Space Shuttle Base Heating

Terry F. Greenwood* and Young C. Lee*
NASA/Marshall Space Flight Center, Huntsville, Alabama
Robert L. Bender†
REMTECH, Inc., Huntsville, Alabama
and
Robert E. Carter‡
Lockheed Missiles & Space Company, Huntsville, Alabama

This paper describes in detail the Shuttle first and second stage base heating environments and presents selected flight heating rate data from Shuttle flights STS-1 through STS-5. A comparison of preflight predicted design environments with actual flight data is also given for a few locations, but a detailed description of the preflight base heating methodology developed for the Shuttle is not presented. In general, the Space Shuttle base heating environment is a combination of Orbiter main engine and booster plume radiation, freestream air convective cooling, and reversed plume flow convective heating. Each base region design point receives differing levels of radiation and convective heating depending upon its location relative to the plumes, base gas absorption, structural blockage, general base configuration, and local surface temperature. At the conclusion of the Shuttle development program, a flight data base has been assembled which shows outstanding repeatability in the data and general independence of the measured environments from small changes in trajectory and operational parameters. There was general good agreement between flight data and preflight prediction which provides overall validation of the prediction methods.

Introduction

THE Space Shuttle is a launch vehicle transportation system composed of a reusable Orbiter vehicle, reusable Orbiter hydrogen-oxygen main engines (SSMEs), reusable Solid Rocket Boosters (SRBs), and an expendable propellant tank (ET). The three SSMEs operate continuously throughout first and second stage flight, while the two boosters are expended, separated, and recovered after first stage flight. During first stage operation, the combined five exhaust plumes from the SRMs and SSMEs induce a base heating environment which was an important factor in the design of the Shuttle base region thermal protection system (TPS). Base heating from the three SSME plumes during second stage flight is lower than the first stage environment and essentially constant with time.

Shuttle Base Geometry

The Shuttle base region configuration is shown in Fig. 1. Significant geometrical features which affect base heating are the close grouping and upper pitch of the SSMEs and the relatively wide spacing of the SRBs. The Orbiter body flap, which protects the lower SSMEs from aerodynamic flow during re-entry, also prohibits flow out of the Orbiter base toward the ET and SRBs. The ET aft dome is well forward of both the Orbiter base and the exit planes of the SRBs; e.g., approximately 400 in. forward of the SRB nozzle exits. As shown in the upper side view of Fig. 1, the aft RCS motors are mounted on the most aft protrusion of the OMS pod and extend almost to the exit plane of the upper SSME. The trailing edge of the vertical stabilizer extends aft and above the upper SSME, while the wing elevons are outboard and forward of the lower SSME nozzle exit plane. Aft attach structure between the Orbiter, ET, and SRBs is composed of several struts presenting surfaces normal to the freestream flow early in flight and to the reversed plume flow later in flight.

Base Environment Description

The Space Shuttle base heating environment is a combination of SSME and SRM plume radiation, freestream air convective cooling, and reversed plume flow convective heating. Each base region design point receives differing levels of radiation and convective heating depending upon its location relative to the plumes, base gas absorption, structural blockage, general base configuration, and local surface temperature. The radiation environment varies with the plume shape, and the incident radiation to any base location depends upon the emission/absorption and afterburning characteristics of each contributing plume and upon the magnitude of attenuation of the base region gases. Convective cooling affects hot base surfaces during initial first stage flight as cool freestream air is drawn through the base by the aspirating action of the plumes. At higher altitudes, when the plumes become highly expanded and interact, hot gases from the SSME and SRM nozzle boundary layers are reversed into the base with resultant base convective heating to most base surfaces.

Typical flight data illustrating the various environment components and their relative magnitudes throughout ascent can be seen in Fig. 2. These data were measured in the center of the Orbiter heat shield. Base heating is significant at this location through main engine cutoff (MECO).

As shown in Fig. 2, radiation during first flight is a maximum near sea level. During the first 70 s of flight, radiation to the heat shield is reduced as the altitude increases while cool freestream air drawn across the Orbiter base convectively cools these surfaces. The plume boundaries intersect and begin to recirculate exhaust gases toward the base at 70 s. There is a rapid buildup in convective heating

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*Aerospace Engineer.

†Engineering Specialist.

‡Research Specialist.

beginning at this time and lasting to about 100 s, at which time SRM thrust tailoff begins to reduce the intensity of the reversed flow. During this time there is a small contribution to the radiation environment component due to radiation from the reversed hot gases in the base region. From 100 s to SRB separation, convective heating drops off as the SRM thrust tailoff continues. Approximately 7 s before SRB separation a sharp spike in heating occurs as radiation from the SRM plumes increase during shutdown.

During second stage flight, the SSME plumes radiate at a nearly constant low level as seen in the shaded area of Fig. 2. Second stage flight convective heating is esentially constant as the flow into and out of the Orbiter base reaches a choked condition and becomes independent of altitude; i.e., not affected by additional plume expansion at the higher altitudes. Convective heating declines at the center of the Orbiter heat shield when the SSMEs throttle down for 3G beginning at approximately 450 s. This decline is a result of flowfield changes in the base due to variations in the main engine pitch position.

