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EXPERIMENTAL INVESTIGATION OF NOZZLE/PLUME AERODYNAMICS AT HYPERSONIC SPEEDS

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Thermosciences Division
Dr. Jim Arnold, Chief
Dr. George S. Deiwert, Technical Officer

Prepared by

ELORET INSTITUTE
1178 Maraschino Drive
Sunnyvale, CA 94087
Phone: (408) 730-8422 and (415) 493-4710
Telefax: (408) 730-1441

Dr. K. Heinemann, President and Grant Administrator
Dr. David W. Bogdanoff, Principal Investigator
Dr. Jean-Luc Cambier, Co-Principal Investigator
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I. SUMMARY

The work performed by D. W. Bogdanoff, J.-L. Cambier, H. A. Zambrana and J. Dunn over the time period 1 December 1992 to 30 June 1993 are summarized in this section. The summary is divided into two sections discussing experimental and theoretical work.

The experimental work will be summarized first. Work continued on the improvement of 16-Inch Shock Tunnel. This comprised studies of ways of improving driver gas ignition, an improved driver gas mixing system, a axial translation system for the driver tube, improved diaphragm materials (carbon steel vs stainless steel), a copper liner for the part of the driven tube near the nozzle, the use of a buffer gas between the driver and driven gases, the use of N_2O in the driven tube, the use of a converging driven tube, operation of the facility as a non-reflected shock tunnel and expansion tube, operation with heated hydrogen or helium driver gas, the use of detonations in the driver and the construction of an enlarged test section. (We note here that the tunnel improvement studies do include both experimental and theoretical work.)

The first test entry with the scramjet combustor model (26 runs) was successfully completed. The fuel system for the combustor model was completed and is fully operational. Small changes will be made in the fuel system in the fall of 1993.

The design of the three inch calibration tunnel is about 90% complete. Final drawings and safety approvals remain to be obtained. This tunnel will be used to develop diagnostics and operating techniques for the 16 Shock Inch Tunnel. A high pressure (~30 ksi), 1.5" shock tube/shock tunnel will be designed. The high pressure tubes may be obtained from Advanced Projects Research Institute or designed (and possibly built) by Physics Applications, Inc. This test facility will be used to test out a number of the techniques discussed above for the improvement of operation of the 16 Inch Shock Tunnel.

Maintenance and developmental work continued on the scramjet combustor continued. This work included support work for the first entry and preparation for the second entry to start in 10/93. A new cowl design was made, the number of data lines available from the combustor was increased

by 40%, and a system for calibrating the hydrogen fuel mass flow was designed, built and tested out. Substantial improvements were made in the Data Acquisition and Reduction System (DARS) of the 16 Inch Shock Tunnel. The DARS room has been completely reconfigured and the number of data channels increased from 132 to 196. New software which greatly speeds up data analysis has been written and brought on line. In particular, software which provides very rapid generation of model surface heat flux profiles has been brought on line.

We now turn to theoretical work. A considerable amount of theoretical work was performed in connection with upgrading the 16 Inch Shock Tunnel Facility. This work was briefly summarized above, since said effort involved both experimental and theoretical work. The summary will not, therefore, be repeated here. Details may be found in Sec. III, below.

A One-Dimensional Godunov code for very high velocities and any equation of state (EOS) has been written, proofed and is now operational without viscous effects. It is intended to add viscous effects in the 10-11/93 time frame.

This code will be used study methods of improving the operation of the 16 Inch Shock Tunnel and also of two-stage light gas guns. A multiphase combustion and general EOS code has been written and also is operational. This code will be used to study reactive phenomena and solid phase detonations. The latter code will be extended to include a two-fluid model. A compilation of various EOS's to be used with these two codes is underway. The latter code has been used for preliminary calculations of the operation of a high-explosive driven ram accelerator concept which appears to be capable of reaching the 10-14 km/sec range. The preliminary calculations give very encouraging results. It is intended to pursue this work further in the winter '93-'94 time frame.

