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SUMMARY OF SOLID ROCKET MOTOR PLUME FLOW FIELD AND RADIATION ANALYSES

FINAL REPORT

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Contract NAS8-28609

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Marshall Space Flight Center, Alabama 35812

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FOREWORD

This report presents a summary of the results of work performed by the Lockheed Missiles & Space Company, Inc., Huntsville Research & Engineering Center under Contract NAS8-28609 for the NASA-Marshall Space Flight Center (MSFC); Huntsville, Alabama. The NASA-MSFC Contracting Officer's Representatives for the study were Dr. Terry F. Greenwood and David C. Seymour, ED-33.

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1. INTRODUCTION

Studies conducted under this contract were directed at inclusion of solid propellant plume flowfield effects in analyses and design of the Space Shuttle vehicle. The major tasks of the contract include: (1) development of a two-phase nozzle and plume program; (2) analysis of solid particle impingement and convective heating on the Space Shuttle vehicle during staging separation maneuvers; (3) description of the orbiter plume flow field with afterburning; (4) prediction of the physical properties of the nozzle boundary layer to aid in determination of base heating from reversed flows; (5) development of a solid rocket motor (SRM) radiation model; (6) verification of the SRM radiation model using experimental data from the SRM developmental motor tests; (7) use SRM radiation model to predict the radiation environment on the orbiter, ET and SRBs; (8) develop and verify mixing models which are applicable to the SRM and SSME afterburning plumes; (9) generate detailed SRM and SSME plumes at various altitudes and include attitude effects in the radiation environment predictions for the orbiter, ET and solid rocket boosters (SRBs); (10) include solid particle effects in the PLIMP program; (11) determination of the effect of the SOSM exhaust flow field on the radiation environment to the Shuttle vehicle; and (12) determine the overpressure and thermal environment on the KSC Mobile Launcher Platform (MLP) due to the SRM and SSME impingement.

The tasks performed under this contract were documented at the completion of each phase of the study. The results of these analyses were presented in the reports listed in the Reference section. Consequently, the following section provides a summary of the reports which documented the tasks.

2. DESCRIPTION OF TASKS PERFORMED

Tasks performed under this contract investigated various problems related to SRM plume flow fields and their effects on the Space Shuttle vehicle and launch complex.

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

SPACE SHUTTLE ROCKET PLUME RADIATION*

Considerable attention has been directed toward the prediction of the Space Shuttle vehicle base thermal environment required for the design of the vehicle thermal protection system. During the span of this contract the geometrical shape and relative positions of the vehicle's orbiter external tank (ET) and solid rocket booster (SRB) have been changed as a result of improved design modifications. Each geometrical modification and/or change in computational technique required an updated evaluation of the thermal protection system's thermal environment. This study provides the thermal radiation environment defined as the vehicle's rocket plume radiation heating rates. Every effort has been made to improve the computational techniques and correlate these data with experimental data when available.

The following review of the predicted Space Shuttle vehicle's rocket plume thermal radiation heating rate environment, the computational methodology, and the experimental evaluation and correlation with analytical predictions is submitted in accordance with the requirements of the subject contract and describes the work accomplished.

*See Refs. 1 through 37.

SPACE SHUTTLE ROCKET PLUME ANALYSES*

Several problem areas concerning plume impingement heating rates during Space Shuttle vehicle staging have been identified. The Space Shuttle launch vehicle utilizes large booster solid rocket motors (BSRM) and smaller solid motors for BSRM staging. The BSRM plumes significantly impact the base thermal environment of the launch vehicle through radiation and convection heating. The smaller solid propellant staging motors impinge on the orbiter drop tank and orbiter, resulting in severe solid particle radiation and impingement heating. The plume-related effects on the thermal environment must be accurately predicted in order to design the Space Shuttle thermal protection system. This was accomplished by including solid propellant plume flow fields in the thermal environment description and applying those analyses to the Space Shuttle vehicle. A review of the plume related analyses performed during this contract is presented in this report.

*See Refs. 38 through 54.

- **SRM Plume Radiation Heating to the Space Shuttle MCR-200 (Ref. 1)**

An estimate was made of the Space Shuttle ascent base region radiation heat transfer from the two solid rocket motor boosters (SRB) plumes. It updates and replaces a previous memo, S&E-AERO-AT-73-9, dated 29 March 1973. The thermal environments supplied include the launch configuration (MCR-200) orbiter, external tank (ET), and updated SRB. These data are valid from launch until staging. Modifications of the SRM geometry and the change in rocket motor nozzle and SRM plume shape were required.

- **SRM Plume Radiation Heating to Inside Structure (Ref. 2)**

The SRB plume radiation heating rates were predicted at the inside surface of the orbiter airbrake located on the tail fin. SRB plume radiation heating rates were also predicted at the OMS left inside nozzle surface. Results of this study show that the heating rates are significant. The definition of the heating rates and their locations are defined.

