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SPACE SHUTTLE BASE HEATING ANALYSIS

Final Report

on

Contract NAS8-29270

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ABSTRACT

This report summarizes work performed in support of radiation and convective base heating predictions in developing the Space Shuttle thermal environment. The work included: plume radiation predictions and the development of prediction methods, convective base heating predictions due to both reversed flow and direct plume impingement, and evaluation testing of a REMTECH designed gas temperature probe used in short-duration base heating model tests.

FOREWORD

This report was prepared by REMTECH, Inc., Huntsville, Alabama, for the National Aeronautics and Space Administration, Marshall Space Flight Center, Systems Dynamics Laboratory, in partial fulfillment of Contract NAS8-29270.

The work summarized in this report was performed with the technical coordination of Dr. Terry Greenwood and Mr. David Seymour of the Thermal Environment Branch, ED-33.

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1 INTRODUCTION

Tasks performed on Contract NAS8-29270 were directed at prediction of the Space Shuttle base thermal environment. The work included predictions of thermal environments due to both plume radiation and convective heating and development testing of a gas temperature probe designed by REMTECH for use on short-duration base heating models. Results were documented in a series of reports and memos (Refs. 1-23) as each task was completed to provide timely data for thermal environment predictions and thermal analysis on the Space Shuttle. This report summarizes the work performed and the progress achieved. Detailed results are available in the referenced documents.

Some of the most important accomplishments were those which provided a basis for future base thermal environment predictions. These included: (1) development of a flowfield transformation program (Ref. 1) and a significantly improved plume radiation prediction program (Ref. 8); (2) documentation and analysis of data obtained during Space Shuttle base heating test IH-39 at the NASA/LeRC 10 x 10 supersonic wind-tunnel (Ref. 19); and (3) evaluation testing of the REMTECH gas temperature probe (Refs. 22 and 23) which has become an essential instrument in base heating model tests. Most of the other work under the contract provided documentation of specific thermal environment conditions.

A summary of the work performed will be presented in the following Technical Discussion and conclusions and recommendations for future work will be summarized in the final section.

2 TECHNICAL DISCUSSION

Plume radiation work will be described first in this section followed by convective base heating and finally the gas temperature probe evaluation test.

2.1 SSME PLUME RADIATION

Although most work involved radiation from the Space Shuttle Main Engine (SSME) plumes, the methods developed are applicable to a larger range of problems, and predictions included radiation from burning insulation (SOFI) on the External Tank (ET) and a proposed Liquid Booster Motor (LBM) for thrust augmentation. The following paragraphs will summarize: the two computer programs developed; supporting studies evaluating prediction methods; and the various predictions performed.

Since the engine axes in the SSME cluster are not parallel and the SSME vacuum plume prediction technique supplied the plume properties in several pieces (two-plume interaction, three-plume interaction, and free plume), a procedure was needed to assemble a flowfield property description compatible with the gaseous radiation (GASRAD) program. The procedure developed was the DTRANS program described in Ref. 1. It requires input describing gas properties in the three plume regions along with the predicted shock angle between regions and the cant angle between the engine and the cluster axes. The output is gas property data in a cylindrical system about an axis parallel to the cluster axis which is compatible with the GASRAD input requirements.

The GASRAD program (Ref. 8) was developed from previous NASA/MSFC plume radiation codes. It uses a statistical band model with the necessary coding to predict radiation from H_2O, CO_2, CO, HCl, HF, and small carbon particles. Significant changes have been made in the geometry procedures of the new code to provide: better simulation of shading surfaces; selection of integration limits corresponding to a cone bounding the plume; and increased flexibility of locating surfaces and multiple plumes. A subroutine has been provided to predict H_2O radiation using the Intuitative Derivative band model formulation for inhomogeneous gases rather than the Curtis-Godson approximation used in the remainder of the program.

Although derivative formulations provide improved representation of hot H_2O radiation through a long cold path, an evaluation of a typical base heating prediction (Ref. 2) indicated the simpler Curtis-Godson approximation is adequate for heat transfer applications in the base region.

Radiation measurements were made on the SSME plume to evaluate the radiation prediction model (Ref. 7). The measurements were made during static firings on the A-1 Test Stand at the National Space Testing Laboratory (NSTL). Two heat-transfer gages were mounted on the test stand for one firing on Sept. 8, 1977 and a series of thirteen tests between June 5 and Sept. 18, 1978. Results indicated that the plume gas property model and radiation prediction methods used in the most recent radiation model (Ref. 5) overestimate the measured radiation by 40 to 47 percent. Considering the uncertainties in measurement, the difficulties involved in plume radiation prediction, and the desire for slight conservatism in the predicted environment, the agreement between prediction and experiment was considered acceptable.