One and two-dimensional calculations have been made of the flow in the 16 Inch Shock Tunnel facility nozzle. Calculated test section stagnation pressures were found to be in reasonably good agreement with with experimental data. Calculations have also been made of the flow in the inlet to the scramjet combustor model currently in the tunnel. These calculations will aid in interpretation of experimen-

tal data from the model. Unsteady two-dimensional CFD calculations have been made of the flow in the Ames EAST shock tunnel facility. Excellent agreement has been found between the calculations and the experimental data.

CFD calculations have been made of the use of detonations inside a scramjet combustor. The detonations were found to provide added thrust and to improve mixing and combustion within the combustor.

CFD calculations were made of the flow in the Ames DCAF facility. These calculations use a non-equilibrium, multi-temperature model. These models are very useful for flows in which the degree of ionization is falling rapidly. High temperature shock layer calculations were made for flow around the Rosetta Martian re-entry vehicle.

A non-equilibrium code was developed for plasma simulations. A single-fluid full collisional-radiative model was used. The model strongly couples all relaxation phenomena. This code was validated against experiments done in the Ames EAST facility.

A CFD study was done of the use of additives, particularly ammonia, to reduce NO_x production in turbojet engines.

II. DETAILED DISCUSSION, EXPERIMENTAL WORK

A. Improvement in operation of facility

In this contract period several techniques for improvement of the operation of the Ames 16 Inch Shock Tunnel were implemented and preliminary studies were made on a number of other techniques. Reduction of the voltage of the capacitor bank used to heat the driver ignition wires has already been shown to improve the quality of (i.e., smooth out) the driver burn. In earlier work, this voltage was reduced from 18.5 to 11.3 kV. This voltage reduction was accomplished without reducing the maximum wire temperature by using finer wires and increasing the capacitor bank capacitance. Still finer wires were purchased and additional capacitors for the capacitor bank were located. Using the latter wires and the additional capacitors would allow the bank voltage to be still further reduced to 8-9 kV in the future. Other methods being studied for improving ignition are (1) increasing the number of wires from 4 to 5-7 to reduce the free running flame path length and (2) reversing the current flow direction in 2 of the 4 wires to symmetrize the ignition system electrically to try to eliminate slosh waves in the driver.

Design work is continuing on the mix-on-the-fly driver gas loading system. The final system may allow for independent loading of three gases so that the gas mixture may be varied readily. Variation of regulator pressures or needle valves acting as orifices would allow the gas mixtures to be readily changed. Pumps and intermediate gas storage vessels may be used to allow almost all of the gas in the storage trailers to be used. Chuck Cornelison (code RTF) and Tom Kowalski (Calspan) will visit Seattle shortly to check out the Boeing and University of Washington mix-on-the-fly systems. The better mixing obtained with this system should produce smoother driver burns and lessen the danger of detonations, would eliminate the driver manifold and the associated expense and labor and would eliminate the 2 hour wait after driver gas loading (for mixing) before ignition.

Three other facility improvements have been implemented. These were (1) the modification of the driver support system so the driver can be translated axially to facilitate diaphragm changes, (2) installation of a 13" inside diameter ring upstream of the main diaphragm to improve flow quality and (3) changing from stainless steel to mild steel

diaphragms to eliminate the problem of losing diaphragm petals. (The design of these improvements was done by Chuck Cornelison and Tom Kowalski.) The mild steel diaphragms, with scoring depths of 27% of the diaphragm thickness produced 2 excellent breaks at break pressures of about 3200 psi. Complete retention of diaphragm petals and petal tips was obtained. This is a large improvement over the earlier use of stainless steel diaphragms, when loss of 2 to 4 petals and separation of the petal tips from the main petal masses were regular occurrences.

