This assumption must be tested and to do this a program to test them was devised. We plan to resort to the vortex-in-cell code as a test devise.

As stated earlier, the vortex-in-cell code formulation focuses on the interface between the hot rising fireball gases and the surrounding cold air. It makes the assumption that the flow is incompressible and that the hot and cold gases do not diffuse into each other. The interface between the two gases is then defined and followed with vortex particles. One can assume that vortex particles move and vorticity grows in a deterministic manner according to the following three equations:

$$\frac{\partial \zeta_i}{\partial t} + (\mathbf{v} \cdot \nabla) \zeta_i = 0 \quad \text{Convection} \quad (12)$$

$$\frac{\partial \zeta_i}{\partial t} = g \Delta \rho \Delta z_i \quad \text{growth} \quad (13)$$

$$\nabla^2 \psi = \sum_i \nabla \times \zeta_i \quad \text{potential} \quad (14)$$

where ζ_i is the vorticity of the i th particle; $\mathbf{v}$ is the fluid velocity as determined through Equation (14), the potential equation; g is the acceleration due to gravity; $\Delta \rho$ is the change in density across the interface; and Δz_i is the difference in altitude over the region covered by the i th particle.

Microstructure theory can be used to formulate an algorithm which addresses the interface structuring issue by extending the particle code technique. The basic idea of the extended algorithm is that the position and value of each particle vortex is a random value and these random values are characterized through their mean and variance which the algorithms

predict. The structuring of fireball interfaces in the azimuthal direction (which, for instance, is apparent at later times near the bottom of ORANGE) is quantified through the variance of the interface position.

The features of the algorithms which have been established are that the variance in vorticity and vortex position will contribute through the potential equation, Equation (14), to variances in the flow velocity. Variance in the flow velocity will lead to variance in the vortex position through the convection equation, Equation (12). Variance in the vorticity of each particle is created by the variance in the value of Δz which is a component of the position variance. Features that remain to be established are the detailed nature of these equations. A crucial point that requires resolution is what approximations are to be made in the convection step to account for correlation between the position variate of a particle and its velocity variate. An assumption of no correlation could lead to an overestimate of the actual structuring. This issue and similar issues will be addressed through experiments with high resolution runs of the VINCE code and with further analysis.

To summarize this aspect of our work. We believe that the vorticity may play the role as the primary structure quantity, the existence or variation of which will indicate structure. Considering the statistical properties of this quantity in much the same manner as the the properties of n_e was considered in the high altitude may provide the necessary information for a structure algorithm. These assumptions will be further tested and numerical examination of them seems possible.

SECTION 4

CONCLUSION

Under contract no. DNA001-84-C-0018 the following tasks have been completed. A vortex-in-cell code, VINCE, has been constructed in two dimensions. It has been tested and several multiburst like calculations have been run. The results are intriguing. Their correspondence to the real multiburst situation has yet to be calibrated but will be against full-fledged hydrodynamic calculations. As configured, the code can do buoyantly rising bubbles or cylinders since these are 2-D and ballistic rising bubbles as well. It is extremely fast with the calculations shown in the report, taking less than a minute of CRAY-1 time. This speed will allow a large variety of parameter studies into the various structuring mechanism.

We believe we have found a way to apply the microstructure concepts to the mid and low altitude problem. Further work on the statistical properties to be convected will have to be done and the VINCE code will play a role in evaluating the adequacy of any future model. If our concepts prove valid, structure and convection models for the mid and low altitude should be possible.

Finally, we investigated the possibility of extending VINCE into three dimensions. After considering various problems it appears that it can be done. We will be making this extension in future research. This will allow us to do much more realistic studies of the flow fields resulting from multiburst situations. These calculations will begin from either a bubble like form or may use the results of hydrodynamic codes as starting conditions.

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