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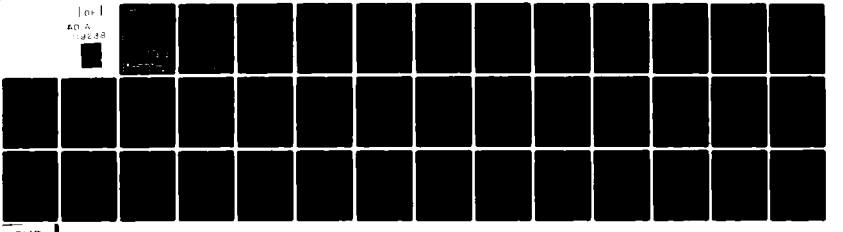

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Boron Particle Combustion

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Progress in the development of analytical models of reacting high-speed flow is described, with specific emphasis on the modeling of reacting two phase flows and the aerodynamics of the ducted rocket configuration. A near dynamic equilibrium, thermal nonequilibrium detailed two phase flow analysis has been developed. Comparison with available data for spray vaporization shows excellent agreement for overall flowfield structure. In addition, the model also provides predictions of spray evolution, in terms of droplet size and number density distribution as a function of distance in the flow. A

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Boron combustion analysis incorporating a model for the finite-rate kinetics of the surface oxidation of boron has been developed. When compared with available data, the model is shown to accurately predict particle burn times as a function of particle size, ambient oxygen concentration, initial particle and gas temperature, and pressure. Analysis of these results demonstrates the critical importance of the chemical and physical properties of the particle and its immediate environment. A combined analytical and experimental program has been initiated with the NWC. The objective of this program is to develop a fundamental data base on boron slurry combustion phenomena through the interactive comparison of experimental and analytical results during the program. Initial work has demonstrated the utility of the approach in defining data requirements and in analyzing experimental results for completeness, consistency, and accuracy. Aerodynamic modeling of the ducted rocket flowfield has been carried out using a 3-D elliptic aerodynamic calculation procedure. This work has resulted in an initial delineation of flowfield regions in this configuration, to be used in the development of a modular model of the ducted rocket.

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COMBUSTION IN HIGH SPEED AIR FLOWS

Annual Report

F49620-80-C-0082

by

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May 1982

TABLE OF CONTENTS

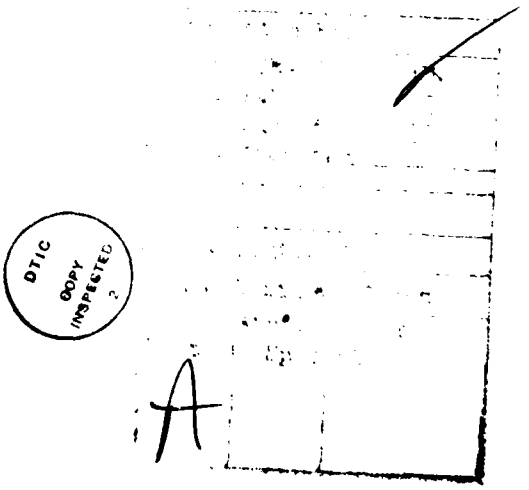

TABLE OF CONTENTS

LIST OF FIGURES

1. RESEARCH OBJECTIVES

The results described in this report have been obtained from work whose overall objective is the analysis of reacting multiphase flows in advanced air-breathing propulsion systems. This work involves the formulation and evaluation of new theoretical descriptions of multiphase turbulent mixing and chemical kinetic phenomena in subsonic and supersonic air flows, and the generation of new experimental data on these phenomena. The specific objectives of this research may be described as follows:

(a) Spray Modeling: This task area involves the development of analytical models of the phenomena occurring in the multiphase turbulent reacting flows involved in spray flame evolution. The model is to include the effects of heterogeneous and homogeneous finite rate chemical reactions, turbulent transport and velocity and temperature nonequilibrium between the droplets and gas phase. Both liquid fuels and slurries are to be considered.

(b) Modeling of Boron Combustion Processes: In this task area advanced analytical models of the combustion of boron particles are to be developed. A survey of the existing boron kinetics literature is to be performed to provide the data base for the development of advanced boron kinetics models. This survey leads to the definition of an advanced model for boron particle combustion, to be incorporated in modular models of the slurry combustion process in ramjets. Required boron kinetics data are also to be defined.

(c) Modular Models of Ramjet Combustion Processes: The modular modeling approach to the analytical characterization of high speed combustion processes is to be further refined and developed, and applied to the analysis of experimental results generated from experiments relevant to high speed combustion processes. Specific areas of development involve the characterization of the spray combustion of liquid fuels and of slurries, particularly boron slurries. Thus in this task area the models developed under task areas (a) and (b) are to be incorporated into ramjet combustion models and applied to the characterization and analysis of experimental data. Of specific

importance is the experimental data on gas-phase, liquid-phase, and slurry-fuel combustion phenomena being obtained at the Naval Weapons Center under a joint AFOSR/NWC sponsored program.

(d) Modeling of the Ducted Rocket Combustion Process: This task area involves the formulation and development of a modular model for the ducted rocket combustor. This model is to be based on a delineation of flow characteristic regions obtained through the use of three-dimensional elliptic areodynamic calculations, and is to be used to develop a broad base of new and fundamental information on three-dimensional multi-stream interaction in reacting ducted flows.

2. RESEARCH STATUS

2.1 SPRAY MODELING

For many potentially-important heavy hydrocarbon fuels the low volatility of the fuel results in the persistence of fuel droplets well into the combustion process. With slurry fuels, both droplets of the carrier fuel and the particulate fuel carried in the slurry are involved in combustion. Accurate analysis of the combustion phenomena associated with these fuels requires a two-phase flow model suitable for use within a combustor analytical tool. The development of such a spray model is the objective of the task area of this program described in paragraph 1(a).

In general droplets and/or particles embedded in a two-phase flow may be moving at different velocities and have a different temperature than the gas phase. This is the case of velocity and thermal nonequilibrium, and the analysis of this general case taking into account the momentum- and mass-transfer cross-coupling terms is complex. Thus a complete analysis of the most general case of a two-phase flow, while a continuing effort of this program, represents the long-term objective. A more tractable approach, which still offers considerable generality, is the near dynamic equilibrium, thermal nonequilibrium analysis described in Ref. 1. In this approach the droplet mean velocity is assumed to be that of the gas phase. However, as even when the droplet mean velocity is that of the gas phase, the droplets/particles do not necessarily follow the turbulent fluctuations in the flow which give rise to turbulent diffusion, in the near dynamic equilibrium approximation the droplets/particles may diffuse relative to the gas phase. Full thermal nonequilibrium is also incorporated, so that the droplets/particles can be at temperatures different from the gas phase and heat up or cool through convective and radiative heat transfer mechanisms.

From the standpoint of a spray flame analysis the near dynamic equilibrium/thermal nonequilibrium approach is directly applicable primarily to a particle-laden gaseous stream injected into another gaseous stream where diffusive transport is the primary interactive mechanism. However, for sufficiently small droplets and particles injected at velocities considerably different from the gas phase velocity, near dynamic equilibrium can be achieved very

shortly after injection. The analysis thus applies for most of the lifetime of small droplets and particles, and empirical estimates which result in the development of a near-field droplet/particle distribution function can be used to initiate the calculation.

It is implicit in the development of the equations for the near-dynamic equilibrium limit that the droplets or particles can be treated as dilute continuum species, with each "species" representing a given droplet class, where droplet class is defined as those droplets residing in a given size range about the class average diameter. Given an initial droplet size and number density distribution, the problem of the analysis of the transport of a spray in a gas phase flow becomes one of determining the rate of change of droplet number density and size distribution in the flowfield. This transport process is described by the droplet spray equation, which is a Boltzmann-like equation accounting for the time-rate-of-change of the droplet size caused by droplet formation and desctuction processes, droplet collisions, and advection and diffusion processes. However, this integrodifferential equation is extremely difficult to solve, and the problem may be considerably simplified if the droplet distribution function is discretized into a number of size intervals, whereupon the independent variable becomes the particle number density of a particular size, defined as the total particle mass of a given size range per unit volume. An example of this discretization is shown by Figure 2.1-1, which represents a droplet distribution reported for an air-blast atomizer by Khalil and Whitelaw (Ref. 2). As Figure 2.1-1 shows, the necessary discretization of the droplet distribution is carried out by dividing the curve into ten sections, and defining an approximate average size (and thus number density) for each class of droplets. This can then be used to obtain a mass fraction for each droplet class, providing the initial condition required for the computation.

As part of the development process for the spray flame analysis, the code has been applied to the prediction of the two-phase flowfields described by Shearer, et al. (Ref. 3). In the work described in Ref. 3, measurements of mean velocity, total concentration (both liquid and vapor phase), and Reynolds stress were made in a two-phase Freon-11-air jet mixing with still air. The jet was produced by the injection of Freon-11 into the air using an air-atomizing nozzle: based on data presented by Shearer, et al. the injection

