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Thermal Modeling of Shuttle Solid Rocket Motors on the Launch Pad

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A three-dimensional thermal model of the Space Transportation System redesigned solid rocket motors has been developed. The thermal model, which employs the SINDA-85 code, was developed to provide a reliable methodology for predicting motor surface and component temperatures. A discussion of the model development and the required boundary conditions, including the calculation of the convective and radiative fluxes, is presented. Predicted surface temperatures are shown to be in good agreement with available data on experimental measurements. The method has also been used to predict the propellant mean bulk temperature. This methodology provides not only reliable predictions of temperatures in critical locations but also global thermal information, and it possibly provides a substitute for the instrumentation.

Nomenclature

K_T = solar clearness index
LCC = launch comment criteria

Subscripts

a = ambient
dp = dew point

Introduction

PAST experience has shown the necessity of ensuring that all components of a redesigned solid rocket motor (RSRM) are within an acceptable temperature range before a launch of the Space Transportation System (STS). During the redesign efforts, a safe temperature margin was assessed for each component. These temperatures are currently monitored by an experimental package referred to as ground environmental instrumentation (GEI). The system consists of thermal sensors that are strategically placed at different locations around both motors to ensure that the surface and components of each motor are within acceptable temperature limits.

In the redesign effort, the need for a numerical technique that could reliably predict motor surface and component temperatures before launch was recognized. The sensors have posed several problems, e.g., scheduling the replacement of damaged sensors without inhibiting launch dates and recognizing spurious signals that might otherwise prevent launch. The purpose of this paper is to describe a procedure, referred to as the global thermal model (GTM), which produces an in-depth analysis of the RSRMs and their components. The discussion will provide insights on code operations and requirements and will illustrate code reliability by comparison with experimental results. The capability of predicting the propellant mean bulk temperature will also be discussed.

Experimental Data

During the redesign of the STS solid rocket motors, temperature limits at various locations on each motor casing and their components have been established. Thermal sensors have been installed at these locations to measure the response before launch. This group of thermal sensors is called the GEI package. The locations of these sensors (54 total) and 12 joint heater sensors are shown in Fig. 1. Temperature measurements at 23 of these locations have been defined as critical, and the temperatures must be within a defined limit before a decision to launch. The sensors are checked only for shorts and are monitored to determine any high or low readings. Schedule delays to fix a malfunctioning sensor are prohibited.

Boundary Conditions

The boundary conditions used in this analysis are as follows: 1) local heat transfer coefficient,[1] 2) solar flux input,[2] 3) radiation interchange between the motors and the surround-

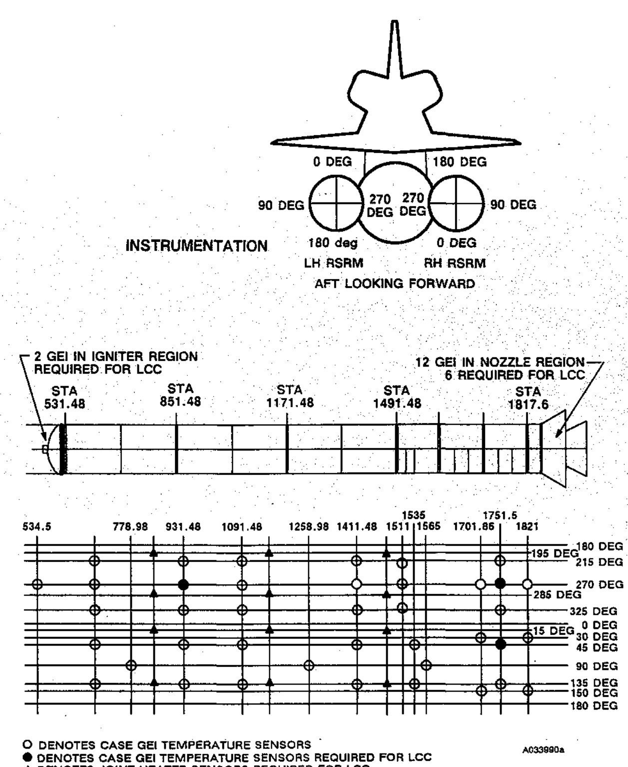

Fig. 1 Ground environmental instrumentation and joint heater instrumentation.

