FINAL TECHNICAL REPORT

DNS and Linear Stability Analyses of Unsteady 3-D Hypersonic Wall-Bounded Flows with Real-Gas Effects

(11/15/1997 to 02/14/2000)

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Prepared for:
Air Force Office of Scientific Research
AFOSR/NM
801 North Randolph Street, Room 732
Arlington VA 22203-1977
Grant Monitor: Dr. Leonidas Sakell
Grant Number: F49620-97-1-0030

June 2, 2000

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1 SUMMARY

The goal of this research project is to develop new advanced numerical methods and to perform DNS studies of transient hypersonic reacting flows over full 3-D maneuvering vehicles. The DNS tools and supporting theoretical approaches are used to gain new fundamental understanding of transition phenomena of 3-D chemically-reacting hypersonic boundary layers. In the three-year period, significant progress has been made in the DNS of hypersonic boundary-layer flow instabilities in the following areas: 1) receptivity of 3-D hypersonic flows over blunt elliptical cones, 2) nonlinear breakdown of 3-D Görtler vortices, and 3) reacting hypersonic flow receptivities and stabilities. We have also finished the development of linear stability codes for hypersonic flow and have started the work on developing new parallel implicit algorithms for DNS of reacting hypersonic flows. So far, we have developed new methodologies and have demonstrated the feasibility of our approach as a practical DNS tool to explore transient hypersonic reacting flow physics. The focus of future work is on the DNS studies of the hypersonic flow physics related to the hypersonic boundary layer transition, and to extend these DNS and theoretical studies to 3-D transient hypersonic flows with complex real-gas models and complex geometries, and the DNS of nonlinear breakdown and interactions of instability modes in hypersonic boundary layers.

2 OBJECTIVES

Objectives and Tasks

Hypersonic boundary layer laminar-turbulent transition and unsteady hypersonic aerodynamics are fundamental problems which have important practical applications in design and control of hypersonic lifting vehicles but are currently not well understood. In recent years, direct numerical simulation (DNS) has become a powerful tool in the studies of the stability and transition of boundary layers. However, available DNS methods cannot be applied to hypersonic boundary layers over realistic blunt bodies because the effects of nose bluntness, the presence of shock waves, and the real-gas effects at high temperatures are neglected in the conventional DNS approach.

The objective of this research project is to develop new numerical methods and perform DNS studies of laminar-turbulent transition of hypersonic boundary layers and transient hypersonic flows over complex 3-D maneuvering vehicles. The DNS numerical tools, as well as other theoretical approaches such as the linear stability analysis and the parabolized stability equations, are used to gain a new fundamental understanding of transition phenomena of 3-D chemically-reacting hypersonic boundary layers. In order to reach the research goal, the following tasks were undertaken during the report period:

1. To develop and validate new high-order massively-parallelized numerical methods and parallel computer codes for DNS of general 3-D hypersonic reacting flows over realistic maneuvering hypersonic vehicles. The new methods include new parallel methods for time-accurate viscous flow simulations, high-order spatial schemes, third-order semi-implicit Runge-Kutta schemes for reacting flow equations, and semi-implicit spatial schemes for viscous flow equations.
2. To perform DNS studies of the receptivity and stability of 3-D hypersonic boundary layers over elliptical blunt cones with bow shock interaction.
3. To conduct DNS studies of nonlinear wave interaction involving Görtler vortices in hypersonic inlets and over 3-D blunt leading edges with concave surfaces.
4. To conduct the DNS studies of instability and transition of 3-D reacting hypersonic boundary layers over blunt bodies. The fundamental physics of the real-gas effects on transition are investigated.
5. To conduct fundamental studies of the instability properties associated with hypersonic boundary layer transition. In the current research period, the focus was mainly on the linear stability analysis of hypersonic flow with bow shock effects and with a blunt leading edge.

3 ACHIEVEMENTS

The goal of this research project is to develop new advanced numerical methods and to perform DNS studies of transient hypersonic reacting flows over full 3-D maneuvering vehicles. The DNS tools and supporting theoretical approaches are used to gain new fundamental understanding of transition phenomena of 3-D chemically-reacting hypersonic boundary layers. Major accomplishments in the report period are documented in the publications listed in Section 7. They are briefly summarized below.

A. DNS of Receptivity of Hypersonic Flows Over Elliptical Cones and Wedges.

We have conducted a DNS study of 3-D hypersonic flows over elliptical cross-section cones and other 3-D flows by using our 14-node IBM SP-2 parallel computer purchased through AFOSR funds. We have conducted DNS studies of boundary layer receptivity for 3-D hypersonic flows over elliptical cross-section cones and over blunt leading edges. We are currently performing parametric DNS studies on the hypersonic receptivity physics for hypersonic flow over elliptical blunt cones and wedges. Such studies are valuable in prediction and control of hypersonic boundary layer transition.

C. DNS of Hypersonic Görtler Vortices Over Concave Inlet Surfaces

We have finished the parametric studies of the linear stability analysis of Görtler instability in hypersonic boundary layers. Subsequently, we conducted the DNS study of nonlinear development of 3-D Görtler vortices on concave surfaces with the effects of the bow shock. We are currently pushing the simulation domain further downstream to study the nonlinear breakdown of the Görtler vortices in hypersonic boundary layers.

B. DNS of Nonequilibrium Reacting Hypersonic Flows

We studied the real-gas effects on hypersonic boundary-layer flow stability and transition by using the DNS approach. So far, we have finished the reacting flow code validation and have conducted the DNS of the receptivity of 2-D reacting hypersonic boundary layers over blunt bodies. We are currently working on the DNS of stability and nonlinear breakdown of hypersonic reacting boundary layers over a flat plate. The use of a simpler flat-plate geometry enables us to simulate nonlinear breakdown better and to gain a better insight into the real gas effects on the reacting hypersonic boundary layers.

D. Parallel Implicit Numerical Algorithms

During the report period, we worked on developing new parallel implicit DNS algorithms for massively parallel computers to simulate 3-D transient reacting hypersonic boundary layer flows. The purpose is to overcome the inter-node communication bottleneck which dramatically reduces parallel simulation efficiency when many parallel nodes are simultaneously used in simulations. We are currently investigating the possibility of using a divide-and-conquer parallel algorithm to increase the parallel efficiency for implicit Navier-Stokes solvers.

E. PSE and LST Stability Analysis of Non-Parallel Hypersonic Flows

In order to support our DNS studies, we have been developing PSE and LST codes for non-parallel hypersonic flow with bow shock effects. So far, we have developed and validated two independent linear stability codes and have extended this parallel stability tool to include the non-parallel effects by using the PSE approach. This aspect of the work has now been finished.

These research accomplishments are discussed further in the following sections.

4 ACCOMPLISHMENTS AND HIGHLIGHTS

The major accomplishments and highlights of our research are summarized in this section. Our publications in the reporting period are listed in Section 7. The paper numbers cited in this section refer to those used in Section 7.

DNS of 3-D Hypersonic Flow Over Elliptical Cross-Section Cones.

Hypersonic flow over a 3-D blunt body experiences strong lateral pressure gradients that turn the streamlines away from the axial direction, inducing a skewed boundary layer profile with crossflow. The inflected crossflow velocity profile exhibits an inviscid instability. The character of the crossflow instability is well-established for subsonic and moderately supersonic flows over swept wings and certain model problems such as rotating disks, cones, and spheres[1]. Stability computations[2] have shown that crossflow increases the amplification rate and skewness of the most unstable first mode wave, and the most amplified second mode wave may be oblique to the freestream flow. Recently, Poggie and Kimmel[3] have done experimental work to examine stability and transition on a full 3-D configuration and to demonstrate a case in which the crossflow stability had a significant influence on boundary layer transition.

Our purpose is to conduct numerical studies of both steady and transient 3-D hypersonic flow over elliptical cross-section cones. We (Publications [1, 11, 14]) have extended our previous study of the receptivity of hypersonic boundary layers over parabolic blunt leading edges to the DNS of 3-D hypersonic flows over the cones. The first test case is the receptivity of a hypersonic boundary layer to freestream monochromatic planar acoustic disturbances for a Mach 15 and Reynolds number 6026 flow over a 2:1 elliptical cross-section blunt cone as shown in Fig. 1.

Figure 2 shows 3-D steady solutions for Mach number contours for the steady viscous hypersonic flow over a 2:1 elliptical cross-section blunt cone at Mach number 15. The bow shock is captured exactly as the outer computational boundary. The uneven strength of the bow shock in the major and minor axes creates the circumferential pressure gradient and cross flow velocity. The cross mass flow thickens the boundary layer and enlarges the standoff distance in the minor axis. The cross flow generates a streamwise vorticity component in the shock layer. Figure 3 shows the contours of streamwise vorticity components in a x =constant grid station. The figure shows that the vorticity is generated by cross flow velocity on the wall. It is expected that the cross flow instability plays an important role in the transition of the hypersonic boundary layers.

Having obtained the steady flow solutions, the generation of boundary-layer waves by freestream acoustic disturbances is simulated for 3-D hypersonic flow over a blunt elliptical cone with a freestream disturbance wave. The receptivity studies are carried out by imposing acoustic disturbances in the freestream. The subsequent interaction with the bow shock and wave development in the boundary layer are simulated by using the full nonlinear Navier-Stokes equations.

Figure 4 shows the 3-D contours for the instantaneous entropy perturbation s' after the unsteady computations are carried out for enough periods in time that periodic solutions have been reached in the entire flow field. Figure 5 shows instantaneous entropy and pressure perturbations in the major and minor axes. The instantaneous contours show the development of a single wave mode in the boundary layer along the surface. The receptivity simulation results show that new schemes can resolve 3-D transient hypersonic flow with physical bow-shock oscillations accurately.

DNS of 3-D Hypersonic Boundary Layers Over Axisymmetric Blunt Cones

In addition, we have also extended the previous planar 2-D work to the receptivity of axisymmetric boundary layers to freestream disturbances in Mach 15 flows over a parabolic cone (Publication [17]). The receptivity characteristics of axisymmetric and planar hypersonic boundary layers over blunt bodies were compared. The test case is the receptivity of an axisymmetric boundary layer to weak freestream acoustic disturbance waves for a Mach 15 hypersonic flow past a parabolic blunt cone at zero angle of attack. The axisymmetric steady and unsteady solutions for velocity vectors are shown in Fig. 6. The bow shock and development of boundary layers along the body surface are shown in this figure. The figure also shows the unsteady instantaneous perturbations of the velocity vectors for the receptivity of the axisymmetric Mach 15 flow over the parabolic cone with zero angle of attack.

The results show that new schemes can resolve 3-D transient hypersonic flow with physical bow-shock oscillations accurately. The receptivity characteristics of axisymmetric and planar hypersonic flow over blunt bodies are studied and compared. Compared with the planar case, the axisymmetric flow over a blunt cone has much higher after-shock Mach numbers and much fuller boundary layer profiles. Consequently, the axisymmetric first mode wave generated by the receptivity process has longer wave lengths and smaller growth rates than the planar case.