- **Estimation of Solid Rocket Motor Booster Plume Radiation Heating Rates to the Space Shuttle ET Tank Shroud and Solid Rocket Motor Nozzle Wall (Ref. 3)**

An analysis was conducted to estimate the Space Shuttle ascent region radiation heat transfer from the two solid rocket motor booster (SRB) plumes. Radiation heating rates are presented for the external tank (ET) shroud. Heating rates are provided to both the external and internal cylinder shroud surfaces, the aft facing shroud base and hemispherical base. Also provided are predicted radiation heating rates to the external surface of the SRB nozzle wall.

- **Estimates of Solid Rocket Motor Plume Radiation Heating Rate to the Space Shuttle (2.25% Scale Model) (Ref. 4)**

Instrumentation locations, for the 2.25% Space Shuttle wind tunnel model test, were made available to Lockheed for prediction of SRB radiation. The total heat transfer and radiation gauges are not located in the positions of previous calculations. A review of these locations and an estimate of plume view factors from previous calculations were studied. Following this review view factors were calculated at the critical, not previously predicted, scale model locations. These data were used to evaluate convective heating rates, from the total heat transfer gauge test data, and to correlate SRB radiation predictions.

- Prediction of Radiation Heat Transfer Characteristics from Solid Rocket Plumes Using the Monte Carlo Techniques (Ref. 5)

This report describes a Monte Carlo solution to the solid rocket plume radiation problem. A brief review of Monte Carlo techniques is presented and derivation of the Monte Carlo model for solid rocket plume radiation is outlined. The principal aim of this analysis is to identify the character of solid rocket plume radiation as delineated by the simple model employed and to discern the effect of parameters that govern the emitted radiation. Emphasis is placed on defining the influences of plume optical diameter and the scattering phenomenon as simulated by isotropic and anisotropic scattering distributions.

The model geometry for the plume used in this analysis consists of a finite right circular cylinder with a uniform dispersal of $A\ell_2O_3$ particles throughout its volume. Only the contribution from the $A\ell_2O_3$ particles to the radiative heat transfer is considered. The target is considered to be an infinite plane passed through one end of the cylinder at right angles to the axis of the cylinder. Individual targets in the plane are taken to be a set of concentric rings centered about the plume axis. The first ring has its inner radius coincident with the cylindrical plume. The ring widths are 1/2 R.

The use of the Monte Carlo technique in this analysis has allowed the searchlight effect and anisotropic scattering in a homogeneous cylindrical plume to be considered. The influences of spatial distributions of local otpical depth (as influenced by particle size and number density), particle temperature, and the effects of concentrated emission points due to local high number densities were not investigated. These spatial distributions of plume non-homogeneities may have significant local effects on the spatial distribution of the radiation emitted by the plume. It was demonstrated for the homogeneous cylindrical plume that direct emission from the rocket plume dominates the heat load radiated toward the base plane. The searchlight effect has only a second order influence at targets within one exit diameter of the plume. At larger distances from the plume, the searchlight effect is essentially negligible. It is demonstrated, for the anisotropic scattering simulation, that solid rocket plumes tend to emit diffusely. This characteristic allows a convenient scaling law to be derived for the effects of optical diameter of the plume. The apparent emissivity of solid rocket plumes is shown to approach a limiting value of approximately 0.8 for large optical diameters (larger than 10). Thus, it is shown that heating rates from solid rocket plumes may be attained if knowledge regarding the plume optical diameter, temperature, and view factor to the target of interest is available.

- SRM Experimental Data Comparisons (Ref. 6)

The proposed Space Shuttle launch propulsion configuration involves the use of two single-nozzle, solid propellant rocket boosters. This vehicle solid propellant motor is similar in size to the: Titan IIIC, preliminary Poseidon C3 (Polaris B3) vehicle, and Poseidon C3 vehicle. It is expected

that the Space Shuttle will realize radiation and convection heating trends that are similar to the above vehicle scale model tests, full-scale systems tests and flight tests.

The primary method of dealing with base heating problems from solid motor plumes is to obtain the heating rates from experimental data. Presented in this report is a review of vehicle base thermal environments from the Titan IIIC full-scale ground and flight tests, Titan IIIC 1/33-scale model test, preliminary Poseidon C3 design (Polaris B3-single nozzle) static test, and the Poseidon C3 first stage ground and flight test data. The objective of this study is to investigate these data and evaluate a possible correlation that may be applied to the prediction of the Space Shuttle vehicle base thermal environment. Results of this study show favorable comparison with the solid plume radiation prediction model currently being used for Space Shuttle plume heating predictions.

- SRM Plume Radiation Heating to SSME Eyelids (Ref. 7)

A study was made to predict the solid rocket motor (SRM) booster radiation heat flux to the orbiter main engine nozzle bulge (EYELIDS) affixed to the vehicle base. Heat flux to the upper nozzle and offset lower nozzle locations are estimated on three type surfaces: (1) the bulge affixed to the vehicle base thermal protection system (TPS); (2) the bulge affixed to the gimbaled nozzle; and (3) a cone-shape sealed region between the bulged surface gap.

- SRM Plume Radiation Heating to the Space Shuttle MCR-500 (Ref. 8)

This report documents the analysis conducted to estimate the Space Shuttle SRM booster plume radiation heating rates to the MCR-500 vehicle configuration during the vehicle launch ascent. This study updates and replaces previous documentation for the Space Shuttle MCR-200 configuration. This study also includes surfaces not studied for the MCR-200 configuration. These surfaces are: the reaction control pod, the updated OMS nozzle and ribs, the orbiter main engine bulged heat shield affixed to the nozzle and orbiter heat shield and the cone TPS separating these two surfaces, the vertical tail aft-facing fin, the updated SRM ring and ET support structure.

