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Final Report on Contract DAAL 03-90-G-0031

# HIGH ALTITUDE HYPERSONIC FLOWFIELD RADIATION

**Submitted to**

**Army Research Office**

**P. O. Box 12211**

**Research Triangle Park, NC    27709-2211**

Department of Aeronautics and Astronautics

Stanford University

Stanford, California 94305-4035

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Professor Robert W. MacCormack, Principal Investigator

Professor Dean R. Chapman, Co-Investigator

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Methods for computing radiation spectra and intensity are compared with available experimental data from three flight tests and five laboratory experiments. These involve both nonequilibrium and equilibrium flow. The comparison was facilitated by development of an improved radiation code, termed NEQAIR 2, incorporating vectorized programming to enable fine-structure spectra to be computed in a practical amount of time.

The main sources of computational inaccuracy are found to stem from imperfect understanding of: (1) what temperature or combination thereof in a multi-temperature flowfield governs electronic excitation; (2) the physics of rotational relaxation at very high temperatures; and (3) the reaction rates for NO production at very high temperatures. Computed radiation is most accurate at low altitudes and hypersonic velocities, and least accurate at high altitudes and velocities.

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# HIGH ALTITUDE HYPERSONIC FLOWFIELD RADIATION

ARO Contract DAAL 03-90-G-0031

Work Conducted up to March 31, 1994

## Scope of This Report and
## General Objectives of Research

A very detailed and complete technical account (415 pages) of the overall research project has recently been prepared as a Stanford University Department of Aeronautics and Astronautics Report:

Moreau, Stéphane. "Computation of High Altitude Hypersonic Flow-Field Radiation," *SUDAAR 650*, December 1993.

The present report, therefore, is of an executive summary type outlining a rather broad view of what are believed to be the most salient results of this investigation. Detailed references are not given herein. They are cited in the SUDAAR report.

The main objective of the research was to compare methods of computing hypersonic flow-field radiation with *all known* reliable experimental data; and, anticipating discrepancies therefrom, to revise or improve computational methods in appropriate manner to better conform with the wide spectrum of available experimental data on flow field radiation. In approximate chronological order of year conducted, the radiation experiments to which computations have been compared, and results analyzed, are:

AVCO shock tube experiments (early 1960's)

PAET flight test (1973)

COCHISE experiment (1984)

NASA Ames shock tube experiment (1990)

BSUV1 flight test (1990)

BSUV2 flight test (1991)

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CALSPAN shock tube experiments (1993)

Stanford plasma torch experiment (1993)

With this extensive scope of experiment and analysis thereof, it was not expected that a method of radiation computation could be devised that would agree closely with all parameters measured in all of these experiments. It was expected, however, that such a broad investigation would illuminate some critical aspects of radiation modeling upon which the accuracy/unaccuracy of computation depends most importantly. Towards this end, we believe that considerable progress has been made.

## Primary Results of Research

Early in the research program it was found that for conditions of thermodynamic and chemical equilibrium, the then existing methods of flow-field radiation computation were in reasonably good agreement with flight experiments; but, for conditions of strong nonequilibrium, they were in severe disagreement. Varying methods of modeling the physics of radiation and of fluid mechanics revealed that the uncertainties in nonequilibrium radiation physics were orders of magnitude greater than the uncertainties in fluid mechanics. These uncertainties increase considerably as altitude, velocity, and temperature are increased. In consequence, our research emphasis shifted from fluid mechanics aspects to those involving the molecular physics of nonequilibrium radiation.

From a very broad viewpoint, the most fundamental source of computational inaccuracy stems from imperfect understanding of nonequilibrium molecule/atom/electron physics at very high temperatures, the order of $10^4$ °K or higher. Such temperatures are not generally accessible in the laboratory, but are encountered in hypersonic flight. Three primary sources of this inaccuracy that were revealed in the overall research program are:

(1) The uncertainty for nonequilibrium multi-temperature flow fields of not knowing which temperature (translational, rotational, vibrational) or combination thereof, governs the electronic excitation process leading to radiation of a given chemical species. This uncertainty can produce several orders of magnitude difference in computed radiation at

high altitudes where pronounced nonequilibrium exists. Trial and error computational showed that for NO the translational temperature leads to least inaccuracy.

(2) The uncertainty of not knowing how to model rotational relaxation at very high temperatures. Direct laboratory measurements of rotational relaxation exist only up to temperatures the order of $10^3$ °K, so that extrapolation must be made to temperatures ten-times higher. When computations are made with conventional extrapolations (e.g., Parker), the results were in pronounced disagreement with the NASA Ames shock tube experiments in nitrogen (Sharma, 1990). Agreement was achieved after constructing a revised "diffusional-type" model for rotational relaxation at high temperatures analagous to that constructed by Park for vibrational relaxation at high temperatures. This revised model corresponds to *much longer* rotational relaxation times than the conventional Parker extrapolation model would indicate. Unfortunately, when the revised model is applied to the many experimental results to which our computations have been compared, good agreement was not obtained in all cases. We believe that additional shock tube experiments should be conducted to check on the rates of rotational relaxation at very high temperatures. The present uncertainty in this relaxation process, which is large, can lead to an order of magnitude uncertainty in radiation at high altitudes.