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ings,[3] 4) ambient temperature around the motor, 5) wind speed and direction,[1] and 6) induced cooling effects from the external tank cryogen vapors and chilled local ambient air.[1] All of these boundary conditions play significant roles in the case surface temperatures of the motor, which in turn impact the conditioning of the entire motor.

Local Heat Transfer Coefficient

Accurate heat transfer coefficients around the entire motor are difficult to obtain. They are also one of the most critical boundary conditions. The air movement around each motor varies with wind speed and direction. The wind speed varies also with elevation above the ground. Complex flow patterns are developed around the vehicle on the launch pad and the supporting structures and launch pad components.

The parabolic hyperbolic or elliptic numerical intergration code series (PHOENICS) code has been used to develop a model[1] of the STS on the launch pad that includes the launch pad structures. For recent flights, steady-state runs using the model have been made for the most likely wind speeds and directions at the time of launch. This flow model is one of the sources used to obtain heat transfer coefficients. The NASA large cylinder empirical equation[4] is also used to obtain heat transfer coefficients. It is used extensively when flow modeling results are not available.

Thermal Model

Every component on the motor cannot feasibly be monitored by the GEI system during a planned launch. In addition, the calibration and checkout of each instrument to ensure accurate measurements are not possible. Finally, the launch schedules prohibit delays to repair an instrument. These conditions, along with the desire to eliminate debris around the launch site due to the closeout of cables and the need to reduce costs, have given rise to considerations of eliminating the GEI in future flights. However, before eliminating the GEI package, it is important to have operational a reliable means of monitoring the pad for predicting the solid rocket motor case temperatures. An analytical method would overcome many of the objections to the experimental system as well as provide global information.

There are objectives in developing the thermal model. The model must be able to 1) run in near real time during the launch countdown, 2) quickly incorporate the weather boundary conditions, and 3) provide good resolution for the critical components of the motor hardware. These expectations make the problem very difficult based only on the motor size [125 ft (38.1 m) high and 12 ft (3.66 m) in diameter]. The model must be able to run on a near-real-time basis to make correct decisions during Shuttle countdown procedures and to make future predictions using projected weather data. The model must also be able to start from a given point in time and run different projected scenarios to aid in decision-making processes during countdown. This capability enables propellant mean bulk temperature predictions to be made for the eight days before launch (L-8) and two days before launch (L-2) requirements and also allows for different scenarios to be run during actual launch countdown procedures.

A thermal model of the solid rocket motors at their components has been developed.[5-8] The model, referred to as the GTM, is being checked out and validated with the GEI. Currently, the GTM provides backup support to the GEI data as well as global thermal response information. The GTM is structured so that it may use either GEI data as imposed surface temperatures or climatic (environmental) data provided by four weather stations near the pad. Modeling refinements are being made from the evaluation of the results using climatic data compared with actual GEI. A database of weather conditions and GEI temperatures is being made. The model is being refined with the use of this database. With each flight, GEI and climatic scenarios are established to help with model verification. In future flights, the GEI instrumentation may be removed, and this verification of the model will be essential. Start and stop times of different motor operations and boundary conditions are input in hours from the beginning of the year. Subprograms translate data, time, and year into hourly time for the thermal model input and back into actual Kennedy Space Center time for output. This capability avoids the conflict concerning how many hours into the run the different operations should be started and stopped.

The GTM used the systems improved numerical differencing analyzer SINDA-85 code to develop the desired thermal representation of the solid rocket motors and their components. The VAX version of the SINDA-85 finite difference thermal code is set up so that submodels can be executed along with the principal model. The whole program is modular, and a detailed model of a certain region can be incorporated by simply including the desired submodel to be run with the program. The different boundary conditions and operations of a typical countdown scenario are stored. The thermal model is composed of 2420 nodes (diffusion, arithmetic, and boundary nodes). It is generated in a two-dimensional plane and then rotated into a three-dimensional geometry. The nodes are numbered circumferentially by adding 2000 onto the previous node number. Each node encompasses a span of 30 deg circumferentially.