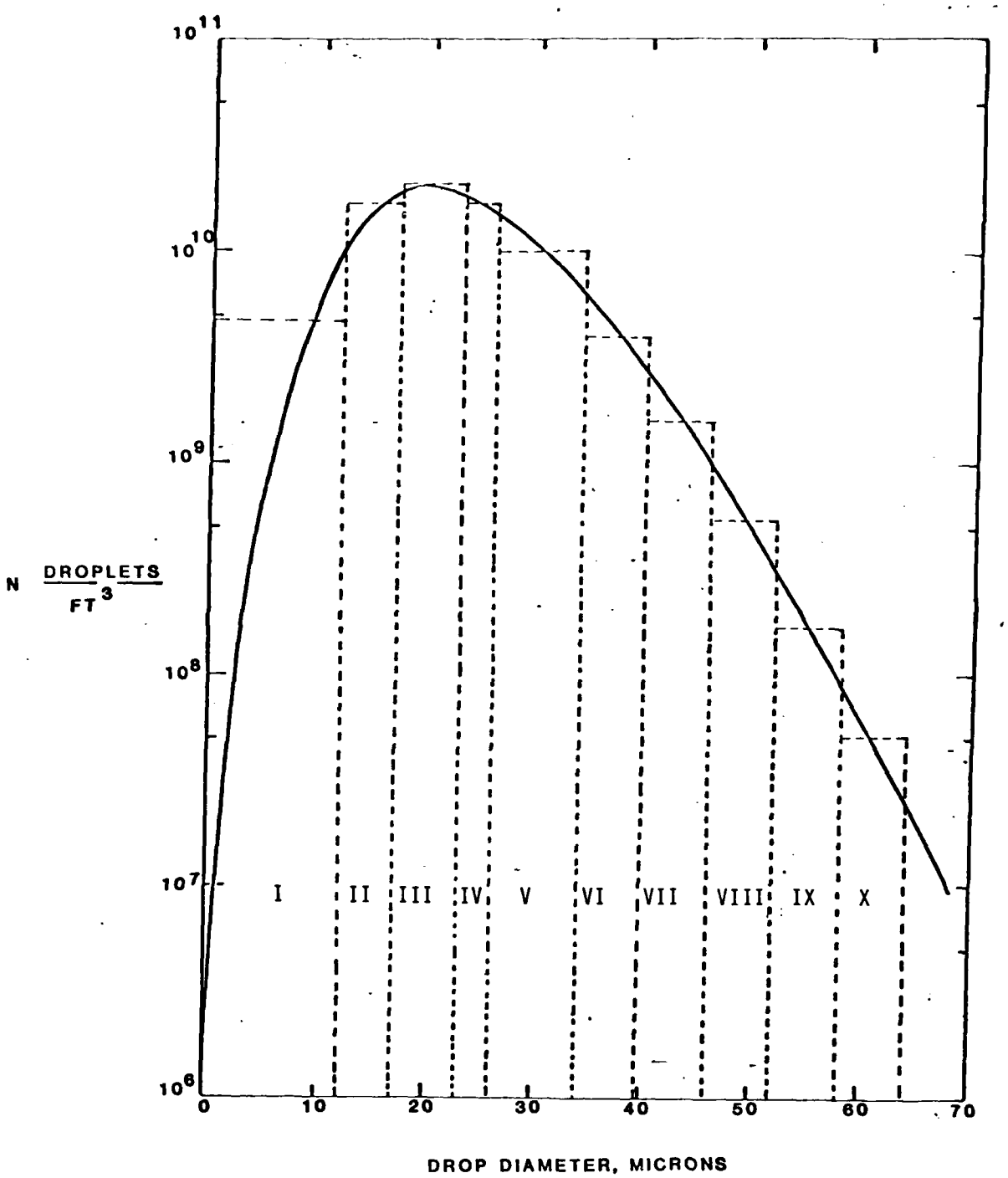

FIGURE 2.1-1 Initial Droplet Size Distribution and Discretized Approximation. Roman numerals indicate droplet class.

velocity was 554.7 ft/sec and the initial liquid-phase Freon mass fraction was 0.87. Shearer, et al. do not report droplet distributions; however, they give the initial SMD (Sauter mean diameter) of the Freon-11 droplets as 29 microns. The injection temperature of the Freon-11 was just below its saturation temperature, which in turn was just below the ambient air temperature. Thus the vaporization process for this jet was driven primarily by concentration gradients. Within the context of the model, this vaporization process was approximated by assuming a transfer number, B, of ten, in the droplet vaporization expression which results in a d^2 droplet vaporization law. Vaporization was assumed to initiate when the droplet temperature reached the saturation temperature.

The initial droplet distribution was approximated using the distribution shown in Figure 2.1-1; this distribution has an SMD of 29 μ. All other initial conditions (i.e., velocity, temperature and droplet mass fraction) were taken to be uniform across the jet. A two-equation turbulence model was used, with coefficients $C_\mu = 0.09$, $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.84$, $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.20$: the turbulence model and coefficients were identical to those used in computations using the locally-homogeneous-flow (LHF) by Shearer, et al. In the present computations all droplet classes were taken to diffuse at the same rate as the gas phase, but the phenomenon of phase separation, or relative diffusion, is included in the formulation as a function of the response characteristic of droplets of various sizes.

Axial variations of centerline velocity and species mass fractions are compared with the data of Shearer, et al. (Ref. 3) in Figure 2.1-2. As noted on the figure, these computations have been carried out for a turbulent Prandtl number of 0.70. These results indicate that the predicted velocity profile compares reasonably well with the experiment, but that the centerline Freon concentration (both liquid and vapor phase) is somewhat underpredicted. More accurate predictions of the centerline Freon concentration can be achieved by using a unity turbulent Prandtl number assumption, but additional computations carried out under this assumption strongly underpredict the width of the concentration profile. As can be seen from Figures 2.1-3a and 2.1-3b, these computations (at a turbulent Prandtl number of 0.70) provide very accurate predictions of the shape and width of both the velocity and concentration profiles.

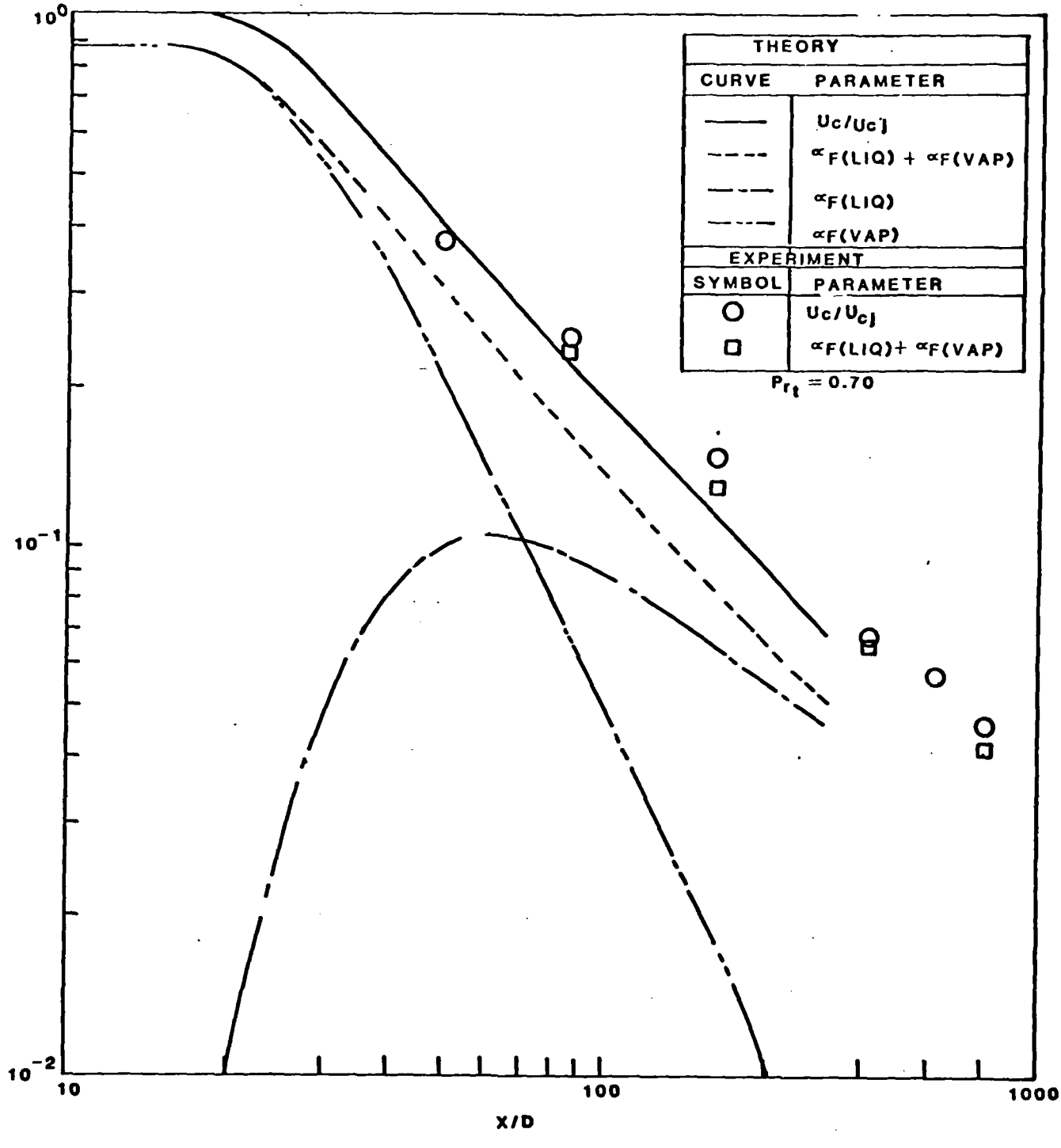

FIGURE 2.1-2 Axial Variation of Centerline Velocity and Species Mass Fractions, Vaporizing Spray Jet

