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# New Method for Shuttle Orbiter Thermal Analysis

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**A new, simplified, approximate method of on-orbit transient thermal analysis of complex operational space vehicles in varying environmental conditions is described. When applied to the Space Shuttle Orbiter simulation, the standard deviation of error in results compared with flight data for over 50 missions is typically between 5 and 10°F. The method requires first running detailed orbiter thermal mathematical models for a steady-state solution in a systematized variety of on-orbit Earth–sun orientations. These steady-state temperatures form a database that is loaded and permanently stored in a personal-computer-based program package. An exponential extrapolation method derived from a classical simplified energy balance and using empirically derived time constants is applied to convert from the steady-state temperature to the actual transient response. Now in use routinely for thermal analysis of the Space Shuttle Orbiter, the method has reduced the days of engineering manpower and hours of mainframe computer usage previously required to a simple, painless, and short session on a personal computer. The results, although approximate and sometimes limited in certain special situations, have been found generally to yield excellent agreement with flight data.**

## Nomenclature

$A$ = surface area for radiation, ft$^2$
$c_p$ = thermal specific heat, Btu/lb · °F
$\mathcal{F}$ = radiation interchange factor, dimensionless
$G$ = thermal conductance, Btu/h · °F
$k$ = exponent in effective conductance–temperature relation
$m$ = mass, lb
$Q_s$ = internal heat source, Btu/h
$T$ = node temperature, °F
$\bar{T}$ = average temperature between $T_i$ and $T_{ss}$, °F
$t$ = time, h
$\mathrm{TR}$ = absolute node temperature, °R
$\overline{\mathrm{TR}}$ = average temperature between $\mathrm{TR}_i$ and $\mathrm{TR}_{ss}$, °R
$\sigma$ = Stefan–Boltzmann constant, Btu/h · ft$^2$ · °R$^4$

*Subscripts*

$e$ = effective equivalent
$i$ = node of interest
$j$ = surrounding node
$l$ = linear
$n$ = number of surrounding nodes
ss = steady state
$t$ = property at time $t$

## Introduction

SPACE Shuttle Orbiter operations require extensive thermal analysis support to ensure operation within the certified orbiter thermal limits and to prevent violation of thermal constraints. Analyses are also performed to predict heater electrical power requirements, since the resulting consumables usage affects the mission duration capability. These temperature assessments are made using past flight data for similar attitude sequences where possible. However, with the extreme variety of on-orbit attitude combinations possible, such data often are not available, so that large computer mathematical models that simulate orbiter thermal performance have to be executed. These consist primarily of the Thermal Radiation Analyzer System (TRASYS)[1] geometrical models simulating solar and earth environmental radiation heating and radiation interchange between orbiter surfaces, and Systems Improved Numerical Differencing Analyzer (SINDA)[2] thermal models simulating orbiter thermal response. These models consist of many thousands of thermal nodes, entail extensive engineering setup and data input, and require hours of mainframe computer usage.

The extensive detailed orbiter thermal analyses described above typically require long lead times, and are not well suited to real-time contingency analysis, attitude timeline deviations, and anomaly evaluation often necessary during Shuttle missions. For such quick-response situations, an alternate simplified thermal prediction tool was needed. The Simplified Thermal Evaluation Program (STEP) method was developed to satisfy that need. In its present form, STEP represents the Shuttle Orbiter on-orbit configuration with open payload bay doors. While it does not have the fidelity and accuracy of the large detailed thermal models, it offers rapid approximate thermal solutions and can be used as a screening tool to identify potential thermal problems and aid in their resolution. STEP also minimizes the need for detailed model analyses to support flight planning, resulting in significant manpower and mainframe computer cost avoidance.