A number of other techniques for facility improvement continued to be studied. These included short term, intermediate term and long term items. The short term item was:

- Reduction of contamination from wall ablation by the use of a copper liner for the last 3-4 ft of the driven tube

The intermediate term items were:

- Use of (1) a buffer gas, (2) an annular barrier at the nozzle entrance and (3) N_2O driven gas to increase the driver-gas-free test time

The long term items are listed below. Further discussion of these items is presented in Secs. IIE and IIIB.

- Use of converging driven tube to increase the driven tube reservoir pressure and enthalpy
- Operation of the tunnel in the non-reflected shock mode
- Operation of the tunnel in the expansion tube mode
- Operation of the tunnel with a much enlarged test section allowing the test of a 1/3 scale model of a complete scramjet engine

B. Combustor model

The first full entry (26 tunnel runs) has been successfully completed. Tare, mixing and combustion runs have been made at Mach 12, 14 and 16 at driver after-burn pressures of 6000 psi. Since the results are classified, they cannot be discussed here. Three papers have been presented at classified conferences and one paper at an unclassified conference.

C. Hydrogen fuel system for combustor model

The hydrogen fuel system has been completed, leak and

pressure checked, calibrated and has been fully operational through the first entry with the combustor model. Small modifications are being made in preparation for the second entry. Each of the two fuel lines will be divided in two and in-line flow venturis will be installed to measure mass flow rates. The modifications are being designed by Chuck Cornelison and Tom Kowalski in conjunction with GASL.

D. Three inch calibration/development tunnel

It is intended to construct a three inch shock tunnel in 1993 in order to support the work of the 16-Inch Shock Tunnel. The tunnel is being designed by a team consisting of R. J. Miller (code RTF), C. Park (code RTA) and D. W. Bogdanoff (Eloret). This team is working together with safety personnel (E. B. Irby, code RTF and B. Askari, Bentley) and CAD design personnel from code RTF to provide the final drawings. The final CAD drawings are about 90% complete. Final material specs and safety approvals are still to be obtained. It is intended to start procurement of components in 10/93.

This tunnel will be used to develop and calibrate diagnostic techniques and to develop operational techniques

which will be useful on the Ames 16 Inch Shock Tunnel. The development and calibration work will include surface, probe and non-intrusive optical measurements. The work on surface and probe measurements may include studies of pressure transducer thermal protection and shielding geometries, skin friction gauge development and calibration of heat transfer gauges as well as the other types of gauges. The work on optical techniques will include studies of holographic interferometry, dye laser absorption techniques (for OH and NO), fiber optics and diode laser techniques, resonant holography (RHIS) and PLIF.

E. High pressure facility development tunnel

This will be a small (~ 1.5 inch diameter) very high pressure facility. The pressure capability will be in the 30,000-40,000 psi range. NASA is currently attempting to obtain the 1.5 inch diameter surplus tubes from APRI's SBIR ram accelerator effort. If negotiations are not successful for these tubes, a new set of tubes could be designed by Physics Applications, Inc., which has 30 years experience in these areas. The tunnel operational techniques which may be investigated include the following.

- Use of detonation drive in the driver tube
- Operation of the tunnel in the expansion tube mode
- Use of a buffer gas or cylindrical annular barrier at the nozzle entrance or N_2O in the driven tube to increase the test time
- Use of a converging driven tube to increase the driven tube reservoir pressure and enthalpy
- In the expansion tube mode of operation, use of additional diaphragms to reduce the secondary diaphragm problems and reduce test gas temperature
- Use of molybdenum, tantalum or columbium nozzle throat inserts to reduce nozzle ablation problems (contamination of flow, retreat of nozzle surface)
- Measurement of driver gas arrival time using spectroscopic techniques or the variation of shock angle on a wedge