Prediction Methodology

Methodology for generating the Shuttle base heating design environments consisted of a combination of techniques, analytical tools, and experimental programs to determine the radiation and convective heating components of the total environment. Details of the original design prediction methods are presented in Ref. 1. Each environment component prediction utilized different methods and was computed independently. Radiation was determined analytically utilizing plume math models with computerized view factor calculations. Convective heating predictions were based on scaled model test data from hot firing, short duration model tests. Gas temperature estimates relied on analytical nozzle boundary layer calculations in combination with experimental model data. The availability of Shuttle flight data and subsequent comparisons with prediction resulted in some minor changes in both the radiation and convective heating calculation methods.[2,3]

Flight Data

Development Flight Instrumentation (DFI)

Flight instrumentation to monitor ascent base heating consisted of total calorimeters, radiometers, and gas temperature probes. The number of instruments greatly increased from STS-1 to STS-2 and subsequent flights; the quality of the measurements was also improved on STS-2 and subsequent flights at some base locations. A variety of different type gages and different mounting and data retrieval systems were used throughout the various base components. With the exception of the gas temperature measurements, the data were generally good, consistent from component to component, and were of significant value in understanding the base heating environments. Total calorimeter sensor temperatures were generally less than 200°F throughout ascent so the measured total heating rates reflect an essentially cold-wall convective component. No valid gas temperature measurements were obtained on any Shuttle components for any flights.

Base heating environment data have been measured on the four development flights as well as the first operational flight. A limited amount of data was obtained on STS-1 due to bad instrumentation initially installed on the Orbiter and main engines, and reduced instrumentation on the ET base. The bad instruments were replaced on STS-2 and a complete base heating data base was obtained on all subsequent flights with

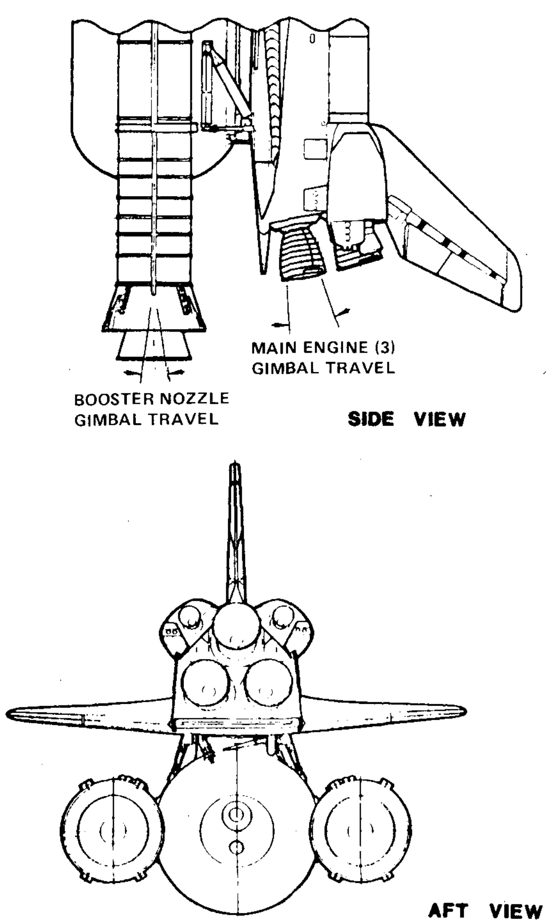

Fig. 1 Shuttle base configuration.

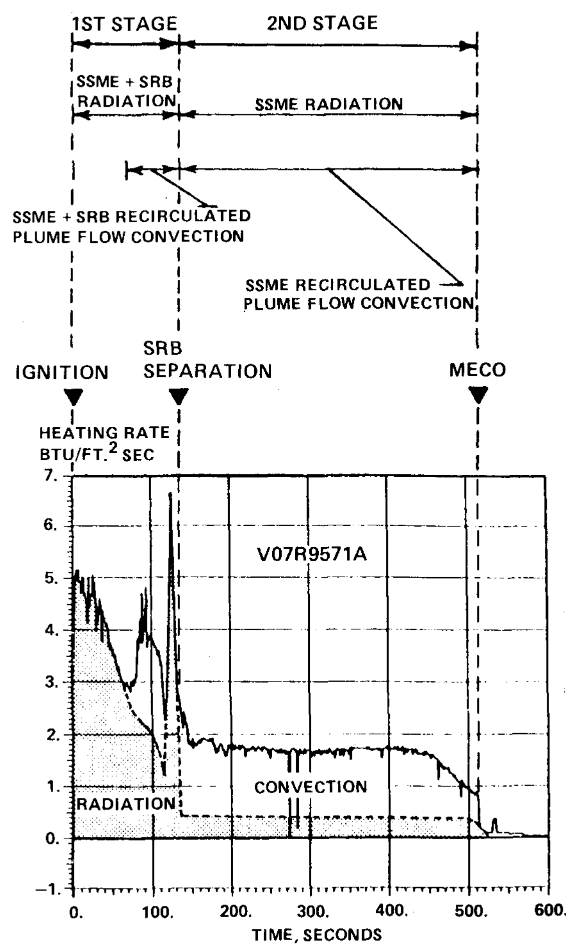

Fig. 2 Typical ascent base heating environment.

the exception of the SRB data on STS-4, which were lost when the boosters sank following water impact. Operating conditions which affect base heating and typical flight data are described in the following paragraphs.