The GTM is basically two programs, one each for the right and left motor. The reasons for requiring two programs are 1) the solar, radiative, and convective boundary conditions are not the same because of different locations; and 2) the coordinate system used to locate position is different for each motor. The coordinate system, for ease of manufacturing, starts at 0 deg (north) for the right-hand (east) motor and 0 deg (south) for the left-hand (west) motor and rotates counterclockwise if the perspective is from an aft position.

The star-shaped propellant grain configuration (Fig. 2) in the forward end of the RSRM is represented by arithmetic nodes placed between the diffusion nodes. The volume of the diffusion nodes is adjusted, and the arithmetic node simulates the air gap as a contact resistance. The model is very coarse, and the propellant nodes extend axially from field joint to factory joint locations (Figs. 3 and 4). The field joint air gap between segments is also modeled by an arithmetic node by setting a contact resistance. Detailed models of the regions within the forward and aft skirts of the solid rocket boosters have been developed and incorporated into the GTM.

A two-dimensional, detailed submodel of the aft field joint and external tank attach ring area has been made. It has been implemented for predicting GEI response. With SINDA-85, submodels may be developed and easily incorporated into the thermal model. For example, if a joint heater failure occurs during a countdown, the detailed submodel in that region may

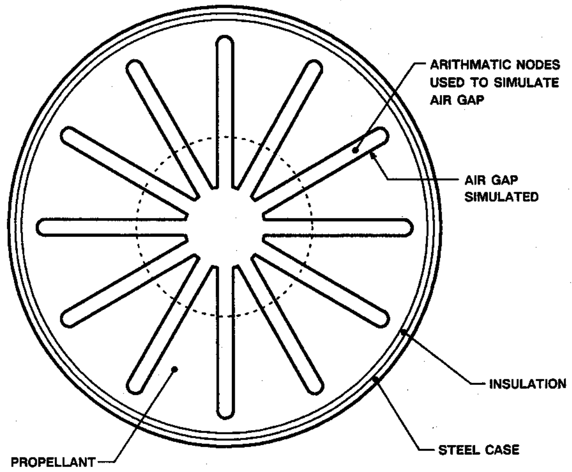


Fig. 2 Diagram of star propellant simulation.

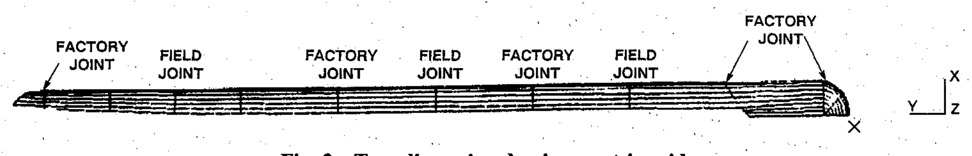


Fig. 3 Two-dimensional axisymmetric grid.

be used. The temperatures of the O-rings and other components in the area will be predicted during cooldown.

The PHOENICS code solves the full Navier-Stokes equations. The three-dimensional model solves for density; pressure; U, V, and W velocity components; concentration of each effluent in each cell; viscosity; specific heat; thermal conductivity; mass fraction; and binary diffusion coefficient. These variables are determined by these equations at each cell during each iteration. When the model converges or a run is completed, the parameters solved for are Prandtl number, Schmidt number, Grashof number, Rayleigh number, heat transfer coefficient, and Nusselt number. The grids are detailed enough to capture the recirculation zones around objects and also the critical flow modeling between solid rocket motors and the external tank. They are also coarse enough that the entire pad environment may be encompassed to ensure proper flow modeling around the vehicle. The code can be run on an IBM 3192 or Cray computer. Full three-dimensional scenarios have been run, using historical weather data, for the most likely wind speed and direction of recent launches.