DNS of Hypersonic Görtler Vortices Over Concave Inlet Surfaces

The concave compression surfaces in front of hypersonic inlets are susceptible to Görtler counter rotating instability vortices, in addition to other hypersonic instability waves in hypersonic boundary layers [4]. Such Görtler instability is important in the prediction of the transition phenomena in inlet flow. In addition, the Görtler instability can also be exploited to enhance the instability and mixing if fuel injection is applied to the compression surface before entrance of the inlet. The DNS studies provide an ideal tool to study the characteristic and on-set of Görtler vortices for hypersonic flow over a concave surface and the receptivity of the Görtler instability to the disturbances introduced by the fuel injection. To achieve maximum mixing, it is possible to artificially excite the Görtler instability by specifying the fuel injection amplitudes and frequency. We have been working on the DNS of hypersonic boundary layer stability and transition over a concave surface with the effects of bow shock interaction. The main focus is to gain a better understanding of the destabilizing effects of the Görtler vortices on the boundary layers. In this project, Görtler vortices in hypersonic boundary layers are investigated mainly by DNS while LST is also conducted to support and help validate the DNS analysis.

In the report period, we have conducted a series of studies on linear and nonlinear interactions of Görtler vortices in hypersonic boundary layers. These results are documented in Publications [2], [9], [12], and [13]. Some sample results are shown in this section.

We have obtained both steady mean flow and unsteady flow solutions for a case of hypersonic flow over a blunt concave body, where the mean flow is two-dimensional but the unsteady flow of the Görtler vortex is three-dimensional. The specific flow conditions are $M_\infty = 15$ and $Re_\infty = 150753.175$. Both linear and nonlinear development of the Görtler vortex in the boundary layer have been studied. Figure 7 shows steady temperature and pressure contours for Mach 15 mean flow. Both figures show the effects of concavity of the wall. After obtaining the steady flow solutions, DNS of the linear and nonlinear growth of the Görtler vortices are simulated by imposing inlet disturbances in a localized computational domain shown in Fig. 8. The inlet disturbances are eigenfunctions obtained from linear stability analysis using the simulated mean flow. We have started to study spatial Görtler instability. In spatial linear stability analysis, eigenfunctions do not depend on time, and initial disturbances at the inlet are fixed as time increases. Initial disturbances propagate spatially and converge to steady state condition. In the current computation, the spanwise nondimensional wave number β is 0.1, which is nondimensionalized by boundary layer thickness, δ. Figure 8 shows the temperature perturbation contours in the simulation. The growth of the Görtler vortex in the streamwise direction is shown by the increase of the intensity of the disturbances. The numerical solutions agree very well with linear predictions for the current case of small inlet disturbances.

In addition, we have also developed a linear stability computer code to study the Görtler instability on an arbitrary shape surface. We have validated the LST code for the Görtler instability by comparing with published results by other researchers for both incompressible and compressible flows. It was shown that the code gave good agreements with previous results. Figure 9 shows the streamwise velocity contours for the eigenfunctions of the first and second Görtler modes for an incompressible flow case. The two peaks in the figure represent that there are two vorticity layers which are stacked together. Mode II contains one more layer than Mode I. Dashed lines represent negative values. However, higher modes are rarely observed in experiments because the growth process of these modes is much slower than one of the primary mode. The shapes of eigenfunctions are similar to those in Herbert [5]. Figure 10 compares eigenfunction distributions with those published by Kahawita et al [6]. The shape of eigenfunctions obtained by our calculations agree reasonably well with those by Kahawita.

After these initial studies, we have extended our studies to the nonlinear development of the Görtler vortices and the nonlinear interaction of Görtler vortices with other instability modes. The nonlinear breakdown of the Görtler vortrices is a critical step in the laminar turbulent transition process of concave hypersonic boundary layers. Experiments showed that it is mainly due to the interaction of nonlinear growth of Görtler vortices and other forms of disturbances. In the nonlinear growth process, mushroom shaped vortices are produced since the counter-rotating vortices pump fluid with a low streamwise velocity away from the wall. There are two regions in Görtler vortices are the peak region (low velocity region) and valley region (high velocity region). These two regions produce the mushroom shaped vortices. Interaction between these vortices and traveling waves is the main factor resulting in break down to turbulence.

As an example of the DNS results on nonlinear development of Görtler vortices in hypersonic boundary layers, figure 11 and 12 show streamwise mean velocity distributions as flow moves downstream. The development of mushroom shaped vortices is well represented in the figure. The bow shock does not have much effect on the flow field, since Görtler vortices develop in the viscous layers. The peak and valley regions are clearly shown in the figure. While the middle region (peak) tends to go up, others become narrower. The Görtler vortices pump vertically, the low-speed fluid, away from the wall in the peak region and push the high speed fluid toward the wall in the valley region. However, there is the limitation of growing thickness of the peak, and high speed fluid starts to transfer to the peak region near the wall and the low speed fluid to the valley away from the wall. As a result, the mushroom shaped vortices are produced. Details of the results can be found in [2], [9], [12], and [13].

DNS of Nonequilibrium Reacting Hypersonic Flows

For high-enthalpy hypersonic flows, real gas effects are expected to have a strong impact on the flow structure and heating rates. We (Publications [8]and [15]) have been working on the DNS studies of instability and transition of 3-D reacting hypersonic boundary layers over blunt bodies and flat plates. We have extended our ideal-gas DNS shock-fitting 3-D codes for nonequilibrium real-gas flow simulations. The effects of thermo-chemical reactions on boundary-layer transition are investigated by both DNS and theoretical analysis based on the boundary layer approach. The real-gas model is a five-species air model with both chemical and vibrational nonequilibrium. Figure 13 shows steady vorticity contours obtained by using the fifth-order shock fitting schemes for Mach 15 hypersonic reacting flow over a blunt parabolic leading edge. The real-gas viscous flow solutions are compared with the corresponding solutions obtained by neglecting the real-gas effects. In the real gas case, the bow shock is more significantly curved , and the standoff distance of the shock is smaller than that in the perfect gas case. As a result, larger vorticity is generated across the shock in nonequilibrium flow. The figure shows that the real gas effects have a strong influence on flow properties. The real-gas solution has much stronger entropy and vorticity layers which can be expected to induce entropy layer instability for hypersonic flows [7].

We then used DNS as a tool in studying the entropy and boundary layer instability for reacting 3-D hypersonic flows over blunt leading edges. In the unsteady simulation, the freestream disturbances are superimposed on the steady mean flow to investigate the development of T-S waves in the boundary layer with the effects of the bow shock interaction. The contours of vertical velocity perturbations are shown in Fig. 14.

Meanwhile, we have also finished the code validation and evaluation of numerical accuracy in our high-order nonequilibrium flow code. To validate this numerical method and computational code, steady hypersonic flow past cylinders at the same flow conditions as Hornung's [8] experiments is computed. The freestream flow conditions are partially dissociated nitrogen flow past a 2 inch diameter cylinder at $u_\infty = 5590\ m/s$, $T_\infty = 1833°K$, $p_\infty = 2910\ Pa$, 92.7% N_2 and 7.3% N by mass, $T_w = 1833°K$. Two nonequilibrium chemistry models were used in the simulations to test their effects of real gas models on reacting hypersonic flows. The first model was the Park model [9], and the second model was the Dunn-Kang rate coefficient model [10]. Figure 15 compares computational results using the two models (shown in the bottom half of the figure), to an experimental interferogram published by Hornung [8]. The computational shock shape and standoff distance agree very well with the experimental data. The inference fringe shapes of the Park Model are very similar to the experimental photo. For the result of the Dunn-Kang Model, there are visible differences between the inference fringe shapes of the computation and experiment. A comparison of fringe number profile along the stagnation line between the two chemical models is shown in Figure 16. Compared with experimental data, the Park model yielded better results than did the Dunn-Kang model. The results indicated that the choice of thermochemical model can have large effects on the shock shape and standoff distance. The results demonstrate the capability of our numerical method to accurately model flows in thermochemical nonequilibrium. In addition, we have done extensive validation calculations on our high-order nonequilibrium reacting code, including the comparison of stagnation heating rates for both perfect-gas and nonequilibrium flows with the classical theory of Fay and Riddell [11]. The theoretical prediction in the heat transfer at the stagnation point agrees well with numerical simulations of full Navier-Stokes equations.

The real gas effects on hypersonic boundary layer stability and transition involve complex flow physics of nonequilibrium reaction and relaxations. In order to better study the mechanism of real gas effects on boundary layer stability and transition, we have focused on a simple flow domain of a flat plate with nonequilibrium. Again, DNS is used to study the linear and nonliner stabilities of nonequilibrium reacting flow over a flat plate. Some initial results have been presented in Publication [15]. The numerical solutions are validated by boundary layer theory and linear stability analysis. Figure 17 shows the contours of instantaneous pressure perturbation after the flow field reaches a periodic state for a case of development of instability waves in a flat plate boundary layer.

Parallel Implicit Numerical Algorithms for DNS of Reacting Hypersonic Flows

In Publications [5], [10], [20] and [21], we continue to develop and validate new parallel computer codes using our new semi-implicit schemes for the DNS of 3-D hypersonic boundary layers over blunt bodies.

In [10], we developed new parallel implicit DNS algorithms for massively parallel computers to simulate 3-D transient reacting hypersonic boundary flows. The computational domain is decomposed into a number of smaller computational domains. Parallel programming with the Message-Passing Interface (MPI) model is applied to parallelize the 3-D code to compute the different domains by using different computer processors respectively at the same time. We used a divide-and-conquer parallel algorithm to increase the parallel efficiency for implicit Navier-Stokes solvers. The purpose is to overcome the inter-node communication bottleneck which dramatically reduces parallel simulation efficiency when many parallel nodes are simultaneously used in simulations. From the results of studying the convection-diffusion model equation and the instability of supersonic Couette flow, the computational efficiency can be improved by using parallelized semi-implicit methods while maintaining the same accuracy as that of the parallelized explicit methods. We can also get the satisfactory results by using the new parallelized semi-implicit methods for the direct simulations of hypersonic boundary layers over blunt bodies to freestream acoustic disturbances.

During the report period, a set of new high-order upwind schemes with and without the shock-fitting procedure were also validated and tested in computations for the linear wave equation and nonlinear Navier-Stokes equations. The numerical tests show that the new schemes can achieve efficient and high-order numerical simulation for reacting hypersonic boundary layers over three-dimensional blunt bodies. A semi-implicit high-order upwind finite difference shock fitting method has been tested and validated in Ref. [12], which includes several test cases: 1-D linearized model convection-diffusion equation, 2-D DNS of stability of supersonic Couette flow, 2-D DNS of stability of supersonic flat plate boundary layer, and the DNS of receptivity to freestream acoustic disturbances for 2-D hypersonic boundary layer over a parabola. The CPU time reduction for the semi-implicit method for both cases is typically in the range of 8-10 times over those required by the explicit calculations with the same numerical accuracy.

