LMSC-HREC TR D496700

LOCKHEED

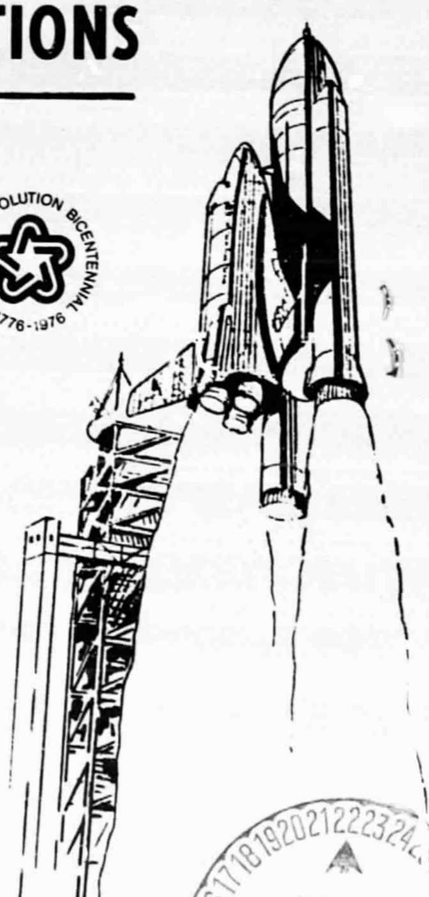
SUMMARY OF NOZZLE-EXHAUST PLUME FLOWFIELD ANALYSES PERFORMED IN SUPPORT OF SPACE SHUTTLE APPLICATIONS

Final Report

AMERICAN REVOLUTION BICENTENNIAL 1776-1976

Contract NAS9-14517

January



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(NASA-CR-147529) SUMMARY OF NOZZLE-EXHAUST PLUME FLOWFIELD ANALYSES PERFORMED IN SUPPORT OF SPACE SHUTTLE APPLICATIONS Final Report (Lockheed Missiles and Space Co.) 21 p HC $3.50 CSCL 21H G3/20

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FOREWORD

This report presents a summary of the results of work performed by the Lockheed-Huntsville Research & Engineering Center in fulfillment of the requirements of Contract NAS9-14517 with NASA-Johnson Space Flight Center, Houston, Texas, in support of Space Shuttle related exhaust plume applications. The contracting officier's technical representative for this study was Mr. Barney B. Roberts of the Aerodynamics Systems Analysis Section.

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Section 1
INTRODUCTION AND SUMMARY

The development and design of the Space Shuttle vehicle has focused much attention on the exhaust plumes of the vehicle. Current configurations utilize a combination of liquid and solid propellant booster motors to provide vehicle thrust during the launch phase. Solid propellant motors are also used to effect separation of the booster motors from the orbiter. Interaction of the exhaust plumes from these motors (both during the launch phase and stage separation) with the external surroundings produce hostile environments which must be considered in the respective design phases.

Plumes formed by the exhaust gases of the solid propellant rocket boosters and the orbiter main engine propulsion system interact with the freestream air flowing over the vehicle surfaces, thereby affecting the vehicle aerodynamic characteristics. In particular, plume-induced separation of the boundary layer occurs on the vehicle aft surfaces. Performance of the aerodynamic control surfaces (such as elevons and control surfaces on the vertical fin) located in the separated flow region is adversely affected resulting in a reduction of the vehicle aerodynamic control effectiveness. Also affected is the vehicle base drag. The extent of the influence of the propulsion system exhaust plumes on the vehicle performance and control characteristics is a complex function of vehicle geometry, propulsion system geometry, engine operating conditions and vehicle flight trajectory. Therefore, the magnitude and significance of the plume/vehicle aerodydynamics interaction must be determined for each launch vehicle system being considered. This interaction is ascertained from scale model launch vehicle test programs. The test programs, in general, utilize "cold" gas simulations of the various exhaust plumes. Appropriate similarity parameters are selected and applied to determine the model requirements to match the prototype plume shapes at the various trajectory points being considered. In addressing the problem of exhaust plume

shape simulation the three basic problem areas which must be considered are: (1) defining the full-scale exhaust plume characteristics; (2) selecting and applying the appropriate similarity criteria to determine model requirements; and (3) analysis of test data (including nozzle calibration data). Some of the studies conducted under this effort were directed primarily toward these items.