The ambient temperature is the most critical variable (actual measurements are needed) in the calculation of the propellant mean bulk temperature. Ambient temperature data are measured at the launch pad. Historical averages may be used for other required boundary condition inputs such as wind conditions and solar radiation, and they permit a fairly good approximation of the mean bulk temperature. Previous analytical experience comparing the use of historical (except for actual ambient temperature) vs actual boundary conditions has shown a difference of 3°F (1.67°C). The burn rate of the propellant varies by 0.001 in./s (0.00254 cm/s) for every 4°F (2.22°C) change in mean temperature. Because of other uncertainties in the burn rate, the 3°F (1.67°C) error can be accounted for by the burn rate uncertainty. The propellant mean bulk temperature predictions are used for calculating the thrust that can be delivered for a mission and for determining the best flight trajectory.

Induced cooling effects are reflected within the thermal model by use of the local boundary conditions. Significant cryogen vapors are vented to the atmosphere at two locations. These locations are accounted for at the oxygen venting arms on top of the external tank and at the Space Shuttle main engines oxidizer seals. These are the coolest vapors dumped into the STS environment, and they have the highest flow rates. A primary concern is that, with a steady westerly wind, stagnation regions around the motor are formed, which, in conjunction with the continual dumping of a large amount of cryogenic vapor into the atmosphere, will significantly cool the RSRM case.

Solar Input

The solar radiation heat flux input to the thermal model is one of the most predominant heat sources. Both the direct and diffuse components have to be considered in the modeling. Also, the clearness of the sky and the shading effects created by the STS surroundings must be taken into account. The time of day and the day of the year fix the position of the sun. The absorptivity of the material is a significant factor in the amount of heat flux that is received by the motor. The solar effect varies greatly between the motors, the left-hand (west) motor being much more shaded than the right-hand (east) motor. A monthly solar flux database has been created.

Methods developed for solar space heating applications[9] are used for estimating the direct (beam) and diffuse components of the solar radiation incident on a surface of a specified tilt and azimuthal orientation. These methods are based on two algorithms. The first algorithm computes the solar incidence angle, defined as the angle between the surface normal vector and a vector collinear with the rays of the sun. The routine considers the day of the year, the time of day, and the local latitude. The second algorithm computes the instantaneous values for total and diffuse solar flux on a horizontal Earth surface. The surface in question is assumed to intercept the full amount of diffuse radiation regardless of the surface orientation. The portion of the beam radiation intercepted by the surface is determined by the incidence angle.

The problem of obtaining an accurate solar effect would be very easy if the direct solar flux was the only necessary parameter. The solar intensity striking a surface is directly affected by the clearness of the sky, the humidity, and the material (smog) in the air. A clearness index K_T value, or solar flux measurement, at the launch site would greatly increase the accuracy of the model. Ideally, the average K_T should be reported with ambient temperature and wind conditions for the given selected time span. The K_T value should be evaluated on, or close to, the launch pad to ensure the accuracy of the measurement taken. At this time, the long-term monthly average value of K_T is the value used for Daytona Beach,[2] which is adjusted by on-pad projected weather environments.

The case surface absorptivity is another variable affecting the solar flux received by the motor. This absorptivity is set for each element on the GTM surface. The absorptivity changes with the length of time that the STS spends on the pad because the white painted (white Hypalon paint) motor surface degrades through extended weather exposure. Currently, the code uses an absorptivity value for a clean, new surface of 0.25. The corresponding emissivity value is 0.9.

The shading for all times of the day was determined by the use of a Heliodon[10] as shown in Fig. 5, along with a subscale model of the launch pad, the Orbiter, and the pad supporting structures and other surrounding objects. In this manner, the shading of each surface element of the model was determined. The Heliodon gave a visual picture of what is happening throughout the day; it is very important in obtaining a better engineering judgment of what the GTM response should be. These shading factors are stored in a database for each month and are used to generate the GTM solar effects. Within the thermal model, the surface of the solid rocket motors is basically subdivided into 120 different regions. Partial shading by clouds on the vehicle could be handled if there was a rapid procedure to determine the shading on the 120 elements and implement this near-real-time information into the code.