In general, most heating rate estimates are lower than predicted for the MCR-200 configuration as a result of increased distance between the SRM plume and the vehicle surfaces. The SRM nozzle and shroud geometry were changed on 6 June 1974 prior to completion of this study. A study to determine the radiation heating rates to the new baseline shroud and nozzle, external tank and tank support structure, where the heating rate estimates are significant, was conducted. The modifications reduced the SRM radiation heating rates to the shroud base by approximately 14%, reduced the outboard external tank support structure heating rates by approximately 1% and increased the inboard support structure heating rates by approximately 3%.

- Space Shuttle (MCR-500) with Gimbaled SRM Nozzle (Ref. 9)

Space Shuttle (MCR-500) SRM plume radiation heating rates are computed with the SRM nozzles in the 8-deg (maximum) gimbal position. In general, radiation heating rates increased over the values predicted for the null gimbal position by gimbaling both SRM motors in the same direction. The predicted heating rates are provided for the SRM, cylinder, shroud, shroud base, nozzles, ET and support structure. Provided with each table is a schematic of the surface investigated. Each table defines the direction of nozzle "gimbal" at each "station" location. The null position and gimbal position radiation view factors (F_a, F_b) and computed heating rates $\dot{q}_a$ are also provided in each table. Comparison of the view factor values will show how the gimbal position changes the amount of shading and corresponding influence of plume radiation contribution.

- Space Shuttle (MCR-500) Addendum to Ref. 8 (Ref. 10)

The Space Shuttle SRM booster plume radiation heating rates to the MCR-500 vehicle configuration during launch ascent were documented in Ref. 8. This document provides SRM radiation heating rates to additional vehicle surface points located on: (1) the orbiter upper and lower nozzle aft facing rim; (2) the Orbiter Maneuvering System (OMS) nozzle internal surface; (3) the Reaction Control System (RCS) nozzles 8 and 9, inside surface; and (4) the OMS base heat shield.

- Wing Flipper Door (Ref. 11)

An estimate of the plume induced heating to the "flipper door" located on the orbiter wing top surface above the elevon cove has been calculated. Estimates of the heating environment were evaluated at five span locations for two door deflection angles (20 and 40 deg) close to fuselage, wing tip and above SRB centerline. At each span location, heating rates on the "flipper door" top, bottom, and trailing edge surfaces and on the back facing surface of the exposed cavity were calculated.

- SRM Full-Scale Test Instrumentation (Ref. 12)

The instrumentation requirements for the radiation measurements for the SRM firings to be conducted at the Thiokol Wasatch Test Range, Utah, have been defined. The instrumentation locations and radiation heating rate ranges are provided. The instrumentation includes: 18 wide angle radiometers at positions that correspond to critical Space Shuttle base area design points, seven narrow-view angle radiometers along the plume that will define solid rocket plume radiation distribution, five wide angle radiometers axially along the plume in the approximate region of the MLP vertical launch tower, and one AGA Thermovision System 680, an infrared camera system, that will provide a thermal picture of the rocket plume. These data were used to correlate full-scale radiation with the 6.4% (acoustic test) SRM scale model data and to verify and improve analytical prediction capability.

- Ascent Rocket Plume Radiation Heating Rates (Ref. 13)

Estimates of solid rocket motor (SRM booster and orbiter main engine (SSME) plume radiation heating rates have been computed to the following Space Shuttle surfaces: external tank (ET) aft dome and cylinder, ET/SRM and ET/orbiter support members, LH_2 and LO_2 feed, pressure and recirculation lines. These data published in Ref. 12 are presented in a format compatible with the Shuttle Aerodynamic Heating Data Handbook, SD-73-SH-0181-2A. This report is divided into four sections: a review of the RAVFAC code method of calculation and definition of the updated RAVFAC SSME sea level plume model, free-flight ascent where the surface node radiation heating rate is provided by both the SSME and SRM plumes, liftoff phase where the SSME and SRM free-flight node values are modified to correct for the influence of the launch stand environment history and SRM nozzle gimbal where an estimated limit of the node heating rate change is computed.

- The Space Shuttle Vehicle Base Thermal Environment Scale Model Test and Analytical Evaluation* (Ref. 14)

Radiation heat flux to the base of a vehicle from both a solid propellant rocket motor plume containing a high percentage of aluminum oxide particles, and an optically thin liquid propellant rocket plume may be empirically predicted with reasonable accuracy for the design of the Space Shuttle vehicle base thermal protection system and structural thermal environments. The purpose of this paper is to provide a correlation and analytical evaluation of the radiation and total calorimeter heating rate data measured during a 6.4% acoustic scale model test conducted at NASA-Marshall Space Flight Center. The radiation heating rate data, measured at various liftoff positions relative to the modified Saturn mobile launch platform, were normalized to the free-flight heating rates where the influence of the mobile launch platform on the rocket engine exhaust is a minimum. Test data show that radiation heating rate levels measured, to the vehicle base, are significantly greater than predicted for low altitude flight. The Space Shuttle main engine and solid rocket motor plume radiation was analytically predicted using gray body methodology and provided a prediction of radiation heating rate levels close to those expected to be found in a free-flight situation. Comparison of the analytically predicted radiation heat flux that incorporate rocket plume shading by the mobile launch platform with measured data shows similar trends