We have also conducted code validation on hypersonic flow over an axisymmetric body at zero angle of attack for the new high-order parallelized shock-fitting code. A sphere is chosen as the validation case since there are a lot of experimental results for a sphere in supersonic flow [13, 14]. Grid refinement comparisons are also used to ensure that solutions are grid independent. The flow conditions are $M_\infty = 5.25$ and $Re_d = 36,159.3$. Figure 20 shows the steady solution for a set of $90 \times 60 \times 32$ computational grids obtained by the numerical simulations for Mach number 5.25 flow over a sphere. Since these steady flows are axisymmetric, we present the results only in a computational surface of a fixed azimuthal angle. This figure also shows the contours of steady axisymmetric flow solutions of Mach numbers and the computed and experimental pressure coefficients. The agreement is good within the scatter in the experimental data.

PSE Studies of Non-Parallel Hypersonic Flow Instability

In order to support our major efforts in the DNS studies, we have developed two linear stability codes for hypersonic boundary layer shear flows and have been conducting LST studies of hypersonic wave characteristics. In Publications [16] and [19], we studied the linear stability of 3-D hypersonic boundary layers over blunt leading edges. The linear stability analysis is performed using a global spectral collocation method accounting for the shock effects by using Rankine-Hugoniot shock conditions on the upper boundary. It is shown that in addition to the boundary layer first modes and higher modes (Mack modes), the linear stability of the hypersonic flow between a bow shock and a parabolic leading edge has a new family of modes, shock modes. The shock modes are important mainly in the shock layer. In addition, the boundary layer modes are also affected by the existence of the shock. In comparison with the DNS results, it is found that both the LST and DNS resolve the boundary layer modes well in terms of the wave number and the shape function of the pressure disturbance. However, disagreement in the growth rates between LST and DNS solutions has been observed. The difference may be due to the fact that the underlining assumptions of LST is the parallel assumption, which may not be proper for the blunt bodies.

PSE (parabolized stability equations) methods, which account for weak non-parallel effects, are currently being developed to improve the comparisons with DNS for hypersonic blunt body flows. The purpose of using PSE in addition to DNS is to provide an alternative means of analyzing the stability of the hypersonic blunt body flows where nonparallel effects are important.

We have since developed a nonparallel PSE code for hypersonic flow over blunt bodies. Currently, some benchmark tests have been conducted for a flat plate supersonic boundary layer. The results shown in Fig.18 are the growth rates vs R at $F = 40, b = 0.15, T_0 = 311K$ where $b = \beta * 10^3/R_0$, R_0 is the initial Reynolds number. Our PSE results differ slightly from the results from Bertolotti [15] which may be due the use of different viscosity models and different approaches in obtaining initial conditions. Nonetheless, our PSE results agree with the result from El-Hady's multiple scale analysis [16]. Another case with $b = 0$ is computed with both LST and nonparallel PSE, wavenumbers and growth rates from both methods are shown in left and right sides of Fig. 19 respectively. Results from Bertolotti [15] are also shown to compare with our growth rate data. Notice that Bertolotti's results with parallel basic flow are LST results. The difference again is due to the reasons mentioned earlier as one can see that the use of $Pr = 0.72$ gives a better match with Bertolotti's data where Pr is not a constant, than that of $Pr = 0.7$. The nonparallel effects in this case stabilize the flow as the growth rates from PSE are observed to be smaller than the LST results. The wavenumbers from both methods are quite close.

5 FUTURE WORK

So far, we have developed new methodologies and have demonstrated the feasibility of our approach as a practical DNS tool to explore transient hypersonic reacting flow physics. The focus of future work is on the DNS studies the hypersonic flow physics related to the hypersonic boundary layer transition, and to extend these DNS and theoretical studies to 3-D transient hypersonic flows with complex real-gas models and complex geometries, and the DNS of nonlinear breakdown and interactions of instability modes in hypersonic boundary layers. The specific tasks are:

1. To perform DNS of the receptivity and transition of 3-D hypersonic boundary layers over blunt elliptical cross-section cones with cross flow instability, nonlinear breakdown, and general 3-D geometries.
2. To perform DNS of the receptivity and transition of 3-D nonequilibrium reacting hypersonic boundary layers over flat plate, blunt leading edges, and blunt cones. The real gas effects on linear development and nonlinear breakdown of instability modes will be studied by the DNS approach.

3. To perform DNS of the receptivity and transition of hypersonic boundary layers over concave blunt bodies with Görtler instability, as a first step in the DNS of complete inlet flow fields with fuel injection. The focus is on the late stage of nonlinear breakdown and interaction of the Görtler and other instability modes.
4. To develop new accurate and efficient parallel numerical algorithms for reacting hypersonic flow DNS schemes. The main focus is on the development of efficient parallel implicit algorithms for massively parallelized computers.

6 PERSONNEL

The following personnel conducted research for the grant and were partially supported by the grant:

1. Professor Xiaolin Zhong, principal investigator.
2. Chong W. Whang, a Ph.D. student.
3. Yanbao Ma, a Ph.D. student.
4. Haibo Dong, a Ph.D. student.
5. Sean H. Hu, a Ph.D. student. He left UCLA in July 1999.

7 PUBLICATIONS

The following publications were completed from work supported by this grant:

In Journals or Books:

1 X. Zhong, "DNS of Boundary-Layer Receptivity to Freestream Sound for Hypersonic Flows over Blunt Elliptical Cones," in **Recent Advances in DNS and LES**, D. Knight and L. Sakell, editors, Kluwer Academic Publishers, pp 493-504, 1999.

2 C. Whang and X. Zhong, "Direct Numerical Simulation of Görtler Instability in Hypersonic Boundary Layer," in **Recent Advances in DNS and LES**, D. Knight and L. Sakell, editors, Kluwer Academic Publishers, pp 473-484, 1999.

3 T. Lee and X. Zhong, "Spurious Numerical Oscillations in Numerical Simulation of Supersonic Flows Using Upwind Schemes," **AIAA Journal**, Vol. 37, No. 3, pp. 313-319, 1999.

4 X. Zhong and G. H. Furumoto, "High-Order Numerical Methods for Unsteady Hypersonic Flow Simulations," **in Computational Fluid Dynamics Review 1998**, Vol. 2, M. Hafez and K. Oshima, editors, pp. 758-784, 1998.

5 X. Zhong "High-Order Finite-Difference Schemes for Numerical Simulation of Hypersonic Boundary-Layer Transition," **Journal of Computational Physics**, Vol. 144, pp. 662-709, 1998.

6 S. H. Hu and X. Zhong, "Linear Stability of Viscous Supersonic Plane Couette Flow," **Physics of Fluids**, Vol. 10, No. 3, March, 1998, pp. 709-729.

In Conference Proceedings:

7 X. Zhong, "Receptivity of Hypersonic Boundary Layers to Freestream Disturbances", AIAA paper 2000-0531, the 38th Aerospace Sciences Meeting and Exhibit, Jan 10-13, 2000, Reno, Nevada.

8 Y. Ma and X. Zhong, "Direct Numerical Simulation of Instability of Nonequilibrium Reacting Hypersonic Boundary Layers", AIAA paper 2000-0539, the 38th Aerospace Sciences Meeting and Exhibit, Jan 10-13, 2000, Reno, Nevada.

9 C.W. Whang and X. Zhong, "Nonlinear Interaction of Görtler and Second Shear Modes in Hypersonic Boundary Layers", AIAA paper 2000-0536, the 38th Aerospace Sciences Meeting and Exhibit, Jan 10-13, 2000, Reno, Nevada.

10 H. Dong and X. Zhong, "A Parallel High-Order Implicit Algorithm for Compressible Navier-Stokes Equations", AIAA paper 2000-0275, the 38th Aerospace Sciences Meeting and Exhibit, Jan 10-13, 2000, Reno, Nevada.

11 X. Zhong, "DNS of Boundary-Layer Receptivity to Freestream Sound for Hypersonic Flows Over Blunt Elliptical Cones", In Proceedings of IUTAM Symposium on Laminar-Turbulent Transition, Sedona, Arizona, September 13-17, 1999

12 C. Whang and X. Zhong, "Direct Numerical Simulation of Görtler Instability in Hypersonic Boundary Layers", In Proceedings of IUTAM Symposium on Laminar-Turbulent Transition, Sedona, Arizona, September 13-17, 1999

13 C. W. Whang and X. Zhong, "Direct Numerical Simulation of Görtler Instability in Hypersonic Boundary Layers", AIAA Paper 99-0291, January, 1999.

14 X. Zhong and H. Dong, "Hypersonic Boundary-Layer Receptivity to Freestream Disturbances Over an Elliptic Cross-Section Cone", AIAA Paper 99-0409, January, 1999.

15 Y. Ma and X. Zhong, "Numerical Simulation of Transient Hypersonic Flow with Real Gas Effects", AIAA Paper 99-0416, January, 1999.

16 S. Hu and X. Zhong, "Stability Analysis of Compressible Boundary Layer using 3-D PSE", AIAA Paper 99-0813, January, 1999.

17 X. Zhong, 'Direct Numerical Simulation of 3-D Hypersonic Boundary Layer Receptivity to Freestream Disturbances," AIAA paper 98-0553, January, 1998.

18 T. K. Lee and X. Zhong, "Spurious Numerical Oscillations in Numerical Simulation of Supersonic Flows Using Shock Capturing Schemes," AIAA paper 98-0115, January, 1998.

19 S. Hu and X. Zhong, "Hypersonic Boundary-Layer Stability over Blunt Leading Edge with Bow-Shock Effects," AIAA paper 98-0433, January, 1998.

20 H. Dong and X. Zhong, "High-Order Semi-Implicit Simulation of Hypersonic Boundary Layer Stability and Transition," AIAA paper 98-0127, January, 1998.

21 J. J. Yoh and X. Zhong, "Low-Storage Semi-Implicit Runge-Kutta Methods for Reactive Flow Computations," AIAA paper 98-0130, January, 1998.

8 ACKNOWLEDGMENTS

The author gratefully acknowledges the support and encouragement of Dr. Leonidas Sakell, the program manager of this AFOSR grant, on the research work reported in this report.

9 REFERENCES

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10 FIGURES

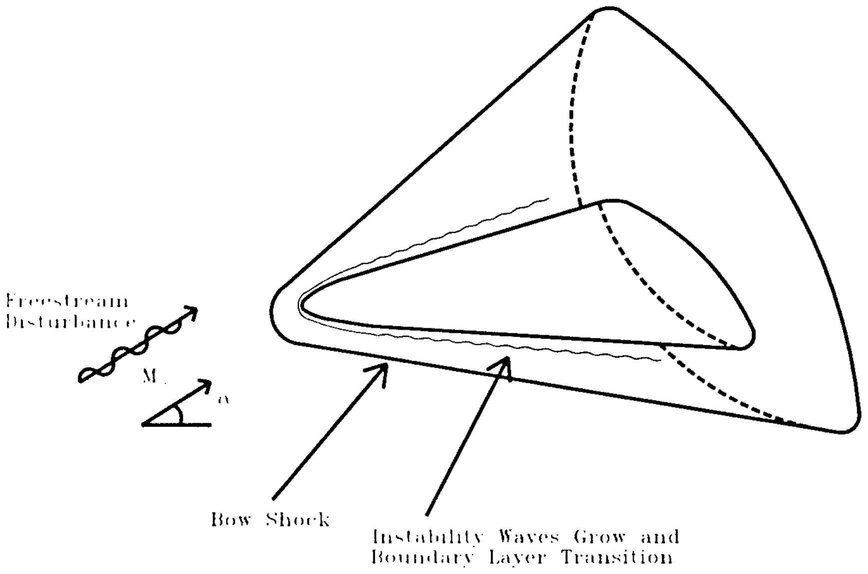

Figure 1: Hypersonic flow field in the direct numerical simulation of 3-D reacting hypersonic boundary-layer transition and receptivity to free-stream disturbances over a blunt elliptic cross-section cone.