The solar radiation is directly added to the boundary arithmetic node on the surface of the GTM. These boundary nodes have no capacitance, and the surface temperature is calculated as a simple energy balance. The code at this time cannot handle partial cloud cover. The percentage of time that the launch site is shaded by clouds is incorporated into a historical clearness index K_T. With total cloud cover, the diffuse solar flux component is the only one used. The measured direct normal and diffuse solar radiation is measured and received from the Florida Solar Energy Center and used when available.

Radiation Interchange

Radiation interchange between the solid rocket motor and the ground, surroundings, and sky can be important. However, this effect in the thermal analysis is typically less than the

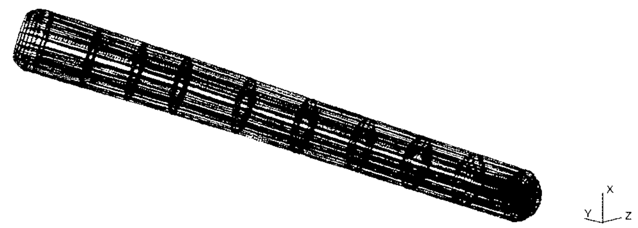


Fig. 4 Three-dimensional grid used by GTM rotated from two-dimensional grid of Fig. 3.

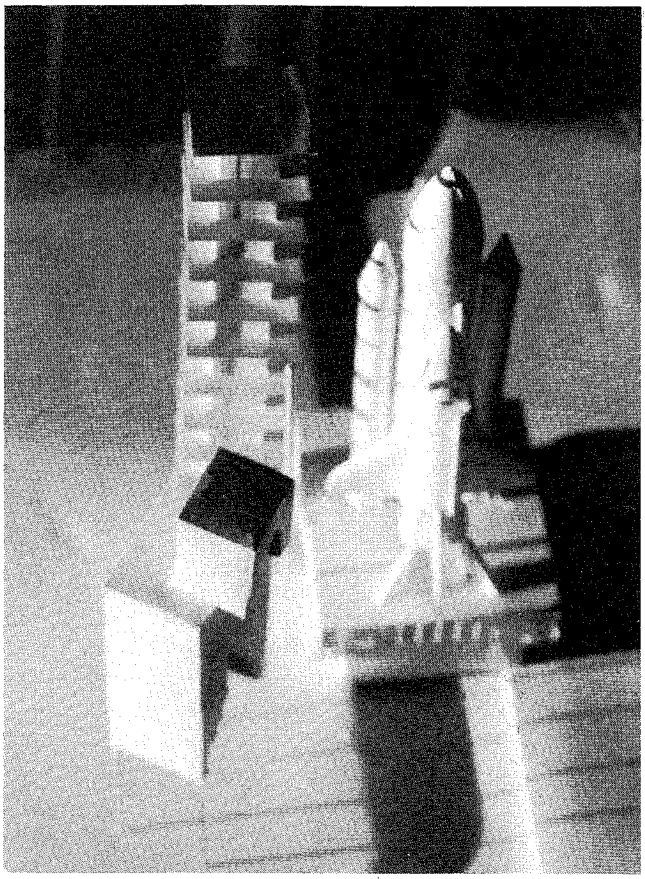


Fig. 5 Model of launch pad on the Heliodon in the late afternoon.

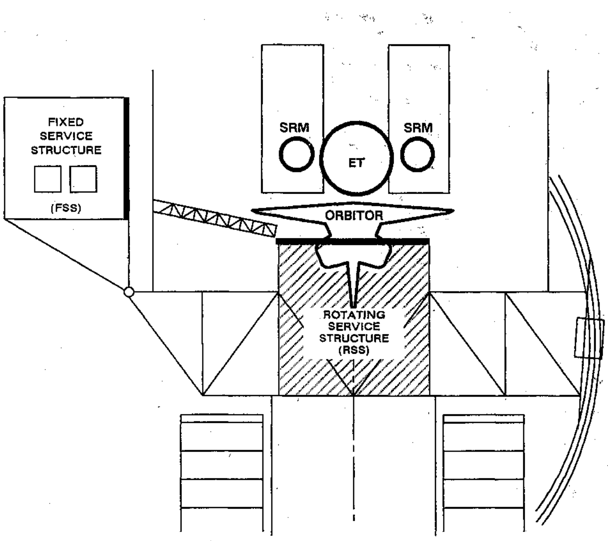


Fig. 6 Diagram of surfaces included in the two-dimensional FACET model.