For applications associated with plume simulation, the full-scale data normally required are the plume initial expansion angle and the corresponding plume shape over a region of interest. After the test data are reduced the respective vehicle performance data are usually correlated with respect to the plume initial expansion angle. Consequently, for full-scale design applications one simply needs the full-scale initial plume angle as a function of the vehicle trajectory.

Calculation of the orbiter exhaust plumes are rather straightforward since these result from the operation of liquid propellant motors. However, the flow in the booster exhaust plumes is complicated by the presence of particles in the flow. These are primarily aluminum oxide particles resulting from the reaction of aluminum and oxygen in the motor chamber and nozzle. The particles are accelerated through the nozzle-plume flow field due to the drag exerted by the surrounding gas. During the gas flow expansion through the nozzle and plume flow field, the gas cools rapidly. However, since the particles are accelerated by the gas, the particle temperature is not reduced by the flow expansion process. Instead, the particles cool by heat conduction and radiation to the surrounding gas as the gas cools. The particles are thus hotter than the exhaust gas. Therefore, to correctly determine the exit plane properties and consequently the exhaust plume shapes, the effect of the interaction of the particles with the gas exhaust must be treated.

Previous studies have been directed toward developing a nozzle-exhaust/nozzle-plume computer code for treating the flow of a chemically reacting gas-particle mixture. Efforts under this contract were directed toward completing development of the code in the areas of finite rate chemistry and free molecular flow. For any computer code to be useful, good documentation is

necessary. A major task under the present study was to fully document the Reacting Multiphase (RAMP) Computer Code. A document consisting of two volumes describes the RAMP code. Included in the RAMP documentation is a discussion of the finite rate and free molecular capabilities.

Once a computer code is developed it is necessary to determine its validity and application. One of the tasks performed under this study was to provide analytical support in the area of pre-and post-test analysis of the Two-Phase Plume Verification Test Program which is currently in progress at NASA-MSFC. The results of this effort are presented in pretest predictions which were used to size the instrumentation. Ultimately the final data generated by the test program will be used to verify and determine how to best use the RAMP code.

The numerous studies performed under this contract are detailed in Section 2 (Task Summaries) of this document. Each task performed under this contract was documented at the conclusion of the respective task. Consequently, the following section provides a summary of each test.

Section 2
TASK SUMMARIES

The tasks performed under this contract were directed toward: (1) completion of the development of the two-phase plume flowfield model, including finite rate chemistry and free molecular effects; (2) analyses of exhaust plume simulation studies; (3) verification of the analytical two-phase plume flowfield model; and (4) complete documentation of the two-phase plume computer code.

The following discussion summarizes the various tasks performed under this contract.

2.1 GAS-PARTICLE FLOWS

Gas-particle flows in nozzle exhaust plume flow fields have received considerable attention during the development of the Space Shuttle. Solid propellant formulations are used in both the booster and stage separation motors. Exhaust plumes create hostile environments to surfaces immersed in the flow. These are in the form of structural loads, contamination and heating. Heating results from both gas and condensates impinging on the surfaces. Particulates in the flow can also cause surface erosion and other structural damage.

Exhaust plume applications and plume impingement problems typically occur during launch, staging and rendezvous. The current Space Shuttle design offers several illustrations of areas where exhaust plume flowfield properties and flow structure must be known. During the Space Shuttle launch the solid rocket booster motor exhaust plumes impinge on the launch stand hardware. While the launch vehicle is in the vicinity of the launch pad, reradiation from the launch pad to the orbiter is a potential problem. The solid rocket motor exhaust plume affects the shuttle base drag and aerodynamics during

the boost phase. The solid rocket separation motors mounted on the booster motor's forward and aft ends used to effect stage separation can potentially subject the orbiter and external hydrogen/oxygen tank to a rather severe environment.

Exhaust impingement applications require a detailed definition of the gaseous plume structure as well as particle trajectories and dynamic properties. Plume simulation studies require that plume shapes be known. The exit plane pressure must be known along with the gas thermodynamics. To adequately describe the flowfield properties, the mutual effect of gas on particle and particle on gas must be calculated. Also "real gas" effects can be significant and should be included in the gasdynamic considerations.