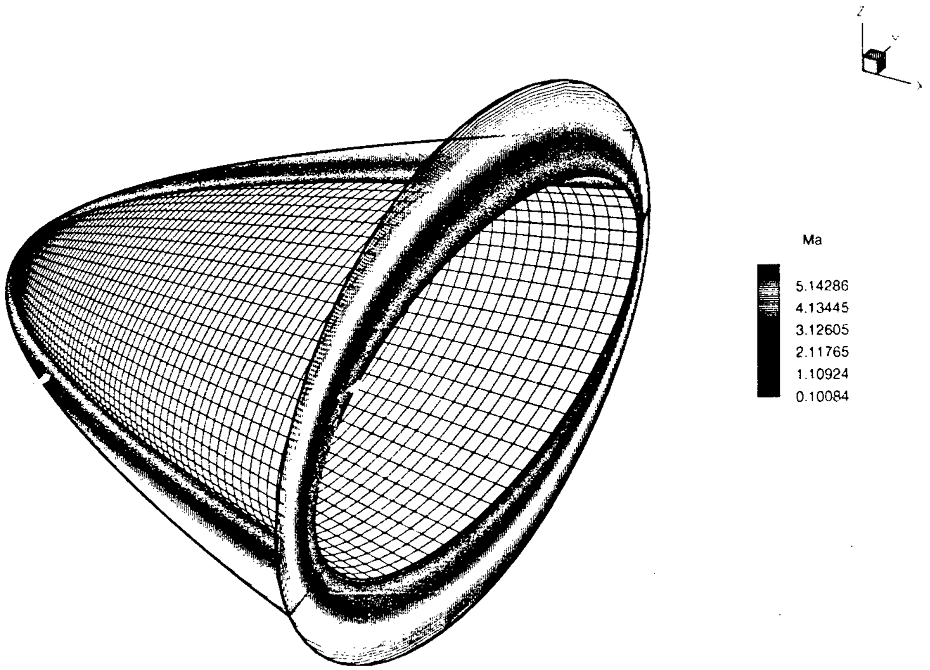

Figure 2: Mach number contours for steady viscous 3-D hypersonic boundary layer flow fields over a 2:1 elliptic cone. ($M_\infty = 15$ and $Re_\infty = 45561$).

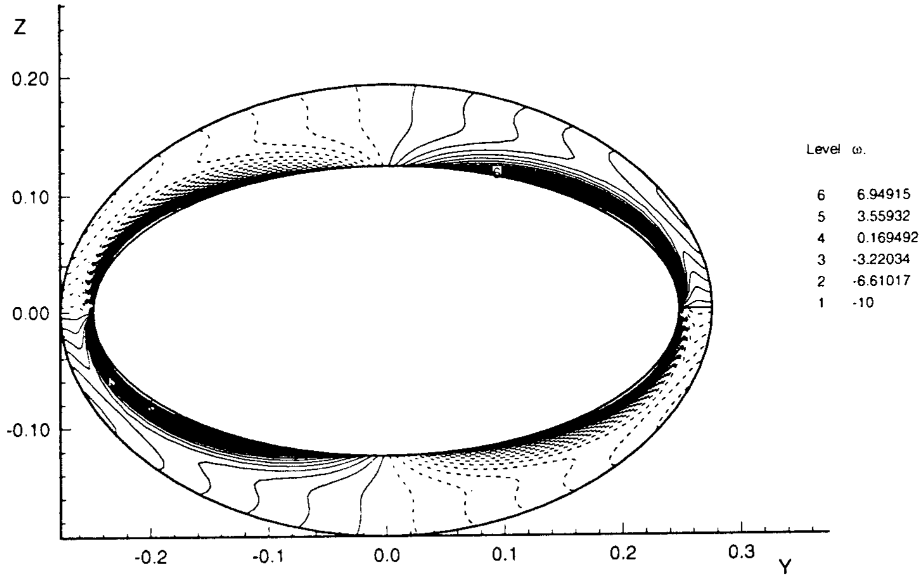

Figure 3: Contours of streamwise vorticity components at the $x = -0.55$ grid station.

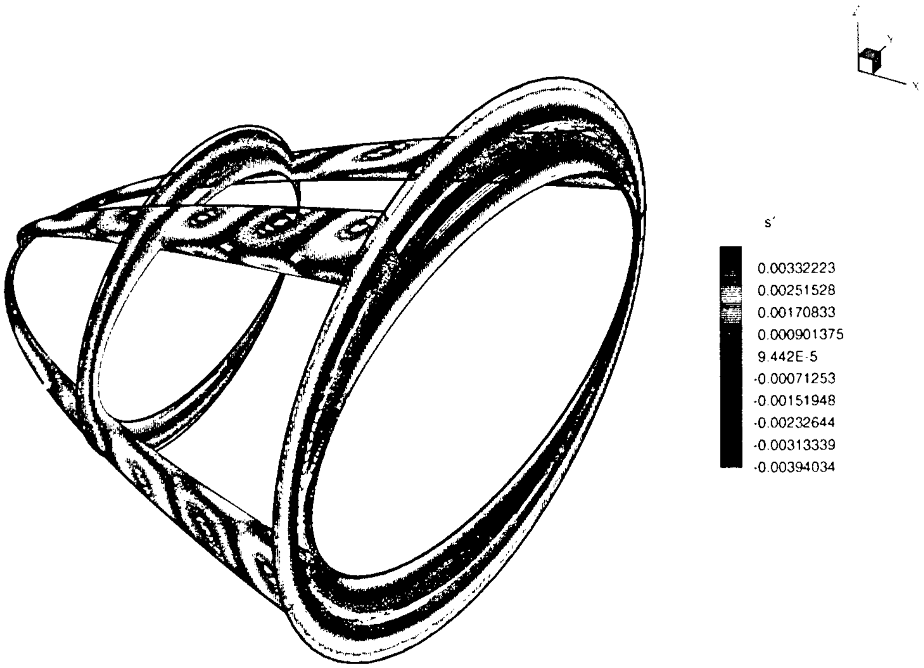

Figure 4: Instantaneous 3-D entropy perturbations induced by freestream planar acoustic disturbances.

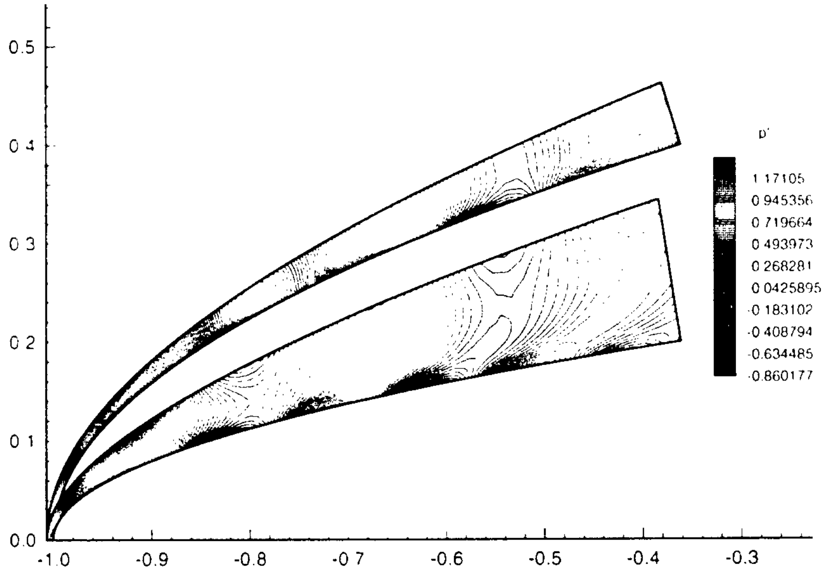

Figure 5: Instantaneous pressure perturbations induced by freestream planar acoustic disturbances in the major and minor axes.

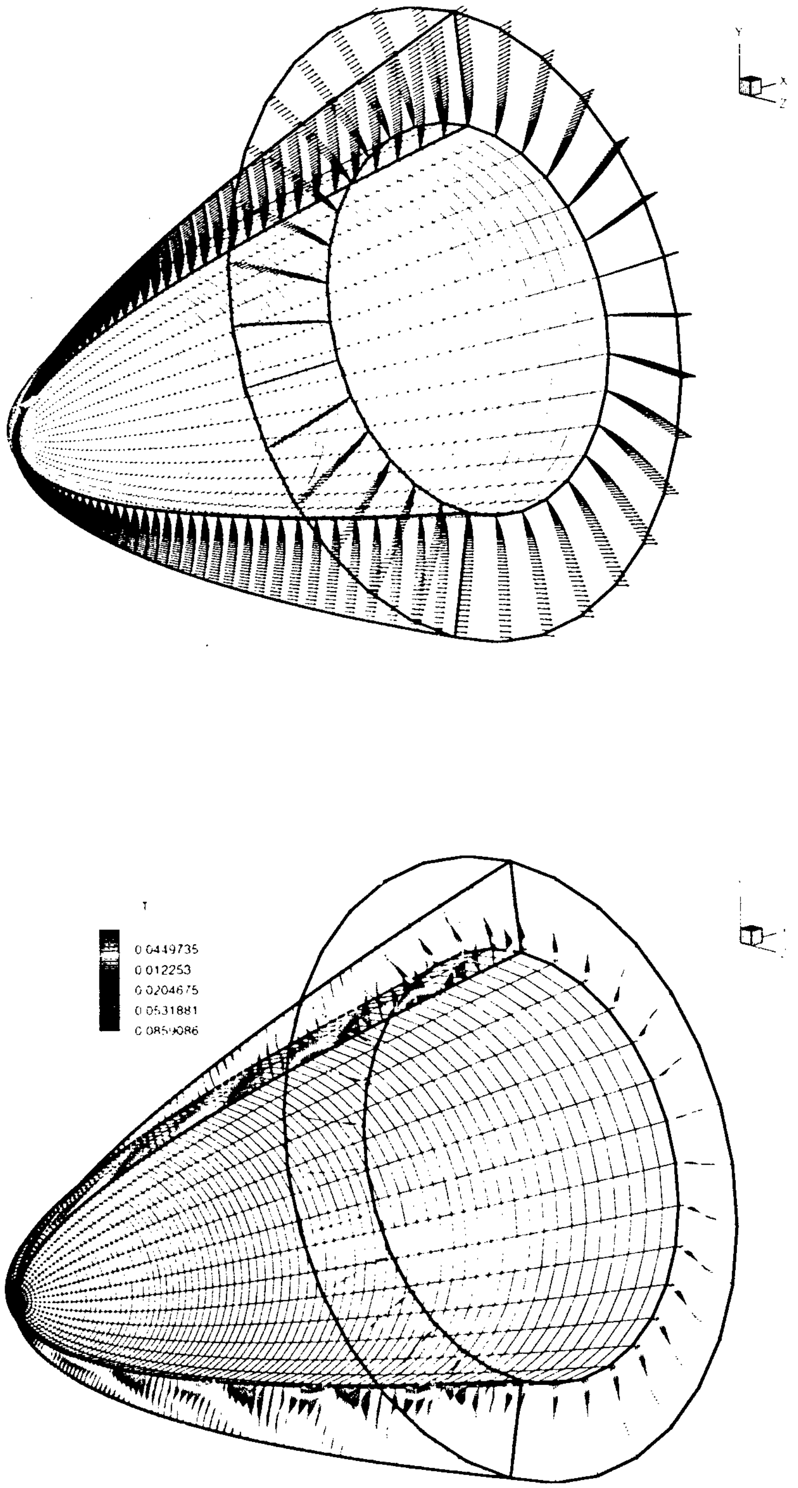

Figure 6: Solutions of steady and unsteady simulations of axisymmetric Mach 15 viscous hypersonic flow over a blunt cone (Upper figure: steady velocity vectors, lower figure: instantaneous perturbations of velocity vectors caused by the receptivity to freestream sound at a nondimensional frequency $F = 1770$).