*This study as supported by the National Aeronautics and Space Administration under this contract was accepted for presentation at the 9th JANNAF Plume Technology Conference.

and explains the source of radiation magnitude. State-of-the-art computer codes and evaluation of solid propellant motor base thermal environments from the Titan IIIC ground and flight tests, Titan IIIC 1/33-scale model test, and other ground and flight test data were utilized to formulate the solid motor plume analytical model.

- SRM Altitude Dependent Plume Radiation Models (Ref. 15)

During vehicle ascent the SRM plume half angle will increase from 9 deg at sea level to 40 deg at approximately 136,000 ft while the average emissive power will change from 31.5 Btu/ft^2-sec at sea level to 3.2 Btu/ft^2-sec at approximately 136,000 ft. To predict the emissive power change along the SRM plume boundary and change with altitude, a Monte Carlo Code (Ref. 15) was used to estimate the radiation transport properties. This Monte Carlo Code accounts for the influence of chamber pressure, propellant composition, altitude, approach Mach number, after burning, and spatial variations in plume properties on the magnitude and distribution of thermal radiation emanating from the SRM plumes.

- SSME and SRM Plume Heating Rates to Space Shuttle Orbiter During Ascent (Ref. 16)

Approximately fifteen hundred Space Shuttle Orbiter body points have been analyzed to obtain estimates of SSME and SRM plume radiation heating rates. The results are presented for sea level conditions and appropriate correction procedures have been included for altitude effects on plume radiation. In general, the estimates of radiation heating rates are considerably higher than those published (Ref. 9). The analysis required to prepare the report was a joint effort of the following personnel: Robert E. Carter, Lockheed-Huntsville, under NASA Contract NAS8-28609; John E. Readon (REMTECH, Inc., under Subcontract 510-10000 to Northrop Services, Inc.); and Wallace W. Youngblood (Northrop Services, Inc., under Contract NAS8-21810).

- Monte Carlo Code Parametric Study (Ref. 17)

The thermal radiation properties of a two-phase plume are defined by the output data from the gaseous plume flowfield calculation and particle plume calculation. These data are: number density, particle temperature, particle size, particle cross section, gaseous temperature, gaseous pressure and mole fraction of CO, CO_2, H_2O and $HC\ell$. The volume of a plume is divided into certain sections along its axis and certain sections along the radial direction. This set of data is given at each nodal point. A Monte Carlo scheme is used to generate the emission, absorption and reemission of photon paths within the plume volume. A basic data deck which consists of a set of data at each nodal point, is required for each trajectory point of the plume. An extensive parametric study was completed with the 37,000 ft plume. Each parameter in the plume property array was varied from 50 to 200% of its normal value. The average emissive power, which is defined as the total thermal radiation from the 37,000 ft plume divided by its surface area, is normalized and plotted versus the variation of each parameter.

- Orbiter Radiation Correction Factors During Launch (Ref. 18)

Radiation heating rates to the Space Shuttle vehicle have been shown to be significantly greater during the launch phase than during the ascent free-flight. Radiometer data from the 6.4% scale model acoustic tests at MSFC were used to construct heating rate multiplication factor design curves for the vehicle during launch. Examination of the multiplication factors indicate that the water spray on the MLP reduces the heating rate on the orbiter vehicle during the launch phase of the flight compared with the previous design curves with no water. Water cooling tends also to skew the SSME maximum value of multiplication factor with time. The point of maximum heating rate from the SSME plumes is therefore delayed as much as two seconds. Water did not have any significant skewing effect when compared with the previous orbiter multiplication factor for the SRM plume radiation.

- Plume Radiation Heating Prior to Launch (Ref. 19)

An estimate of the radiation heating rate to the Tail Service Mast LO_2 and LH_2 umbilical carrier prior to vehicle lift-off was made. The SSME plume radiation to the two umbilical lines were computed. Water cooling is believed to have little effect on reducing the level since the major radiation to this point comes from the SSME plume located between the SSME nozzle exit and the top of the MLP at a time prior to lift-off. This part of the SSME plumes is not affected by the water spray. With water cooling the 6.4% acoustic scale model test shows that the radiation from the heated deflector is attenuated by the presence of low temperature steam and the heated walls are cooled by the water spray system.

- External Tank SRM Radiation Heating Rate Parameters (Ref. 20)

Data decks were generated for the RAVFAC code that define the solid rocket booster (SRB) plume half cone angle and average total plume emissive power at ten axial positions for 13 altitudes ranging from sea level to 136,000 ft. These data were derived by a revised code of the Monte Carlo radiation model. The RAVFAC code was then used with the newly defined altitude SRB plumes to predict SRB radiation to the Space Shuttle External Tank and support structure. The computed data were normalized by the free-flight radiation heating rates to provide a correction heating rate function for altitude. Results of this study show that following lift-off the vehicle base heating is reduced below that predicted for free flight.