F. Maintenance and development of combustor model instrumentation

The work involved (1) support for Test Entry 1 in the Ames 16 Inch Shock Tunnel with the hypersonic scramjet model

and (2) preparation for Test Entry 2 in the tunnel with the same model. This work was performed by Mr. J. Dunn of Eloret Institute. During the first test entry the work included instrumentation and maintenance of pressure, heat transfer and skin friction gages on the scramjet model. This work continued until the end of March 1993. Prior to the end of the first entry, planning had already been underway to modify the scramjet model for the second test entry. During the three month period between April and June, Mr. Dunn was responsible for the implementation of design changes and instrument upgrades to the model as instructed by Dr. Mark Loomis of MCAT. The first task was to design a new cowl inlet flow surface made of 17-4 PH stainless steel to replace the previous flow surface which was made of 7075-T651 aluminum. The purpose of this modification is to improve the flow quality into the injector and combustor region by minimizing the amount of damage that driver debris does to soft aluminum surfaces. This debris include diaphragm petal fragments, copper wire holders, and tungsten ignition wires. Furthermore, the new design eliminates flow surface mounted fasteners. It was becoming extremely dif-

difficult and frustrating to maintain the aluminum surface because the aluminum-epoxy filler that was used to fill the countersunk flathead fasteners would frequently come off after each shot. The second task was to redesign the model instrumentation data bus to accommodate approximately 40% more instrumentation. This increase in the number of data lines is crucial to providing our test team with an increase of pressure and heat transfer measurements. Lastly, a mass flow calibration device was designed and fabricated to measure and confirm discharge coefficients of the hydrogen fuel injectors used in the scramjet model during the first test entry. This experiment was performed in June, 1993, at NASA Ames' Transitional Flow Facility.

G. Data acquisition and reduction on combustor model

This work involved acquisition and reduction of static and total pressure, heat flux, skin friction and fuel flow data from the combustor model, development of software and increasing the number of data channels. This work was done mainly by Mr. H. A. Zambrana of Elorete Institute. From January to April 1993, Mr. Horacio Zambrana collaborated in testing for the GWP 53 first test entry (scramjet combustor

model). Mr. Zambrana was responsible for the Data Acquisition and Reduction System (DARS). Data was successfully acquired for all test runs throughout the entry. As part of his responsibilities for the DARS, Mr. Zambrana helped to coordinate and implement most changes and modifications to the 16 Inch Shock Tunnel surface instrumentation, including pressure, heat transfer and skin friction measurements. During this time, Mr. Zambrana finished the development of a set of Igor (Scientific Software) macros and functions that helped to automate the data reduction process.

At the end of the first test entry, Mr. Zambrana became heavily involved in the analysis of the combustor model experimental heat transfer data. Parallel efforts for heat transfer CFD analysis took place at Langley Research Center. The results from the data analysis were presented at the NASP Technology Review in Monterey, California (April 14-16, 1993).

From late April 1993 onwards, Mr. Zambrana's efforts were devoted to: 1) enhancing and upgrading the DARS from 132 to 196 A/D channels; 2) automating the generation of heat transfer profiles (Q vs. x); 3) reconfiguring the DARS

control room, including patch panels, computer equipment, amplifiers, power supplies, etc.; 4) coordinating and supervising the activities of three summer students and 5) working closely with Mr. J. Dunn (Eloret Institute) on issues regarding model surface instrumentation and continuity tests for the system. During this time Mr. Zambrana also collaborated with Mr. J. Dunn to calibrate the fuel injectors utilized for the first test entry.

III. DETAILED DISCUSSION, THEORETICAL WORK

A. General

The theoretical work performed during 1993 is mostly a continuation of that of 1992. As before, the primary focus of the investigations concerned the shock tunnel, and particularly the computations for the NASP GWP 53 activity. Other topics include the evaluation of new concepts in hypersonic propulsion, development and validation of a plasma code for shock tubes and/or reentry flows. A new task was initiated concerning the simulation of two-phase flows for new concepts in propulsion and experimental facilities. The work performed is described below.