STEP incorporates a large database of orbiter steady-state temperatures that were generated from detailed thermal models. The primary algorithm used in STEP is a method to convert from steady-state temperature to actual transient conditions. To the author's knowledge, this method was first applied to thermal analysis of complex physical systems in widely varying environments in a simplified orbiter model developed for Air Force payload thermal integration analysis.[3] The method is best suited to vehicles with hardware configurations of mature design that will be exercised in a large variety of thermal environments. Shuttle-mission thermal support was an ideal application, and the above method has been greatly extended and refined during the development of STEP. A feasibility study was first conducted to examine the application of the STEP method to the orbiter aft fuselage temperature and heater power prediction. As a result of that study, an initial design goal was set for STEP to predict within ±10°F of the detailed models.

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## What is STEP?

STEP is a personal-computer-based computer database and program package designed to provide fast approximate predictions of Shuttle Orbiter on-orbit thermal performance and electrical heater power usage. To implement the STEP method, the four orbiter compartment thermal models (forward, mid and aft fuselage, and OMS pods) must first be executed to generate a large steady-state temperature database covering a comprehensive range of possible on-orbit locations and orientations. Temperatures of key nodes required by STEP to represent measurement locations and other areas of interest are then extracted from this database, reformatted, and stored in STEP. These data represent the temperature each node would ultimately reach if the orbiter were held fixed at a given orbital position and orientation (i.e., constant environment) for an infinite time.

STEP internally analyzes the user-input orbit profile and attitude timeline to determine the continually varying look angles from the orbiter to the sun and Earth. These look angles are used as interpolation parameters at each time step in a STEP analysis to select the steady-state cases in the STEP database most closely representing the current orbiter position. By interpolating between the nearest cases, the steady-state temperature for every sensor or node selected by the user is determined. With the continually varying steady-state temperature calculated from the above procedure, an exponential function, derived from a classical simplified energy balance equation with empirically obtained time constants, is applied to calculate the transient temperature response. This method, though grossly oversimplified compared with the actual transient heat transfer processes occurring throughout the complex orbiter structure, insulation, and systems, has been found generally to approximate the true physical response quite accurately.

## STEP Operation Overview

STEP requires user input through screen-formatted menus, in three categories:

1) attitude timeline (and launch parameters where applicable)
2) sensor and/or node selection
3) output plot and table format selection

The attitude timeline can be input in two modes, GMT and BETA, as follows:

1) GMT: Launch parameters are specified. Attitude tracking is computed by STEP, starting from launch. Attitudes are input in standard pitch–yaw–roll rotations using a local-vertical, local-horizontal Earth-referenced coordinate system or a celestial inertial system.

2) BETA: Generic attitudes (e.g., bottom sun, nose north) are specified, at fixed input beta angles.

In the BETA mode, the user only specifies the angle between the solar vector and the orbit plane (beta angle) to define the orbit. In the GMT mode, the user specifies the actual mission launch time and orbit inclination, and STEP will compute the continually changing beta angle.

STEP data processing begins following completion of the first two input categories. STEP internally analyzes the user-input orbit profile, starting from liftoff and including ascent effects when in GMT mode, calculating state vectors to track orbiter position. Attitude rotations are performed to determine orientation and, most important, the continually varying look angles from the orbiter to the sun and Earth.[4]

Following the orbit and attitude analysis. STEP proceeds to calculate temperatures in a manner depicted in Fig. 1. Given the sun and Earth angles throughout the mission, STEP first determines the steady-state temperature at every time step for each node or sensor being analyzed, as discussed later. This steady-state temperature is shown for a typical node for the three example attitudes in Fig. 1. Given the steady-state temperature, an exponential function with appropriate time constants is then applied to calculate the transient temperature response, as described later.

## Steady-State Temperature Determination

All STEP thermal predictions are made utilizing a large 2398-case steady-state temperature database. Each case in the database corresponds to a particular Earth and sun look angle with respect to the orbiter, and contains the temperature that each node included in STEP would ultimately reach if the orbiter were held motionless in space for an infinite period of time at the on-orbit location and orientation defined by the Earth and sun look angles. The steady-state temperatures were obtained by running the detailed orbiter thermal mathematical models for steady-state thermal solutions at each of the 2398 Earth–sun angle combinations. Temperatures of the nodes desired in STEP were then extracted from the output temperature files, reformatted, and saved for use in STEP.