(3) The uncertainty of not knowing how to model accurately the Zeldovich exchange reaction rates for NO formation at very high temperatures. Both vibrational and translational temperatures appear to be important in these reaction rates, and temperature scaling either as $T^{0.7}T_v^{0.3}$ (Treanor and Williams, 1993) or as $T^{0.5}T_v^{0.5}$ (Moreau, 1994) has been found to be reasonably compatible with the Calspan shock-tube experiments at 3.5 km/sec. Unfortunately, these two temperature dependences yield greatly different results for radiation at the high altitude conditions of the BSUV$_2$ flight test. We believe, therefore, that shock tube experiments on these critical reaction rates at very high temperatures should be conducted to resolve this uncertainty.

Perhaps the most significant result of the research, from the viewpoint of long term consequences, has been the development of a much improved computational code for nonequi-

librium gas radiation. This code, termed "NEQAIR 2", represents a generalization and improvement in the original NEQAIR code of C. Park and colleagues at NASA Ames. The new code has been efficiently vectorized (at least for Cray type supercomputers) and requires only about 1/20th of the computer time required by its predecessor code. This has enabled fine-structure spectral computations to be made in a reasonable amount of time, and has provided thereby a most valuable diagnostics tool for analyzing discrepancies between computational and experimental data on radiation from air and other gases. Others now are also using the NEQAIR 2 code to advantage. Clearly, the integrated radiation intensity might fortuitously be computed accurately, but be dead wrong in reality due to spectral inaccuracies that happen to compensate in overall radiation intensity. Comparison of the computed radiation spectra with experimental spectra, therefore, is the most severe and revealing test of a computational code.

Many less broad conclusions from the project, especially about detailed aspects of certain molecular physics modeling, have been noted in Moreau's SUDAAR report which represents his Ph.D. thesis. The interested reader is referred to that report for details and numerous (293) references on gas radiation cited by Moreau.

## Feasibility of Direct Numerical Simulation of Boundary Layer Turbulence as Basis for Reliable Computation of Aero-Optical Distortion

Some preliminary research on this subject, which is an entirely different subject than reported on above, has been conducted during the final six months of the present contract. It has relevance, however, to radiation signature detection. An outline of the main considerations and results of this investigation are summarized below in bullet-type fashion for brevity.

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## Physical Characteristics of Turbulence Relevant to Aero-Optical Distortion

- Density fluctuations which create optical distortion are geatest in the inner portion of a turbulent boundary layer, and increase significantly with increasing Mach number.

- For low subsonic speeds the length scales of eddy structures in the inner portion of a boundary layer are different in the streamwise, spanwise, and normal directions. Structures near a wall are highly elongate, the characteristic length scales streamwise being an order of magnitude greater than spanwise.

- For supersonic velocities, present data on these structures are meagre, but indicate somewhat greater structural coherence than in low speed flow. The eddy length scales are not quantitatively defined at present.

## Present Computations on Aero-Optical Distortion by Turbulence

- Current aero-optical computations of light distortion by turbulence are semi-empirical, based upon a concocted model equation for turbulence energy dissipation, from which only a *single length scale* is computed.

- Relationship of this single scale to the three different physical length scales (streamwise, spanwise, normal) of turbulent density eddies is not known.

- Present technology for computing optical distortion by turbulent boundary layers is over simplified and of questionable reliability.

## Direct Numerical Simulation of Turbulence

- During the 1980's it has been established firmly that the direct numerical simulation (DNS) of turbulence in low-speed flows—using the full time-dependent Navier-Stokes equations—accurately computes all fluctuating quantities as well as characteristic turbulence length scales in each of the three directions.

- Near a wall, DNS with adequate grid resolution can be more reliable in determining fluctuations statistics than experimental methods which encounter real difficulties close

to a surface.

- DNS for supersonic/hypersonic turbulent boundary layers is currently in an early stage of development, the primary effort of which is at the NASA Ames–Stanford Center for Turbulence Research (CTR).

- A body of experimental data exists on the fluctuating and time-averaged characteristics of turbulence at high Mach numbers which is adequate for testing and validating a DNS code for compressible-flow turbulence. Such test/validation has not yet been conducted.

- Primary constraint for DNS is that the maximum Reynolds numbers up to which such computations feasibly can be made is limited by supercomputer power.

- Two new computational techniques currently under investigation at CTR will increase substantially the Reynolds number range amenable to computation by:

  (1) development of Spalart-type code for compressible flow,

  (2) development of embeded grid algorithms for the near-wall region where scales are smallest.

- Advanced parallel computers expected to become available in a few years will make DNS feasible over a sufficiently wide Reynolds number range to establish the scaling laws for turbulence aero-optical distortion; and thereby enable reliable extrapolations to be made to much higher Reynolds numbers than those directly computed.

Although it may not be appropriate to go into further details here on the subject of aero-optical distortion of a radiation source, it was thought relevant to note briefly the main conclusions drawn from the preliminary investigation since it was supported in part by our ARO contract for research on radiation in hypersonic flight.