Flight Parameters and Operating Characteristics

Shuttle flight parameters which significantly influence base heating are: vehicle trajectory, vehicle angle of attack, and SRM and SSME chamber pressure histories. Other flight and operating conditions affecting base heating include SSME and SRM gimbaling and vehicle sideslip. Altitude and SRM thrust decay history have the most impact; other flight and operating conditions have a second order effect. Model data indicate that SSME gimbaling can have significant effects on Orbiter base heat shield second stage convective heating if the gimbal angles significantly deviate from current baseline nominal. However, on all Shuttle flights to date, the SSME gimbal angles flown on each flight have not varied from this nominal and the measured flight data have been similar.

The altitude histories, Fig. 3, during first stage ascent have been remarkably similar on all five flights as have the engine operating conditions, Fig. 4. Therefore, it was expected that the measured environments would be similar in magnitudes and trends. Flight-to-flight differences noted in the data are primarily a function of local flowfield differences, gage contamination, TPS outgassing, flight to flight gage replacement, and range changes, etc. The global base region flowfields, plume shapes, gas temperatures, and TPS and instrumentation temperature were generally the same on all flights.

The combined SRM and SSME exhaust plumes immediately following liftoff and at approximately 100,000 ft can be seen in the photographs of Figs. 5 and 6, respectively. These photographs were taken by ground tracking cameras mounted near the launch pad and south of the launch site at Melbourne Beach. The SSME plumes are not visible except for the shock (Mach) discs which appear as a series of cone shaped luminous areas aft of the nozzles. Aluminum oxide particles in the SRM plumes make them very visible and show the extent of the high-temperature portion of the plumes. Insulation outgassing around the ET aft dome is also clearly visible in the photo of Fig. 5.

Typical Flight Base Heating Data

All base heating data for STS-1 through STS-5 are presented in Refs. 4 through 8. Selected data from the major base components are shown in the following figures. Where possible, data from a radiometer and total calorimeter at the same location are shown together so that the convective component of the environment can be deduced.

SRB

The right SRB aft skirt, kick ring, and SRM nozzle were instrumented on all flights.[2] Data from an inboard top surface on the kick ring and from the trailing edge of the aft skirt are presented in Figs. 7 and 8, respectively. The rapid drop in radiation measured by the aft facing radiometer on the SRB aft skirt (Fig. 8) is due to attenuation of the incident radiation and gage contamination resulting from the disintegration of the SRB thermal curtain protective cover during early first stage flight. These gases are clearly visible between the SRM nozzle exit and aft skirt in Fig. 5. The measured environments were very repeatable and exhibit general trends and magnitudes as expected. STS-4 data were not retrieved as mentioned previously.

External Tank

Flight data measured on the ET/Orbiter aft attach structure and on the upper left quadrant of the ET aft dome are presented in Figs. 9 and 10, respectively.[2] Particular notes of

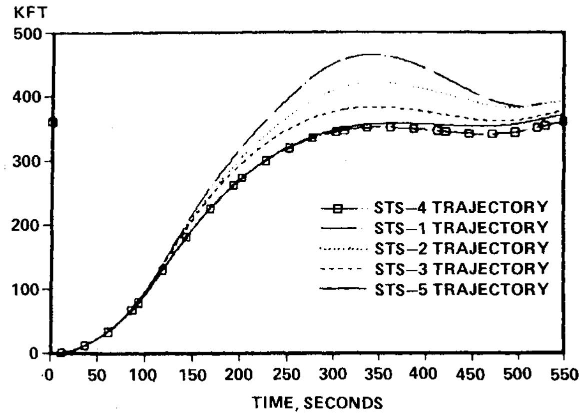

Fig. 3 Shuttle ascent trajectories.

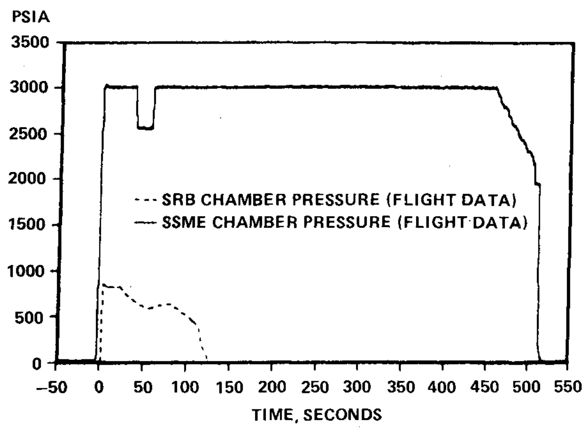

Fig. 4 Typical SSME and SRB chamber pressure histories.