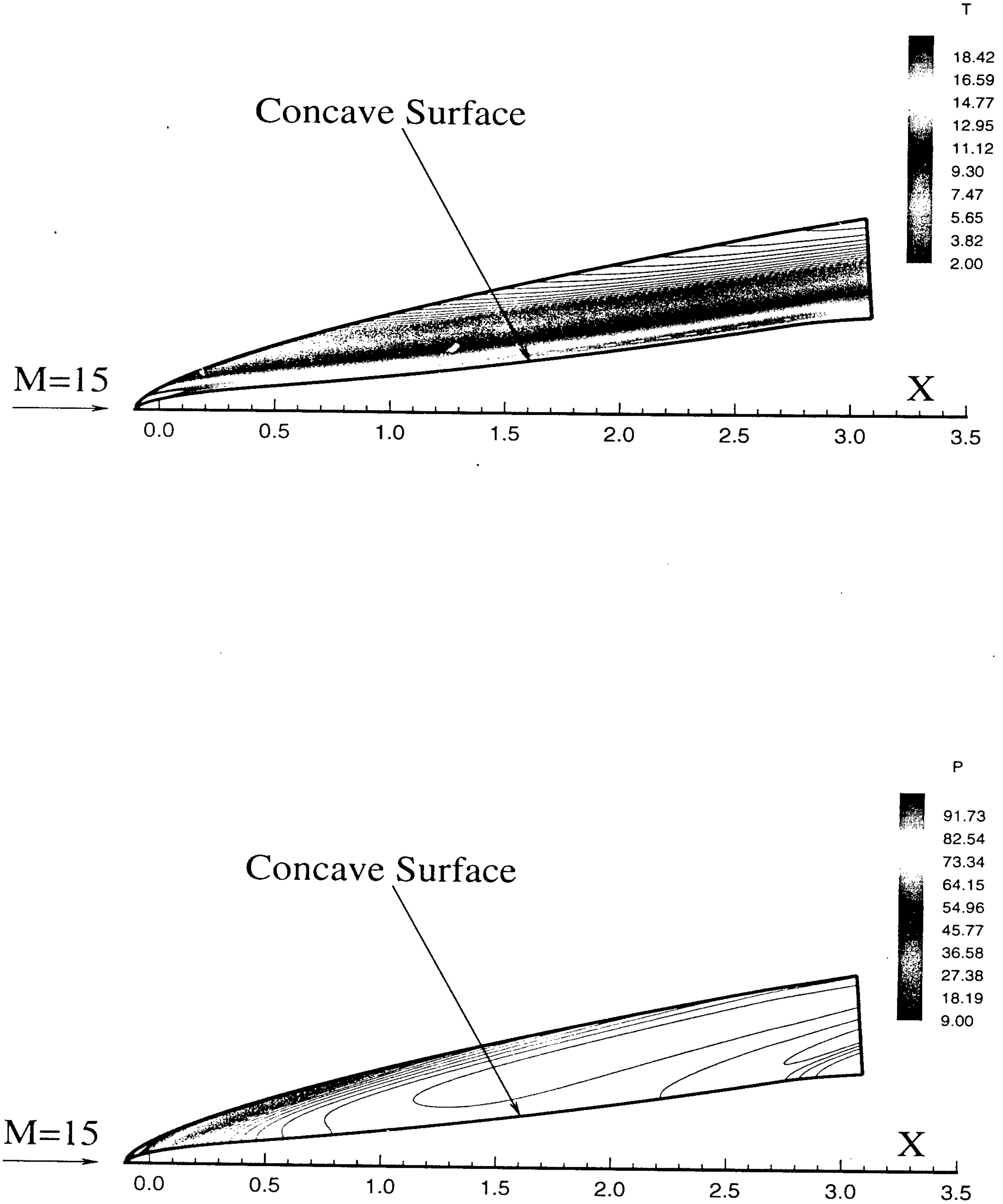

Figure 7: Temperature and pressure contours for the steady hypersonic mean flow over a concave blunt body at $M_\infty = 15$, $T^*_\infty = 101.059$ K, $P^*_\infty = 10.3$ Pa, $T^*_w = 1000$ K, $Re_\infty = 150753.17$.

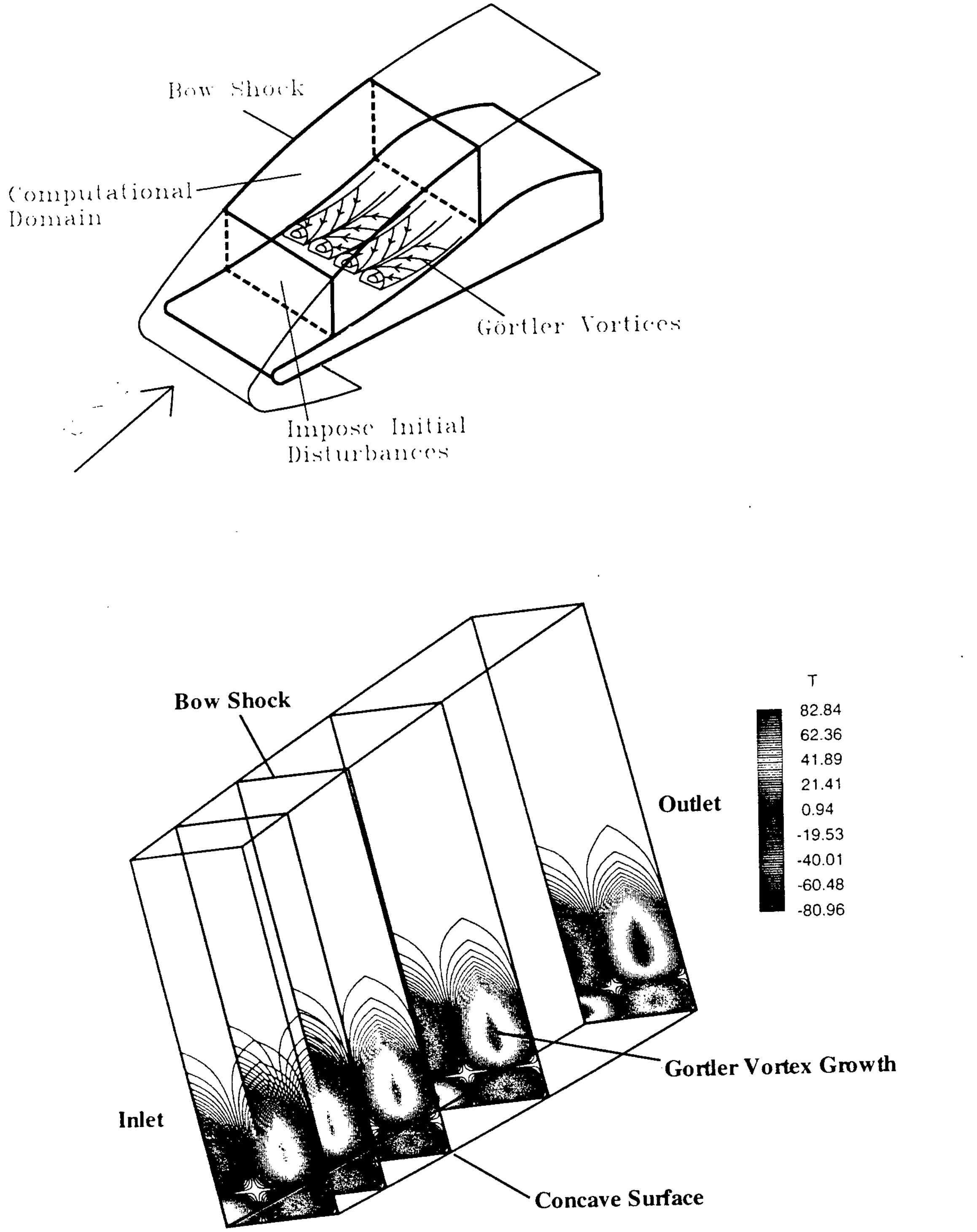

Figure 8: A schematic of the concaved body(engine inlet) on which shock and Görtler vortices exist. Temperature contours from DNS results, showing Görtler vortex growth over a concaved body surface on which shock and Görtler vortices exist. Flow conditions are $M_\infty = 15$, $T^*_\infty = 101.059$ K, $P^*_\infty = 10.3$ Pa, $T^*_w = 1000$ K, $Re_\infty = 150753.17$.