The initial radiation predictions for the vacuum plume described in Ref. 1 have been superseeded by environments published in 1976 (Ref. 24) and 1978 (Ref. 5) using an improved plume model developed on this contract (Ref. 25).

Recent radiation environment changes have been due to refinements in the low altitude plume predictions which were made to improve comparisons between plume radiation predictions and measurements made during static firings of the SSME (Refs. 7 and 26). A result of the plume refinements was a general lowering of the predicted radiation environment and the chronology of this process is summarized in Ref. 27. The most recent environment (Ref. 5) uses SSME low altitude plumes described in Refs. 28-30 and the vacuum plume model of Ref. 25. Other plume effects considered were the impingement region between SSME and SRB (Solid Rocket Booster) plumes and the flow reversal from the SSME and SRB plumes in the base region. The entire environment including SSME and SRB plume radiation was published in Refs. 31-33.

Ground tests of the SOFI (sprayed-on-foam-insulation) used on the ET indicated that the high radiation heating rates in the base region could cause decomposition of the SOFI and combustion of the carbon and gaseous products. Although the test conditions could not accurately simulate the conditions on the ET base at launch, it was necessary to prepare an environment on the assumption that burning of the SOFI could occur. A radiation model and convective heating environment were developed for the burning SOFI (Ref. 6) and the complete radiation and convective environment was published in Ref. 34.

Plume radiation environments are often required for ground tests, and one such application considered under this contract was the Flight Readiness Firing (FRF) of the SSME cluster conducted on the launch stand prior to flight. The flight launch environment could be used to estimate thermal environments for the vehicle during the FRF, but detailed predictions of SSME plume radiation to the LO_2 and LH_2 umbilical connections were required. The procedure used in these predictions and the results were reported in Ref. 4.

A few radiation predictions were also made on one of the thrust-augment shuttle concepts using a Liquid Booster Motor (LBM) consisting of two Aerojet LR-87/11 engines. Radiation from the LBM plume to 24 points in the base region were compared to the current environment in Ref. 9.

2.2 CONVECTIVE BASE HEATING

Convective base heating studies (Refs. 9-21) concerned prediction of first-stage thermal environments and plume impingement effects. The work on first-stage thermal environments included: updates based on new model test data, a data analysis report for the IH-39 test, an environment for a SSME failure, an environment for the planned orbital flight test (Generic OFT) trajectories, and estimates of the impact of Thrust-Augmented Shuttle concepts. Plume impingement studies were made for the RCS plume on the OMS nozzle and deployed speed brake, the OMS plume on the vertical tail, and the booster separation motor (BSM) on its cover plate. The purpose or conditions for each study will be briefly reviewed below.

Predictions of convective base heating rely on model test data, so during Space Shuttle development, tests were run on two models. A 2.25 percent short-duration model was tested in wind tunnels to simulate both first stage and early second stage conditions, and a 4 percent model was tested in vacuum tank facilities to obtain data on high altitude conditions where the effect of ambient flow on the base environment in negligible. The base heating tests conducted in wind tunnels were Space Shuttle tests IH-5, IH-34, IH-39, IH-75 and IH-83, and the vacuum tests were OH-3, OH-64, OH-78, and OH-79.

Much of the work on the contract was associated with IH-39. It was conducted in the NASA-Lewis Research Center 10x10 foot supersonic wind tunnel from October 1976 through April 1977 to provide first and second stage simulation of the fully integrated launch vehicle. Altitude conditions simulating 50,000 to 130,000 feet were used with complete hot flow simulation of the SSME and SRB plumes. Test IH-39 represented a significant improvement over previous tests because it was more heavily instrumented and provided better simulation of the configuration and flight conditions. An extensive document (377 pages) was prepared (Ref. 19) which provided details of the data obtained and an analysis of the results.

Results of the IH-39 test were used to update the current convective heating environments in the SRB base region (Ref. 10) and the ET base region (Ref. 12). In addition, engine-out conditions for a SSME simulated in IH-39 allowed development of a SSME out environment (Ref. 13). Base Heating Tests IH-75 and IH-83 in 1977 and 1978 provided additional data that led to refinement of the environment around the upper SSME and the center of the SSME cluster (Ref. 18).

When specific trajectories were selected for the first Orbital Flight Test (OFT-1), a first stage base heating environment (Refs. 20 and 21) was prepared based on Generic OFT Missions A and C. Mission C, which stages at a lower altitude (147,000 feet), was used for the orbiter base environment (above the body flap), while Mission A, which stages at a higher altitude (167,000 feet), was used for the ET and SRB base environments.