- Orbiter Base Plume Radiation Heating Rate (Ref. 21)

This report provides an estimate of the thermal radiation from the three Space Shuttle Main Engines (SSME) and the two Solid Rocket Motor (SRM) plumes to the Space Shuttle Orbiter. All radiation heating rate values contained herein are to be used with the IVBC 2.1 Plume Radiation Ascent Heating Design Trajectory. The contents of this report are updated from those of Ref. 16 dated April 1976. The major changes include a more detailed launch stand interference correction procedure for the SSME and SRM plumes and a methodology for obtaining altitude radiation heating rates from the SRM plumes. The SSME altitude correction procedure remains unchanged from that of Ref. 16.

- External Tank Plume Radiation Heating Rate (Ref. 22)

This document provides an estimate of the Space Shuttle rocket plume radiation heating rate to the Space Shuttle External Tank aft dome and the support structure. This document provides an update of the launch stand interference correction procedure for the SSME and SRM plumes, and a methodology for obtaining altitude radiation heating rates for the SRM plumes. This document is in a format compatible with the document published for the orbiter base of Ref. 21.

- Space Shuttle Solid Rocket Booster Plume Radiation Heating Rate Prediction with Altitude Corrections (Ref. 23)

This technical memorandum is divided into three parts. Section 2 is a review of the method of calculation used to predict the solid rocket booster radiation heating rates to the Space Shuttle Orbiter External Tank, Solid Rocket Motor and KSC Launch Complex 39. Section 3 is a review of a newly developed SRB plume Monte Carlo radiation model that utilizes the RAMP-predicted two-phase flowfield properties that couple the solid particle and gas energy/momentum conservation laws. The total plume emissive power distribution along the plume boundary is provided (Appendix), for each plume at altitudes ranging from sea level to 136,000 ft. Section 4 provides sample results of the SRB radiation predicted by the RAVFAC code. SRB experimental and analytical radiation heat flux comparison are made for the full-scale Space Shuttle solid booster ground test (Thiokol Corporation, test DM-1, 18 July 1977) and solid booster flight test (Lockheed Corporation, Trident C4X-01 flight). Results of this study show that the analytical models defined will predict SRB altitude plume radiation that is compatible with ground and flight test base radiation heat flux measurements.

- **Space Shuttle Main Engine Abort (Ref. 24)**

A study was conducted to determine the SSME and SRB plume radiation heating rates to the internal and external surface of the left SSME nozzle, with the assumption that this rocket motor failed to ignite. The SRB plume radiation heating rates predicted at altitude were computed using the plume radiosity derived by the Monte Carlo code. Results of this study show that the maximum plume radiation heating rate is approximately 27 Btu/ft^2-sec, located at the top aft edge of the lower nozzle wall.

- Orbiter RCS Pod Vernier Thruster Radiation Heating Rate Study (Ref. 25)

A study to determine the SSME and SRB plume radiation heating rates to the internal surface of the orbiter reaction control pod vernier nozzles has been completed. The SRB plume radiation heating rates predicted at altitude were computed using plume radiosity derived by the Monte Carlo code. Results of the study show that the maximum plume radiation heating rates to the pitch vernier nozzle is 13.27 Btu/ft^2-sec during launch and 7.77 Btu/ft^2-sec following launch to the approximate 40,000 ft altitude. The radiation heat flux above 40,000 ft is reduced with increasing altitude and plume expansion. The maximum radiation heat flux to the yaw thruster is significantly lower (0.83 Btu/ft^2-sec) since the SSME plume radiation is shaded by the pod wall.

- SSME Plume – MLP Radiation Barrier (Ref. 26)

A radiation barrier was considered for the purpose of shielding the aft dome of the Space Shuttle External Tank (ET) from the SSME plumes during test firings on the mobile launch platform (MLP). An estimate of the SSME plume radiation to the ET was predicted using a simplified plume radiation model and a radiation view factor computer code. The splitter plate located between the MLP and the orbiter base flap was modeled and provided shading between the SSME plume and the ET. This study differed from that of Youngblood, (M-9224A-77-20, 12 May 1977) and allowed more radiation to pass between the splitter plate and the orbiter base flap.

- Preliminary Augmentation Motor Study (Ref. 27)

Preliminary predictions of the augmentation motors mounted aft of the External Tank have been predicted to 28 vehicle surface NAR-node positions for the configurations using four and two augmentation motors.

- **Space Shuttle Base Heating Environment Update (Refs. 28 through 32)**

Documentation of the vehicle base radiation heating rates from the SSME, SRM and burning SOFI has been updated. These reports provide the methodology, launch and altitude correction factors, and pertinent experimental data that support the methodology used for analytical predictions.

- **Revision to Document LMSC-HREC TR D568521 (Ref. 33)**

Pages 3-26, 3-28, 3-30, 32, 3-42 through 3-47 of the referenced report have been revised to the orbiter wing radiation heating rates.

- **SOSM Plume Radiation Environment (Ref. 34)**

Preliminary estimates of the two solid motors have been made to 15 points on the Shuttle vehicle, orbiter, external tank, and solid rocket booster. Results of the preliminary estimates are provided. The maximum heating rate of approximately 22 Btu/ft^2-sec is predicted to the SRB radiation curtain (node 2352) while the SRB shaped charge (node 2650) increased from 1.34 to approximately 12 Btu/ft^2-sec.

- **Space Transportation System Flight/(STS-1) (Ref. 35)**

Design assessment of the Space Shuttle transportation system flight (STS-1) vehicle base heating environment for the flight instruments has been computed for the SRM and SSME plume radiation heating rates. This report provides a schematic of the vehicle component surface and defines the location of the flight instrument. The method of calculation remains unchanged from that defined in Refs. 28 through 31).

- **Space Shuttle Liquid Booster Module (Ref. 36)**

This document provides estimates of the SRM and SSME rocket plume and the Liquid Booster Module (LBM) plume radiation heating rates to the proposed LBM External Configuration 1.

- **Estimation of Solid Rocket Motor Plume Radiation Heating to the Parachute in the Abort Ejection System (Ref. 37)**

Determination was made of the plume impingement and plume radiation heating rates from the Space Shuttle solid rocket motor (SRM) plumes to the main parachute in the mission abort ejection system. No SRM plume impingement occurred on the parachute in any of the trajectories, therefore, only the calculation of radiation heating was required. The values of the radiation heat transfer from the SRM plume to the three ejection trajectories were presented graphically.

- Definition of the Space Shuttle Main Engine Plume at Sea Level (Ref. 38)

A description of the plume of the Space Shuttle orbiter main engine was necessary to calculate the plume radiation heating to the base regions of the vehicle. Two sources of possible high radiation heating loads in low level plumes are the afterburning region in the shear layer along the periphery of the plume; and the other is the region of high temperatures and pressures behind the Mach disk formed by the compression of the overexpanded plume. Separate analyses of the different portions of the plume were combined to construct the "sea level" plume used to establish the conditions for radiation calculations. An inviscid analysis was used to describe the flow from the nozzle exit to the Mach disk. The viscous portion of the plume was described using an equilibrium mixing program. The flow properties in the subsonic region behind the Mach disk were varied in a simplified fashion to approximate the flow processes expected to occur as the gases expand and accelerate.

- Definition of a 5 and 16% Aluminum, $A/A^* = 7$ Space Shuttle Separation Motor Gaseous and Solid Particle Flow Field (Ref. 39)

A study was performed to provide gaseous and solid particle flow fields for 5 and 16% aluminum, area ratio of seven Space Shuttle separation motors. The flow fields can be used to determine impingement pressures and heating rates on the Space Shuttle orbiter and ET due to the separation motors firing during separation of the SRB from the orbiter vehicle.

Both flow fields were generated in two parts; the gaseous flow field and the solid particle flow field. The gaseous flow fields were generated using Lockheed's Method-of-Characteristics program and equilibrium thermochemical data generated using the Chemical Equilibrium Composition program.

Centerline distributions were predicted of Mach number, static pressure, static temperature, density and pitot total pressure of the gaseous flow fields for both the 5 and 16% motors. Plots were made of the iso-contours of Mach number, static pressure, static temperature, density and pitot total pressure for the 5 and 16% $A\ell$ motors.

The solid particle flow field in each motor was generated using the Chrysler-Aeroneutronic uncoupled two-phase particle trajectory tracing program. The particle trajectories were traced for six particle sizes (0.5, 1.5, 2.25, 3.0, 4.0 and 4.75 micron radii). For each particle size a limiting centerline and three intermediate particle trajectories were traced.

Plots were made of the predicted particle velocity, temperature, density, kinetic energy and thermal energy for the limiting, intermediate and centerline trajectories versus axial location for the 5 and 16% Aℓ motors for each of the six particle sizes.

- Convective and Solid Particle Plume Impingement Heating Analysis for the SRB Separation Motors Impinging on the Space Shuttle Orbiter and ET Geometries (Ref. 40):

The purpose of this study was to predict the heating rates on the Shuttle orbiter/external tank vehicle during separation due to gaseous convective and solid particle impingement of the forward and aft solid rocket booster separation motors. Solid particle impingement heating and convective heating environments for the Shuttle geometries which are primarily affected by gaseous and solid impingement of the SRB separation motor plumes were presented. The solid particle impingement heating rates for the orbiter nose showed an increase with time during the separation maneuver to 1.5 sec at which point the heating falls off. Although the nose was farther away from the engines and plume centerlines, as time increased, the percentage of particle mass that was impinging was greater because the larger particle streamlines expanded farther from the plume centerline. The solid particle heating rates were shown to be a strong function of the amount of aluminum in the propellant. The gaseous convective heating rates showed almost no dependence on the Aℓ percentage. The impingement heating environment due to the separation motors can probably be significantly reduced by altering the separation trajectory, relocating the forward and aft separation motors or changing the propellant composition.

- Selected Boundary Layer Property Profiles at Several Axial Locations of the Boundary Layer of the Space Shuttle Orbiter Main Engine (Ref. 41)

The boundary layer property profiles were calculated for the orbiter nozzle in this case using two boundary layer programs. The profiles were initially calculated using the Mass Addition Boundary Layer (MABL) program. The same profiles were generated using the Boundary Layer Integral Matrix Procedure (BLIMP) program.

The MABL program uses a finite difference approach to provide a detailed boundary layer profile, i.e., up to 130 points through the boundary layer. That sort of detail was obtained with the expenditure of rather long computer run times. The BLIMP program is an integral solution of the boundary layer. The computer run times are considerably less for BLIMP than MABL. The profiles in the boundary layer calculated by BLIMP are nevertheless limited to 15 points.

The resultant profile properties produced by MABL and BLIMP for the Space Shuttle orbiter main engine boundary layer were compared and presented here. The good agreement of the profiles indicates that the BLIMP program should be used in future boundary layer analyses of this type.

- **Calculation of the Space Shuttle Main Engine Plume at 40,000 Feet (Ref. 42)**

The plume of the Space Shuttle orbiter main engine is a source of radiation heating to the base regions of the vehicle. The 40,000 foot altitude was chosen to match the pressure obtained if the main engine combustion gases were expanded one-dimensionally to the area ratio of 77.5. The plume would then be balanced in the one-dimensional sense. Separate analyses of the inviscid and viscous portions of the plume were combined to construct the plume. A method-of-characteristics solution was used to describe the inviscid flow. The viscous portion of the plume was described using an equilibrium mixing program.

- **Definition of the Space Shuttle Solid Rocket Motor and Orbiter Main Engine Plumes at Sea Level (Ref. 43)**

The plumes of the SRM and the SSME were calculated to define the environment of the launch pad during lift-off. Separate analyses of the inviscid and viscous portions of the plumes were combined to construct the plumes. A two-phase method-of-characteristics solution was used to describe the inviscid flow of the gas and particles in the SRM plume. A gaseous method-of-characteristics program was used to calculate the SSME inviscid plume. The viscous portions of the two plumes were calculated using equilibrium chemistry mixing programs. Radial plots are presented for the particle flow field and gaseous flow field of the SRM plume. The particle integrated fluxes of kinetic energy, thermal energy, mass and momentum are presented for the SRM plume. The gaseous flow field for both the SRM and SSME plumes is described by radial profiles of local static temperature, velocity, static pressure, pitot pressure, Mach number and total temperature. The SRM particle flow field is described for 60 ft downstream of the nozzle exit. The gaseous plumes for the SRM and the SSME were calculated for distances up to 5000 ft downstream of the nozzle exit plane.

- **Evaluation of Auxiliary Power Unit Exhaust Plume-Induced Heating to the Vertical Tail of Space Shuttle Vehicle 101 (Ref. 44)**

Estimates were made of the Auxiliary Power Unit (APU) exhaust plume induced heating to the vertical tail of the Space Shuttle vehicle 101. The heating is defined for the vehicle during the approach and landing flight tests (ALT). For these tests the vehicle has a simulated thermal protection system (TPS) urethane foam tiles but these presently do not protect the vertical tail from any heating loads. The APU-induced heating loads were calculated for use in determining if it was necessary to provide thermal protection It was determined that there was no induced heating when no cross flow exists. A 25 deg crossflow situation was taken as a worst case and the induced heating calculated. The heating loads for the 25 deg cross flow were evaluated at altitudes of 28,000, 14,000 and 0 ft.

- **Definition of the Space Shuttle $A/A^* = 5.83$, 2% Aluminum Separation Motor Plume Flow Field (Ref. 45)**

This study was performed to provide gaseous and particulate flow fields for the 2% aluminum, area ratio of 5.83 Space Shuttle separation motor. The flowfield calculation technique was described, and detailed plots showing the flowfield characteristics were presented. The results of this study could then be used to determine impingement pressures, heating rates and particulate fluxes on the orbiter and ET during SRB staging.

- Prediction of SRM Nozzle Plug Heating Rates (Ref. 46)

During system check out of the Space Shuttle systems, the three Space Shuttle main engines (SSMEs) will be fired while the vehicle is tied to the mobile launch platform (MLP). A plug-type device will protect the SRM nozzle during this checkout procedure. Some of the SSME plume gases are expected to cross over the crest of the deflector and go down the SRM trench. The radiation heating rate levels to the SRM plug from the SSME plume gases in the SRM trench are required.

In acoustic model tests at Marshall Space Flight Center, one of the radiometers was located on the shroud of the SRM and was facing downward into the trench. This radiometer should provide a good measure of the radiation heating rates present on the SRM nozzle plug. Using the radiometer reading, a heating rate to the SRM nozzle plug was predicted.

- External Tank Radiation Heating Rate Environment During the Launch Phase of the Space Shuttle Ascent (Ref. 47)

Radiation heating rates to the Space Shuttle vehicle have been shown to be significantly greater during the launch phase than during the ascent free flight. Radiometer data from the 6.4% scale model acoustic tests at Marshall Space Flight Center were used to construct heating rate multiplication factor design curves for the vehicle during launch. Additional instrumentation was installed on the external tank aft dome portion of the model to obtain a distribution of heating rate multiplication factor over that area during launch. This report presents the heating rate multiplication factors for each of the points on the external tank aft dome that radiation heating rates have been calculated. The location of these points and the predicted heating rate at those points are given in tabular form.

- Space Shuttle Solid Rocket Motor (SRM) Exhaust Plume Definitions – Sea Level to SRB Separation (Ref. 48)

This study was directed toward defining the exhaust plume structure of the Space Shuttle SRM from the time of liftoff to SRB separation.

A complete definition of the SRB exhaust plume is important for many Space Shuttle design criteria. The exhaust plume shape has a significant effect on the Shuttle base pressure. The SRB plume characteristics are also important to the Shuttle base heating, aerodynamics and the influence of the exhaust products on the environment. It is also possible that the Shuttle SRB plumes can affect communications with the vehicle due to radar attenuation. For these reasons and perhaps others which have not been mentioned, a detailed knowledge of the SRB exhaust plume characteristics is necessary.

The analysis of the inviscid SRM exhaust plumes was performed using Lockheed-Huntsville's Reacting Multiphase Computer Program (RAMP). The RAMP code is a fully coupled solution in which both momentum and energy are transferred between the gas and particle phases. The analysis was performed using the equilibrium chemistry assumption.

Thirteen nozzle-plume analyses were performed at various trajectory points from sea level to SRB separation. The calculations were performed out to approximately five exit diameters from the nozzle exit plane. The data presented in this report consist of: (1) radial distributions of gas and particle properties at the nozzle exit plane; (2) plume gas property contour and radial plots; and (3) centerline and radial distributions of particle energy, momentum and mass fluxes.

- Collection of Heating Rate Data on the Space Shuttle Acoustic 6.4% Scale Model to Simulate the Launch Portion of the Ascent Flight from the Mobile Launch Platform (Ref. 49)

A 6.4% scale model of the Space Shuttle vehicle was used to collect data on acoustic loads and heating rates during tests conducted at NASA-MSFC. A total of 151 test runs was made during this series of acoustic studies. The first part of the series (Runs 1 through 58) was made with no water added to the Mobile Launch Pad or in the flame trenches. Runs 59 to 151 were carried out with various configurations of water spray patterns. The water was added for sound suppression to the exhaust plume flows with different ratios of water flow rate to engine mass flow rates. The water sprayed during these tests for sound suppression changed the heating rates.

- Revised Predictions of the SRB Plume Impingement Pressures on the MLP (LC39) During Liftoff (Ref. 50)

During the first few seconds of flight the SRM plumes impinge on the MLP and other launch complex structures, resulting in extremely high thermal and pressure loads. In order to adequately design the MLP and other launch complex structures, detailed and accurate definitions of the SRM exhaust plumes are necessary. This report discusses the evolution of SRM plume flowfield predictions and recommends a current "best" SRM plume flow field. Included in the report is a description of the modeling technique, definition of the "best" SRM plume and predictions of the pressure distribution at certain locations on the MLP deck.

- Calculation of the Space Shuttle Main Engine Plume Operating at 40,000 Foot Altitude (Ref. 51)

The Space Shuttle main engine plume operating at 40,000 ft altitude was calculated. The plume properties are presented in graphical form. The SSME plume is given for 100 ft downstream of the nozzle exit plane. Separate analyses of the different portions of the plume were combined to construct the plume used to establish the conditions for the radiation calculation. An inviscid analysis was used for the description of the flow from the nozzle. The viscous portion of the plume was described using a finite rate chemistry mixing program.

- Calculation of the Space Shuttle Main Engine Plume Operating at 20,000 ft Altitude (Ref. 52)

The plume of the Space Shuttle orbiter main engine must be described to calculate the plume radiation heating to the base regions of the vehicle. A source of possible high radiation heating loads in low level plumes is the afterburning region in the shear layer along the periphery of the plume. The Space Shuttle main engine plume operating at 20,000 ft altitude was calculated. The plume properties are presented in graphical form. The SSME plume is given for 100 ft downstream of the nozzle exit plane.

- Definition of the Viscous Sea Level Space Shuttle Solid Rocket Motor (SRM) Exhaust Plume, Impingement Flow Field and Thermal Properties Necessary to Perform a Thermal Response Analysis of the LC 39 MLP (Ref. 53)

This study was directed toward determining an appropriate particle flow field in the sea level SRM viscous plume and determining a thermal model which could be used along with the SRM particle and gaseous flow field to predict the thermal response of the MLP and launch complex structures due to SRM impingement. The referenced report describes the flow field and the detailed model which was necessary to develop to match some available test data. The flowfield data in the report, along with the model described in the report, could then be used to determine the LC 39 thermal response.

- Mixing Analysis of Water Injection Into the Plume of NASA Test Rocket Engine (Ref. 54)

A series of test firings of a small rocket is scheduled at MSFC in which cooling water will be used to protect the deflector during the tests. To aid in the analysis to determine the cooling water requirements, thermal energy balances and viscous mixing calculations were performed. The thermal balance indicated that if the water was thoroughly mixed with the exhaust plume the deflector would not be damaged. The spraying of small jets of water about the periphery of the plume was not an effective protection method for the deflector. A mixing analysis predicted that three large water jets even if they could penetrate only five inches into the exhaust plume would adequately protect the deflector from thermal damage.

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