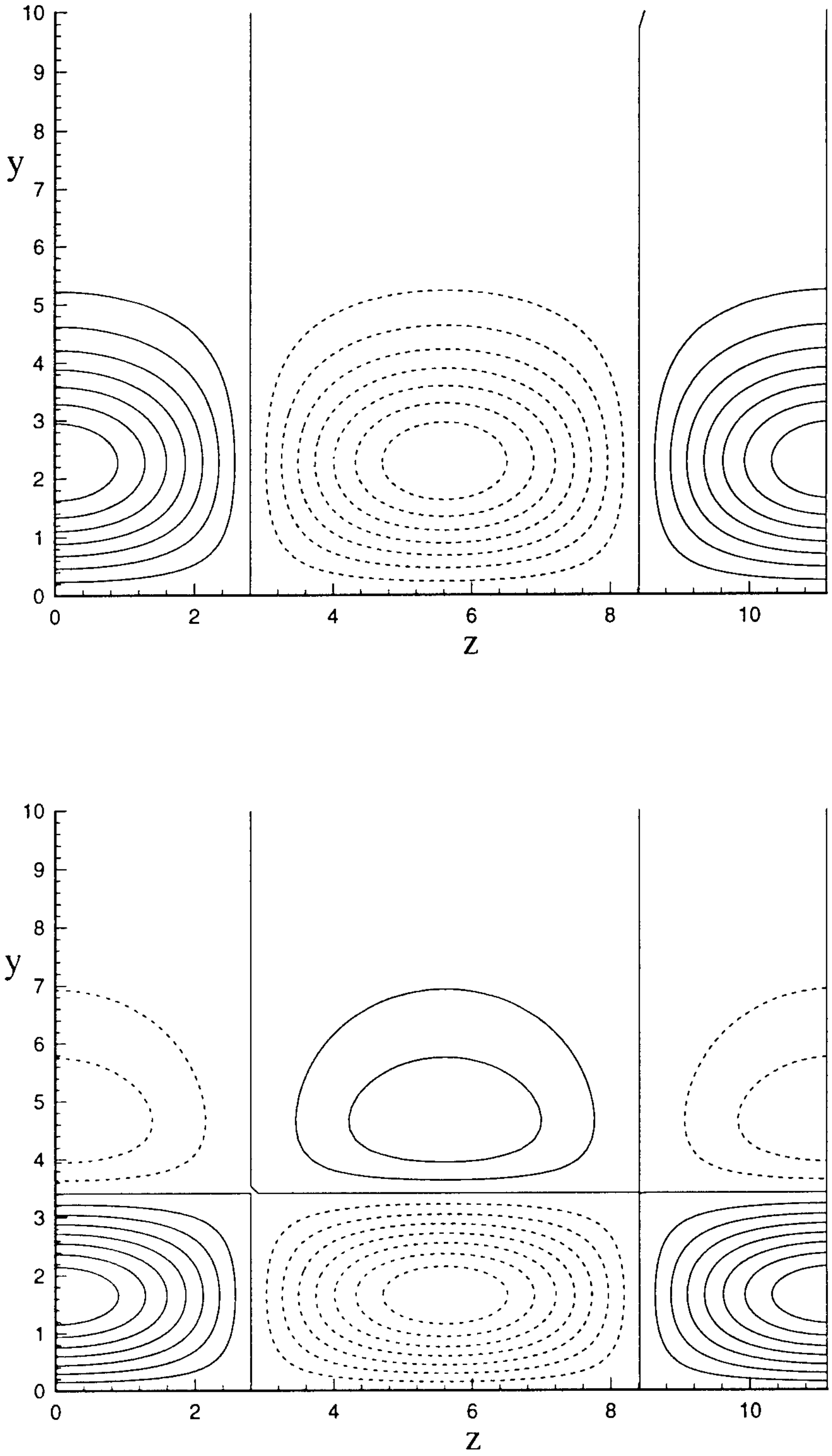

Figure 9: Streamwise velocity contours of Görtler instability mode I (top) and mode II (bottom) for incompressible flow over a concave wall, as part of a validation study, at $G = 6.55$, $U^*_\infty = 5\text{m/sec}$, $R^* = 3.2m$, and $\beta = 0.56$.

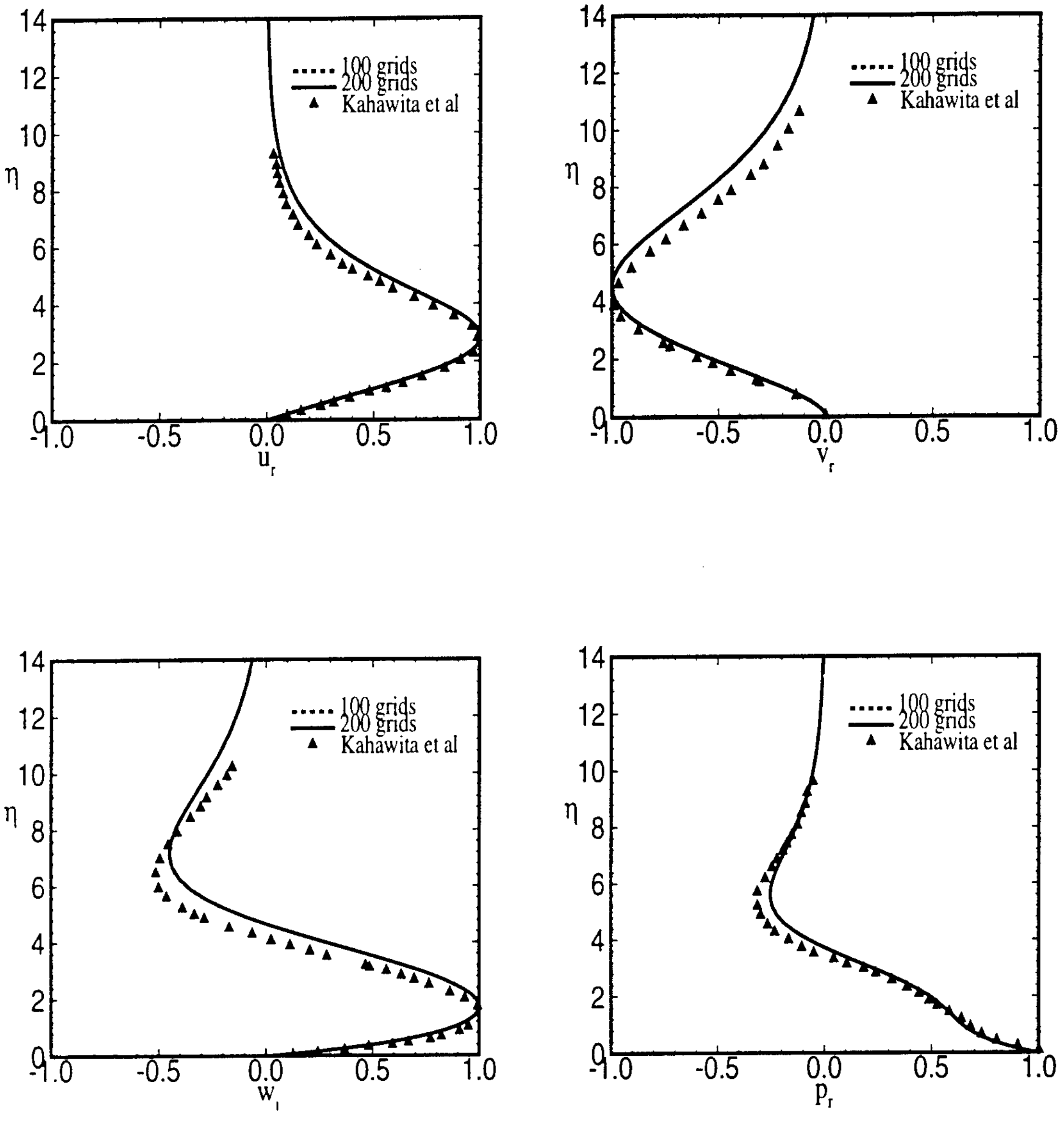

Figure 10: Eigenfunction distributions of the Görtler instability first mode, for incompressible flow over a concave wall, in two different sets of grids at $G = 2.569$, $R = 3.2m$, $T^*_\infty = 292.4K$, $U^*_\infty = 5m/sec$, and $\beta = 1.0$ (Streamwise velocity, normal velocity, spanwise velocity, and pressure). Results are compared with Kahawita et al(1979).

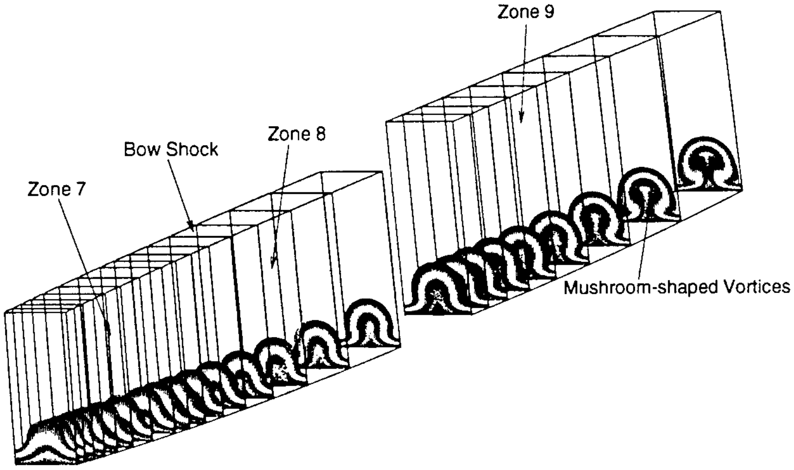

Figure 11: Distributions of iso-contours of streamwise mean velocity along the streamwise direction for zone 7, 8 and 9. The size of grids is $483 \times 121 \times 64$. Mushroom shaped vortices develop, as flow moves downstream, due to nonlinear effects.

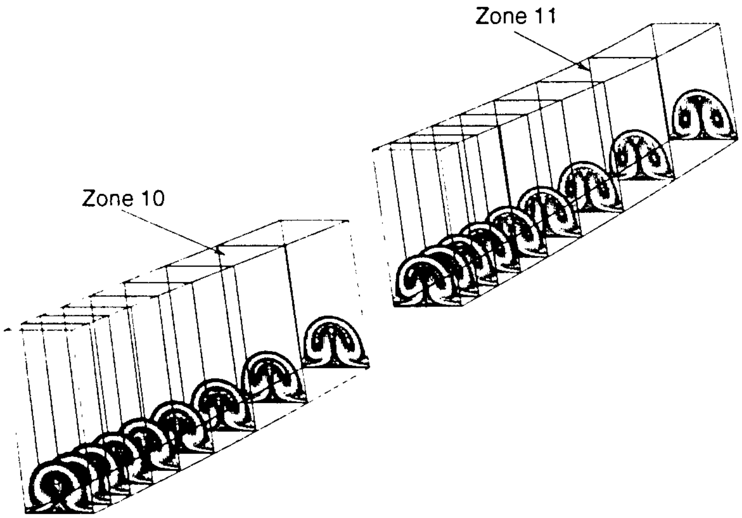

Figure 12: Distributions of iso-contours of streamwise mean velocity along the streamwise direction for zone 10 and 11.