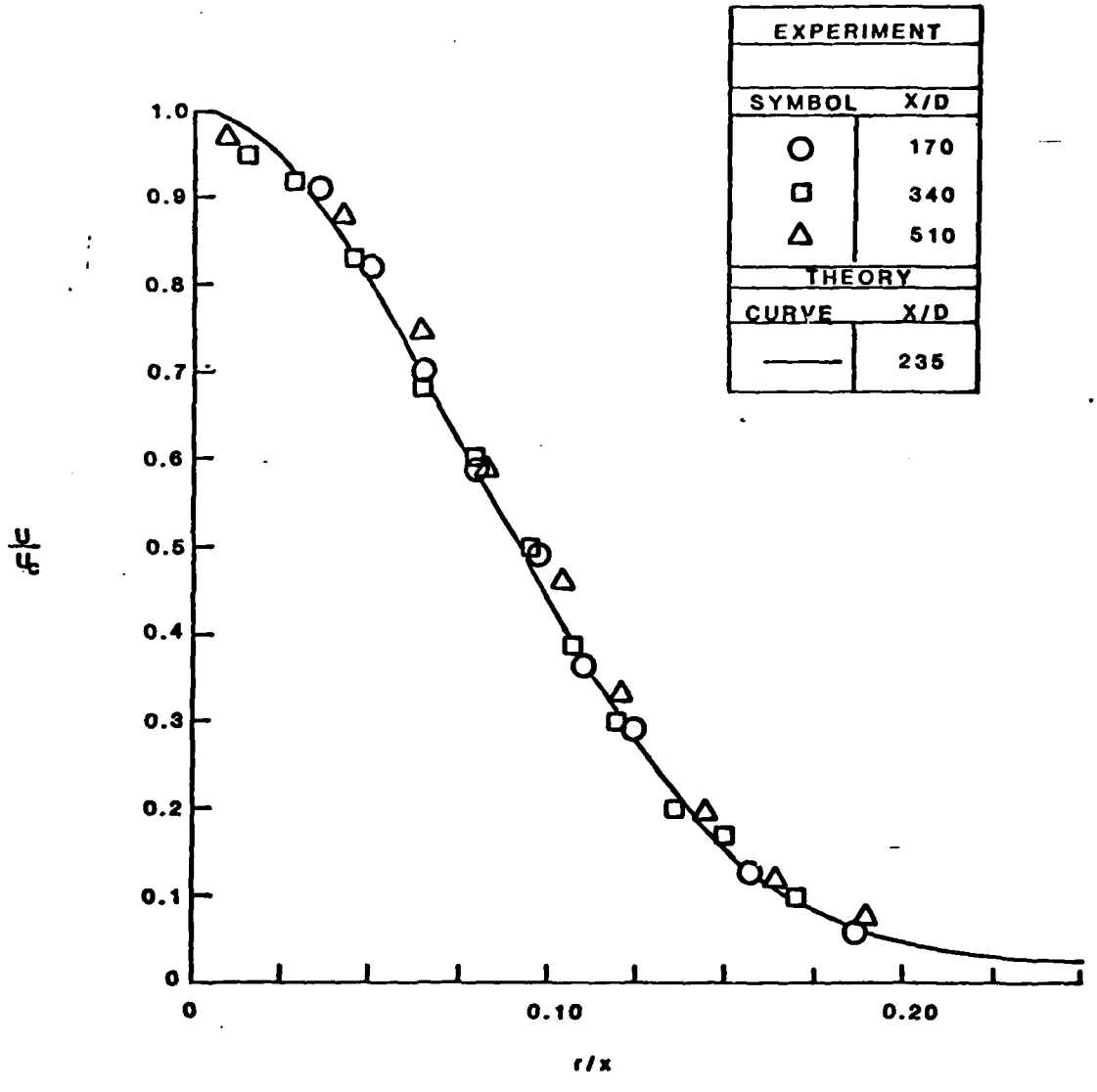

FIGURE 2.1-3a Radial Variation of Mean Velocity, Vaporizing Spray Jet

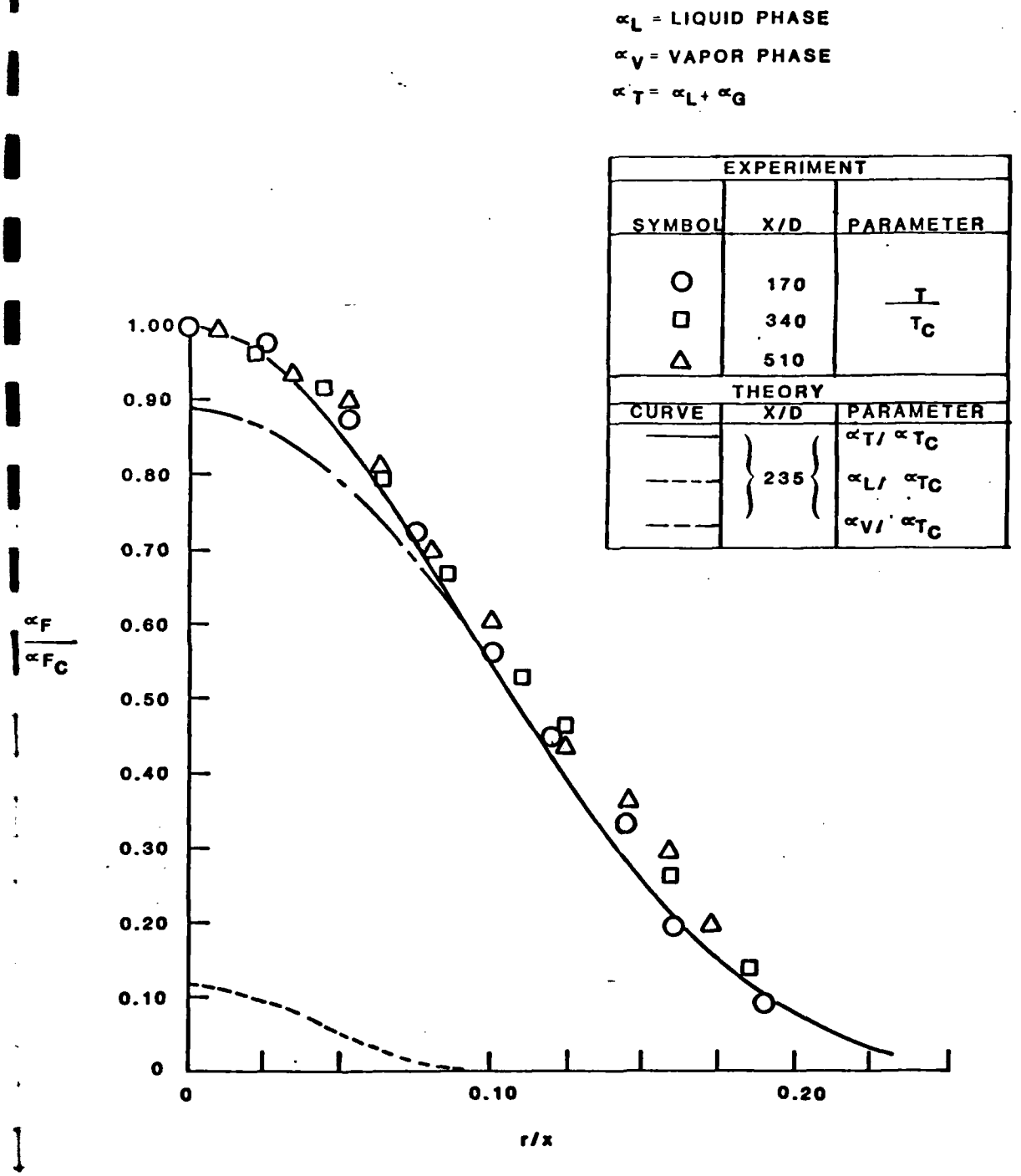

FIGURE 2.1-3b Radial Variation of Freon Concentration, Vaporizing Spray Jet

The computations reported by Shearer, et al. (Ref. 3) were made using a locally -homogeneous-flow (LHF) model in which the only effect of the presence of droplets is through the equation of state on the local density. Droplet distribution evolution and finite-rate interphase mass transfer processes are not modeled in the LHF approximation, but they are included in the present approach. Thus, while the LHF model indicates that the liquid phase is completely vaporized at x/D = 165 (Ref. 3), in the present model droplets persist for a considerably greater distance. The persistance of droplets is strongly affected, in the present predictions, by the turbulent Prandtl number assumed: at x/D = 250, the centerline liquid phase mass fraction ranges from 6.5×10^{-3} for $P_{r_T} = 0.70$ to 4.4×10^{-2} for $P_{r_T} = 1.0$.

In addition to the use of the LHF approximation, the computations reported by Shearer, et al. (Ref. 3) make use of a probability-density-function technique to obtain the mean value of any variable other than the turbulence model quantities, the mean velocity and mean mixture fraction of Freon, and the turbulent viscosity. In particular, the energy equation is not incorporated in the equation set; rather, the temperature is obtained from the local mean mixture fraction as that obtained when an amount f of injector fluid and (1-f) of ambient fluid, at their initial states, are adiabatically mixed and brought to thermodynamic equilibrium at the ambient pressure of the jet. With the present approach, both a mixture energy equation and energy equations for each of the particulate species are used to get both particle- and gas-phase temperatures, which may be different. However, despite these rather large differences in the modeling approach, the results obtained here are in good agreement with both the data and the computations reported in Ref. 3. In part at least, this may represent an insensitivity of the parameters reported in Ref. 3 and shown in Figures 2.1-2 and 2.1-3 to the details of the modeling relation to this Freon jet problem: the present model which predicts the evolution of a spray distribution, provides considerably more detail than is available from the results described in Ref. 3.

Further development of the near-dynamic equilibrium, thermal nonequilibrium spray model is continuing, for both vaporizing and burning sprays. Parametric calculations are to be carried out to investigate the sensitivity of the results of the theoretical formulation to parameters such as the droplet diffusivity relative to the gas phase and the initial distribution of

droplets. These calculations will be performed in reference to available experimental data, and with detailed spray droplet distribution evolution data that is to be obtained in continuing work on this program.

2.2 MODELING OF BORON COMBUSTION PROCESSES

The research effort identified under Section 1(b) emphasizes the development of a fundamental understanding of the mechanisms controlling boron slurry ignition and combustion. Particular attention during this period has been devoted to the description of the heterogeneous kinetics of boron particle combustion. The reason for emphasis on this process is that it has received minimal consideration from a theoretical point of view, although data suggest that kinetics effects are critical to the energy conversion process for boron in particle sizes of interest in advanced Air Force airbreathing propulsion system applications.

A review of existing boron ignition and combustion analyses was conducted during the first phase of this task, Ref. 4. That assessment showed that conclusions about boron consumption rates based on a priori diffusion controlled oxidation assumptiona are misleading. This is particularly true with respect to pressure effects and scaling to practical particle sizes and operating conditions for which minimal data currently exist. Particle sizes in the 1 μm diameter range are typical of practical applications while the bulk of existing data involve particle sizes greater than 30 to 40 μm. Examination of the burn time data showed that this latter size range is in the heart of a transition between diffusion controlled and kinetically controlled oxidation. This observation could not be generalized because of the dependence of the process on properties including pressure, temperature, and local oxygen concentration. All of these properties depend on environmental conditions that can, in practical applications, vary significantly from those associated with the existing data. As a consequence of this deficiency an analysis was formulated that includes the coupled effects of chemical kinetics and diffusive transport. This model also includes convective transport and radiation. Unlike prior models which use overall balance equations, the current formulation involves the solution of a coupled set of differential conservation equations. This solution provides detailed information on the properties, from the particle surface out to the environment in which the particle is contained, Ref. 4. Thus, this

model is structured to span the range of conditions where the oxidation process may be dominated by diffusion or chemical kinetics or both mechanisms. In this way the model is capable of covering the range of conditions involved in the existing data base for validation and interpretation purposes, and allows for extrapolation to conditions where data is sparse or non-existent.