The STEP steady-state database (Fig. 2) covers the complete range of possible Earth and sun look angles. The spheres in the figure do not depict the Earth, as might appear at first, but rather they represent the range of Earth and sun directions with respect to the orbiter. The points on the surfaces of the spheres represent each Earth and sun angle included in the database. The first 86 cases in the database cover nighttime conditions (orbiter in the Earth's shadow), with Earth angles included approximately every 22.5 deg

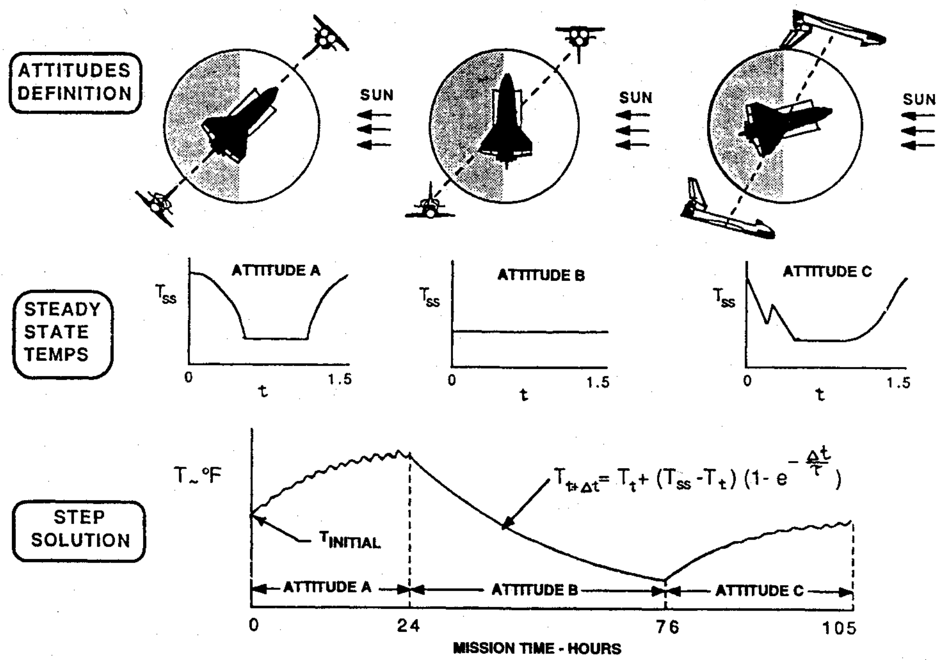
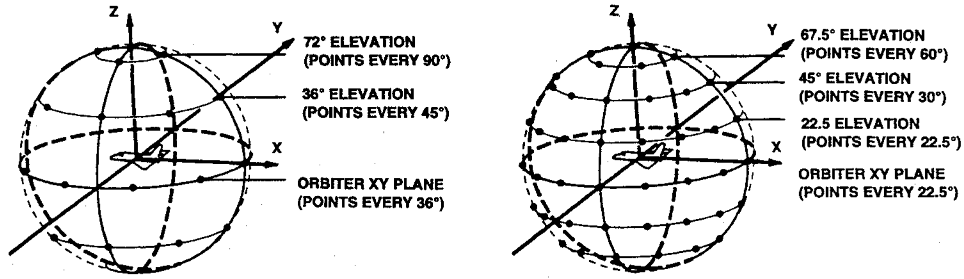



Fig. 1 STEP method of determining temperature.