B. Upgrades for 16 Inch Shock Tunnel

A theoretical investigation of options for upgrade of the Ames 16 Inch Shock Tunnel was carried out by D. W. Bogdaoff (Eloret), G. Wilson (Eloret), C. Park (Code RTA) and Myles Sussman (Stanford). All calculations were one-dimensional and inviscid. Calculations methods included (1) zone calculations with frozen driver gas and equilibrium driven gas, (2) full kinetics steady flow calculations in nozzles, (3) full kinetics unsteady for a few cases of expansion tube operation of the tunnel and (4) equilibrium steady calculations of flow through the ramp compression shocks leading to a combustor model. Further details of the computational methods can be found in Ref. 1.

Techniques for achieving smoother combustion of the driver gas were investigated. Operation of the facility as a reflected shock tunnel, a non-reflected shock tunnel and an expansion tube were analysed. The use of electrically heated hydrogen or helium driver gas (replacing combustion driver gas) was studied, as was the use of detonations in the driver tube. Use of a converging driven tube to increase the driven tube reservoir enthalpy and pressure was studied.

Finally, the fitting of the tunnel with an extra-large test section to allow the testing of a 1/4 scale NASP model was investigated. Pros and cons of all the options were assembled and a number of the options were found to be capable of yielding strong benefits for particular research programs. Details of the analyses are to be found in Ref. 1. Some of the less costly recommendations of the study are currently being implemented. It is planned to implement other recommendations of this study over the 1993-95 time frame.

C. One-dimensional Godunov code

A quasi-one-dimensional unsteady Godunov code has been developed (D. W. Bogdanoff, Eloret) and is now operational. Currently, frictional and heat transfer effects are not included, but it is intended to add these effects to the code and to improve the computational efficiency of the code in October or early November, 1993. The code can operate at very high velocities (up to 20 or more km/sec) and can use various non-ideal gas or dense media equations of state in analytical or tabulated forms. The code has been proofed on (1) ideal gas shock tube problems at pressure ratios up to 10^6 , (2) plate slaps of dense media at closing velocities up

to 20 km/sec, (3) subsonic-supersonic steady flows through nozzles with 16:1 area changes and (4) gunpowder burns in a closed bomb.

The first results obtained with this code are three solutions (without friction) for the Ames 0.28" two stage light gas gun. The code will be used to study operation of the Ames 16 Inch Shock Tunnel in various modes, possibly including the reflected and non-reflected shock tunnel and expansion tube modes and with detonation drive in the driver tube. Effects of friction and heat transfer in the tunnel and the use of an extra diaphragm in the expansion tube mode may also be studied. Other uses of the code will include efforts to improve two-stage light gas gun performance. This will involve studying the effects of varying piston and projectile masses, initial hydrogen load pressure, break valve pressure, pump tube length and gunpowder load. The use of a extra diaphragm in the pump tube and an extra electro-thermal side breech part way down the barrel will also be studied. These techniques may allow increased muzzle velocities and/or lower projectile and high pressure section pressures to be achieved.

D. Multi-Phase Combustion and General EOS Code

The development of an advanced code for the simulation of reactive shock propagation in condensed matter or high pressure gas with non-ideal equation of state (EOS) was recently initiated. Preliminary tests of the code on shock propagation in solid aluminum showed excellent agreement with experimental data. The code was extended to include reactive phenomena and heterogeneous phases and applied to detonation propagation in solid explosives. Because the EOS of the explosive and reaction products was approximated only, no validation was possible. Further development is planned, notably a two-fluid version of the code, and a systematic compilation of the correct EOS's for various materials of interest. Further applications of the code are also planned, i.e., for the Ram Accelerator concept and for the study and design of new impulse test facilities, also proposed by Dr. Cambier and Dr. Bogdanoff.