The two-phase flowfield model previously developed under Contract NAS9-13429 has been further developed under the present contract. Finite rate chemistry and free molecular effects have also been incorporated into the flowfield model. The tasks performed are described in the following paragraphs.

<u>Comparison of Rocket Nozzle Flow Fields Calculated with RAMP Computer Code Using Different Transonic Start Lines (Ref. 1)</u>

To predict solid rocket motor (SRM) exhaust plume interaction with the Space Shuttle structure and aerodynamics, analytical techniques have been developed for calculating the exhaust plume flow fields of solid propellant rocket engines. The Lockheed Two-Phase Plume Program (RAMP) (Ref. 2) calculates the supersonic portion of rocket nozzle flow fields and rocket exhaust plume flow fields of solid propellant rocket engines. In order to start the supersonic RAMP calculations, a supersonic start line must be calculated. To model the two-phase effects of gas-particle flows, a transonic approximation developed by Kliegel (Ref. 3) has been used to calculate gas and particle properties on a supersonic start line. The Kliegel transonic analysis is restricted to nozzles with a nozzle radius of throat curvature to throat radius ratio greater than one. For motors such as the Space Shuttle booster,

the use of the Kliegel analysis requires an analytical modification to the nozzle throat region to generate a start line for the supersonic RAMP solution.

To avoid the restriction on nozzle throat radius of curvature, a computer code (Ref. 4), ODPART, has been developed to calculate one-dimensional gas-particle flows and to generate a start line for initiating the RAMP supersonic solution. Because it is one dimensional, ODPART is not restricted by the throat radius of curvature. A study was conducted to compare the results of RAMP nozzle calculations using start lines calculated with the Kliegel computer code with RAMP nozzle claculations using start lines calculated with ODPART.

To compare the results of RAMP calculations using different start lines, gas and particle properties were plotted comparatively for each case. Comparison of gas properties was accomplished by plotting nozzle wall static pressures and nozzle centerline static pressures. Comparison of particle properties was accomplished by plotting particle limiting streamline locations and particle temperature and velocity on the nozzle center line. The particle properties of the largest and smallest particles in each distribution were chosen for comparison.

ODPART-RAMP calculations with a start line Mach number of 1.15 produced the most favorable agreement with the corresponding Kliegel-RAMP calculations. Nozzle solutions generated using the one-dimensional ODPART start lines are comparable with the nozzle solutions using the Kliegel start lines. The ODPART-RAMP calculation provided nozzle pressure distribution agreement sufficiently accurate to predict initial plume expansion angles and exhaust plume pressure distributions. The difference between the ODPART-RAMP and Kliegel calculation of the particle limiting streamline locations would have some effect on particle impingement calculations. It has not been determined which calculation produces the most valid particle limiting streamline locations.

RAMP Program Development

The finite rate capability was made operational and checked out during this contract. This capability is discussed in the program documentation of Refs. 2 and 16.

The free molecular option was a so made operational under this contract. The free molecular calculation is described in Ref. 16.

2.2 EXHAUST PLUME SIMULATION ANALYSES

Definition of the Space Shuttle Main Engine Exhaust Plume Initial Plume Expansion Angle for Several Trajectory Conditions (Ref. 5)

The exhaust plumes from the Space Shuttle propulsion systems can have a significant effect on the base pressure and base drag of the Shuttle vehicle. Previous studies have shown that base pressure can be correlated to the plume initial expansion angle, δ_j. These same studies indicate small changes in δ_j can result in significant variation in base pressure. Therefore, it is important that a correct prediction of δ_j be obtained so that the effect of the plumes on vehicle drag can be determined.

The objective of this study was to generate the nozzle and initial plume flowfield for several trajectory conditions. The resulting data is presented in a form so that the initial plume expansion of the shuttle main engine can be determined throughout the entire trajectory.

SSME 1.2-A Model Nozzle Flow Calculation with Thermodynamic Variables Modified to Account for the Presence of Oxygen Condensation (Ref. 6)

To compensate analytically for the condensation of oxygen inside of model nozzles, a technique was developed for adjusting the thermodynamic data used in a method-of-characteristics (MOC) computer code for predicting the model nozzle exhaust plume flow field. The technique requires that experimental nozzle wall static pressure distribution data be obtained for the model nozzle being investigated at operating conditions for which condensation

was present. The technique does produce improved agreement between analytical calculations and experimental data for a subscale nozzle flowing cold air. The technique is not a rigorous analytical solution which includes a treatment of the mechanics of the condensation process. Each problem solution is valid for only one operating condition and must be recalculated for each operating condition investigated. The solution technique requires that experimental nozzle wall static pressure distribution data be available for each operating condition being investigated.

The heat released by the condensation process is a non-adiabatic and non-isentropic process with the result that the expansion after condensation is defined by a different isentrope. The results of this analysis substantiate that condensation shifts the flow expansion from one isentrope to another. Results indicate that for plume simulation applications the expansion process can be treated by a single phase calculation such as the MOC code if the correct thermodynamic properties are known downstream of the condensation front.

Space Shuttle SRM Plume Expansion Sensitivity Analysis (Ref. 7)

The exhaust plumes of the Space Shuttle solid rocket motors (SRM's) can have a significant effect (Ref. 1) on the base pressure and base drag of the Shuttle vehicle. Previous studies (Ref. 2) have shown that base pressure can be correlated to the initial plume expansion angle, δ_j. These same studies indicate that small changes in δ_j can have a significant effect on the vehicle base pressure. Therefore, it is necessary to predict the value of δ_j as accurately as possible before a realistic assessment of the exhaust plume effect on the vehicle base pressure can be ascertained.

A parametric analysis was conducted to assess the sensitivity of the initial plume expansion angle of analytical solid rocket motor flow fields to various analytical input parameters and operating conditions. The results of the analysis are presented and conclusions reached regarding the sensitivity of the initial plume expansion angle to each parameter investigated. Operating

conditions parametrically varied were chamber pressure, nozzle inlet angle, nozzle throat radius of curvature ratio and propellant particle loading. Empirical parameters investigated were mean particle size, local drag coefficient and local heat transfer coefficient. Sensitivity of the initial plume expansion angle to gas thermochemistry model and local drag coefficient model assumptions were determined. The initial plume expansion angle was most sensitive to gas thermochemistry model, propellant particle loading and mean particle size assumption. The initial plume expansion angle was minimally sensitive to chamber pressure, nozzle throat radius of curvature ratio, nozzle inlet angle, local drag coefficient and local heat transfer coefficient. The local drag coefficient model assumption had no effect on the initial plume expansion angle.

Assessment of Analytical and Experimental Techniques Utilized in Conducting Plume Technology Tests 575 and 593 (Ref. 10)

The complexity of the exhaust plume simulation problem necessitates a clearer understanding of the interactions of the various geometric, thermodynamic and gasdynamic parameters which affect exhaust plume shape. To better understand the exhaust plume simulation problem, a comprehensive experimental program was conducted using test facilities at NASA's Marshall Space Flight Center and Ames Research Center. This document reports on a post-test examination of some of the experimental results obtained from NASA-MSFC's 14 x 14-inch trisonic wind tunnel.

This document reports on a study that was conducted to: (1) assess the agreement that could be expected between experimental results and predicted values in future tests; (2) examine in some detail the effectiveness of the various analytical models being employed to generate pretest information and, finally; (3) to specifically recommend analytical and experimental techniques that should be utilized in future tests involving exhaust plume simulation. It is meaningful to note that, although the Space Shuttle application is the driving force behind this study, the results are applicable to other systems employing rocket propulsion.

The following recommendations were made as a result of this study:

1. Predictions of exhaust nozzle and plume flowfield characteristics for systems using air as the working fluid should utilize an equilibrium chemistry (standard equation of state) or ideal gas thermochemical model for the air.
2. Predictions of exhaust nozzle and plume flowfield characteristics for systems using CF_4 as the working fluid should generally utilize the real gas model of Ref. 11 for the CF_4. It should be noted, however, that this model does not adequately treat test conditions involving high chamber pressures (>1000 psia) in conjunction with low chamber (i.e., total) temperatures (< 250°F).
3. Additional investigations should be made to establish an applicable CF_4 gas model for the test conditions not adequately treated if deemed necessary by the experimental program requirements.
4. Transonic effects and boundary layer growth can be neglected for nozzles of the size range considered in this program when operating in the same (or larger) Reynolds number range.
5. The accuracy of the transducers used to assess nozzle performance should be maintained at a significant and consistant level over the range of test conditions.
6. Consideration should be given to the size of the pressure ports in the nozzle walls. The ports should be kept small relative to nozzle length.
7. Future tests should include near field pitot pressure surveys in the exhaust plumes to correlate with optical data. These additional data will aid in more accurately determining exhaust plume characteristics.
8. Calculations made to predict nozzle wall pressure distributions and exhaust plume shapes should utilize nozzle dimensional inspection data in forming the mathematical models of the nozzles.

Requirements for an Analysis to Investigate Condensation Phenomena in Subscale Nozzle Expansions (Ref. 12)

This report summarizes the current status of analytical and experimental data related to condensation phenomena in subscale nozzle expansions. Based on present knowledge of the phenomenon, geometric and operating parameters which affect the condensation process are presented. Nozzle design

and operating parameters which can be controlled to avoid or minimize condensation are discussed. A section is included on how to identify condensation affects in experimental/analytical data comparisons. Attempts at analytical treatment of condensation effects in experimental data are discussed briefly. Finally, a test program matrix and data consolidation scheme are presented for accumulating the data necessary to define condensation phenomena and/or the effects of these phenomena in subscale nozzle expansions.

2.3 TWO-PHASE PLUME PROGRAM VERIFICATION

Preliminary Analysis of Rocket Exhaust Plumes for the Test Program to Verify the RAMP Computer Code (Ref. 13)

An analysis of a preliminary rocket nozzle contour, propellant formulations and operating conditions was performed to aid in the selection of a test facility and for broadly defining test program hardware requirements for the test program to verify the RAMP computer code.

Two-Phase Verification Test Program Pretest Analysis (Ref. 14)

The Lockheed Reacting Multi-Phase (RAMP) computer code was developed for calculating the exhaust plume flow fields of solid propellant rocket engines. To verify the validity and accuracy of the RAMP calculations and empirical input data, an experimental test program was conceived to measure pertinent rocket nozzle and exhaust plume flowfield data for small solid propellant rocket engines. The results of a pretest analysis of this experimental test program are presented. Criteria for the rocket nozzle design, propellant formulations and nozzle operating conditions are discussed. A test matrix for the experimental program is presented and discussed. The results of RAMP nozzle and exhaust plume calculations are presented for the verification test nozzle firing propellants with 2, 10 and 15% aluminum loadings. The RAMP exhaust plume flow fields were generated for a chamber pressure of 1000 psia and altitudes of 50,000 and 100,000 feet. Radial distributions of Mach number, static temperature, static pressure and pitot pressure are presented for an axial location of 8 nozzle exit radii from the nozzle exit plane for each exhaust plume flow field. Radial distributions of these properties are

given for an axial location of 40 nozzle exit radii from the nozzle exit plane for the 100,000 foot altitude exhaust plumes.

Using the exhaust plumes generated with the RAMP computer code, the Lockheed PLIMP computer code was used to generate impingement pressures and heating rates on a flat plate inclined at 30, 45 and 90 degrees to the nozzle centerline. Total impingement pressures and heating rates along the centerline of the flat plate are plotted for an axial location of the flat plate of 8 nozzle exit radii from the nozzle exit plane. For the 100,000 foot altitude exhaust plumes, impingement pressures and heating rates along the centerline of the flat plate are presented for an axial location of the flat plate of 40 nozzle exit radii from the nozzle exit plane.

Prior to use with solid propellants, several of the nozzles will be calibrated using dry air. Nondimensional nozzle wall pressures for the nozzle contour expanding air from chamber pressures of 500 and 1000 psia are plotted. Corresponding exhaust plume boundary and internal boundary shock profiles for altitudes of 50,000 and 100,000 feet are presented.

2.4 TWO-PHASE PLUME PROGRAM DOCUMENTATION

Chemically Reacting One-Dimensional Gas-Particle Flows (Ref. 15)

This report describes a numerical solution for chemically reacting gas-particle flows in rocket nozzles and exhaust plumes. The gas-particle flow solution is fully coupled in that the effects of particle drag and heat transfer between the gas and particle phases is treated. A computer code for calculating the one-dimensional flow of a gas-particle system is discussed and a user's input guide is presented.

The computer code provides for the expansion of the gas-particle system from a specified starting velocity and nozzle inlet geometry. Though general in nature, the final output of the code is a start line for initiating the solution of a supersonic gas particle system in rocket nozzles. The start line includes

gasdynamic data defining gaseous startline points from the nozzle centerline to the nozzle wall and particle properties at points along the gaseous startline.

Supersonic Flow of Chemically Reacting Gas Particle Mixtures — Volume I, A Theoretical Analysis and Development of the Numerical Solution (Ref. 16)

This report describes a numerical solution for chemically reacting supersonic gas-particle flows in rockct nozzles and exhaust plumes. The gas-particle flow solution is fully coupled in that the effects of particle drag and heat transfer between the gas and particle phases is treated. Gas and particulates exchange momentum via the drag exerted on the gas by the particles. Energy is exchanged between the phases via heat transfer and radiation (optional).

Basic assumptions made in the development of the governing equations are similar to those employed by pervious investigators. The primary exception is the treatment of chemical effects in the gas phase. Thermochemistry calculations (chemical equilibrium, frozen or chemical kinetics) are shown to be uncoupled from the flow solution and, as such, can be solved separately.

The solution to the set of governing equations is obtained by utilizing the method of characteristics. The equations cast in characteristic form are shown to be formally the same for ideal, frozen, chemical equilibrium and non-equilibrium reacting gas mixtures. The characteristic directions for the gas-particle system are found to be the conventional gas Mach lines, the gas streamlines and the particle streamlines.

The basic mesh construction for the flow solution is along streamlines and normals to the streamlines for axisymmetric or two-dimensional flow. The analysis gives detailed information of the supersonic flow and provides for a continuous solution of the nozzle and exhaust plume flow fields. Boundary conditions for the flow solution are either the nozzle wall or the exhaust plume boundary.

The particle distribution is represented in the numerical solution by a finite distribution of particle sizes. The particle limiting streamline concept is utilized to define the region of influence for a particular particle. Particle and thermodynamic properties are defined by the particle mass density, distribution of particle sizes and thermodynamic data.

Presented is the development of the set of governing partial differential equations for the gas-particle system. The governing equations are cast in characteristic form and the corresponding difference equations formulated. The numerical solutions for the various point types are described and the corresponding steps of each solution outlined.

Supersonic Flow of Chemically Reacting Gas-Particle Mixtures — Volume II, RAMP — A Computer Code for Analysis of Chemically Reacting Gas-Particle Flows (Ref. 2).

This report describes two computer programs which are applicable to the analysis of chemically reacting gas-particle flow fields. The programs are:

- The NASA-Lewis FORTRAN IV computer program for calculation of thermodynamic and transport properties of complex chemical systems (TRAN72)
- The Lockheed Reacting and Multi-Phase Computer Program (RAMP).

These programs are currently operational on the CDC, Univac and IBM computers. To facilitate the use of the codes, they are constructed such that automatic transmission of data to other computer programs is possible via magnetic tapes.

Section 2 presents a description of the modifications made to the TRAN72 computer program to meet the general requirements of Lockheed's reacting and multi-phase computer program and provides instructions for operating the modified TRAN72 program. Four example cases showing the required input format and resultant output for creation of thermodynamic data

for typical rocket performance problems are presented. No attempt is made to report on the program itself since this information is documented in Ref. 17 and 18.

Section 3 discusses the RAMP program. Included are:

- A discussion of the basic capabilities and limitations of the program
- A user's input guide for the RAMP program
- A description of the typical input/output for a two-phase chemical equilibrium flow problem; a single phase chemical equilibrium flow problem with free molecular considerations and a single phase finite rate chemistry flow problem
- A discussion of typical user problems and possible fixes
- A list of helpful hints and a presentation of example deck set-ups
- A brief description of each of the basic routines in functional groupings
- A discussion of the basic flow of the program
- A detailed discussion of each individual routine used in the program
- Program overlay structure
- A section of typical example problems including a statement of the problem, accompanying figure and sample input and output.

CONCLUSIONS

This study has made significant technological advances in the areas of application and development of analytic tools for solving Space Shuttle plume problems. In particular, considerable understanding of numerous controlling phenomena in subscale simulations has been achieved. The two-phase plume model documented under this contract will allow a more accurate and detailed analysis of solid rocket motor nozzle/plume flow fields.

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