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FINAL REPORT

RESEARCH STUDY:

SPACE SHUTTLE MAIN ENGINE

PLUME FLOWFIELD MODEL

April 1, 1988

Prepared by:

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Contract:

NAS8-34135

For:

National Aeronautics and Space Administration

George C. Marshall Space Flight Center

Marshall Space Flight Center, Alabama 35812

SUMMARY

CONTRACT CHRONOLOGY

Contract NAS8-34135 ends April 1, 1988. It was initiated January 20, 1981, and has been modified ten times; the last modification November 2, 1987. Dr. Terry Greenwood, chief of the MSFC Induced Environment Branch, ED-33, has been the COR throughout the contract.

OBJECTIVES

The initial research effort was an in-depth analysis of the Shuttle Main Engine Plumes in an effort to improve the flowfield model and to enhance Shuttle base heating environment predictions during ascent. As the Shuttle program progressed through the pre-flight phase, the development flight phase, and into the operational flight phase; the contract objectives were amended to incorporate the flight data and flight experience into the plume prediction methodology. Ultimately, a prediction methodology code was developed incorporating the improved plume model into a prediction tool which could consider different trajectories and engine performance variables.

Various plume flow model improvement studies were ongoing at the time of the 51-L accident. Since that time, base heating and plume methodology improvements have continued as part of the overall emphasis on Shuttle design assurance before

resuming the flight schedule.

REPORTS AND CONTRACT ACCOMPLISHMENTS

An assortment of short memos, technical notes, technical reports, and design environment documents have been prepared and released under the contract. A fully documented computer code was also released and distributed by NASA to other contractors. Eighty-six monthly progress reports were also prepared throughout the seven plus years of the contract summarizing individual accomplishments, oral and written reports, meetings, problem areas, and schedules.

Details of the individual reports will not be revisited in this final report. Summaries of work performed under ten broad topic areas have been prepared along with a list of all applicable reports prepared under the contract. REMTECH will retain the originals; clear reproducible copies of all reports will be provided to the COR.

TOPIC: SHUTTLE PRE-FLIGHT ENVIRONMENT PREDICTIONS

SUMMARY

Before the first Shuttle flight and coincident with the availability of the flight readiness firing (FRF) data, base heating environments were predicted for each base heating development flight instrument location. These predictions were based upon the latest (before STS-1) trajectory and engine/booster operational parameters available to MSFC in the spring of 1981. A compilation of the prediction graphs were made available to the flight evaluation working group for comparison with the first flight data. The predictions were also used as substitute flight data to exercise the flight evaluation data reduction programs. Pre-flight predictions were also provided for flights STS-2 and STS-3.

TOPIC: SHUTTLE PRE-FLIGHT ENVIRONMENT PREDICTIONS

DOCUMENTATION		
DOCUMENT NO.	*SUBJECT*	*DATE*
Unpublished Report Input	FRF Data Analysis; STS-1 Pre-flight Environment Predictions	Feb-March 1981
RM 056-2	STS-2 Nominal Convective Base Heating Environments	July 1981
RM 056-3	STS-1 Trajectory Comparisons	August 18, 1981
RM 056-5	STS-3 Convective Base Heating Environments	Nov. 12, 1981
RM 056-7	STS-3 Nominal Convective Base Heating Environments	Jan. 28, 1982

TOPIC: SHUTTLE FLIGHT EVALUATION

SUMMARY

The Shuttle Orbiter, External Tank, and Solid Rocket Booster were all heavily instrumented to measure ascent base heating environments on the four development flights and first operational flight. The measured data were extracted from the data tapes, analyzed, correlated with flight events, compared with predictions and other flights; then officially reported where they became an important part of the final MSFC Flight Evaluation Report. REMTECH performed these functions as part of the Flight Evaluation Working Group in support of organization ED-33. The reports and other supporting material were provided in partial fulfillment of work defined in contract NAS8-34135.

TOPIC: SHUTTLE FLIGHT EVALUATION

DOCUMENTATION		
DOCUMENT NO.	*SUBJECT*	*DATE*
RM 056-1	STS-1 Base Heating Flight Evaluation	June 10, 1981
RM 056-4	STS-2 Base Heating Environment Displays	Oct. 26, 1981
RM 056-6	STS-2 Flight Evaluation Report, Section 6.0 Base Heating	Nov. 1981
RM 056-9	STS-3 Base Heating Flight Data Evaluation	April 23, 1982
RM 056-11	STS-4 Base Heating Flight Data Evaluation	August 6, 1982
RM 056-17	Flight 51-F Ascent Environment Predictions	August 6, 1985
AIAA Paper 83-1544	Space Shuttle Base Heating	June 3, 1985

TOPIC: LOCAL BASE GAS RADIATION

SUMMARY

One of the interesting results of the Shuttle flight data evaluation was the additional radiation to base region surfaces resulting from the local hot plume gases recirculated into the base. An extensive analysis of this phenomenon was necessary in order to correctly identify the convective component of the total heating rate measured by the total calorimeters. Local gas radiation was experienced on the Apollo Saturn V vehicle but the magnitude was unpredictable on Shuttle because the base gas temperature and amounts of water vapor and Al_2O_3 particles in the gas were unknown. By separating the radiation and analyzing the differences in magnitude between the Orbiter and ET base regions, general magnitudes of the base gas temperature were deduced.

TOPIC: LOCAL BASE GAS RADIATION

DOCUMENTATION		
DOCUMENT NO.	*SUBJECT*	*DATE*
RM 056-8	STS-2 Base Heating Environment Distributions	March 9, 1982

TOPIC: SHUTTLE OPERATIONAL BASE HEATING ENVIRONMENTS

SUMMARY

A sequence of operational flight base heating design environment reports were prepared beginning in the fall of 1982 for the External Tank and culminating in the summer of 1984 for the Orbiter and SSMEs. These reports drew heavily on the flight experience, model test data, and dispersed trajectory parameters. The environments became the design against which all operational vehicle thermal protection systems were evaluated. The reports (environments) were the basis for the Plume Heating Data Books published by Rockwell International and imposed on all the STS element contractors.

TOPIC: SHUTTLE OPERATIONAL BASE HEATING ENVIRONMENTS

DOCUMENTATION		
DOCUMENT NO.	*SUBJECT*	*DATE*
RM 056-12	Operational External Tank Convective Base Heating Environment	Nov. 9, 1982
RM 056-13	External Tank Convective Base Heating Environment Comparison	Dec. 2, 1982
RTR 056-2	Operational SRB Convective Base Heating Environment	August 31, 1983
RTR 056-3	Operational Orbiter/SSME Convective Base Heating Environment	July 26, 1984
RM 056-15	Operational SRB Convective Base Heating Environment	July 25, 1983
RM 056-16	Orbiter/SSME Operational Convective Base Heating Environment	June 22, 1984

TOPIC: SSME PLUME IMPINGEMENT TO SPENT SRB

SUMMARY

Prior to the Shuttle development flights, trajectory analyses and plume predictions indicated that the SRBs would pass through the SSME exhaust plumes immediately following separation. Accordingly, design environments specifying the levels of plume impingement heating to the SRBs were analytically determined. Shuttle flight data from STS-1 through STS-3 and STS-5 confirmed that SSME plume impingement to the SRBs does occur and that the total length of the boosters are affected. Therefore, under contract NAS8-34135, a detailed flight data analysis was performed and the plume impingement environment up-dated based upon the development flight experience. This design up-date became part of the SRB operational flight environment.

TOPIC: SSME PLUME IMPINGEMENT TO SPENT SRB

DOCUMENTATION		
DOCUMENT NO.	*SUBJECT*	*DATE*
REMTECH Memo RM 056-14	"Preliminary Shuttle Operational Flight Environments – SSME Plume Impingement to SRBs Following Separation"	Dec. 30, 1982
REMTECH Technical Report RTR 056-1	"Analysis of Shuttle SSME Plume Impingement to SRBs Following Separation"	Jan. 31, 1983

TOPIC: PARALLEL PITCH SSME EVALUATION

SUMMARY

Flight thermocouple data from the cool side of the upper SSME EMHS from flights 41-G and 51-B indicated increased heating to the EMHS with 2nd stage parallel pitch gimbaling of the SSMEs. The increases in convective heating were factors of 3 to 4 above the original design environments which were based upon parallel yaw gimbal positions. Because parallel pitch was to become the operational mode on most future flights to increase performance, it was necessary to up-date the convective environment to the EMHS to reflect the more severe flight data trends. The analysis and reports necessary to up-date the environment were performed under contract NAS8-34135 during 1985.

TOPIC: PARALLEL PITCH SSME EVALUATION

DOCUMENTATION		
DOCUMENT NO.	*SUBJECT*	*DATE*
RM 056-18	Updated Operational Flight Base Heating Environments for the Orbiter EMHS	Aug. 13, 1985

TOPIC: BASE HEATING INDICATOR CODE

SUMMARY

The base heating indicator code was developed under contract NAS8-34135 to provide a simplified analysis of the Shuttle base region convective and radiative base heating components. It uses available trajectory variables as input to determine if the trajectory produces conditions which exceed the operational thermal environment for the Shuttle and ET base regions. The modeling procedures for the exhaust plume radiation component and convective base heating computations were developed separately and reported in separate documents. A user's guide was also prepared containing descriptions of the overall code structure and operation, and operator instructions.

TOPIC: BASE HEATING INDICATOR CODE

DOCUMENTATION		
DOCUMENT NO.	*SUBJECT*	*DATE*
RTR 056-4	Space Shuttle Base Heating Indicator Code User's Guide	June 12, 1985
RTN 109-01	Space Shuttle Base Heating Indicator Code Thermal Radiation Model	June 26, 1985
RTR 056-05	Space Shuttle Base Heating Indicator Code Convective Heating Methodology	August 1986

TOPIC: CONVECTIVE BASE HEATING SCALING

SUMMARY

A scaling study was undertaken to improve our understanding of the model/flight data convective base heating relationship so future model tests for improved Shuttle or other launch vehicles will be more valuable for prototype environment predictions. Base convective heating predictions for most vehicles and particularly for the Shuttle are not determined analytically but rely on scaled model test data. The scaling analysis conducted by REMTECH under contract NAS8-34135 explored the model and flight relationship for all known parameters which influence the base region convective environment, with emphasis on isolating the critical parameters which determine the correct scaling factors.

TOPIC: CONVECTIVE BASE HEATING SCALING

DOCUMENTATION		
DOCUMENT NO.	*SUBJECT*	*DATE*
Unpublished model data, flight data, notes & detailed correlations	Jupiter; Saturn I; Saturn V; Tital II, IIIC, 34D, 4; Shuttle Convective Base Heating Scaling Analysis	1985
RM 056-10	Shuttle Convective Base Heating	May 20, 1982
Paper presented at NASA/Langley conference on Shuttle Performance: Lessons Learned	Calculation of Shuttle Base Heating Environments and Comparison with Flight Data	March 8, 1983

TOPIC: 51-L ACCIDENT INVESTIGATION

SUMMARY

NASA/MSFC provided leak plume definition and plume impingement environment estimates in support of the Shuttle Mission 51-L failure analysis. REMTECH assisted MSFC throughout the effort by providing and analyzing plume data and other flow related information. The plume estimates were determined by state-of-the-art methodology utilizing the RAMP and SPF codes for plume definition and the PLIMP code for impingment environments. Plume deflections were based upon experimental data from transverse firing jets emanating from circular sonic orifices and two-dimensional slots. The plume predictions were qualitatively compared with flight film and good agreement noted.

TOPIC: 51-L ACCIDENT INVESTIGATION

DOCUMENTATION		
DOCUMENT NO.	*SUBJECT*	*DATE*
Paper presented at JANNAF 16th Plume Technology Meeting	Shuttle Mission 51-L Right Solid Rocket Booster (R-SRB) Leak Plume Analysis	9/9 - 9/11, 1986

TOPIC: HYDROGEN LEAKAGE INVESTIGATION

SUMMARY

MSFC and MMC/Michoud became concerned in early 1987 about a potential TPS impact on the ET intertank due to leakage and burning of GH_2 from the hydrogen vent value. JAYCOR was contracted by MMC to provide analytical solutions for the flowfield and resulting thermal environments. REMTECH, under contract NAS8-34135, supported ED-33 by providing external subsonic flowfield data around the ET and boundary layer concentration profiles with hydrogen injection. A computer code, REFLAN, was also obtained to analyze the 3-D burning problem when leaked/vented hydrogen burns in cross-flow air. REMTECH also analyzed data obtained in a hydrogen burning test conducted by MMC at MSFC.

TOPIC: HYDROGEN LEAKAGE INVESTIGATION

DOCUMENTATION		
DOCUMENT NO.	*SUBJECT*	*DATE*
RTR 056-06	Hydrogen Burning Study	March 1988