solar radiation and convective contributions, except under conditions of no solar radiation, constant ambient temperatures, and low winds. This radiation interchange effect can be shown to result in as much as a 3°F (1.67°C) temperature variation during a calm period. The view factors to the sky and to the surroundings were calculated using the radiation view factor computer code (FACET).[3] The original study was done for a two-dimensional, horizontal slice [Fig. 6 (model shown in bold print)].

A radiation exchange occurs with the concrete launch pad and an empty external tank since both absorb heat during the day and remain quite warm during the night and, as a result, significantly influence the case temperature at night. Currently, the assumption used for the surrounding temperatures, which are incorporated in the GTM, is the average ambient temperatures for the previous 24 h. Radiation interchange temperatures will be refined as better information becomes available.

The sky temperature is an important part of radiation exchange, especially during clear nighttime hours. Infrared measurement of the sky is taken at the Florida Solar Energy Center and may be converted directly to a sky temperature. When this is not available, the sky temperature is determined and implemented into the code by the use of Swinbank's

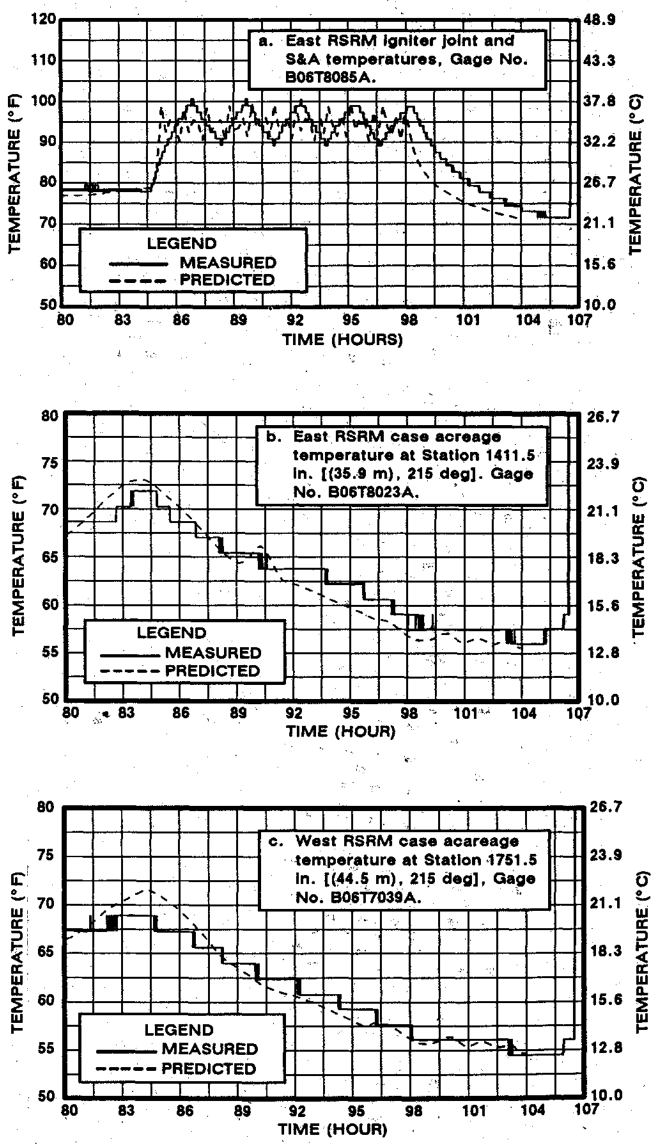
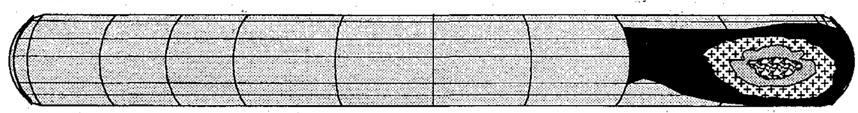
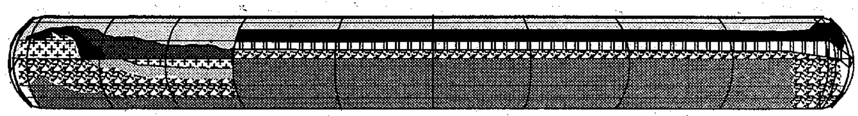