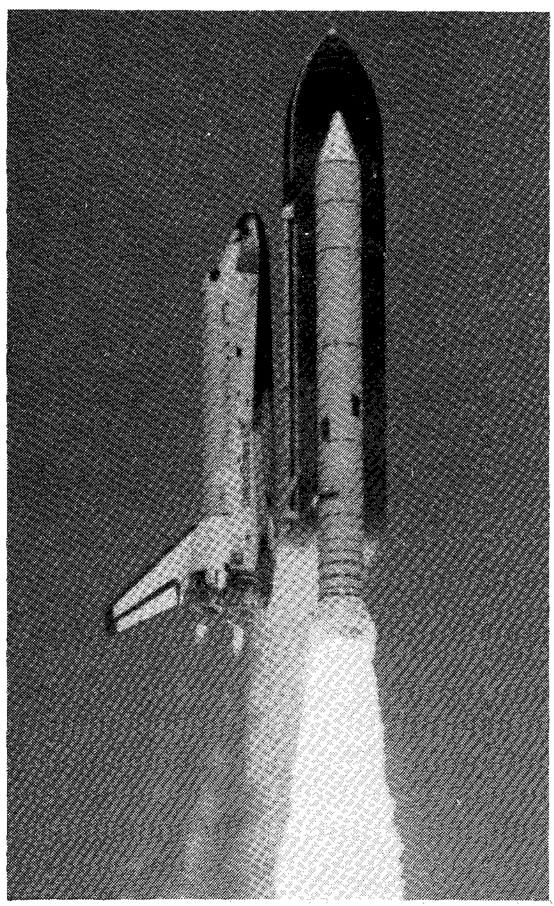

Fig. 5 Shuttle plumes at liftoff.

interest in these data are the reduced heating during the initial 30 s of flight (due to SOFI outgas attenuation of the radiation) and the abrupt increase in convective heating as plume flow reversal intensifies around 95 s.

Orbiter Peripheral Components

The Orbiter body flap, elevon, vertical tail, and OMS Pod were extensively instrumented.[2] Data from flight STS-5 at one instrument location on each peripheral component are displayed in Fig. 11. These environments are primarily radiation. The variation noted at the different locations is an indication of different views of the SRM and SSME plumes during first stage flight. Second stage heating is uniformly low as expected.

Orbiter Heat Shield

Base heating instrumentation was positioned over the entire Orbiter heat shield.[2] Flight measured environments from the lower left corner of the heat shield and from the upper left center are shown in Figs. 12 and 13, respectively. The environments are very consistent from flight-to-flight and apparently independent of trajectory. The upper center heat shield environment, shown in Fig. 13, is higher during second stage flight than the outboard environment, demonstrating the intensity of the reversed flow in the center of the three-engine cluster.

SSME #1

The upper SSME was also extensively instrumented to measure base heating.[2] Data from the aft hat band (facing aft) are displayed in Fig. 14. This location experiences a severe environment during first stage flight as expected. The higher measured total heating environments compared with the radiometer data during the initial 50 s of flight are contrary to expectations. This region should experience significant convective cooling during this time and consequently the total heating rates should be lower than the radiation values. These differences are currently unexplained.

Flight Data Evaluation

The flight data have been extensively analyzed and evaluated to: 1) identify major trends and magnitudes of the flight environments, 2) correlate the environments with major flight events such as liftoff, gimbaling, SRM thrust decay, and staging, and 3) validate the base heating prediction methodology. The following paragraphs summarize the significant results of this flight data review.

Trends, Magnitudes, Flight Event Correlations

Surfaces closest to the plumes—the SRB skirt trailing edge, the body flap trailing edge, and the SSME aft hat bands

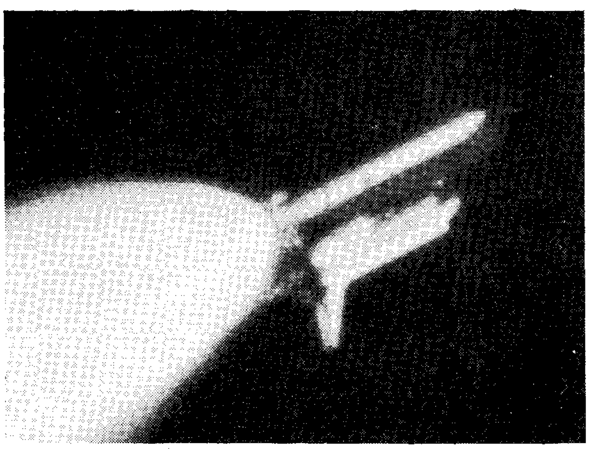

Fig. 6 Shuttle plumes at 100,000 ft.

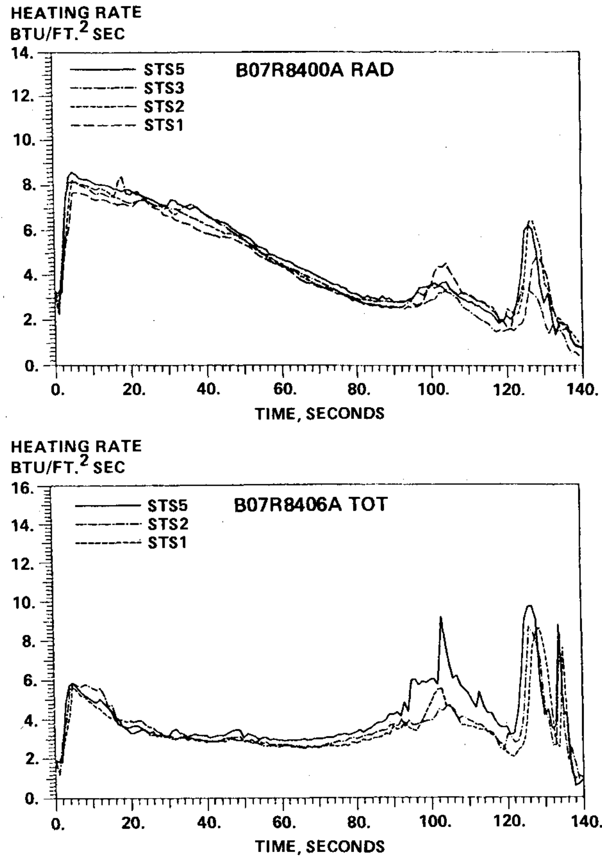

Fig. 7 Right SRB kick ring flight data.