During this period the model was implemented to treat the heat up and burn process for clean, oxide free, particle combustion. Other assumptions include spherical symmetry, quasi-steady flow and quasi-constant physical properties. The latter assumption allows the effects of variable conductivity, diffusivity, and specific heats to be assessed after the differential equations are integrated. The most complete set of boron particle combustion data known to exist was obtained by Macek over the course of several years and these data are consolidated in a recent review by King, Ref. 5. This data base was used to compare with the model predictions for burn times spanning a range of particle sizes, oxygen concentrations and pressures. The results are given in Figures 2.2-1, 2.2-3 and 2.2-3. Figure 2.2-1 gives the burn time in air (21% oxygen) as a function of pressure for a range of particle sizes, at 300°K. The comparison is excellent showing good agreement between the data and predictions for all sizes and pressures. The model predicts the relative sensitivity to size and pressure level with the largest impact of pressure on burn time occurring for the smaller size particles burning at low pressures. The predictions also show that for pressure levels beyond the range of the data, about 23 atm, the effect of further increases in pressure are negligible for these sizes and operating conditions. Figure 2.2-2 shows a comparison of burn time predictions with the data for an oxygen concentration of 40 percent. The agreement between the predictions and the data is excellent indicating that the effects of both oxygen concentration and absolute pressure are properly characterized by the present analysis. These results span a particle size range of 37 μm to 124 μm in diameter. An examination of the details of the model predictions shows that the contribution of finite rate heterogeneous oxidation is important particularly for the 37 μm size particles. For smaller particles the effects of kinetics is dramatic which is shown for the limited data available, in the 1 to 10 μm size range, given in Figure 2.2-3. These data were obtained in a heated environment at an oxygen concentration of 20 percent and at an absolute pressure of 1 atmosphere. The predictions were carried out with the same kinetic and transport property representations used

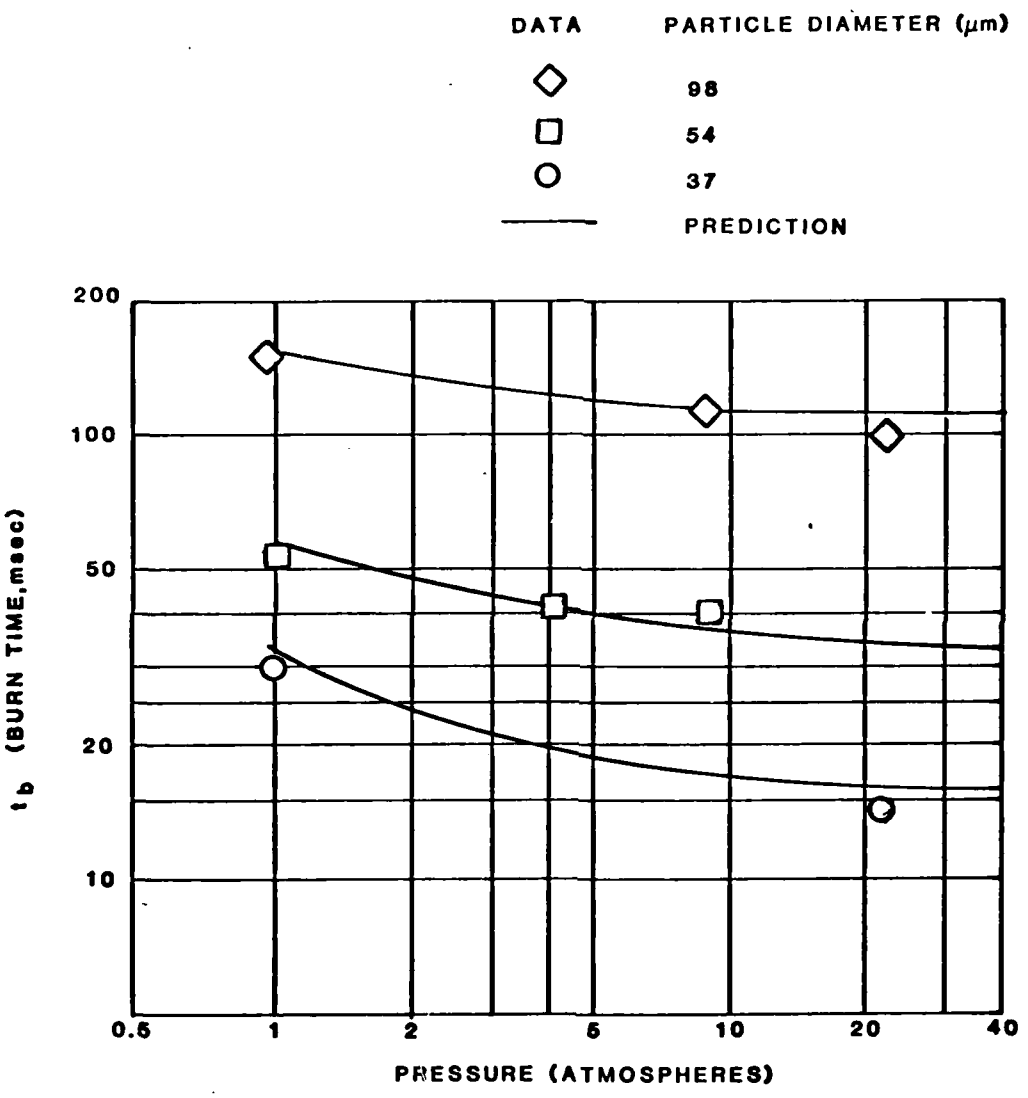

FIGURE 2.2-1 Comparison of Predictions with Data (Ref 5): Oxygen Concentration =0.21, T_{gas} = 300°K

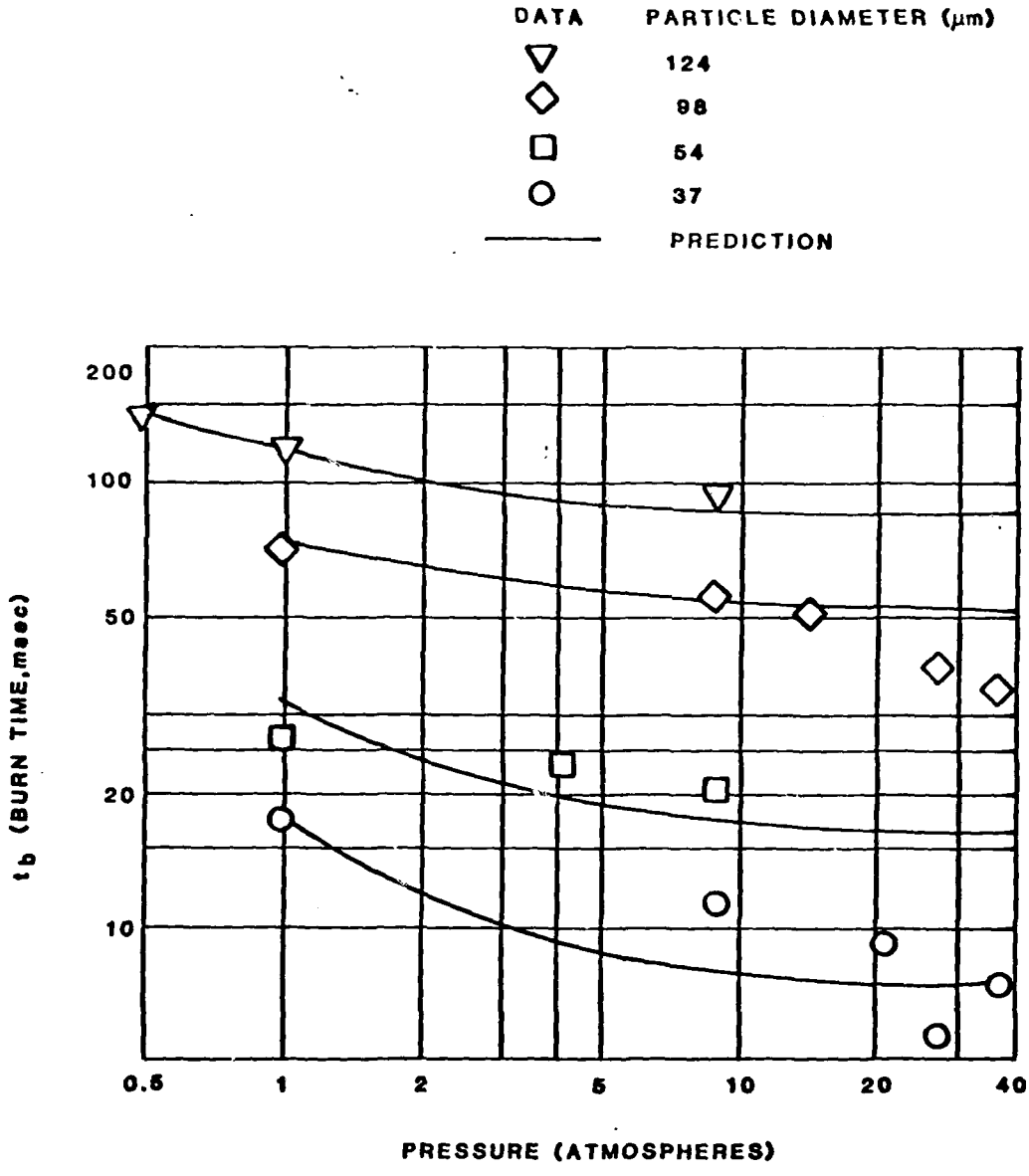

FIGURE 2.2-2 Comparison of Predictions with Data (Ref. 5): Oxygen Concentration =.40, T_{gas} = 300°K