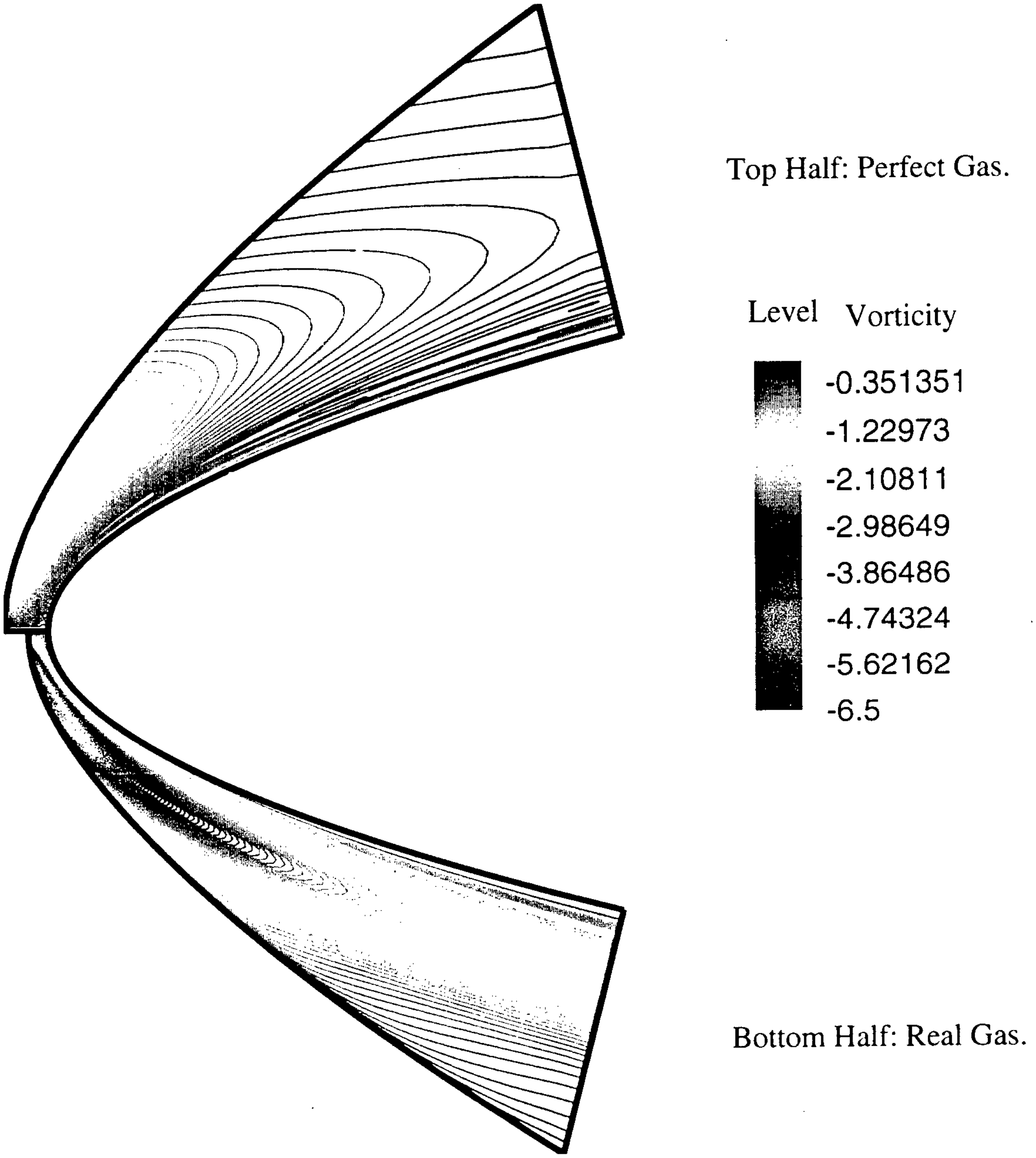

Figure 13: Vorticity contours of 2-D hypersonic ($M_\infty = 15$) viscous flow over a parabolic leading edge, where the reacting flow solution is compared with the perfect gas solution. The solutions are obtained by using fifth-order shock fitting codes with nonequilibrium source terms. The real gas effects introduce much stronger vorticity in the entropy shear layer behind the curve bow shock.

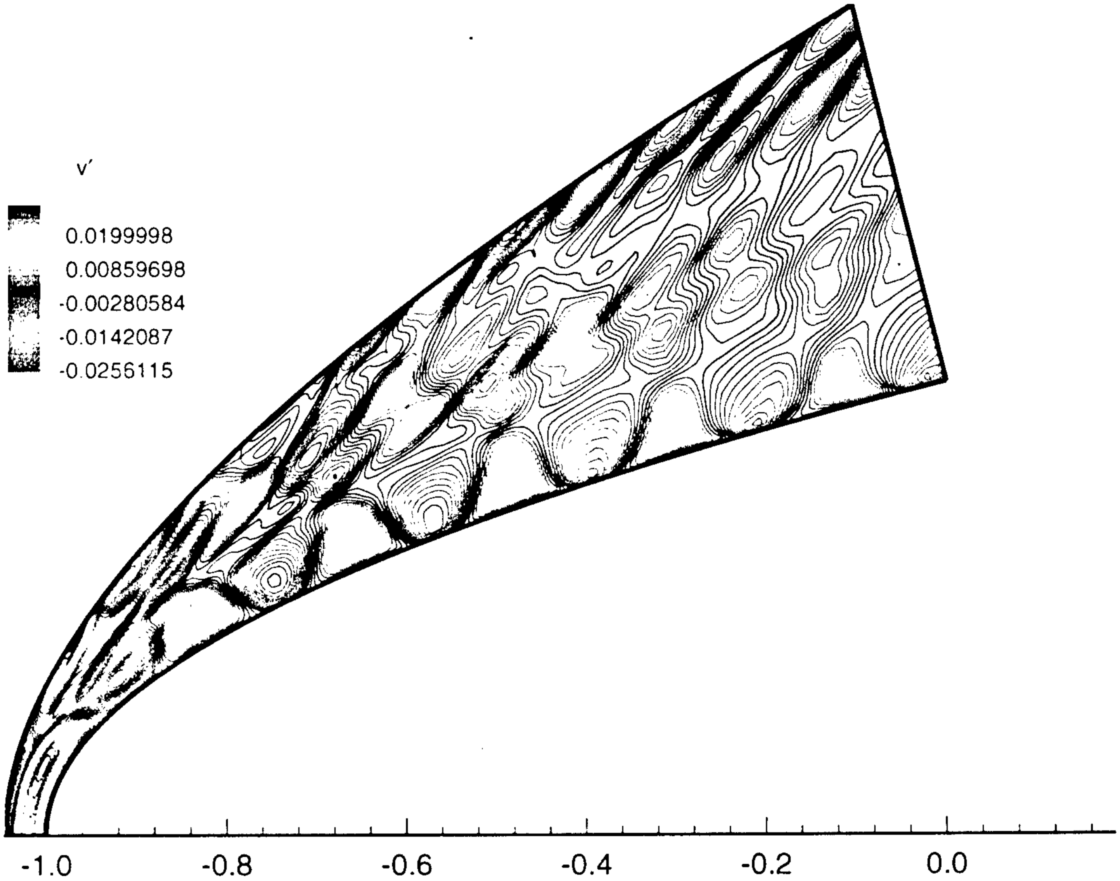

Figure 14: Unsteady vertical velocity contours of 2-D hypersonic ($M_\infty = 15$) viscous flow over a parabolic leading edge. The solutions are obtained by using fifth-order shock fitting codes with nonequilibrium source terms.

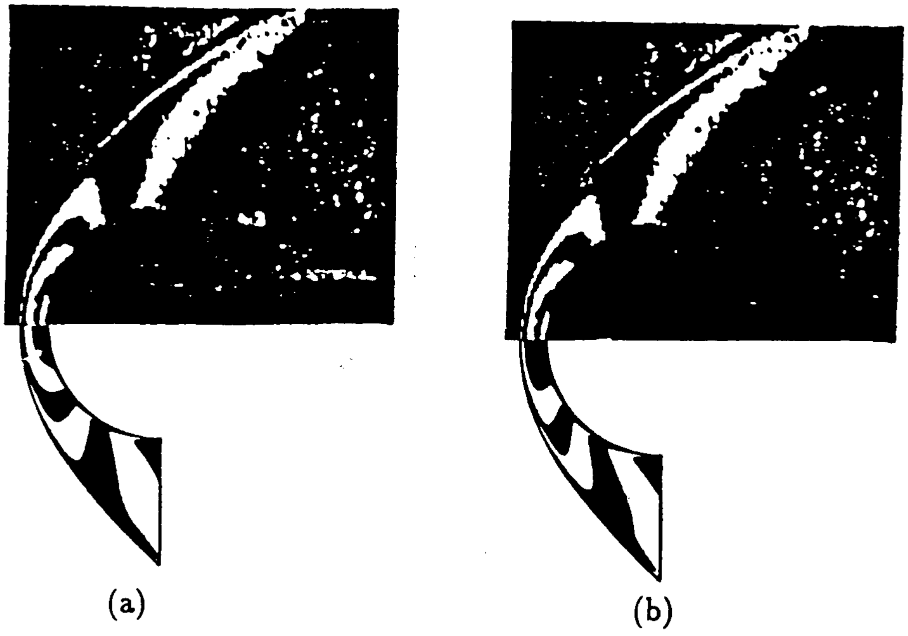

Figure 15: Comparison of computed pressure contours (bottom) with experimental results of Hornung (1991) (top). (a) Park model, (b) Dunn-Kang model for hypersonic flow over a cylinder.

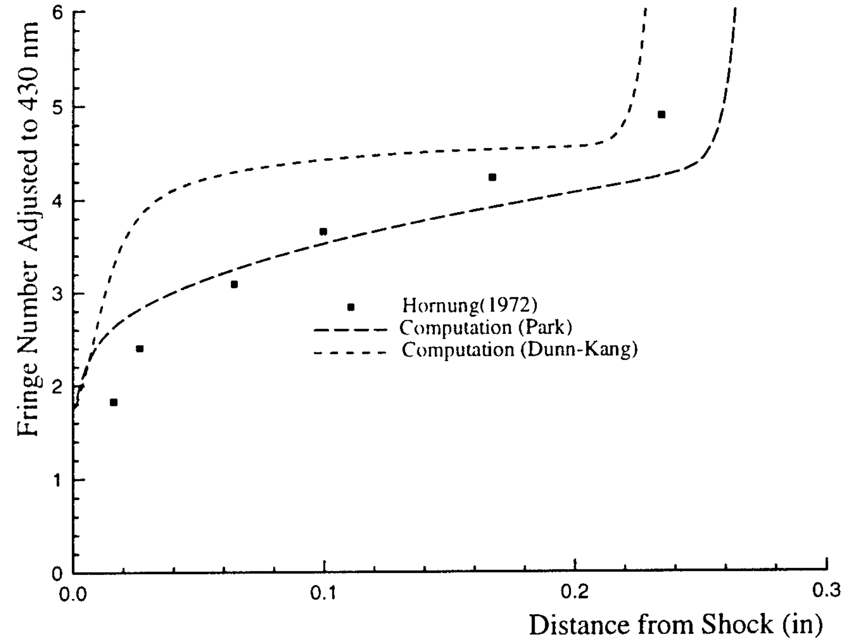

Figure 16: Computed fringe numbers for the two chemistry models compared with experimental values of Hornung (1972) along the stagnation line for hypersonic flow over a cylinder.