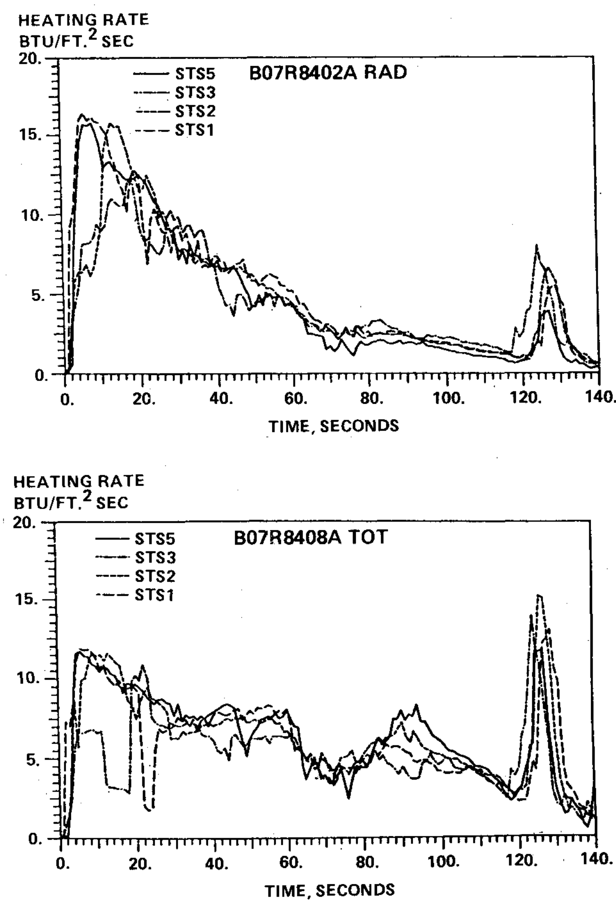

Fig. 8 Right SRB aft skirt trailing edge flight data.

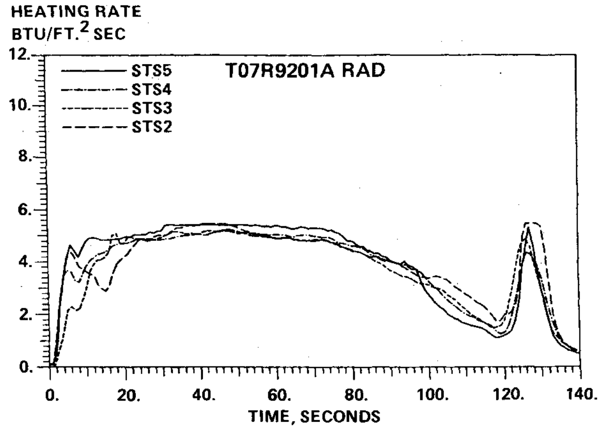

Fig. 9 ET/Orbiter attach structure flight data.

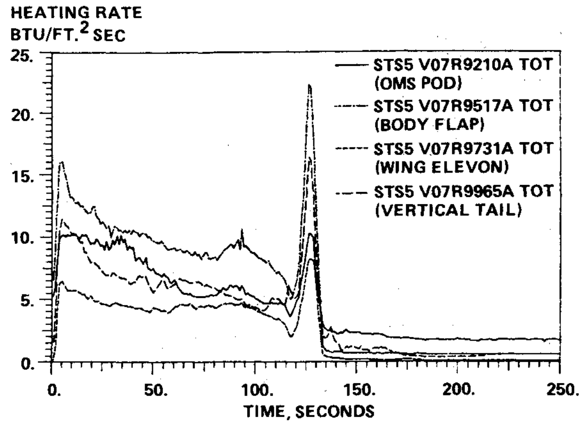

Fig. 11 Orbiter peripheral component STS-5 flight data.

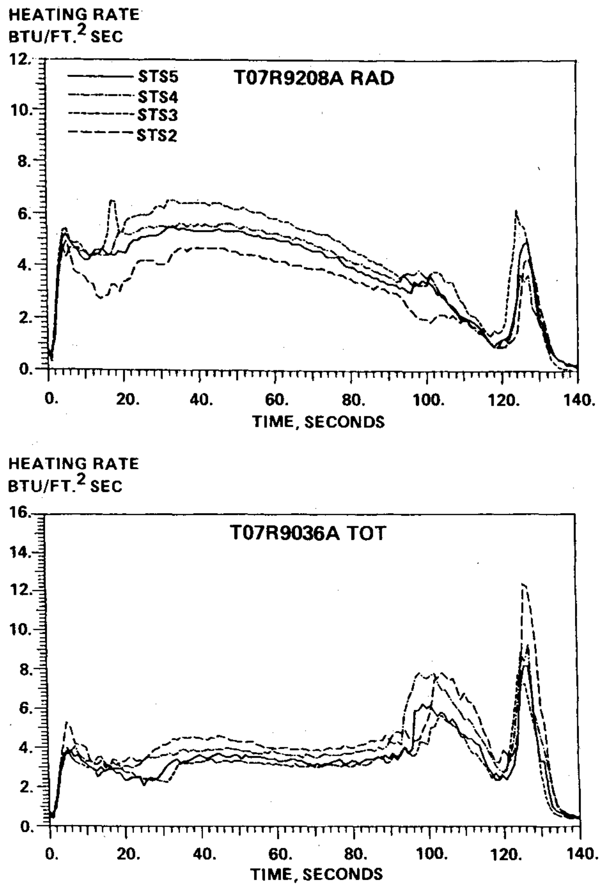

Fig. 10 ET aft dome flight data.

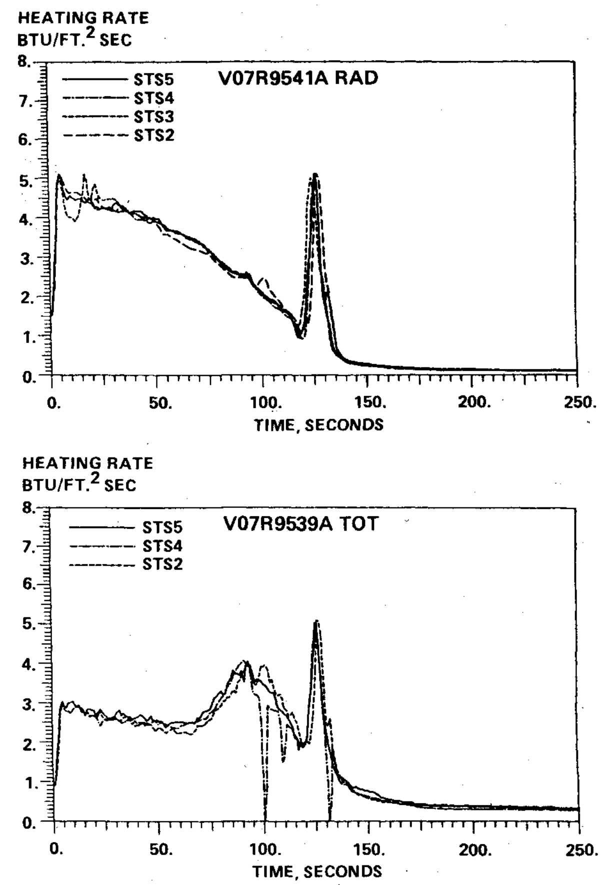

Fig. 12 Orbiter heat shield flight data.

—receive the highest levels of measured radiation, approximately 16 Btu/ft^2 s at liftoff. Convective heating is most intense in the center heat shield region of the Orbiter and in the upper center of the ET dome where levels of heating of 8 Btu/ft^2 s were measured at approximately 100,000 ft altitude. A spike in heating occurs during the last few seconds of SRM shutdown, producing an increase in radiation and convection well above nominal levels. Peak total heating during this period can exceed 25 Btu/ft^2 s at some locations.

Most total calorimeters throughout the general Shuttle base region experienced convective cooling during the initial 80 s of flight as the cool freestream air flowed over the calorimeter sensors. The magnitude of the convective cooling can be obtained from the flight data when the radiation environment is substracted from the measured total heating. A typical plot using this procedure with data measured on the upper ET aft dome is shown in Fig. 15. Shuttle surfaces which are hotter than the calorimeter sensors would experience even greater magnitudes of cooling, estimated to be as high as 6 to 8 Btu/ft^2 s for a 1200°R surface.

Downstream plume radiation to base region surfaces is generally expected to be a maximum near liftoff, followed by a gradual decrease with altitude throughout ascent. Radiation to the ET aft dome, shown from flight STS-3 in Fig. 16, was affected by three factors during first stage flight. All flights have shown significant amounts of luminous gases in the general base region surrounding the ET aft dome immediately following liftoff. These gases are hot SOFI ablation products released by the initial radiation heating load. They reduce the heat load by attenuating radiation to the base region surfaces. The amount of attenuation is noted by the shading at the left of Fig. 16. Later in flight, when hot plume gases are recir-

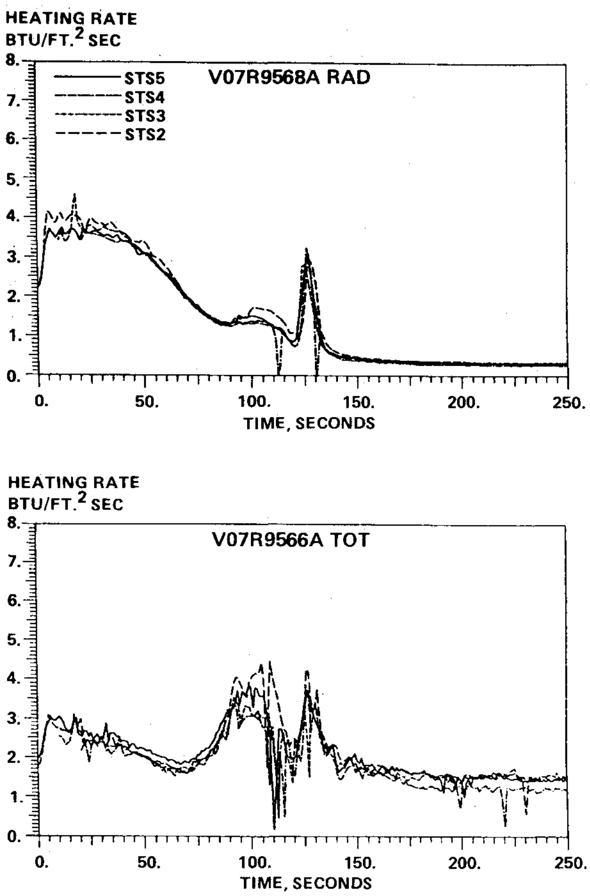

Fig. 13 Orbiter heat shield flight data.

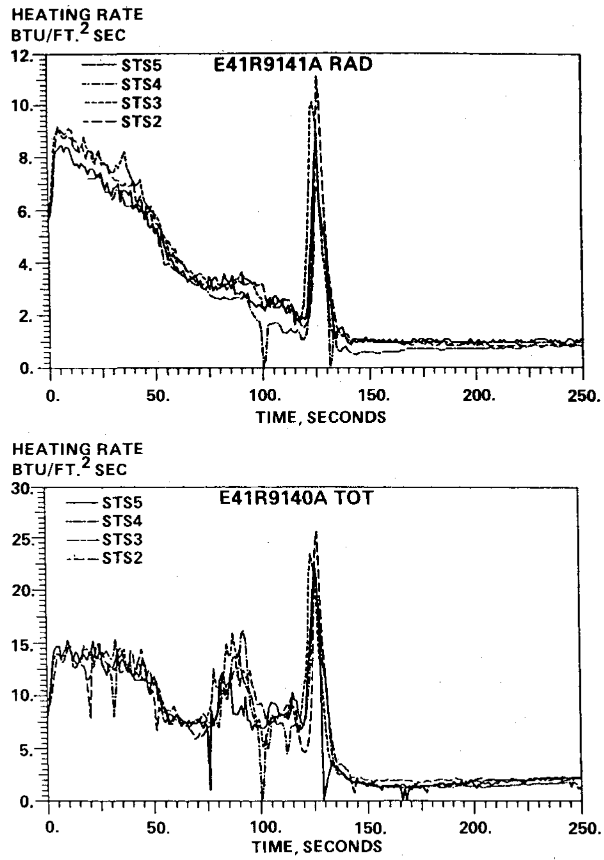

Fig. 14 SSME No. 1 flight data.

culated, the main (downstream) plume radiation is augmented by a small radiation contribution from the local hot gases. During the last seven seconds of SRM shutdown, the SRM plumes become brighter and have greater radiation potential during this time period as propellant residuals and liners are ejected through the nozzle and burn in the plume. The shutdown spike is noted in the shading to the right of Fig. 16.

Prior to the first development flight, many ascent flight events such as liftoff, gimbaling associated with the roll maneuver, SSME throttling, SRM thrust decay, separation, etc., were expected to influence the base heating environment. However, due to limitations in the analytical methodology and in the model data base, the extent and magnitude of these effects were largely unknown. Most were approximated in the original design predictions. Table 1 lists the more important flight events and provides a general assessment of their impact on base heating.

Flight Data—Prediction Comparison

In general, the measured base heating environments from the development flights were in good agreement with the preflight predictions. Major expected trends such as convective cooling during low altitude flight, radiation decrease with altitude, decrease in convective heating with SRB thrust decay, etc., were verified by the flight data. Areas of peak heating and general magnitudes of the environment were as expected, based upon the preflight analysis. However, the flight data did provide new insight into both the radiation and convective heating mechanisms not anticipated before the flights. Radiation on the flight vehicle does not undergo significant launch stand amplification as expected, but is dramatically attenuated by foam insulation outgassing. Afterburning in the SRB and lower SSME plume mixing region increased radiation above predicted levels, as did

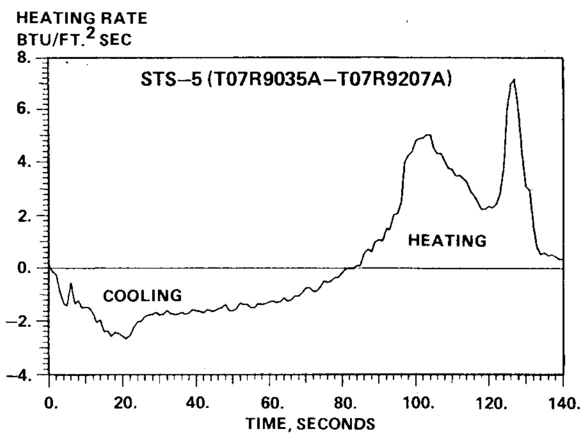

Fig. 15 Convective cooling and heating on the ET aft dome.

Table 1 Flight event impact on base heating[a]

Flight event	Time	Base heating impact
1st Stage flight		
Liftoff (launch stand)	0	Negligible
Roll maneuver	8-20	No effect
SSME throttle, max-Q	45-65	Slight effect on SSMEs
SRM thrust decay	85-122	Major effect on convective heating
SRM shutdown	122-130	Large increase in radiation
SRB separation	130	No effect
2nd Stage Flight		
SSME throttle, 3G	450-505	Significant effect on Orbiter heat shield
SSME shutdown (MECO)	512	All heating to zero

[a]Some flight event effects are evident in Fig. 2.

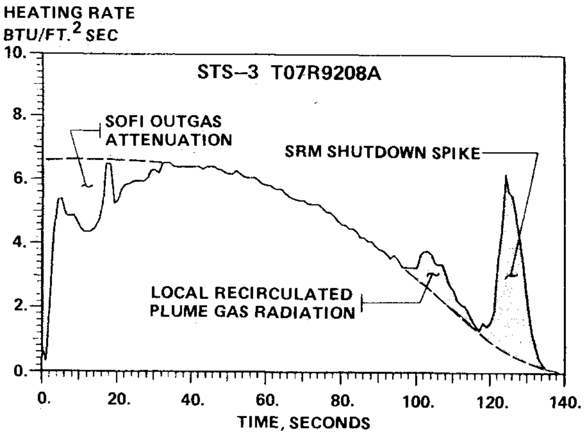

Fig. 16 Radiation measured on the ET aft dome.

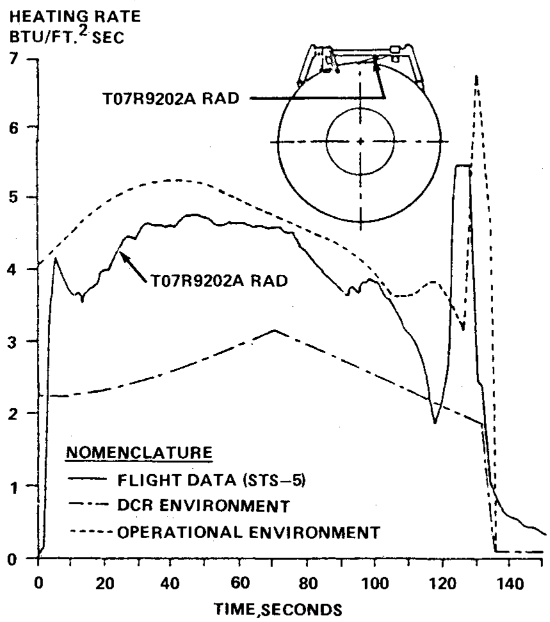

Fig. 17 Radiation prediction—flight data comparison.

fundamental changes in the SRB plume structure and composition occurring during shutdown. Preflight design predictions and postflight operational environment radiation predictions are compared with flight data measured on the ET/Orbiter attach structure in Fig. 17.

Convection was more significant than expected on the upper ET dome and SRB aft skirt region, but less than predicted in the upper center of the Orbiter during the long period of second stage boost. Convective heating within a plume induced flow separation region around the aft end of the ET and SRB aft skirt region was measured on the flight but not anticipated based upon the model test data. A typical flight data convective prediction comparison can be seen in Fig. 18.

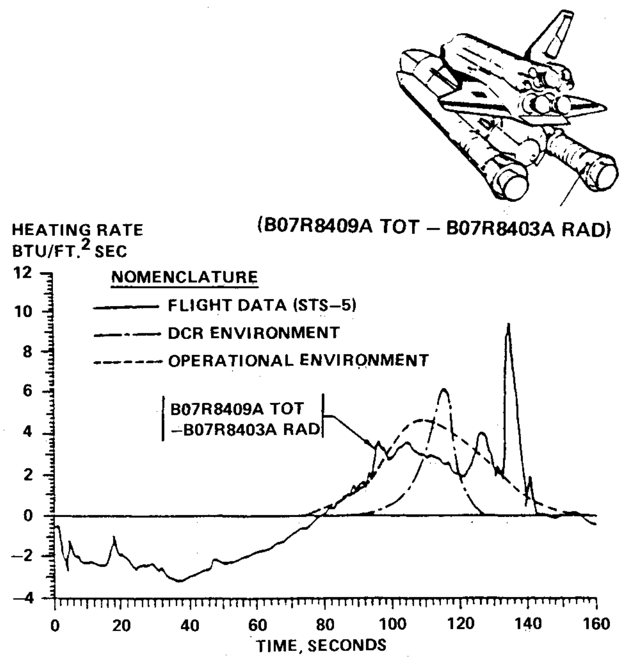

Fig. 18 Convective prediction—flight data comparison.

Conclusion

The four development flights and first operational flight of the Space Shuttle provided measured base heating environments which were essential in assessing the magnitudes and trends of the environment and validating the prediction methodology. A flight data base has been asembled which shows outstanding repeatability in the data and general independence of the measured environments from small changes in trajectory and operational parameters. There was general good agreement between flight data and preflight prediction, which provides overall validation of the prediction methods. Based upon this agreement, the Shuttle base heating environment is adequately characterized for future missions for its current configuration and operating conditions.

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