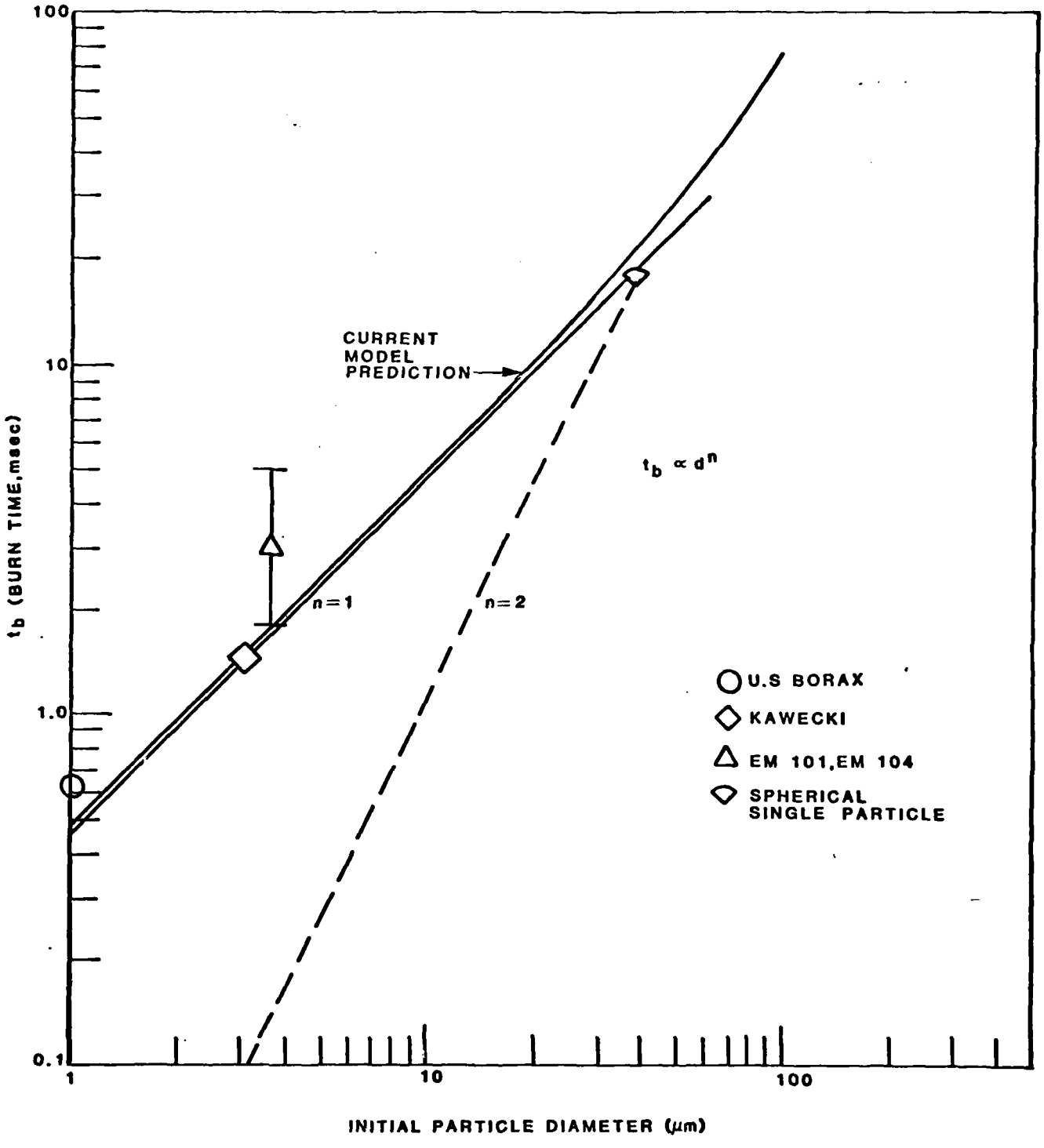

FIGURE 2.2-3 Comparisons of Predictions with Data (Ref. 5): Oxygen Concentration =0.20 T_{gas} = 2240°K

in the previous comparisons. Both the magnitude and the transition to the linear dependence of diameter on time exhibited by the data is predicted by the model. Furthermore, sensitivity studies have been carried out showing that at these operating conditions the burn time predictions for the 1 μm diameter particles are insensitive to the transport properties but begin to affect the results for the larger sizes.

In summary, the studies performed to date show that chemical kinetics plays a significant role in the combustion of boron over most of the size range covered by the experimental data. These results indicate that transition from kinetically dominated oxidation to diffusion controlled oxidation occurs over the 10 to 50 μm size range depending upon the operating conditions, a transitional range significantly larger than previously reported. In addition, it was found that the agreement between the predictions and the data is extremely sensitive to the transport property values used to define the rate of diffusion of heat and mass. The result suggests that the constant property assumption made by all prior investigators can produce misleading results particularly with respect to scaling of size and operating conditions. The continuing research on this task will emphasize these factors and others that relate to boron ignition as well as the combustion process. Research is in progress that includes describing the details of the boron oxide growth and removal process and partial heterogeneous oxidation of boron at the surface producing suboxides which burn to completion by off-surface homogeneous reactions. In addition, work has begun on the analysis of slurry droplet evaporation, ignition and combustion.

2.3 MODULAR MODELS OF RAMJET COMBUSTION PROCESSES

Both the spray flame analysis described in Section 2.1 and the boron kinetics model development described in Section 2.2 provide necessary elements for the development of a comprehensive model of the combustion process in slurry-fueled ramjet combustion chanbers. The framework for the overall model is the modular model approach that has proved successful in the analysis of liquid-fueled ramjet combustors. In this section the development of a modular model for a slurry-fueled ramjet combustor is discussed in the context of the analyses of experiments underway in an AFOSR/NWC cofunded program on boron slurry combustion at the Naval Weapons Center (NWC). The combination of the

analytical tools provided by the modular model approach and the experimental work being carried out at the Naval Weapons Center has as its objective the development of a fundamental data base on boron slurry combustion.

The modular model approach to the analysis of combustion chamber flowfields arises from a recognition that it is not feasible to obtain detailed computations of complex reacting flowfields with a single analytical model that applies to all regions in the flow. Many of the phenomena which occur in a combustor, such as flame stabilization and droplet vaporization and combustion, occur on characteristic time and length scales that are very much smaller than those which apply to the flowfield as a whole; thus an analysis fine enough in detail to apply to these processes is far more detailed than necessary for the rest of the flowfield.

In the modular model approach characteristic flowfield regions are defined, either empirically or through the exercise of elliptic aerodynamic models, Appropriate analytical models are then applied to each region in the flow with the definition of "appropriate" depending on the detail desired and the anticipated importance of the description of the particulat region to the characterization of the overall flowfield. For example, recirculation regions can be modeled as well-stirred reactors, since in these regions considerable backmixing occurs; the region of flow in which convective transport occurs in one major direction may be treated either as a 1 D plug flow or a 2 D flow with diffusion normal to the main flow direction, and the shear layers separating recirculation zones from the directed flow zones can be characterized using empirical or integral analyses. Fuel injection and vaporization and mixing processes may, in the context of a modular model, be treated as empirically defined, or the two-phase flow phenomena involved in fuel droplet vaporization and mixing can, as outlined in Section 2.1, be computed in detail.

Each of these characteristic region analyses are coupled to the others, in some cases iteratively, through their boundary conditions. Thus, for example, the directed flow model applicable to the region of the flow with essentially unidirectional convective transport, which can incorporate a coupled two-phase flow model and models for droplet-scale vaporization and burning, is iteratively coupled to the recirculation region model. This

coupling is provided by the model of the shear layer region, through which mass and energy fluxes into and out of the recirculation zone occur.

While the modular approach requires some empirical input for its application, this empirical input is relatively minimal, and it allows considerably greater calculational detail than is possible with other approaches to combustor modeling. The modular model is thus a very useful tool for the analysis of experimental results, since the experiments can provide the empirical input necessary for the development of the model, while the model provides a means for the detailed analysis and interpretation of experimental data. It is in this vein that the modular approach is being applied in the analysis of the boron slurry combustion experiments underway under joint AFOSR/NWC sponsorship at the Naval Weapons Center.

The objective of the combustor modeling work being carried out as part of task area 1(c) of this program, in conjunction with the AFOSR/NWC sponsored work being done by Dr. Klaus Schadow at NWC, is the development of a fundamental data base for boron slurry combustion. This includes both the development of models of the boron slurry combustion process and the use of these models to analyze and interpret the experimental data on boron slurry combustion obtained at NWC. To provide this comprehensive data base, a building-block approach with steadily increasing complexity is being followed in both the experiments and the analytical model development. In the experiments, the building-block aspect applies both to the configurations to be used and to the type of mixing process involved.

Several of the configurations being studied in the NWC experimental program are shown schematically in Figure 2.3-1. As can be seen from the figure, these configurations range from a simple axisymmetric coaxial flow through an axisymmetric dump geometry to configurations with non-coaxial air injection and with swirl. Similarly, the mixing processes being investigated include gas-phase fuels, liquid hydrocarbon fuels, particulate-laden gas-phase fuels, and slurry fuel injection. Throughout the experimental program the combustor inlet profiles are being carefully characterized and approach-flow turbulence is characterized and controlled. In a similar fashion to the experimental work, a hierarchy of analytical models of increasing complexity are being developed to provide analyses of the experimental data, to aid in the interpretation of the experimental results and to help to determine the

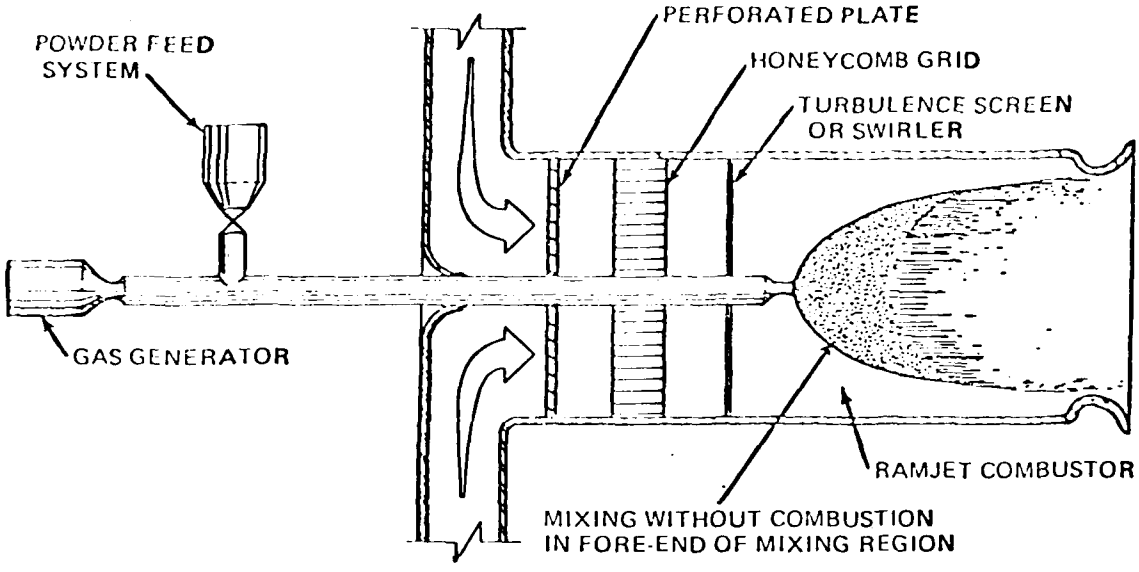

FIGURE 2.3-1a Fuel-Rich Plume Combustion in Axisymmetric Flow

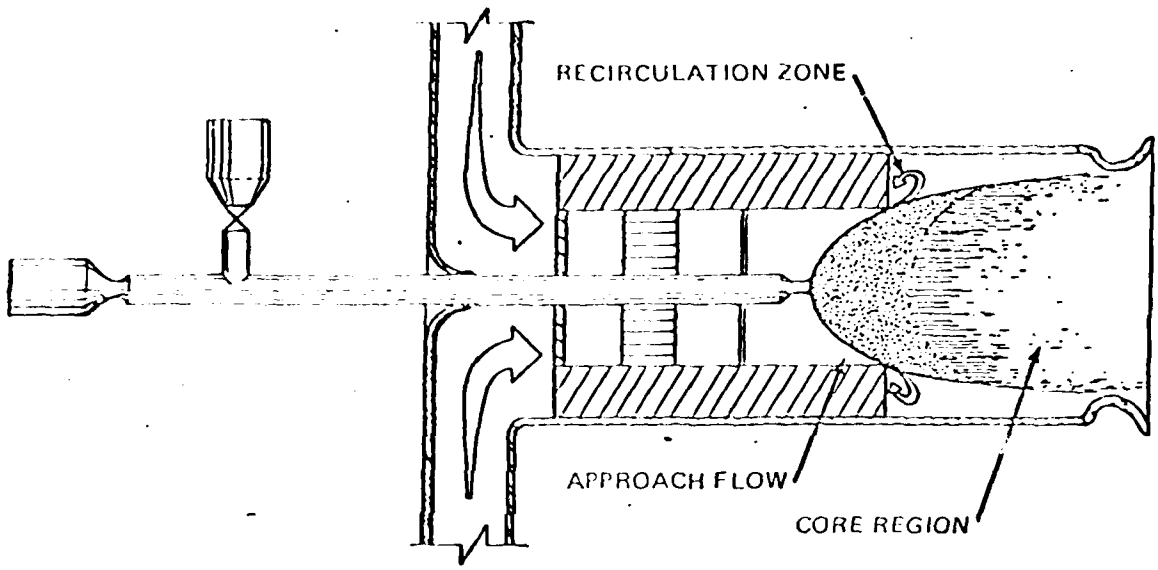

FIGURE 2.3-1b Fuel-Rich Combustion in Axisymmetric Flow with Dump

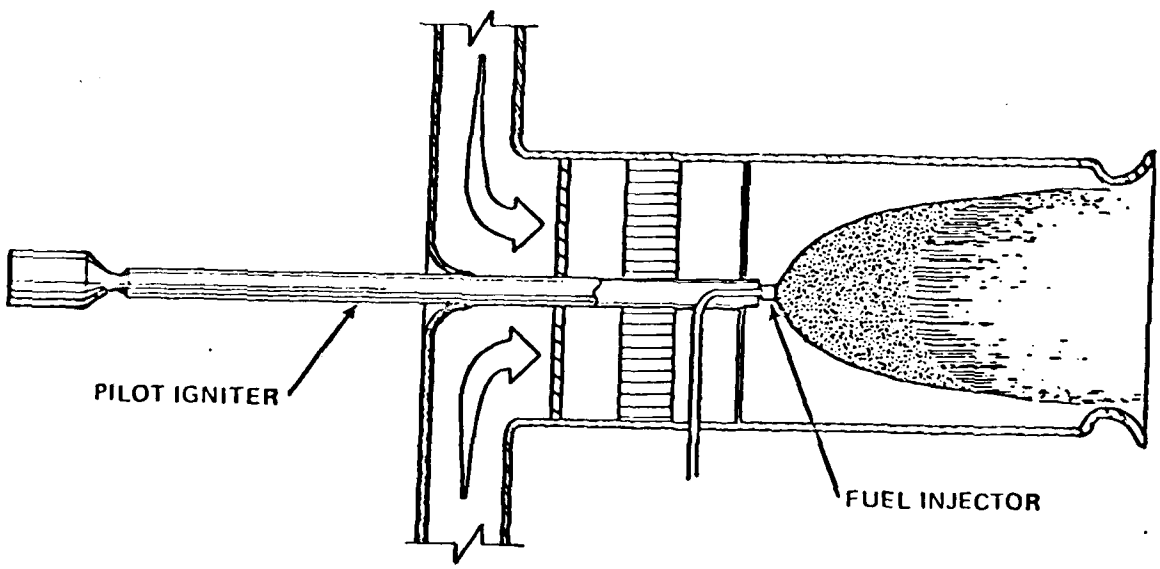

FIGURE 2.3-1c Spray Combustion in Axisymmetric Flow

type and location of experimental measurements required to maximize the data return from the experiments.

Figures 2.3-2 and 2.3-3 show a comparison of predicted temperature and velocity profiles with experimental data for gas-phase ethylene combustion in a simple coaxial-flow configuration. The central jet in this configuration represents the products of fuel-rich combustion of ethylene, diluted with nitrogen. This central jet has a measured temperature of 1600 K, and is nearly in chemical equilibrium (at least with respect to major species). The fuel-rich jet mixes with a surrounding low-speed air stream at a uniform approach velocity of about 21 ft/sec. For the conditions involved in this experiment autoignition of the hot fuel-rich combustion products occurs on mixing with the outer stream air; under combustion conditions the combustor chamber pressure is of the order of 80 psia.

For the computations shown in Figures 2.3-2 and 2.3-3 the autoignition process was simulated by assuming a 2350 K temperature "spike" at the nozzle lip. The subsequent combustion of the hot ethylene with the air stream was modeled using the quasiglobal chemical kinetics formulation (Ref. 6), while the turbulent mixing process was computed using a two-equation k-ε turbulence model, with coefficients as defined in Section 2.1 of this report. These computations utilized the basic code framework of the modular model described in Refs. 4, 7, 8); in particular, for this simple configuration, the analysis required only the directed flow portion of that modular model. The results presented in Figures 2.3-2 and 2.3-3 are in reasonably good agreement with the experimental data. No attempt has been made to optimize the turbulence model for these conditions, since these preliminary calculations have been made primarily to establish a baseline and to determine the requirements for additional measurements in the experimental program. As a result of a comparison of the predictions with the experimental data, the need for additional radial measurements for each profile station and for additional axial profile stations was demonstrated. More importantly, the comparisons showed that a more accurate pressure differential measurement was required to establish the velocity levels in the low-velocity airstream, and led to the identification of an error in the data reduction procedure used to obtain the mean velocity from pressure measurements. While both of these problems would probably have been uncovered as part of an entirely experimental program, the early

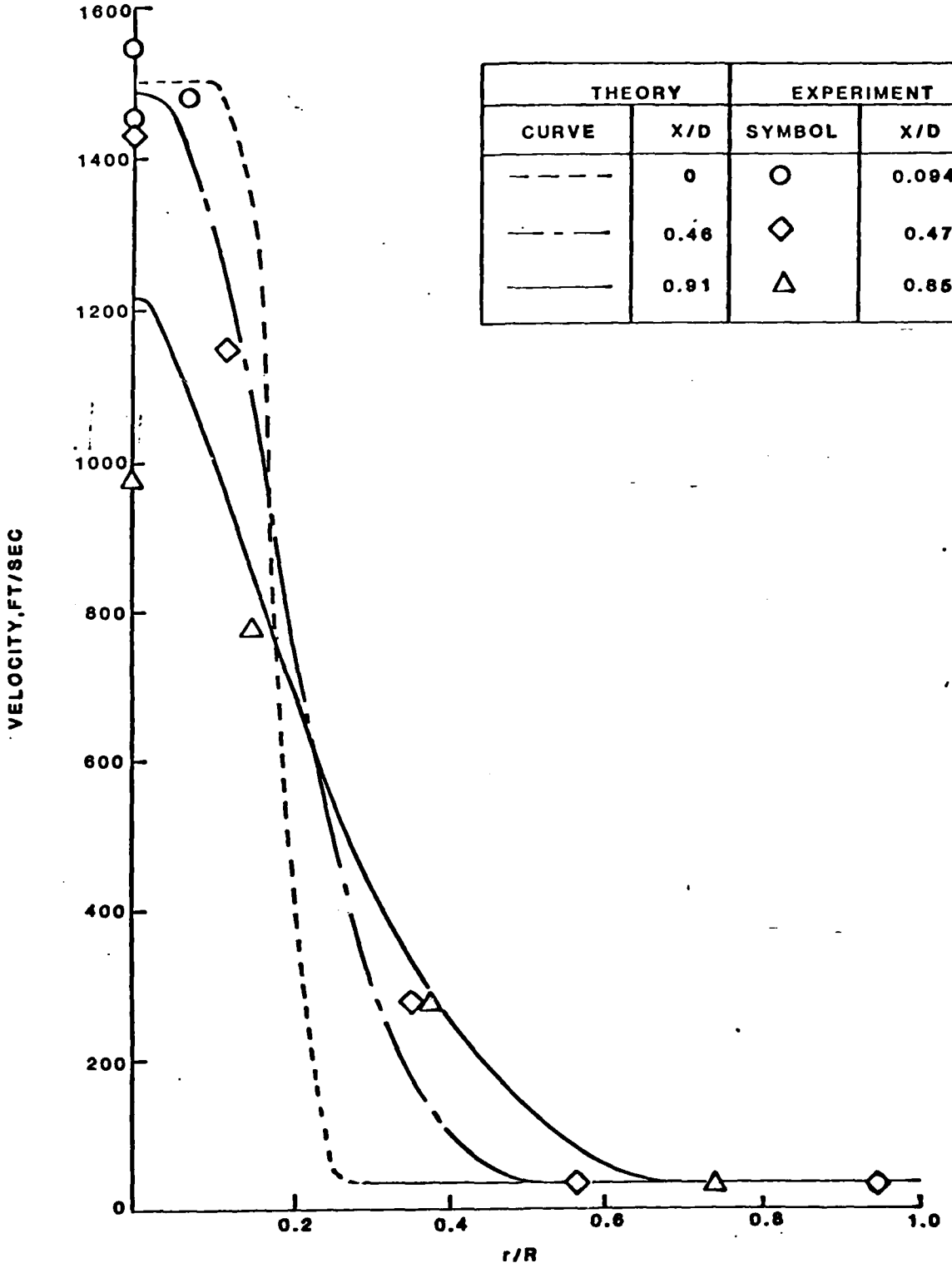

FIGURE 2.3-2 Comparison of Measured and Predicted Velocity Profiles, Ethylene-Fueled Coaxial Combustor

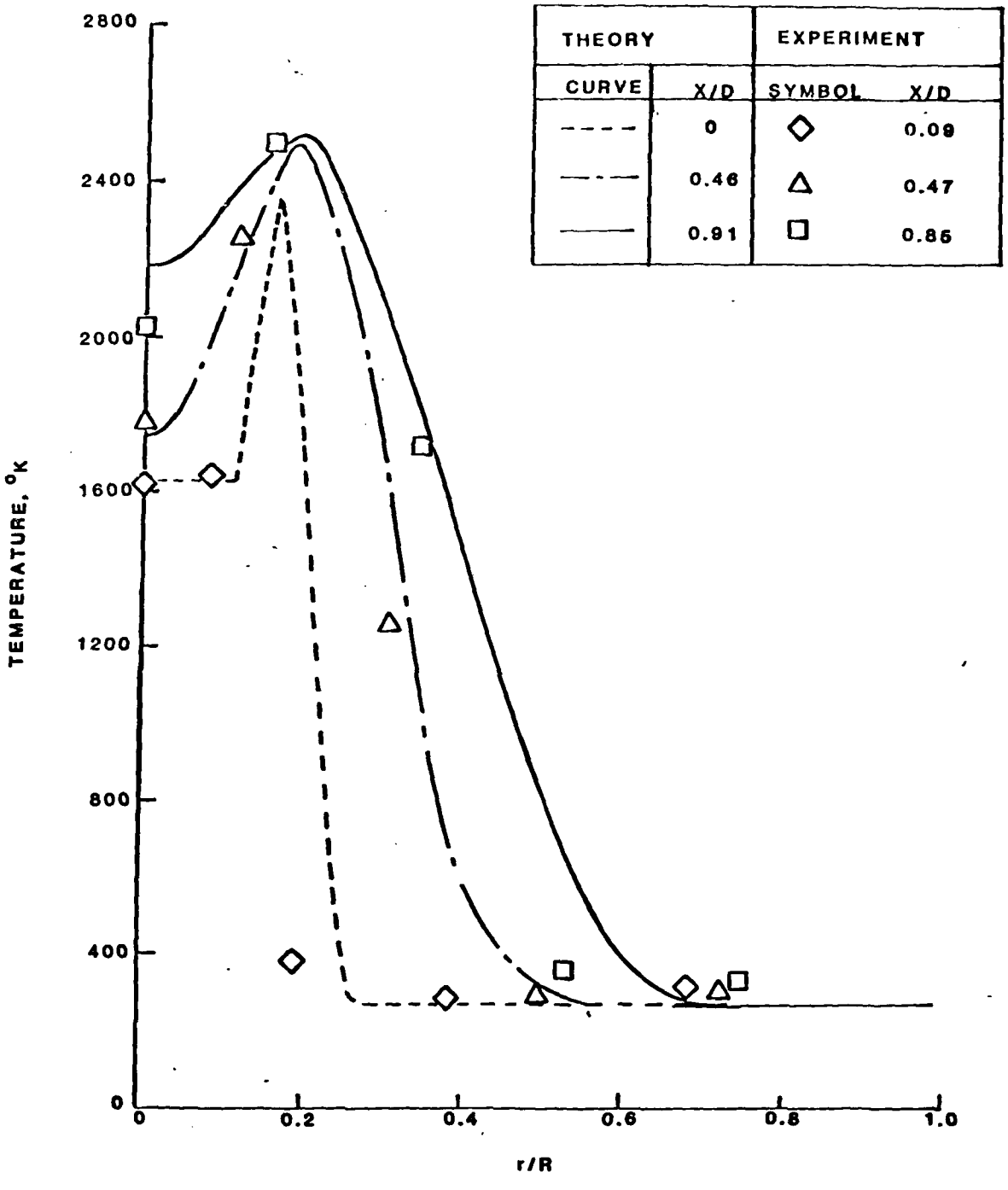

FIGURE 2.3-3 Comparison of Measured and Predicted Temperature Profiles, Ethylene-Fueled Coaxial Combustor

comparison of experimental results with analytical predictions carried out as part of this program resulted in a quick determination that a problem existed, thus minimizing the loss of data that might otherwise have resulted. This demonstrates one of the major applications of analytical combustor models in conjunction with an experimental program: analysis of the experimental results for consistency.

2.4 MODELING OF THE DUCTED ROCKET COMBUSTION PROCESS

The work being carried out in this program under the task area outlined in Section 1(d) has as its objective the development of a new theoretical model to describe the three-dimensional reacting flow typical of multiple-inlet ducted-rocket combustion chambers. It is supported, through AFOSR, by the Ramjet Division (RJT), AFWAL. Because of the paucity of experimental data on the aerodynamics of the ducted rocket configuration, the modular model development work under this task area is utilizing the hierarchy of models concept, in which unified elliptic aerodynamic models are utilized to define characteristic flowfield regions for the development of modular models which incorporate fundamental chemical kinetic formulations required to address the performance aspects of ducted rockets.

Aerodynamic calculations have been carried out for a three-dimensional configuration similar to an experimental ducted rocket combustor tested at AFWAL/RJT. The three-dimensional elliptic analysis used for these computations was a modified version of an analysis similar to the Imperial College TEACH code, incorporating a two-equation turbulent kinetic energy turbulence model similar to that used for the computations described in Sections 2.1 and 2.3. A three-dimensional grid is, of course, required, with 21 axial, 10 radial, and 18 circumferential grid points. This grid is not fine enough to provide grid-independent results, but since it involves 3780 node points it is a compromise between the fineness needed to obtain grid-independence and the limitations of computer storage and speed.* The configuration examined involves two symmetrically-disposed inlets at 180° apart: this is not identical to the

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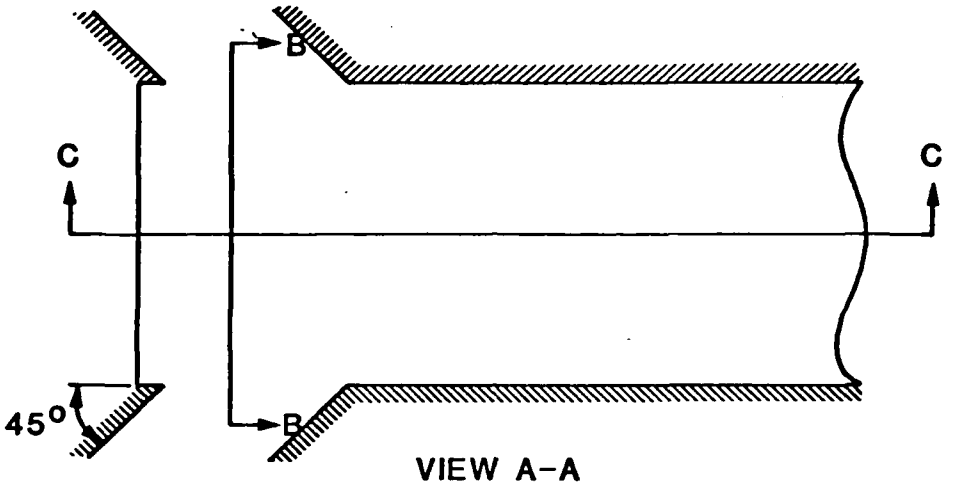
*The solution procedure involves 8 variables: three velocity components, the pressure, the flow enthalpy, and a species used as a tracer, as well as the turbulent kinetic energy and its dissipation rate. Thus for the grid noted, 30,240 locations are required for the storage of the dependent variables alone, for this nonreacting (but possibly nonisothermal) calculation.

AFWAL configuration but was selected to simplify the implementation of boundary conditions for this initial case. A sketch of this combustor geometry is shown in Figure 2.4-1, from which it can further be seen that the inlets are disposed at an angle of 45° to the longitudinal axis of the combustor. The air inlet velocity was selected to correspond to an airflow rate of 2 lb/sec/inlet.

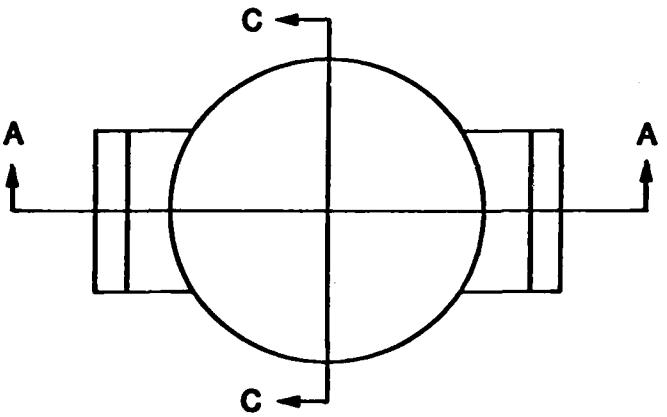
The velocity vectors computed for this flow field in a plane through the inlets and along the combustion centerline are shown in Figure 2.4-2. Two recirculation zones can be seen, one at the head end of the combustor and the second along the outer walls just downstream of the inlets. Contours outlining the approximate sizes of these recirculation regions are shown on Figure 2.4-2. For fuel injection in the inlet arms (i.e., the side-dump liquid fueled ramjet configuration) both of these recirculation regions are potential flameholding sites. However, if fuel is injected from the combustor head end (the ducted rocket configuration) it would be expected that the primary flameholding region would involve the recirculation zone at the combustor head end.

The radial extent of the recirculation zone at the head end of the ducted rocket combustor is depicted in Figure 2.4-3. Of interest in this view are the distinctive four-lobed shape of the recirculation region and the stagnation point shown on the flowfield centerline. Through computations such as represented by Figures 2.4-2 and 2.4-3 it is possible to build up a three-dimensional view of the size and shape of the recirculation zones in the ducted rocket combustor. This provides one of the required pieces of information for the development of a modular model of this flowfield.

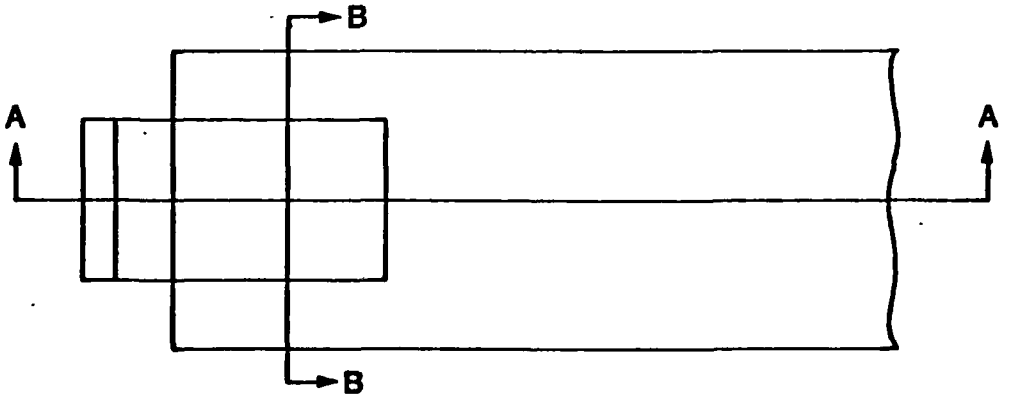
Various types of modular models can be postulated for a flowfield such as shown in Figures 2.4-2 and 2.4-3. However, one of the most useful, because of its computational speed and flexibility, is the well-stirred reactor/plug flow with distributed secondary injection/entrainment approach. In this model the intense mixing that occurs in the region of the inlets in the ducted rocket combustor is modeled using a well-stirred reactor formalism, while the subsequent mixing and combustion of fuel and air not transported into the recirculation zone is modeled as a plug flow with distributed entrainment. While this approach is fast and flexible, it requires, in addition to a specification of the size and shape of the recirculation zone, a measure of the proportion



VIEW A-A

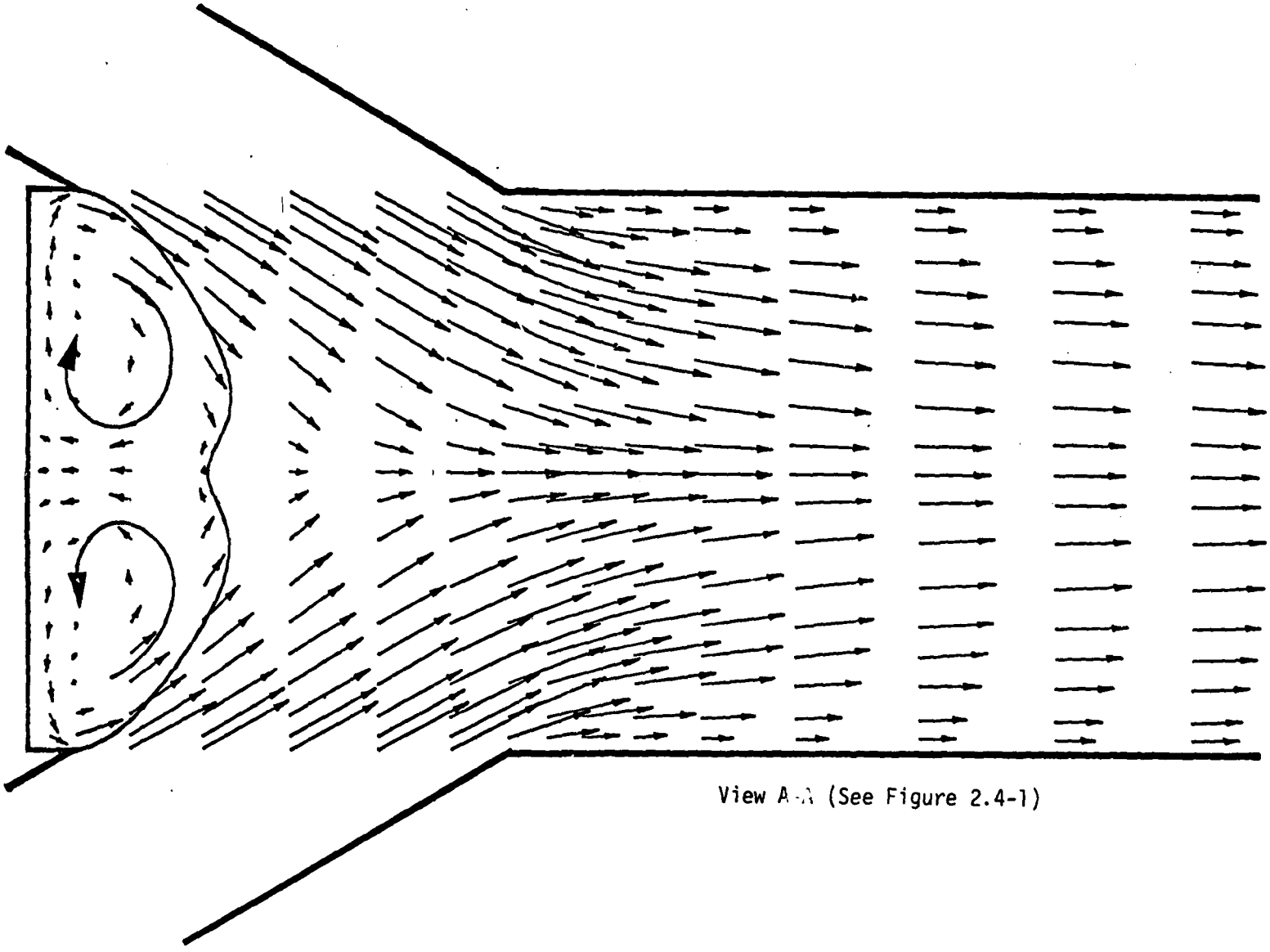


VIEW B-B



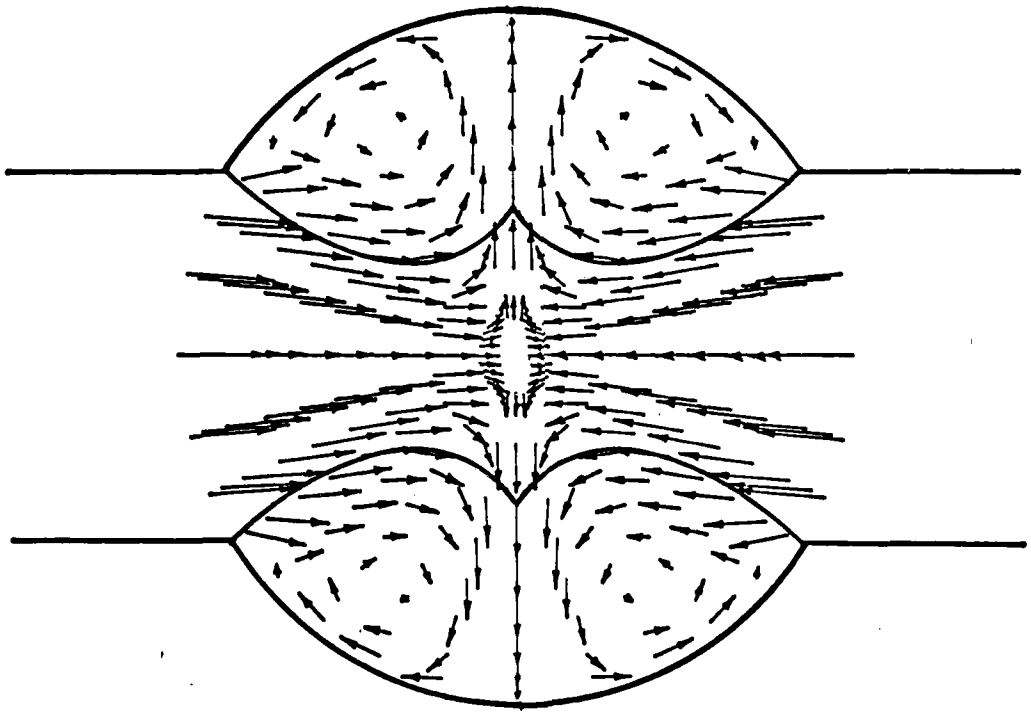
VIEW C-C

FIGURE 2.4-1 Schematic of Ducted Rocket Configuration for Aerodynamic Flowfield Analysis



View A-A (See Figure 2.4-1)

FIGURE 2.4-2 Longitudinal Cross-Section through Inlet Arms, Ducted Rocket Combustor Aerodynamic Flowfield



View B-b (See Figure 2.4-1)

FIGURE 2.4-3 Lateral Cross-Section through Inlet Arms, Ducted Rocket Combustor Aerodynamic Flowfield

of the flow involved in the recirculation region and in the subsequent mixing region. This specification of the proportion of the flow found in different regions can be estimated using the elliptic aerodynamic formulation with a species tracer. Since the proportion of the tracer fluid entering different regions of the flow will be a function of the initial location of the tracer material, a number of computations with different initial tracer locations will be required. However, by carrying out a series of such computations, a picture of the entrainment rates into different regions of a combustor flow-field can be built up, and this in turn can be used to complete the definition of the structure of the modular model.

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4. Harsha, P. T. and Edelman, R. B., "Assessment of a Modular Ramjet Combustor Model," to be published in Journal of Spacecraft and Rockets, July/August 1982.

4. PROFESSIONAL PERSONNEL

1. Dr. R. B. Edelman
2. Dr. P. T. Harsha
3. Dr. John C. Chien
4. Mr. W. N. Bragg
5. Mr. G. C. Cooper

5. INTERACTIONS

5.1 PRESENTATIONS

During this reporting period, the following presentations were made:

1. "Combustion Modeling for Practical Applications," Presented at ASME Fluids Engineering Conference, June 22-24, 1981.

2. "Interpretation of Ramjet Combustor Test Data," Presented at AIAA/SAE/ASME Joint Propulsion Specialist's Conference, July 22-29, 1981.

3. "Combustion Modeling for Ramjet Development Programs," Presented at AGARD Propulsion and Energetics Panel 58th Symposium, 26-29 October 1981.

4. "Mixing, Ignition, and Combustion in Flowing, Reacting Fuel-Air Mixtures," Presented at 1981 AFOSR Combustion Dynamics Contractor's Meeting, 16-20 November 1981.

5.2 CONSULTATIVE AND ADVISORY FUNCTIONS

Two of the task areas of this program involve continuing and formal interactions with other DoD laboratories. The ducted rocket modeling work carried out under the task area outlined in Section 1(d) involves close interaction with the experimental work being carried out by Drs. F. D. Stull and R. R. Craig at AFWAL/RJT. In addition, the boron slurry modeling effort described under 1(c) involves close coordination with experimental work being done by Dr. Klaus Schadow at NWC.


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