E. High explosive ram accelerator analysis

A study has been performed (J.-L. Cambier and D. W. Bogdanoff, Eloret Institute) into ram accelerator operation

using hydrogen working gas surrounded by an annular region of high explosive to provide the energy. This technique has the potential to allow velocities to be obtained which are higher than those achievable using the conventional pre-mixed gas ram accelerator. Velocities up to 10-14 km/sec may be achievable using this technique. The higher velocity capability results from the greater energy density of high explosives and the reduction in in-bore projectile heating and ablation resulting from using pure hydrogen rather than a fuel-oxidizer-diluent mixture as the working gas. Results of these analyses were presented² at Saint Louis, France in September, 1993.

The first preliminary results obtained (and presented at Saint Louis) look very promising. Axisymmetric geometries, mass loadings and high explosive sensitivities giving satisfactory stable ram accelerator operation were found. Possible new non-axisymmetric geometries suitable for rapid launcher turn-around and techniques for operation below the detonation velocity were presented in Ref. 2. Approximate equations of state (EOS) (e.g., the Abel equation of state) were used for the preliminary studies. More

accurate semi-analytical equations of state have been developed and will be implemented shortly. The Los Alamos SESAME equation of state library has been obtained on tape and it is intended to bring this library up on our computers in the 11-12/93 time frame and to compare the SESAME EOS data in depth with our approximate and semi-analytical EOS formulations.

F. NASP GWP 53 task

This work was performed by S. Tokarcik, P. Papadopoulos, and Dr. J.-L. Cambier. The 1D/2D Reacting Navier-Stokes "MOZART", developed by Dr. Cambier, was used for several calculations:

1. Calculation of the steady nozzle flow in the nozzle using the quasi-1D MOZART code, using experimental conditions obtained from the experimental group.
2. Calculation of the steady nozzle flow using another quasi-1D code (NENZF). Results compared well with those of Mozart-1D, although the NENZF code is believed to have lower accuracy.
3. Calculations of the steady nozzle flow using

the axisymmetric 2D MOZART code. The results agreed very well with the quasi-1D results of both MOZART/1D and NENZF, provided the latter are performed taking into account the displacement thickness of the boundary layer in the nozzle. These results did not initially agree very well with the experimental values. In fact, the experimental data points (pitot pressures at nozzle exit) could be interpreted only with absolutely no displacement thickness due to the boundary layer, a physical impossibility.

4. For this reason, the nozzle flow was recomputed near the entrance and throat region, in order to find possible mechanisms for effectively constricting the throat. A calculation was performed with maximization of the turbulence. The results did not show significant improvements. Another calculation was performed assuming a certain level of ablation in the throat region. For that case, the MOZART code was enhanced to treat the case of a boundary condition with mass flux. Again, the results did not show

sufficient displacement at the throat. Finally, the data was reexamined and the analysis procedure was changed to assure that the correct nozzle reservoir pressures in the correct time frame were compared with the corresponding pitot profiles and the method of calculating the pitot pressures was refined. This brought the calculated and measured pitot profiles into reasonably good agreement.

5. Calculations of the combustor inlet were again performed with new experimental conditions, to verify shock impingement locations. The calculations were also performed by R. Venkatapathy, using his ideal gas FL3D code. His calculations showed a very thick boundary layer, which seemed unphysical for these hypersonic conditions. This was puzzling, since the FL3D code was known to have been validated on several cases. Nevertheless, some time was spent double-checking the calculations. After very careful examination, Dr. Cambier was convinced of the accuracy of the MOZART code. Later, Venkatapathy informed Dr.

Cambier that there was some error in the 2D version of his FL3D code, which was used in the comparisons. The correction was made, and the new results agreed reasonably well with the MOZART code.

G. Shock Tunnel Unsteady Flow

An unsteady calculation of the transient flow in a nozzle was initiated by Dr. Cambier and S. Tokarcik, in order to further test the code accuracy. The simulations reproduced two published experiments: these results are excellent validations of the code. Both cases concerned low velocity shocks, for which real gas effects are negligible. The calculations showed excellent agreement with the experimental data. This is a further validation of the MOZART code, in this case for unsteady flows. The results were published and presented³ at the 29th AIAA Joint Propulsion Conference.