Fig. 7 STS-27 ground environmental instrumentation actual vs predicted temperature, (Zero-Ref: 11 p.m., Kennedy Space Center, eastern standard time, 27 Nov. 1988).



a) West Redesigned Solid Rocket Motor, T_{min} = 66.6°F (19.22°C), T_{max} = 72.0°F (22.22°C)



b) East Redesigned Solid Rocket Motor, T_{min} = 66.6°F (19.22°C), T_{max} = 76.2°F (24.56°C)

Symbol	(°F)	(°C)
	68.5 to 69.3	20.3 to 20.7
	69.3 to 70.4	20.7 to 21.3
	70.4 to 71.2	21.3 to 21.8
	71.2 to 71.6	21.8 to 22.0
	71.6 to 74.3	22.0 to 23.5
	74.3 to 76.2	23.5 to 24.5

Fig. 8 Temperature contours on the Shuttle redesigned solid rocket motors at 8:29 a.m. for a typical November day, viewing the motors from the south.

relationship which relates sky temperature to the local ambient air temperature in the simple relationship

$$T_{sky} = 0.0552\ (T_a)^{1.5} \tag{1a}$$

where T_a is ambient air temperature in degrees K.

The preferred and more accurate relationship by Bliss may be used when the humidity or dew point is available:

$$T_{sky} = T_a\ [0.8 + (T_{dp} - 273)/250]^{1/4} \tag{1b}$$

where T_{sky} is the sky temperature in degrees K, T_a is the ambient air temperature in degrees K, and T_{dp} is dew point temperature in degrees K. Currently, humidity is not available on a consistent enough basis to utilize the equation by Bliss. Both equations yield the same results at 25% humidity. The equations differ by 10°C (18°F) in hot moist air and 30°C (86.0°F) in a cold dry climate.

Discussion of Results

A comparison of some of the actual measured GEI vs predicted GEI temperatures, using actual weather data, are shown in Fig. 7. Reference 11 contains all of these comparisons. After each flight, the predicted vs actual values are compared,[12-19] and a decision is made concerning modeling refinements. This provides an opportunity for model verification, which is very important if the case acreage GEI is partially, or totally, removed. The GTM results are also graphically plotted in a near-real-time situation to facilitate the monitoring of the launch countdown procedures. The predicted and the measured temperatures compare very well. Examples of the graphical output to the screen are shown in Fig. 8.

Conclusions

A thermal model to provide a real-time response of the solid rocket motors and their components has been developed and used before and during recent STS launches. The code provides the capability to work problems that arise during countdown procedures; to evaluate its accuracy against (GEI) and, in turn, to tune the model so that it gives accurate results for the propellant mean bulk temperature and the rocket motors and their components under any weather condition; to predict the temperatures where faulty instrumentations are located; to calculate typical component temperatures to be expected during any month of the year; and to verify that all solid rocket motor components are within the acceptable temperature range that will ensure safe operation.

In the near future, it is possible that the case acreage instrumentation will be removed and thermal modeling will be the primary method to insure that all motor components are within acceptable temperature ranges. Therefore, as much refining as is possible must be done on the model at the present time.

At present, it has been demonstrated that the thermal model provides a reliable thermal response of solid rocket motors on the launch pad, the actual experimental data compare very well with the predicted temperatures. It will be necessary to establish a reliable means of obtaining current weather data so that the model may be used effectively.

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