Estimates of critical convective heating effects on the thrust augmented Shuttle were reported in Ref. 9. The concepts considered were strap-on solid motors (SOSM) attached below the SRBs and a liquid booster module (LBM) attached to the ET aft dome. For the SOSM, estimated convective heating environments were provided in both the SRB and SOSM base regions. For the LBM, an estimate was provided for the SRB base region and three areas of the LBM (boattail, propellant tank base, and propellant tank mounting structure). The LBM environment also included an estimate of the increase in heating on the SRB skirt due to LBM plume impingement during SRB separation.

Studies of RCS (reaction control system) plume impingement were made for components in the base region which are immersed in plumes of the upward and aft firing RCS motors located in the RCS pod aft of the OMS (orbital maneuvering system) pod. A review of RCS plume impingement on the OMS nozzle (Ref. 11) was made due to interest in the environment near the lip. Later, the possibility of deploying the speedbrake (rudder) portion of the vertical tail in orbit prompted a study (Ref. 14) of the RCS plume impingement on this configuration. This was followed by a memo (Ref. 15) documenting the RCS plume flowfield which included details of the nozzle, thermodynamic properties and chemical composition of the conbustion products, and contour-plots for pitot pressure, static pressure, temperature and Mach number.

The OMS plume also impinges on the vertical tail, and measurements during Test OH-78 indicated substantially higher heating than had been predicted. For this reason, a study was undertaken to determine if the model data trends could be verified using a completely inviscid plume flowfield prediction rather than the viscous option used to simulate the nozzle boundary layer in the previous prediction. The results of the study (Ref. 16) indicated the inviscid plume prediction was more representative of the model data, and a revised environment was presented based on inviscid plume predictions.

The forward booster separation motors (BSM) on the SRBs include a hinged cover shielding each of the four nozzles in the BSM cluster. These covers pivot about a hinge and are forced open by the BSM firing. They are held in an open position by a pawl/rachet arrangement, and may be impinged upon by the BSM plume. A study indicated that the open positions considered for the nozzle cover were beyond the plume particle boundary, but that plume gases could impinge. Plume gas and particle boundaries were reported along with convective heating rates for the covers in Ref. 17.

2.3 GAS TEMPERATURE PROBES

A technique for measuring gas recovery temperature on short-duration base heating models was developed by REMTECH and used on several Space Shuttle base heating test programs (OH-64, 78 and IH-34, 39, 75, 83). The measurement technique uses simultaneous measurement of the temperature of two fine wires at the tip of a small probe to predict the gas recovery temperature and heat transfer coefficient for the wires. Although the technique indicated reasonable values of recovery temperatures on test programs, insufficient time was available for an adequate qualification test to verify the accuracy and determine application limitations for the measurement method. A test was planned and conducted under this contract to perform tests on the gas temperature probe in the NASA/MSFC Impulse Base Flow Facility (IBFF). The test plan (Ref. 22) set forth the test hardware and operating procedures to obtain test conditions in a range similar to those encountered in short-duration base heating tests. Results of the test reported in Ref. 23 verified the measurement technique for much of the Knudsen Number range encountered in the Space Shuttle base heating tests, but there was evidence that probe tip interference effects could produce variations when the flow was not parallel to the probe axis.

3 CONCLUSIONS AND RECOMMENDATIONS

The radiative and convective thermal environment predictions made under this contract supplied essential design information for the Space Shuttle thermal protection systems. The DTRANS and GASRAD programs provided significant improvements over previous radiation prediction procedures, but rapid advances in computer hardware may make changes in the GASRAD program desirable in the near future. Verification testing of the gas temperature probe for short-duration base heating tests improved confidence in data obtained on Space Shuttle base heating tests and indicated design modifications are desirable on the probe tips to improve accuracy when flow is at an angle to the probe axis. Errors noted in probe performance due to flow angularity in one plane indicates it may be desirable to test the probes with the flow angularity in other planes.

Changes in the GASRAD program mentioned above may be desirable as the speed and internal memory capacity of computers increase. The present program requires a large amount of input/output to secondary storage devices to reduce internal memory requirements. If the program were designed to use more internal memory, use of secondary storage devices could be drastically reduced by computing radiation along each line-of-sight as the plume property interpolation is made rather than sorting the gas property data for later use in computing radiation. Because large spectral intervals (which have been used satisfactorily with water vapor plumes) reduce the memory requirement for the radiation prediction, modification of the program would be especially useful for engines with LO_2/LH_2 propellants.

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