H. Pulsed Detonation Wave Engine

A DDF proposal was written and submitted by Dr. Cambier two years ago, and funded at the beginning of 1992. The pro-

posed work concerned the design and study of a technique for using a Pulsed Detonation Engine in conjunction with a conventional scramjet combustor, for generating additional thrust and also stimulating the mixing and combustion process in the scramjet. The thrust of this work was to demonstrate the effectiveness of the detonation waves in stimulating the mixing and combustion in the supersonic mixing layers. Several configurations were studied by CFD, using the MOZART/2D code. The results were presented⁴ at the 29th AIAA Joint Propulsion Conference and generated much interest, notably from Russian researchers. These results conclude the work performed for the DDF.

I. DCAF Flow Simulation

Another DDF proposal was written and submitted by Dr. Cambier and Dr. H. Adelman two years ago, and was also funded. The work on this DDF was delayed, due to more immediate commitments with the NASP GWP 53 activity. The proposed work was to devise experimental techniques and uses for the high pressure arcjets at Ames for propulsion testing. The work includes the generation of appropriate computational tools for simulating all aspects of the flow in

this type of facility. Last year, the MOZART/2D code was generalized to multiple temperatures, in order to assess the effect of thermal non-equilibrium in the facility. From our past experience in thermal nonequilibrium flow simulations and algorithm and model development, we devised a new and more complete thermo-chemical model. In this unique model, the coupling between chemical processes and internal energy modes is more detailed and fully consistent. Notably, this model has the property of restoring thermal as well as chemical equilibrium from chemical processes alone. This important physical property does not exist in other codes. The model also distinguishes between electronic (excited states and free electrons combined) and vibrational temperatures. This distinction is important in flows where the degree of ionization falls rapidly.

The work plan was then modified to include T. Gokcen as investigator: Dr. Gokcen was to perform the work, while Dr. Cambier was to direct and oversee the work. Dr. Gokcen developed his own code, which does not have some of the capabilities mentioned above. Some results from Gokcen's code showed a higher degree of nonequilibrium past the throat,

and the accuracy of these results are in question. In a late meeting, it was suggested by Dr. Cambier that Dr. Gokcen performed a parametric study for thermal nonequilibrium effects as well as boundary layer thickness effects.

J. High Temperature Shock Layer Simulation

The flow around the ROSETTA probe vehicle was computed, at the request of M. Tauber, for the conditions of peak heating at re-entry. This work was initiated and almost completed last year. The results were then presented⁵ this year at the 28th AIAA Thermophysics Conference.

K. Nonequilibrium Plasma Simulations

A series of codes for nonequilibrium plasma simulations, code-named "MAHLER", were initially developed by Dr. Cambier during the past three years, and have been continually improved. The most advanced version uses a single-fluid description, and has been enhanced to a full Collisional-Radiative model. The thermo-chemical model for molecular species has also been developed, is presently being implemented, and validating calculations will soon be under way. The algorithms are also being improved to use

of a more stable, implicit method which strongly couples all relaxation processes. The calculations were performed for the experimental conditions of a shock tube experiment performed by Dr. Sharma at Ames. The code development also included a new technique for the convection of vibrational energies for each pseudo-species, which is completely accurate in the limit of vanishing density of these species. The results were presented⁶ at the 24th AIAA Plasma Dynamics Conference. S. Moreau, a PhD student at Stanford, was included in this work, in order to benefit from his extensive expertise in molecular radiation and relaxation processes.

L. NO_x Reduction Mechanism

The research work performed by Dr. Henry Adelman and Dr. Cambier on the effect of additives for emissions reduction was presented⁷ by Dr. Adelman at the 29th AIAA Joint Propulsion Conference. This work is part of the HSRP program, and studied the effectiveness of some additives, principally ammonia, in reducing the levels of NO_x emitted in a gas turbine. Dr. Adelman performed most of the work, with assistance from Dr. Cambier.

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