Earth Directions on Sunlit Side

Sun Directions (and Earth Directions on Shade Side)

| CASE | EARTH ANGLE | | SUN ANGLE | | STEADY STATE TEMPERATURES | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | MID | FWD | AFT | OMS |
| 1 | clock | cone | clock | cone | $T_{11}$ $T_{12}$ $T_{13}$ $T_{14}$ ' ' ' | ' ' ' ' | ' ' ' ' | ' ' ' |
| 2 | clock | cone | clock | cone | $T_{21}$ $T_{22}$ $T_{23}$ $T_{24}$ ' ' ' | ' ' ' ' | ' ' ' ' | ' ' ' |
| 3 | clock | cone | clock | cone | $T_{31}$ $T_{32}$ $T_{33}$ $T_{34}$ ' ' ' | ' ' ' ' | ' ' ' ' | ' ' ' |
| 4 | clock | cone | clock | cone | $T_{41}$ $T_{42}$ $T_{43}$ $T_{44}$ ' ' ' | ' ' ' ' | ' ' ' ' | ' ' ' |
| ' | ' | ' | ' | ' | ' ' ' ' ' ' ' | ' ' ' ' | ' ' ' ' | ' ' ' |
| ' | ' | ' | ' | ' | ' ' ' ' ' ' ' | ' ' ' ' | ' ' ' ' | ' ' ' |
| ' | ' | ' | ' | ' | ' ' ' ' ' ' ' | ' ' ' ' | ' ' ' ' | ' ' ' |
| 2398 | clock | cone | clock | cone | $T_{2398,1}$ $T_{2398,2}$ $T_{2398,3}$ $T_{2398,4}$ | | ' ' ' ' | ' ' ' |

**Fig. 2 STEP steady-state temperature database covering complete range of Earth–sun angles.**

in all directions around the orbiter. The remaining 2312 cases cover sunlight conditions, with Earth and sun angles included approximately every 36 and 22.5 deg, respectively, in all directions around the orbiter. When defining these sunlight cases, many of the Earth–sun angle combinations depicted in the figure were in the shade but near the day–night terminator. To enhance the database coverage near the terminator, if such cases were within about 13 deg of the terminator, the Earth angle was moved slightly to create a case just on the sun side of the terminator.

At each time step during a transient STEP run, the steady-state temperature database is searched according to the current Earth and sun angles, to locate a small group of cases which are closest to the desired current orbiter orientation. When the orbiter is in the shade portion of the orbit, the four closest points in the database are selected; when in the sun, the 16 closest points are used. A multivariate linear regression technique[5] using Cholesky's method[6] of matrix coefficient determination is then applied to interpolate between these points to determine the current steady-state temperature for each node being analyzed. To enhance accuracy, data points closest to the desired Earth–sun angle are weighted heavier than more distant points. If a case in the database is within 2.5 and 4 deg of the desired sun and Earth angle, respectively, it is used directly without interpolation.

## Exponential Extrapolation

The steady-state temperature of a node, determined as described in the previous section, is considered as a kind of environmental "driver," controlling the transient response of the node. A node will respond to this steady-state "driver" temperature by an amount dependent on the computing time step as well as on the thermal characteristics of the particular node. To develop a functional relation between the transient and steady-state temperatures, the standard lumped-parameter network energy balance equation was considered at a given node $i$ connected to $n$ surrounding nodes, as follows:

$$mc_p\frac{\mathrm{d}T_i}{\mathrm{d}t} = Q_s + \sum_{j=1}^{n} G_{ij}(T_j - T_i) + \sum_{j=1}^{n}\sigma A_i \mathcal{F}_{ij}\left(\mathrm{TR}_j^4 - \mathrm{TR}_i^4\right) \quad (1)$$

If the radiation term is linearized, an effective conductor to any node $j$ may be defined as follows:

$$G_e = G_l + \sigma A_i \mathcal{F}_{ij}(\mathrm{TR}_j^2 + \mathrm{TR}_i^2)(\mathrm{TR}_j + \mathrm{TR}_i) \quad (2)$$

In STEP, node $i$ is assumed to be connected by a single effective conductor to a boundary driver node $j$ equal to its steady-state temperature ($T_j = T_{ss}$). The effect of any internal heat generation $Q_s$ is included in $T_{ss}$, so the term $Q_s$ may be set here to zero. With these assumptions, Eqs. (1) and (2) reduce to

$$mc_p\frac{\mathrm{d}T}{\mathrm{d}t} = G_e(T_{ss} - T) \quad (3)$$

With the effective conductance $G_e$ and thermal mass assumed constant over a computing time interval, this equation may be integrated over a time interval $\Delta t$ to yield the standard STEP exponential solution algorithm:

$$T_{t+\Delta t} = T_t + (T_{ss} - T_t)[1 - \exp(-G_e\,\Delta t/mc_p)] \quad (4)$$

For on-orbit analysis, $G_e$ would be expected to include both conduction and radiation effects. For linear conduction only, $G_e$ would simply be a constant. For radiation, a linearized conductance, applied at an average temperature $\bar{T}$, would result in $G_e$ being proportional to the third power of temperature. One would expect the combined $G_e$ then to be given by

$$G_e = \alpha\overline{\mathrm{TR}}^k, \qquad 0 \le k \le 3 \quad (5)$$

With this assumption, and also assuming the specific heat is constant (it could also be proportional to some power of the temperature), Eq. (4) becomes

$$T_{t+\Delta t} = T_t + (T_{ss} - T_t)(1 - e^{-\Delta t/\tau}) \quad (6)$$

where

$$\tau = \frac{mc_p}{\alpha\overline{\mathrm{TR}}^k} \quad (7)$$

Equation (6) is the basis for all transient temperature predictions in STEP. The time constant $\tau$ may be selected for each node by comparing Eq. (6) predictions with the detailed thermal model predictions for a variety of attitude combinations, varying $mc_p/\alpha$ and $k$ to obtain an optimum match. In the current studies, $mc_p/\alpha$ and $k$ for most nodes were manually adjusted according to comparisons of STEP with flight data for a selected variety of mission attitude timelines. A detailed discussion of the effects of $mc_p/\alpha$ and $k$ is beyond the scope of this report. In short, $mc_p/\alpha$ is the primary factor determining the overall response rate of a node. The effect of $k$ is to raise or lower the cyclic equilibrium temperature in an oscillatory thermal environment (such as variable solar heating at low beta angles), depending on the degree of radiation dominance for the node.

## STEP Electrical Power Usage

STEP can be used to compute the average electrical power consumption for 190 orbiter heaters. Most of these heater systems are modeled using one of three different methods, depending on their individual system thermal characteristics, as described in the following sections. When heaters are cycling within their thermostat set-point temperature range, the actual sawtooth type of thermostat transient temperature response is not predicted by STEP, and one cannot determine whether the heater is on or off at any given time. Instead, STEP will generally show the average set-point temperature. The specific heater on or off status is not predicted. The computed power will be the time-weighted average power or, in other words, the duty cycle multiplied by the heater maximum power. The thermostat set-point temperatures used for most heaters reflect average flight-inferred values at the sensor location.

For most heaters, STEP utilizes a relationship of duty cycle versus environment temperature (Fig. 3) that has been developed and verified from past flight data. Although the true relationship is somewhat nonlinear, it has been found that a straight-line approximation is usually sufficiently accurate for thermal and consumable analysis purposes (i.e., the degree of approximation is within the general accuracy capability of thermal model temperature and power predictions).

**Low-Mass Component Heaters**

For small components with low mass such as lines, ducts, and valves, STEP first computes the effective local environment temperature surrounding the heater. This environment is not significantly affected by the heater operation. A plot of the thermal response computed by STEP for this type of heater is shown in Fig. 4. The time lag between the component and its environment is neglected. When the environment temperature rises above the thermostat lower set-point temperature, the heater is assumed to be off, the power is set to zero, and the component is assumed to track the environment temperature. When the environment temperature falls below the lower set point, the heater is assumed to operate at an average power level equal to a duty cycle multiplied by the heater maximum wattage. The duty cycle is computed using the linear function of environment temperature shown in Fig. 3.

**Large-Mass Component Heaters**

Heated tanks and hydraulic actuator packages lag well behind the environment temperatures because of their mass and insulation covering. STEP applies a two-pass calculation procedure to determine first the surrounding environment temperature and then the component thermostat temperature for these heaters (Fig. 5). The environment temperature is computed using the standard STEP method [Eq. (6)] with time constants representative of the surrounding structure and radiation environment. That environment temperature is then substituted in the place of $T_{ss}$ in Eq. (6) to compute the transient thermostat temperature, using component time constants empirically derived from flight-data correlation.

Whenever the component (i.e, thermostat) predicted temperature falls below its lower set point, the heater is assumed to turn on. The average power is then determined using the standard curve of duty cycle versus environment temperature, Fig. 3. The average set-point temperature will then be plotted by STEP for the component temperature during this heater-on time. When the predicted environment temperature rises above the lower set point, the heater is assumed to turn off, and the component is reinitialized at the environment (i.e., lower set point) temperature. During the succeeding heater-off time, the component temperature is again computed from Eq. (6) as described above.

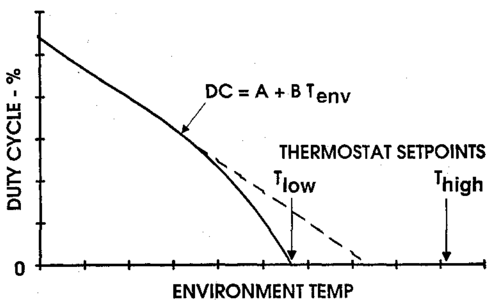



Fig. 3 Typical electrical heater performance curve.

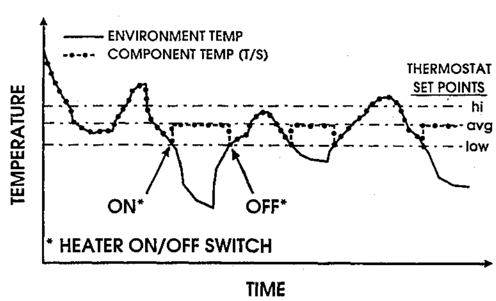



Fig. 4 STEP representation of low-mass heaters.

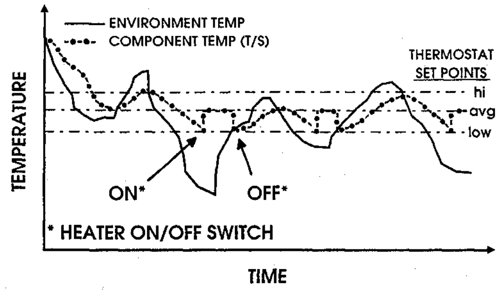



Fig. 5 STEP representation of large-mass heaters.

**Compartment Heaters**

In the orbital maneuvering system (OMS) pods and forward reaction control system (RCS) propellant storage compartments, area heaters control the internal environment, and the standard STEP method does not work. To illustrate the problem, a high steady-state temperature could indicate either 1) a hot attitude or 2) a cold attitude with high heater operation. Since the STEP logic, Eq. (6), only "sees" the steady-state temperature as a driver, both attitudes would normally result in the same predicted thermal response. However, the actual response could be much different. In case 1, the temperature would begin rising fairly quickly; in case 2, the temperature could decrease for a long time until the heater finally turned on, after which it would rise. To handle this situation, two steady-state temperature databases were created: one with the compartment heaters activated, and one with the heaters deactivated. The thermostat temperature is then tracked by the standard STEP method using the appropriate database, and the status of heater operation is determined by comparing it with the set-point temperature. Heater operation is assumed to begin, and the heater-on database utilized, when the predicted thermostat temperature falls below the lower set point. The heater is assumed to turn off, and the heater-off database used, when the thermostat temperature rises above the upper set point. In the forward RCS compartment, two thermostats are controlling; the heater-on database is utilized when either one or both of the thermostats is determined to be on.

## STEP Application to Shuttle Orbiter Mission Analysis

Since its introduction in September 1992, STEP has been used extensively for Shuttle pre-mission and in-flight thermal analysis. The STEP method has proven to be an extremely effective thermal analysis tool, offering rapid and accurate, although approximate, thermal solutions for many components and locations throughout the orbiter. Typical results (Fig. 6) are shown for the orbiter external structure (a), the structure in the payload bay door–side–wing cavity 7.6 ft forward of the door aft edge (b), and an insulated tank inside the aft fuselage (c). The original design goal, to predict within ±10°F of the detailed models, has generally been met by the basic STEP method in most areas most of the time. In addition, temperature-dependent and solar-angle-dependent biases have been internally

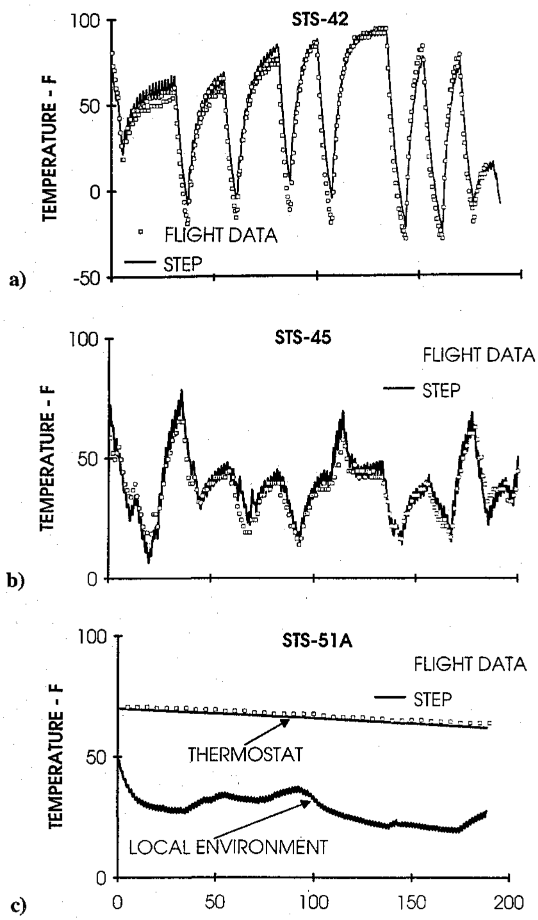



**Fig. 6 Typical STEP temperature predictions compared with flight data: a) forward fuselage canopy top bondline, b) midfuselage starboard side bondline, and c) APU 2 fuel tank.**

added to the steady-state temperature of selected nodes to improve correlation with actual flight data in certain thermally extreme attitudes where detailed model accuracy was deficient. An accuracy study was performed comparing STEP temperature predictions with flight data for over 50 Shuttle missions. The standard deviation of error ranged typically between 5 and 10°F. Maximum errors were generally up to about ±20°F, except in special situations involving certain STEP limitations discussed in the following section.

## STEP Limitations

Although it is extremely useful and quite accurate, the STEP method has limitations which must be understood and allowed for when interpreting the results to avoid misapplication. These generally fall into the following categories.

### Detailed Model Deficiencies

Since STEP predictions are based on a steady-state temperature database generated by detailed thermal mathematical models, deficiencies in those models will also exist in STEP. For example, if the detailed models underpredict flight data significantly in a hot attitude, STEP probably will too, by a similar amount (unless temperature biases are added internally within STEP). Therefore, familiarity with general detailed model performance can aid in the interpretation of STEP results.

### Sun-Shadowing Problem

An accuracy problem exists in STEP on any temperature sensor that is near a sun shadow line. STEP cannot distinguish whether it is shaded or not, and will generally predict an average of the two cases (shaded and unshaded) when it interpolates between the closest points in the database. The detailed thermal models can also exhibit the same problem when the sun shadow line falls midway within a node, again resulting in an average temperature predicted for that node. The cavity region created by the payload bay door–side–wing surfaces is a prime example of this effect, where errors of 50°F or more can result in attitudes with sun entering the cavity. For other attitudes, however, the STEP predictions in this region are more typical and quite good, as seen in Fig. 6b.

### Time Constant Variation

The basic STEP method allows a single time constant for a given node for all attitudes. In reality, the effective time constant will depend somewhat on the attitude timeline being simulated. Average time constants derived from flight data comparisons are used in STEP, and usually give quite good results. With a basic knowledge of the orbiter thermal response, the user may often be able to enhance STEP predictions by an intuitive assessment of the types of attitudes, whether they could be expected to be slower or faster than average.

### Time-Delayed Effects

With the basic STEP method of Eq. (6), a node will begin responding to its new steady-state temperature immediately upon changing to a new attitude. In reality, there is often a time delay due to the node being surrounded by other large-mass structures that must respond before smaller internal components will "see" the change. Or it may respond rapidly at first, then later more slowly. The average time constants used in STEP, which were derived from flight data comparisons, are usually satisfactory for most attitude timelines. However, in some cases the two-pass STEP method described previously for large-mass component heaters is used. This allows a variable time constant, and can account for significant time lags and temperature overshoot and undershoot.

### Single-Configuration Simulation

Since the STEP steady-state temperature database is extensive (2398 cases), it can only be reasonably generated for a single configuration. Therefore, differences between vehicles, such as type of insulation, propellant or consumable loading, subsystem operational configuration, or other structural or component differences, will not be simulated by STEP. For the Shuttle Orbiter, these differences are usually not thermally significant. The STEP method is also not generally applicable to subsystem operations such as engine firing, fluid flow, or electrical or hydraulic component activation.

## Summary and Recommendation

The STEP method of producing simplified, approximate temperature predictions has proven to be an extremely effective thermal analysis tool, offering rapid and accurate thermal solutions for many components and locations throughout the Shuttle Orbiter. The method initially requires the generation of a database of steady-state temperatures for a comprehensive variety of on-orbit orientations. This is a fairly large task, but it is only done once. An exponential relationship is then applied to convert from steady state to transient conditions. This requires only a relatively simple session by the analyst on a personal computer. The method may be applied to any arbitrary attitude timeline. Temperature predictions within ±10°F of detailed model solutions are typically being obtained, and are generally well within a maximum of ±20°F of flight data.

The STEP method is applicable to thermal analysis of all complex operational vehicles that require many flights in a multitude of different environments. The method is useful only when the hardware design of thermally significant elements is mature, since the steady-state temperature database should only be generated once, or at most a very few times, on account of its large size. One promising application of the STEP method is to a generic set of Shuttle payloads, including various sizes, shapes, and properties, integrated into the orbiter in selected cargo configurations. This capability could support preliminary payload thermal design as well as provide parametric studies to supplement detailed payload thermal model analyses.

## Acknowledgments

Dave G. Herbek, NASA/JSC, was responsible for obtaining formal NASA/JSC authorization and funding for STEP and provided consultation throughout its development. In addition, Robert G. Brown, NASA/JSC, was instrumental in obtaining technical approval required for go-ahead of STEP development. John L. Leffler of Rockwell International, now retired, provided the orbital mechanics module for STEP including on-orbit tracking and attitude determination. Technical support for the many thermal analysis tasks required to develop STEP was provided by Rockwell Thermal Control Systems Analysis Unit engineers John W. Andrews, D. Chris Eubanks, Than X. Nguyen, and Eric C. Kanon.

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