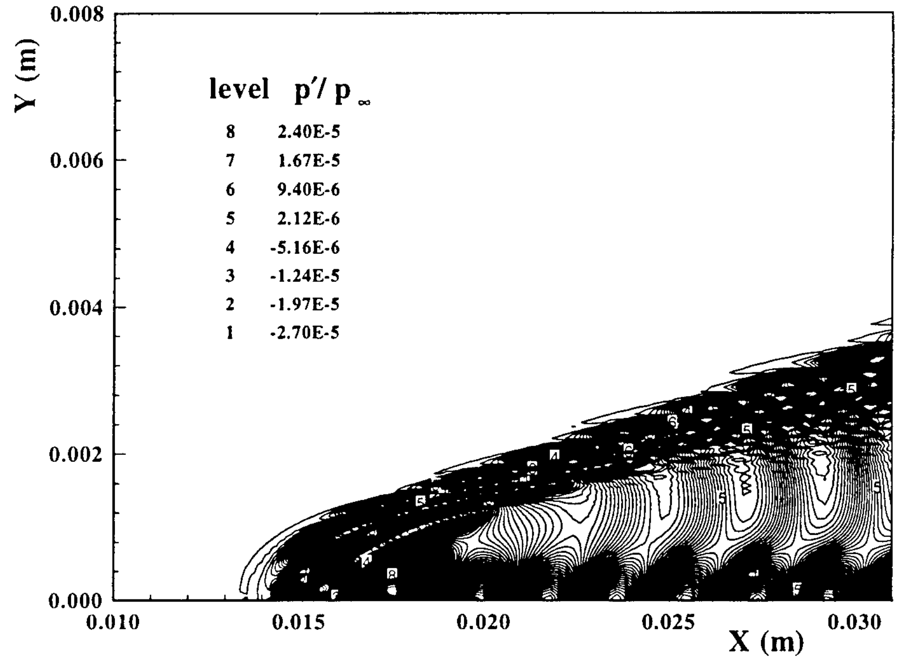

Figure 17: Contours of instantaneous pressure perturbation for the case of $\omega/\omega_0 = 10\pi$ (reacting gas).

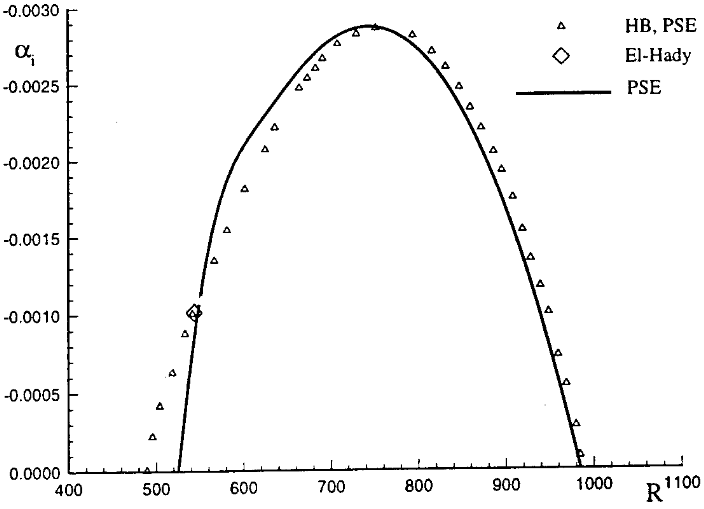

Figure 18: Growth rates vs R at $F = 40, b = 0.15, T_0 = 311K$ at Mach 1.5 computed by PSE for flow over a flat plate. The reference length scale is the local scale δ. Nonparallel basic flow results.

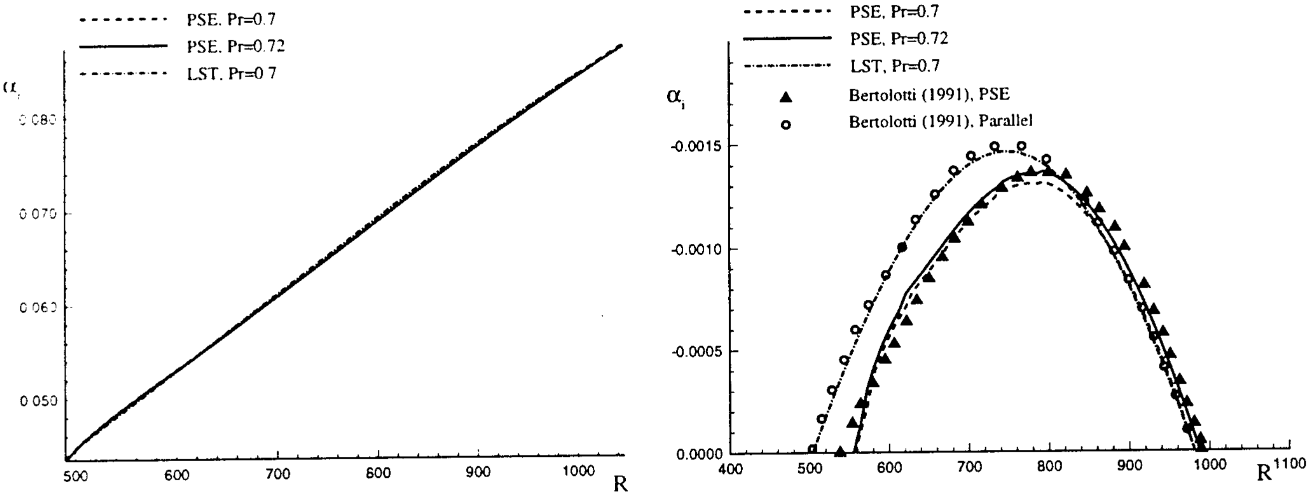

Figure 19: Growth rates (right) and wavenumber (left) from LST and nonparallel PSE vs R at $F = 40, b = 0, T_0 = 311K$ at Mach 1.5, flat plate boundary layer. The reference length scale is the local scale δ. Results from Bertolotti are also shown in symbols.

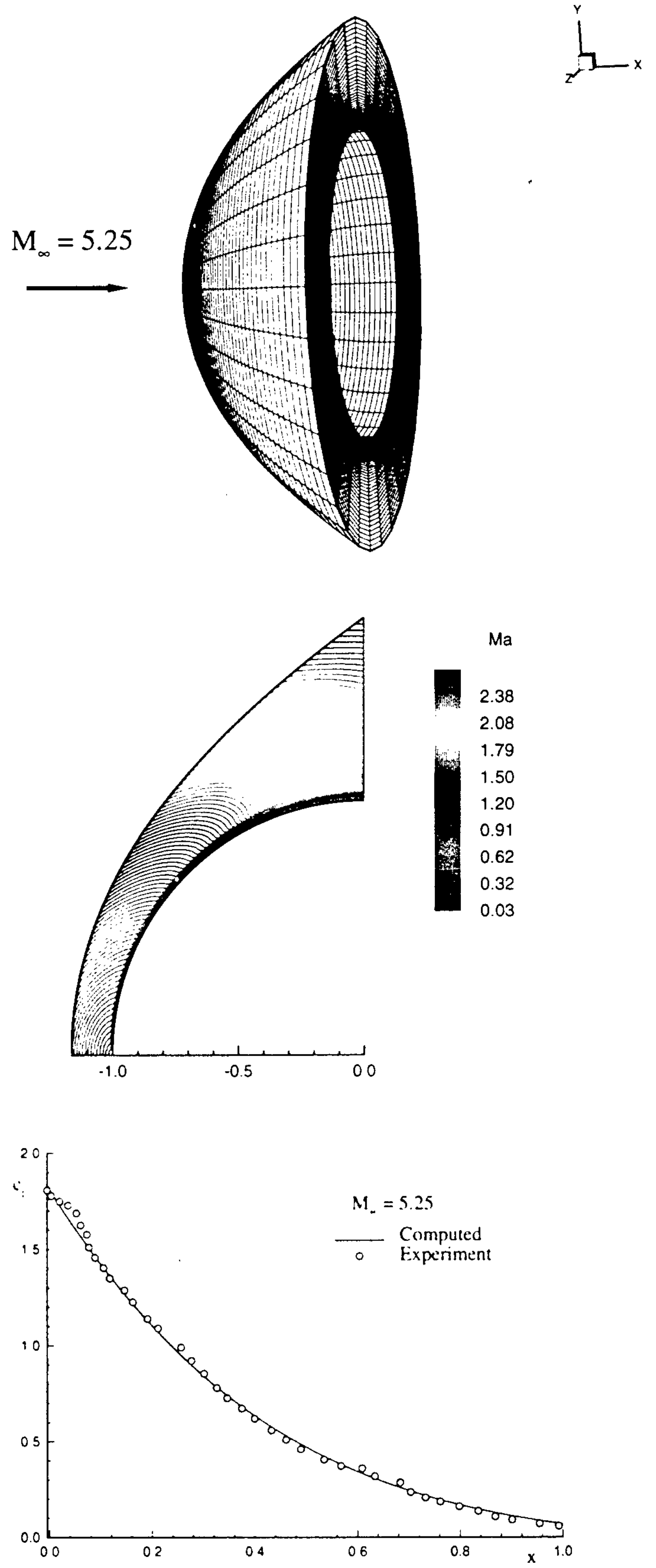

Figure 20: Steady flow solutions for $M_\infty = 5.25$ axisymmetric steady flow over a sphere by using high order 3-D shock-fitting method. (Upper figure: grids, middle figure: Mach number contours, and lower figure: pressure coefficients on body surface).

REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-00-
0239

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE June 2, 2000	3. REPORT TYPE AND DATES COV... Final Technical, 11/15/1997 to 02/14/2000

4. TITLE AND SUBTITLE
DNS and Linear Stability Analyses of Unsteady 3-D Hypersonic Wall-Bounded Flows with Real-Gas Effects

5. FUNDING NUMBERS
F-49620-97-1-0030

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
AFOSR/NA
DIRECTORATE OF AEROSPACE SCIENCES
BOLLING AFB, DC 20332-6448

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE
DISTRIBUTION IS UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The goal of this research project is to develop new advanced numerical methods and to perform DNS studies of transient hypersonic reacting flows over full 3-D maneuvering vehicles. The DNS tools and supporting theoretical approaches are used to gain new fundamental understanding of transition phenomena of 3-D chemically-reacting hypersonic boundary layers. In the three-year period, significant progress has been made in the DNS of hypersonic boundary-layer flow instabilities in the following areas: 1) receptivity of 3-D hypersonic flows over blunt elliptical cones, 2) nonlinear breakdown of 3-D Görtler vortices, and 3) reacting hypersonic flow receptivities and stabilities. We have also finished the development of linear stability codes for hypersonic flow and have started the work on developing new parallel implicit algorithms for DNS of reacting hypersonic flows. So far, we have developed new methodologies and have demonstrated the feasibility of our approach as a practical DNS tool to explore transient hypersonic reacting flow physics. The focus of future work is on the DNS studies of the hypersonic flow physics related to the hypersonic boundary layer transition, and to extend these DNS and theoretical studies to 3-D transient hypersonic flows with complex real-gas models and complex geometries, and the DNS of nonlinear breakdown and interactions of instability modes in hypersonic boundary layers.

14. SUBJECT TERMS
Boundary-layer instability and transition, direct numerical simulation, hypersonic flows, shock/boundary layer interaction, real gas effects, linear stability analysis

15. NUMBER OF PAGES
32

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL