A METHOD OF SPACECRAFT PASSIVE THERMAL ANALYSIS APPLICABLE TO MISSION OPERATIONS

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ABSTRACT

Introduction: An approach to the calculation of unsteady-state heat transfer temperature profiles in materials has been developed to serve as the basis of a workstation application for passive thermal analysis of selected spacecraft components. A prototype application incorporates this technique for solving the unsteady conduction differential equation in one dimension, to calculate temperature profiles through composite material layers as functions of time. An algorithm has been developed within the prototype to accomplish this heat conduction solution, based on the graphical finite-difference methods of Schmidt plots that were used before numerical analysis techniques became predominate. The overall prototype development effort has included analysis of verification data from Orion vehicle design-engineering passive thermal work, development of the algorithm functions, examination of accuracy and operational suitability, and generation of requirements to be applied to final application development.

Discussion: Objectives of this prototype development have been oriented to calculation of vehicle thermal protection system (TPS) tile-to-substrate bond-line interface temperatures. This analytical technique is adaptable to real-time analysis of proposed vehicle attitude timelines, to verify that bond-line temperatures will remain within limits for normal and contingency mission planning.

Incorporation of the Schmidt-plot graphical techniques into analytical sequences of calculations has been accomplished in Excel Visual Basic for Applications (VBA) coding. Subroutines have been developed in which the sequential calculation of finite-difference values of temperature is accomplished repeatedly within the orbital time-steps to represent the unsteady-state, transient temperature profiles. This is applied to a two-layer composite material configuration that represents the Orion thermal protection system (TPS) exterior tile and the honeycomb substrate to which the tiles are attached.

The essential aspect of the Schmidt-plot technique is that by developing a dimensionless axis of a plot of temperature vs. distance through the material, with the values of the generic x-axis steps and time steps being set by the properties of the materials, the graphical technique for finding temperature profiles as functions of time on those plots is relatively simple.

Conversion of the expedited, graphical plot sequence into a step-wise sequential calculation algorithm of VBA subroutine code was an initial challenge of the prototype development effort.

Other challenges were posed by the configuration to which this thermal analysis approach was applied. Those challenges are as follows: the need to represent temperature-dependent specific

heat and thermal conductivity, the need to compute properties of the honeycomb substrate, and the attempt to represent the complex three-dimensional geometry of the Orion tile-to-pressure-vessel configuration by a one-dimensional heat transfer model.

Feasibility and accuracy of the prototype have been verified by comparing output data to design-engineering data for incident heating and selected bond-line temperatures of the Orion Crew Module.

Experience from the prototype development has been applied to the writing of requirements for the final workstation application. By this development effort, it has been shown to be feasible to integrate major passive thermal analysis capabilities into a unified application. These capabilities include providing user-selection of orbit definition and attitude timeline input data, calculating external incident heat rates, accomplishing thermal analysis to compute bond-line temperatures and internal heat rates, and presenting plots of selected output data. Feasible characteristics of the application are demonstrated by the ability to accomplish these capabilities for 10 - 20 bond-line locations at five-minute orbit time-step intervals for up to a 21-day mission, with run-times on the order of five minutes.

Summary

An analytical method of accomplishing spacecraft passive thermal analysis has been developed by adapting a former, graphical technique to Excel/VBA subroutines. The resulting prototype application has been developed and used in a feasibility study. Objectives have been to demonstrate the feasibility accuracy and runtime expectations of an operations-oriented application based on this approach. Complex aspects of dealing with temperature-dependent thermal properties and of representing the three-dimensional passive thermal configuration of sections of spacecraft structure by a one-dimensional heat transfer analysis, have been examined. Results indicate favorable feasibility and adequate accuracy so the prototype development can serve as a basis for final application development.

Concluding Remarks

The prototype development effort has verified the feasibility and accuracy of a rapid and operations-oriented application for passive thermal analysis of limited, pre-defined, specific locations such as TPS bond-lines on the vehicle. This is planned to be used within mission operations for specific analyses which require rapid response, and to be accomplished in coordination with sustaining engineering passive thermal analysis support for the more general and detailed design-engineering, numerical analysis passive thermal applications that require longer runtimes.

Acknowledgements

Appreciation is expressed to the following personnel and groups whose assistance has been essential for the successful conclusion of this work:

JSC Engineering Directorate, Thermal Design Branch ES3/Stephen Miller and others for providing overall guidance, recommendations and Thermal Desktop expedited intermediate model checks of aspects related to thermal capacitance of materials.

Lockheed Martin/Sam Lucas, Alex Walker and others who provided excellent examples of design-engineering numerical analysis results for panels of Orion TPS and substrate materials.

Other personnel within JSC Mission Operations and DS44 Environmental Systems Group for technical support and recommendations.

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INTRODUCTION

Prediction of temperatures and heat transfer rates of environmental control and life support (ECLS) system components of spacecraft during mission operations requires thermal models and applications with characteristics that are in some cases unique and different from capabilities of engineering design models. Analysis support during real-time orbital operations is frequently required to provide rapid results for assessing proposed contingency attitudes and flight plans of the vehicle. This type of examination of effects of changes of attitude timelines (ATLs), power levels and crew activities requires unique capabilities in areas of ease of input of analysis, rapid model run-times, examination of key areas of concern, and formatting of output data. It has been observed during operation of various spacecraft from the Johnson Space Center (JSC) Mission Control Center (MCC) over an extended period of time, that these capabilities needed by operations-oriented applications are frequently not appropriately achieved by the type of numerical analysis models used in vehicle design engineering. Design models based on approaches derived from the common Sinda-Fluint® approach such as Thermal Desktop® have remarkable state-of-the-art capabilities for highly accurate and detailed analysis of components and subsystems; however, achieving this degree of detail and accuracy can often be at a cost of more extensive set-up activities and longer run-times of the model for a given mission analysis than are adaptable for real-time operational requirements.

Meeting the operational requirements for thermal model support has been accomplished for active thermal control systems (ATCS) in the MCC environment by use of analytical models that form the core of applications used at the workstations during mission operations. These models are based on fundamental physical relationships and equations for heat transfer. These relationships and equations are formulated in state-of-the-art software techniques such as C++ classes and libraries of ECLS component simulation modules. Often, the MCC ECLS applications that are developed based on these techniques are focused on specific functional representation of parts of the subsystem, to achieve the needed set-up and run-time capabilities. An example of this focusing of effort in the application for the ATCS, is separating the heat transfer characteristics of heat exchangers, radiators and other loop components from the fluid-flow frictional pressure drops of the loop. Engineering judgment and prior system operational history are employed to make correct inputs and assumptions for those aspects of the system operation such as given flow-rates and pressures, and the application analytical capabilities can be focused on the required unknown parameters of temperature and heat transfer rates. In this way, the operationally oriented application with a facilitated setup and a rapid run-time is based on the same, fundamentally correct basic heat transfer physics as the numerical analysis design-engineering models, but is oriented to specific requirements of mission operations.

A team effort has been employed between Mission Operations Directorate (MOD) and JSC Engineering through the Mission Evaluation Room (MER) interface over the years of operation of various spacecraft from the MCC. Traditionally, the ECLS operations capabilities as described for ATCS operations predictions have been used by Operations personnel for routine and rapid assessment of system parameters for pre-mission planning and contingency ATL acceptance. Analysis and assessment of passive thermal control system (PTCS) components for predicted temperatures and characteristics for mission planning and for contingency mission operations or equipment damage or changes, have been accomplished by engineering personnel of JSC Engineering and contractors through the MER interface. This thermal analysis of PTCS components often requires the use of detailed engineering models and the application of experience associated with design engineering and sustaining engineering. This combination of detailed PTCS thermal models and design-engineering experience is unique to the Engineering discipline and is not duplicated in total in the Operations environment; however, in specific areas such as Thermal Protection System (TPS) tile bond-line temperature prediction, there is a need for Operations personnel to have a capability to analyze and predict temperatures and heat transfer for mission planning and contingency ATL assessment, similar to the assessments made for the ATCS operations. As a result, an evolving capability and relationship between Operations and Engineering for PTCS analysis support features a team aspect. Analysis and assessment of specific parts of the PTCS such as TPS tile bond-lines, with appropriate models and applications, are planned for Operations personnel, while detailed PTCS analysis and certification of the entire vehicle, and analysis of specific, detailed areas as in the case of damage to multi-layer insulation (MLI) or other components, are retained as the responsibility of Engineering through the MER interface.

In establishing this focused, partial capability for PTCS analysis by Mission Operations, an overall approach of the complete ATCS and PTCS models and application capability is being developed as shown in Figure 1. Since the inputs required by both the ATCS and PTCS application are similar, and since both applications would be used in similar ways to provide mission planning and contingency ATL assessment, the overall approach of a combined, total application is envisioned. Current, near-term development, however, has focused on examining a potential basis for a fast, functional technique for a PTCS bond-line temperature-prediction model to serve as the core of the Operations passive thermal model.

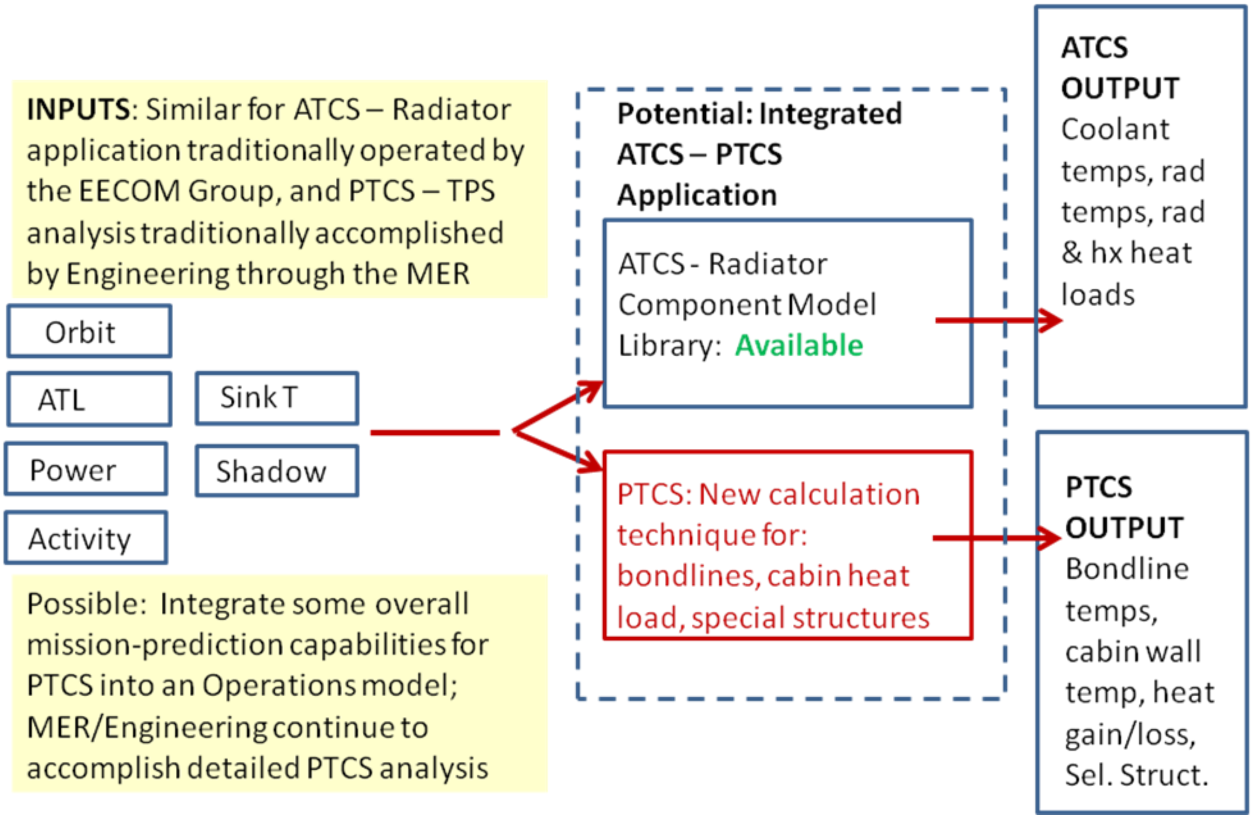


Figure 1: Overview of Operations ATCS – PTCS Application Planning

Development and evaluation of the core techniques to serve as a basis for the Operations PTCS model as described above, are the subjects of this paper. Generic applicability of the proposed method of passive thermal analysis is toward any passive thermal configuration consisting of two composite layers through which heat is transferred and for which the temperature profiles are desired to be known. The specific adaptation of this method which is used for development and evaluation, has been based on the Orion vehicle backshell TPS and substrate materials and configurations, as shown in Figure 2.

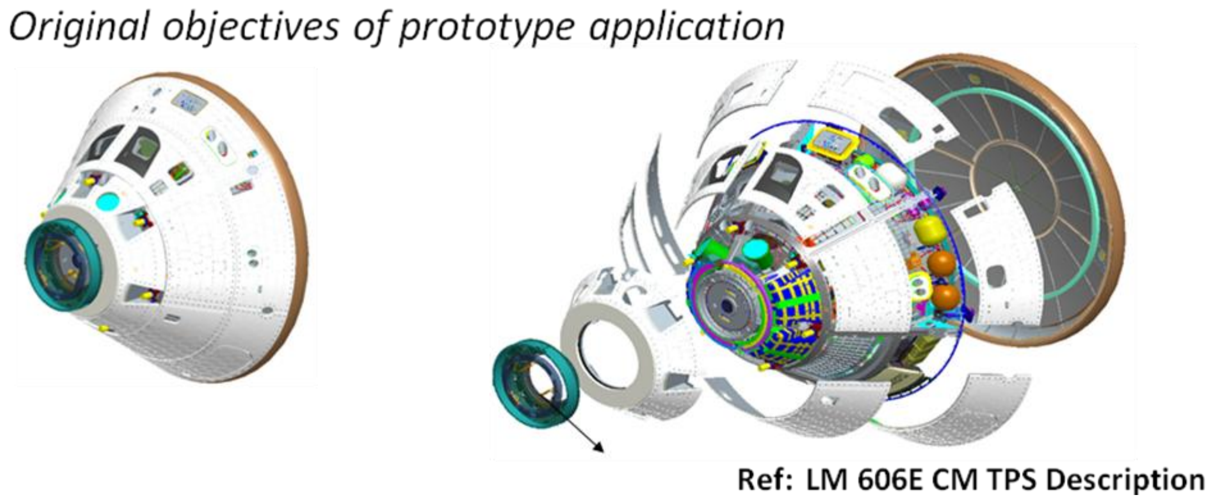


Figure 2: Applicability of Operations Passive Thermal Model

Details of the passive thermal configuration of primary interest and the fundamental heat flows and unsteady-state temperature profiles are represented in Figures 3 and 4. Calculation of the temperature profiles which are changing with time in the composite material is the primary, new aspect of the proposed method that is examined in the prototype development task.

Prototype development activities have included development of the algorithm functions, examination of accuracy and operational suitability, and generation of requirements to be applied to final application development. Overall prototype development has also included analysis of detailed, numerical-analysis-based model data from Lockheed Martin Orion vehicle passive thermal design engineering for comparison and verification of prototype results. These activities have resulted in close coordination and cooperation between the Mission Operations Environmental Systems Group, the Thermal Design Branch of Johnson Space Center (JSC) Engineering Directorate, and Lockheed-Martin thermal design personnel. Presentation and discussion of the prototype approach, planning and issues have been accomplished in forums of the Orion Thermal systems design community. All of these coordinating and planning activities have resulted in a beneficial team-effort environment between Mission Operations and design teams of JSC engineering personnel and contractor thermal design-engineering teams.

Remaining sections of this document provide a description of the derivation of the prototype calculation method, present a summary of the functional flow of the algorithm that implements the calculations, describe the verification comparison of prototype output results with corresponding design model data, and indicate the overall assessment of feasibility of an application based on this prototype.

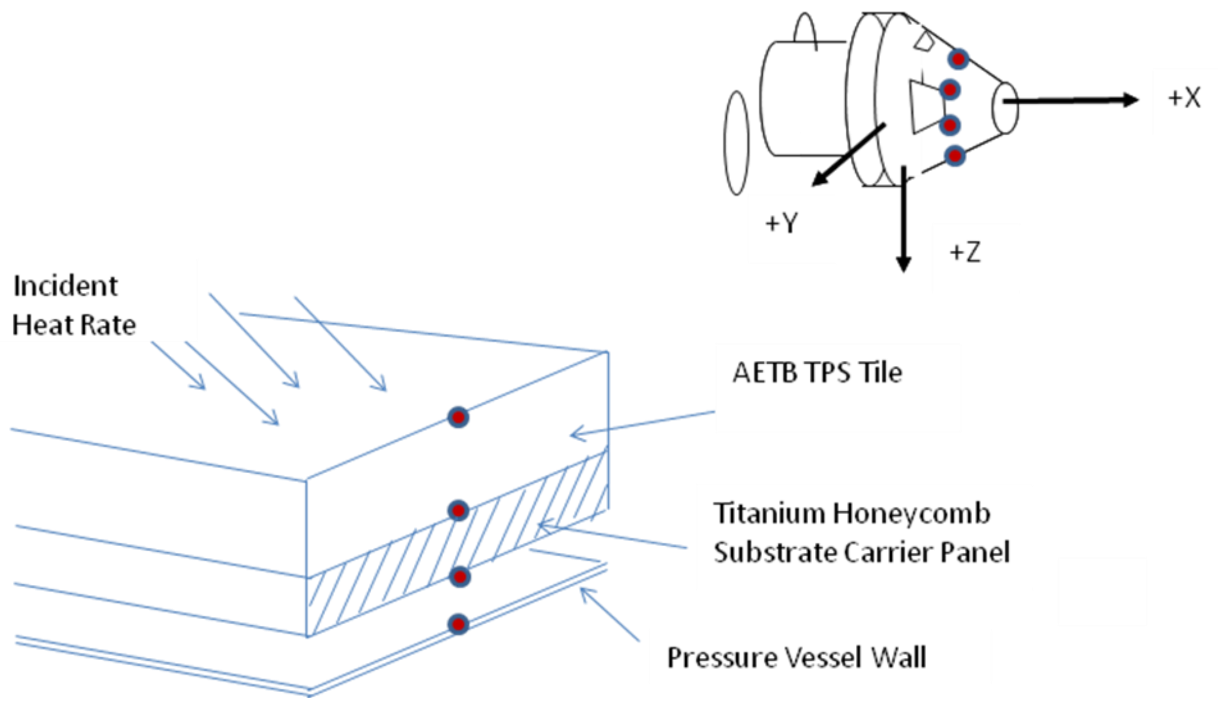


Figure 3: Specific Configuration Examined by Passive Thermal Prototype

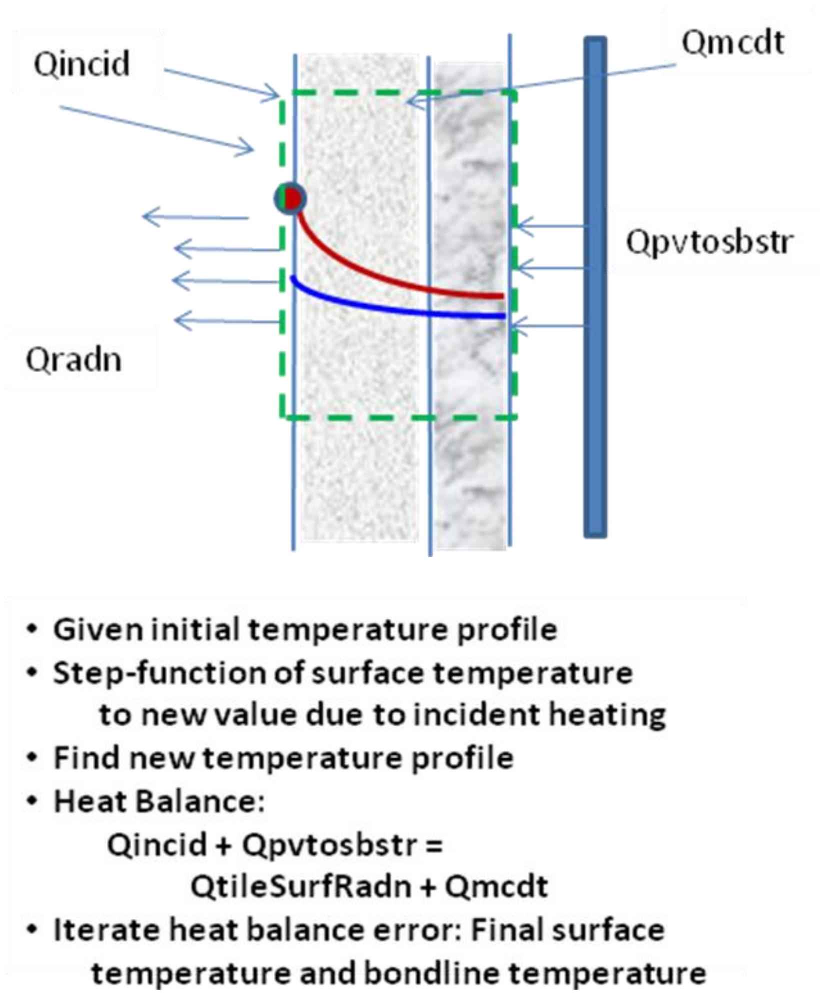


Figure 4: Unsteady-state Heat Transfer in TPS Tile and Substrate

OBJECTIVE AND BACKGROUND

Initial goals and the development environment which formed the overall purpose of the prototype development and evaluation process are described in this section.

OBJECTIVES

Primary objectives of this prototype development activity are to verify the feasibility of the proposed method of calculation of unsteady-state temperature profiles and to generate the requirements upon which a final application may be based to utilize this method for an operations-oriented, generic spacecraft passive thermal analysis capability.

Specific technical representation of the feasibility objective is in the form of verifying that the proposed method of unsteady-state temperatures is of adequate speed and accuracy when applied to calculation of vehicle TPS tile-to-substrate bond-line interface temperatures. This analytical technique required verification that it is adaptable to real-time analysis of proposed vehicle attitude timelines for normal and contingency mission planning. This evolved into two objective aspects as follows: (1) Verifying the accuracy and adaptability, stand-alone, of the unsteady-state heat transfer method by incorporating a formerly graphical technique into an algorithm, and (2) Verifying the capability of incorporating this unsteady-state temperature calculation into time-step sequential analysis of spacecraft orbital heating.

BACKGROUND

A workstation application capable of determining orbital heating upon a spacecraft radiator surface for given orbit and vehicle attitude parameters within the Mission Operations environment, and calculating the resulting temperatures and heat rejection rates, has been available for ATCS analysis as previously noted. Operating characteristics of applications of this type, as they have evolved and have become part of the normal planning and ATL evaluation processes within Mission Operations, include the capability in general of being able to calculate temperatures and heat rates of interest for a 21-day mission with run-times on the order of five minutes.

Prediction of limited sets of PTCS parameters such as bond-line temperatures in a way that is similar to ATCS analysis has evolved as a requirement for an operations-oriented passive thermal model and application. This need for selected passive thermal analysis capability is driven by such operational aspects of PTCS as the temperature limits on bond-line material used to attach TPS tile to the substrate. High and low temperature limits may exist for this material in various possible generic spacecraft configurations and materials. The temperatures experienced within layers of composite material are time-dependent functions of the varying rates of incident heat applied to the tile exterior surface, and to a lesser extent, to the heat transfer from the substrate inner surface to and from the pressure vessel wall. Current operations-oriented ATCS analysis applications use pseudo-steady-state temperatures and assumptions of uniform temperatures at the orbital calculation time-steps so there is not a need to calculate the changing, unsteady-state temperature profiles within materials; however, in the case of PTCS component analysis such as the bond-line temperatures, there is a need for such unsteady-state heat transfer calculations.

Passive thermal material temperature calculation of this nature is accomplished in the spacecraft design cycles by use of proven numerical analysis methods as these are available in standard, commercial heat-transfer design applications such as Sinda-Fluint and the Sinda-derived Thermal Desktop of C&R Technologies. Thermal Desktop is a PC-based design environment for thermal analysis of many materials and vehicles, with particular application to spacecraft thermal design. Thermal Desktop is a CAD-based thermal modeling capability based on Sinda-type numerical analysis methods, with options for adding convection and radiation modeling for integrated, comprehensive thermal design-analysis capability. Characteristics of Sinda/Fluint and Thermal Desktop are described in Reference 1 and Reference 2.

Important points regarding SINDA/FLUINT and Thermal Desktop and possible use of these design-analysis applications in the Operations environment are that these numerical-analysis based systems are applied to many (hundreds and thousands) of nodes representing points in the material, that they are typically used to produce detailed temperatures at small scale for design considerations, and that they involve relatively complex, thorough and variable setup, initialization and input user interfaces.

With the proven capabilities and availability of these thermal-design applications, it is frequently proposed that these numerical analysis tools be used or adapted to meet the analysis requirements of Mission Operations. This can be considered to be attractive in terms of standard software being used by both Engineering and Operations, along with the other advantages; unfortunately, with the characteristics of the numerical analysis applications as they have evolved with a primarily design-oriented focus (Incorporation of interfaces to CAD and other structural and geometric representations, use of nodal representations of the materials in detail, etc.), the option of adapting these to Operations uses for ECLS systems has not proven to be viable. The run-time for a multi-day mission can remain on the order of tens of hours, and extensive modifications or interfaces are needed to adapt the setup and initialization to the sometimes rapidly changing, variable, contingency-oriented real-time Mission Operations environment.

Another option for architecture of an operations-oriented application to accomplish specific parts of the passive thermal analysis task that is often suggested is the use of a data-base, look-up-table technique. This has been a considered possibility during the evaluation of alternatives during prototype task activity. This option would have the advantage of making use of the extensive amount of passive thermal data sets that are generated in the process of vehicle design analyses; however, the data-base alternative has disadvantages to the extent that at this point in the evaluation of alternatives, the prototype example of the unsteady-state analytical method is preferred. The disadvantages include being constrained in data-base applicability to those cases that are pre-established for use in the application, and being unable to easily handle all possible combinations of the various attitude-driven incident heat rates to calculate temperatures of materials. With state-of-the-art of data-base operations, it may be that the first disadvantage, applicability of many pre-calculated, tabulated results could be overcome. The second disadvantage, related to the operational need to analyze any combination of pre-planned or unplanned, contingency vehicle attitudes and determine the temperature response in the materials, greatly favors the proposed analytical approach over data-base techniques.

In some respects, the analytical technique developed for the prototype is a combination of data-base, look-up technique that takes advantage of the stored data of passive thermal design analysis work and the analytical approach that provides greater flexibility for contingency situations. During initialization steps of the prototype approach, data from design analyses or from flight data are used to establish values for some of the parameters used in the sequence of calculating temperature profiles based on incident heat rates. This initialization data would reference specific mission-analysis cases that are on-file in data bases, or flight data sets that are similarly on-file.

Historically, the calculation technique that has been employed in ECLS operations environments, is based representing the portion of a system that is of interest, by the fundamental heat-transfer relationships and equations that are the same physical basis of the heat transfer in any representation, numerical analysis or equation-based environment. In this use of an equation-based, analytical approach rather than the multi-node numerical analysis methods, the difference is in the number of times that the fundamental relationships and equations are applied during the calculation cycles. In the equation-based, analytical approach, a single equation or small set of equations may be used to represent heat transfer and temperatures throughout a heat exchanger or radiator section for example. In this way, a very small number of calculations, on the order of two to ten, can be used to evaluate the equation or equations and arrive at a curve that shows temperature throughout the heat exchanger or radiator section, immediately, and to be evaluated quickly in a plot. A similar numerical-analysis-based approach may involve tens or hundreds of nodes, with the calculations being performed repeatedly in iterations for convergence between the nodes, to arrive at the same final curve of temperature through the heat exchanger for example. That level of detail may be needed in the heat exchanger for design analysis of precise details of metal thickness and thermal stresses, but the overall curve of heat exchanger performance and resulting output temperature of the fluid is the end-result needed by Operations.

By the complex nature of PTCS component shapes and configurations, the detailed numerical analysis type of heat transfer analysis applications has been ideally suited to passive thermal analysis. A passive thermal analog to the ATCS heat exchanger equation-based analysis has not been available, upon which to build an operations-oriented passive thermal application. Because of this fundamental lack of equation-model capability for finding the unsteady-state temperature profile in a composite material such as the TPS tile plus substrate, passive thermal analysis has remained primarily as the responsibility of the Engineering community, and is employed in Mission Operations through the MER interface.

Given the continuing need for a rapid, adaptable core capability within Operations to determine the changing temperatures at TPS bond-lines for example, a consideration of the basics of unsteady-state heat transfer resulted in discovery of a calculation method that appeared to have potential adaptability to passive thermal analysis at an Operations workstation. That calculation method, the Schmidt-plot technique[3], was a proven and useful graphical method that was used before computer technology advances made numerical analysis by finite-element and finite-difference, multi-nodal techniques as in SINDA/FLUINT, practical. Examination of the Schmidt-plot technique and adaptation of it as the core calculation engine of a passive thermal prototype application are the basic parts of the prototype development effort and are the overall subjects of the remaining parts of this document.

CALCULATION OF TRANSIENT TEMPERATURE PROFILE: BASIC TECHNIQUE DESCRIPTION

The essential aspect of the Schmidt-plot technique is similar in analogy to the equation-based, analytical method described earlier in application to finding temperature profiles through the length of a heat exchanger. Finite-difference techniques are used to represent the basic one-dimensional heat-conduction differential equation; however, this is accomplished in such a way that the temperature profile through the material as an output result is calculated directly, not as a result of iterations between nodes as required in numerical analysis. In some respects, this profile of temperature through the material is similar to temperature profiles through heat exchangers or radiators calculated in the ATCS applications.

In adapting this graphical technique to the prediction of spacecraft temperatures in passive thermal analysis, two issues of feasibility and needed verification were identified. The first issue is the question of feasibility of calculating a changing, unsteady-state temperature profile through composite materials, based on the Schmidt-plot technique, for a given step-change in TPS tile surface incident heat and temperature. The second issue of adapting this technique to spacecraft passive thermal analysis is the need to determine and apply a tile-surface temperature to be used as the step-function starting-point temperature at each orbital time-step. Description of examination and resolution of the first issue, calculating the temperature profiles, is provided first in the following sections. This is followed by discussion of the second issue, that of finding orbital step-by step surface temperature from known vehicle attitudes and incident heat rates.

MATERIAL INTERNAL TEMPERATURE RESPONSE

The basis of the Schmidt-plot graphical technique is that by developing a dimensionless axis of a plot of temperature vs. distance through the material, with the values of the generic axis steps and time steps of this plot being set by the properties of the materials, the successive curves of temperature vs. distance through the material are found directly on the plot. The time component of the unsteady-state, changing temperature profiles is represented through material properties to the dimensionless distance axis. In the graphical technique, each unsteady-state temperature-time calculation is represented by a straight line. After the axes and time-step value are established for given material properties, a straight-edge can quickly be used to find points on the temperature-profile curve for any give time of the changing temperature after start of the initial conditions.

Conversion of this expedited, graphical plot sequence into a step-wise sequential calculation algorithm of VBA subroutine code was an initial challenge of the prototype development effort. Incorporation of the Schmidt-plot graphical techniques into analytical sequences of calculations has been accomplished in Excel Visual Basic for Applications (VBA) coding. Subroutines have been developed in which the sequential calculation of finite-difference values of temperature is accomplished repeatedly within the orbital time-steps to represent the unsteady-state, transient temperature profiles. This is applied to a two-layer composite material configuration that represents the Orion thermal protection system (TPS) exterior tile and the honeycomb substrate to which the tiles are attached.

Fundamental aspects of this technique are illustrated in Figures 5 – 7, and the initial, basic approach with heat application to one side of the composite material is first described, followed by a description of the final, integrated method of Schmidt-plot-based calculations applied simultaneously to exterior and interior surfaces of the composite material.

Basic Schmidt-plot Method with Heat Applied to One Surface

Development of the fundamental basis of this technique is described in Figures 5, 6 and 7 for both a single material and for the final configuration of two materials in contact at an interface plane.

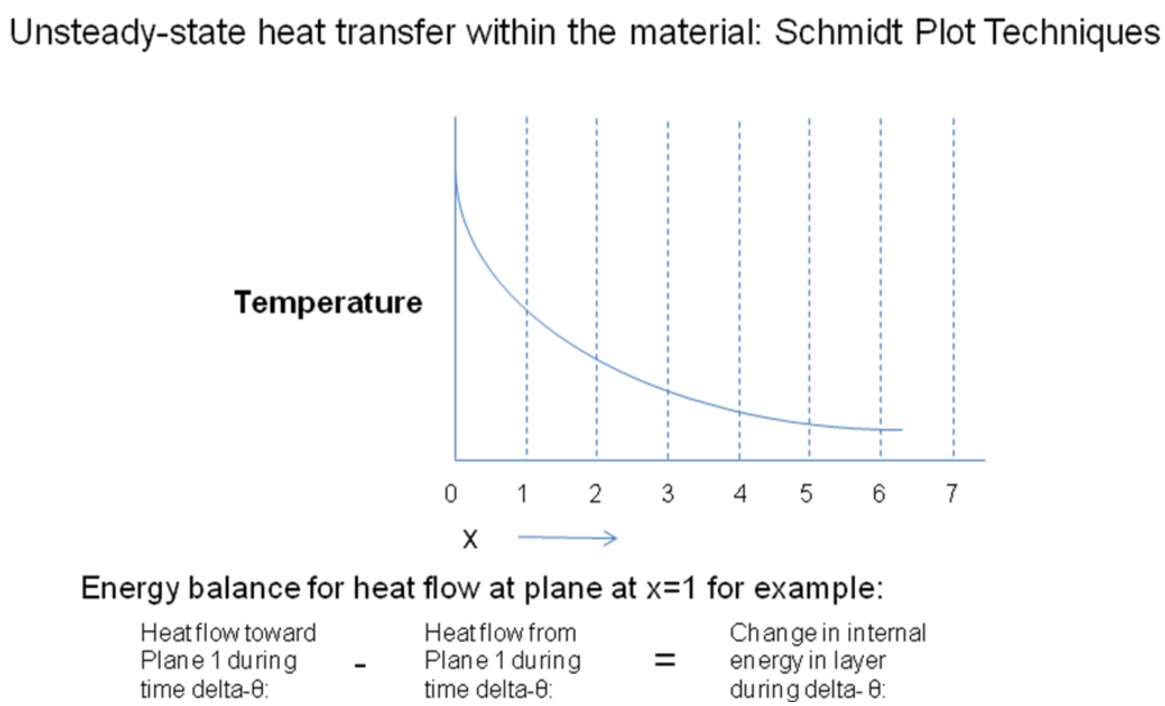


Figure 5: Internal Heat Balance for Unsteady-state Conduction in One Material

Starting with the energy balance shown in Figure 5, the relationship between delta-Theta time-steps and x-distance through the material (based only on material properties) is developed in Reference 3 to lead to the following equation:

Delta-x^2/(2*a*delta-Theta) = c * Density (delta-x^2/(2*k*delta-Theta), (1)

with a = thermal diffusivity = k/(c*density) where
c = specific heat btu/lb-deg F and
k = thermal conductivity, btu/hr-ft-degF

initial conditions.

Employing a plot with x-distance and delta-Theta time-steps related as shown in Equation 1, it is shown in Reference 3 that the temperature at a plane at a new, future time (t+1) is equal to the mean of temperature at a plane on each side of that central plane at a present time, t, as shown in Figure 6.

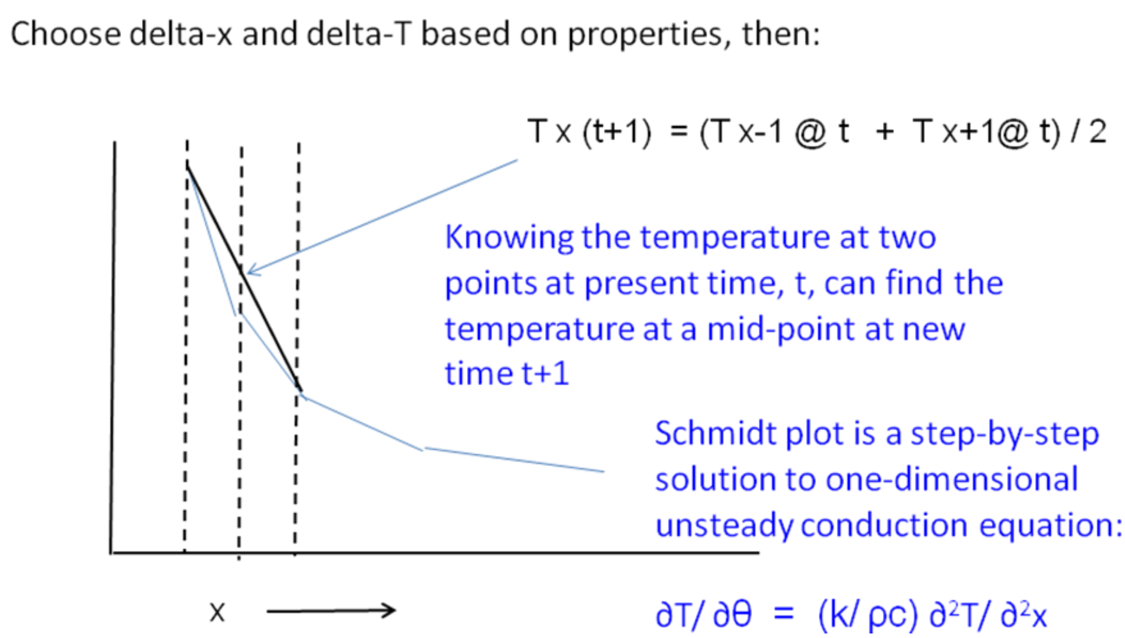


Figure 6: Graphical Finite-difference Solution to Conduction Equation (Reference 3)

Unsteady-state Temperature Calculation in Composite-layer Material

The Schmidt-plot technique derivation is slightly different for the case of composite walls [3], and this is applicable to the two-layer configuration of TPS tile and substrate for which the prototype is designed. For the two-layer composite material, the x-distance and the delta-Theta time-step values are related by the material properties as before, but additionally the number of calculation sections of one layer are related to the number of sections of the other layer by the relationship of the two layers' thermal diffusivity, a. This is derived in Reference 3 to lead to the following equations:

Starting with the basic one-dimensional heat conduction equation:

$$\partial T / \partial \theta = (k / \rho c)\, \partial^2 T / \partial^2 x$$

Define general variables, genDelxFt and genDelThetaSec so that:
delXTileFt(n) = (thickTileIn(n)/12) / NumSectionsTile
and
genDelxFt(n) = delXTileFt(n)/kcondTile
where
kcondTile = thermal conductivity of tile material, btu/hr-ft-degF

The delta-Theta time-step is related to x-axis delta-x, genDelxFt, by the equation,
genDelThetaSec = k * density * c * genDelxFt ^{2} / 2

and the delta-x section distances in tile and substrate are related by the following equations:

delXTileFt(n) / delXSbstrFt(n) = (atile(n) / aSbstr(n) $^{0.5}$

delXSbstrFt(n) = delXTileFt(n) / ([(atile(n) / aSbstr(n)] $^{0.5}$)

This produces the number of sections of substrate as follows:

NumSectionsSbstr = (thickSbstrIn(n)/12) / delXSbstrFt(n)

Based on these relationships and as shown in Figure 7, the calculation loop operates until the summation of genDelThetaSec(n) time steps is equal to the orbit time-step.

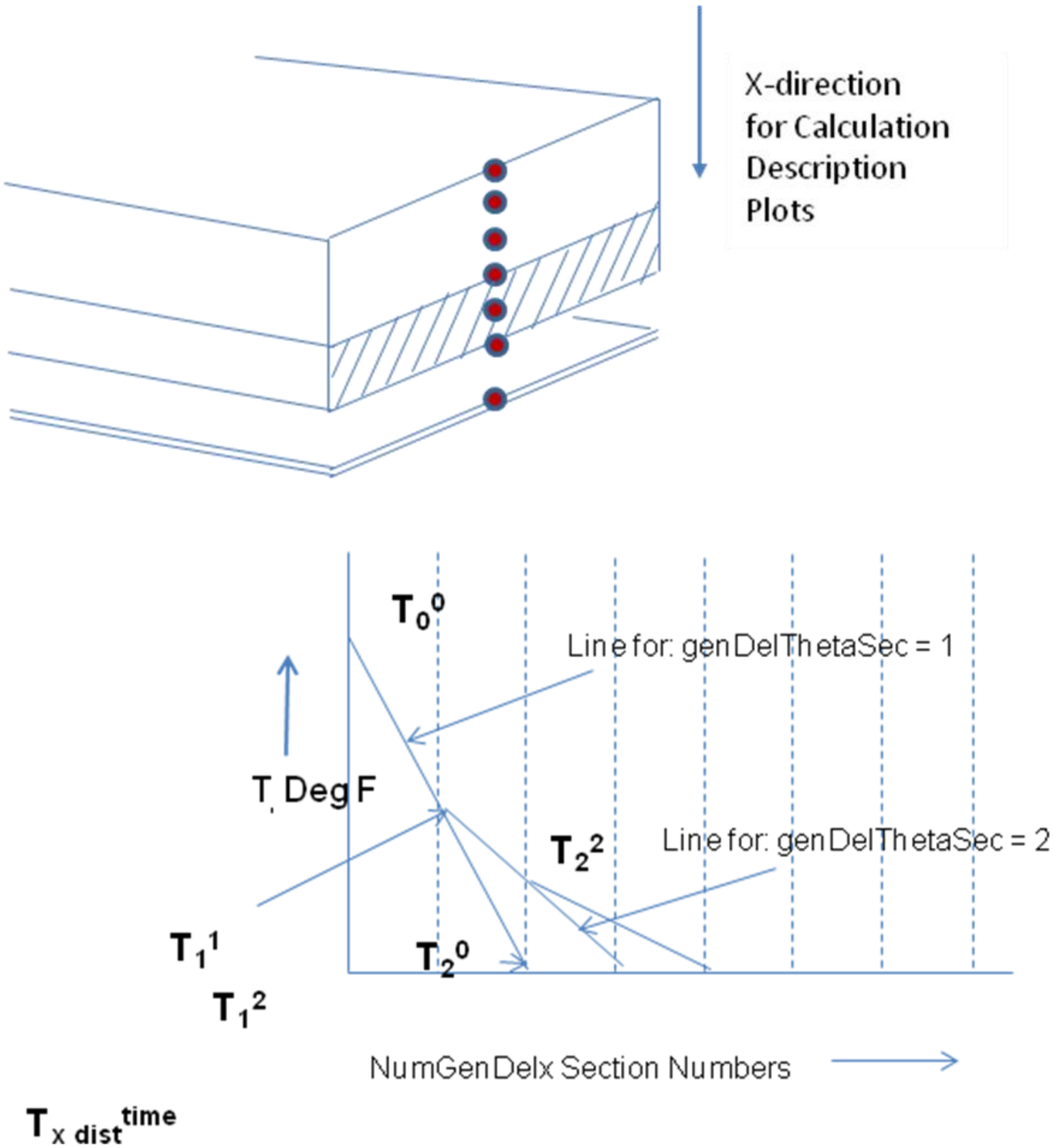


Figure 7: Application of Schmidt-plot Technique to Composite Material Layers

The calculation loops operate to sequentially produce the rows of points that represent temperatures at sections at successive delta-Theta time-steps as shown in Figures 8, 9 and 10.

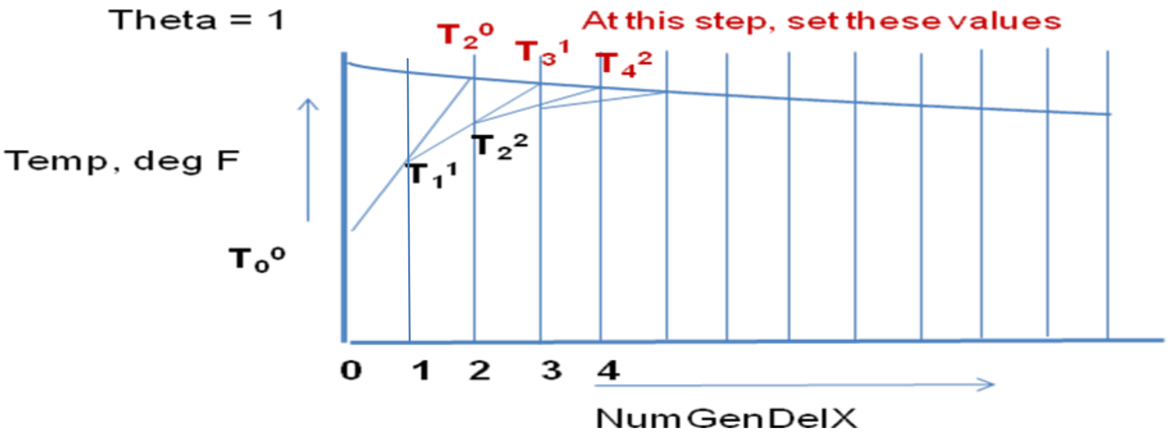


Figure 8: Setting Temperatures from Given Starting Profile into Tx Calculations

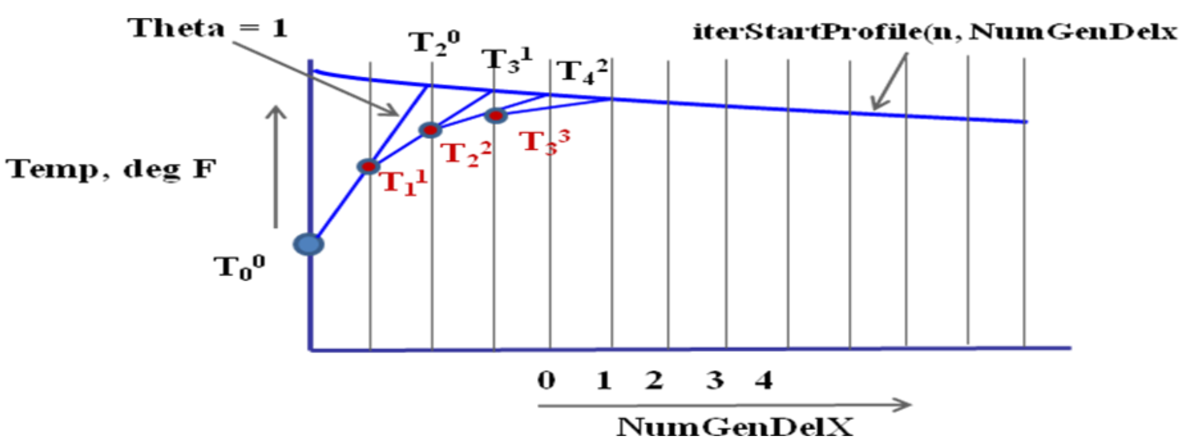


Figure 9: First Cycle of Tx Calculations for Determining Temperature Profile

Remaining Cycles

$\mathbf{T}_{x\ dist}^{time}$

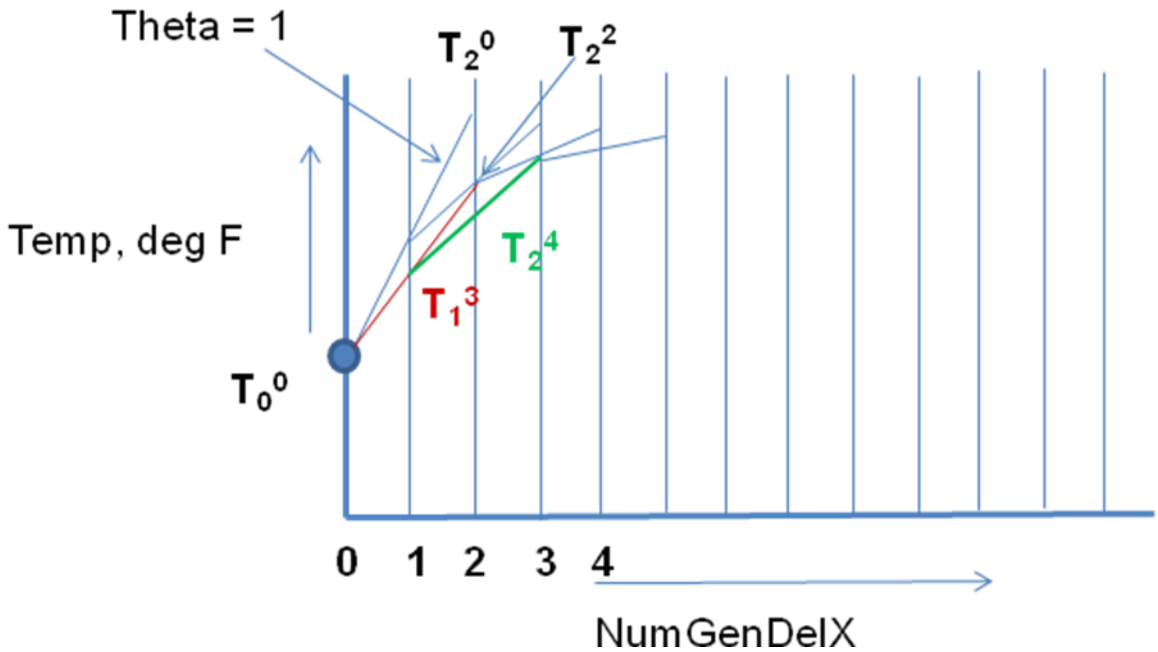


Figure 10: Successive Cycles of Tx Calculations for Determining Temperature Profile

By continuing the sequence of straight-line calculation of temperatures at section points of the x-axis as shown in Figure 10 until the total of delta-theta small time steps is equal to the orbit time-step, a curve of the unsteady-state temperature profile in the material is obtained.

Early results from prototype calculations for Panel A of the Lockheed-Martin (LM) backshell information presentation [4] are shown in Figure 11. Prototype output step-stop data curves are seen to approximate the given LM step-stop data, but with differences that were due to different and incomplete definition of boundary conditions of the substrate-to-pressure vessel interface, at that time. Later examples of prototype step-stop output data with improved accuracy are shown in the Verification and Results section of this paper.

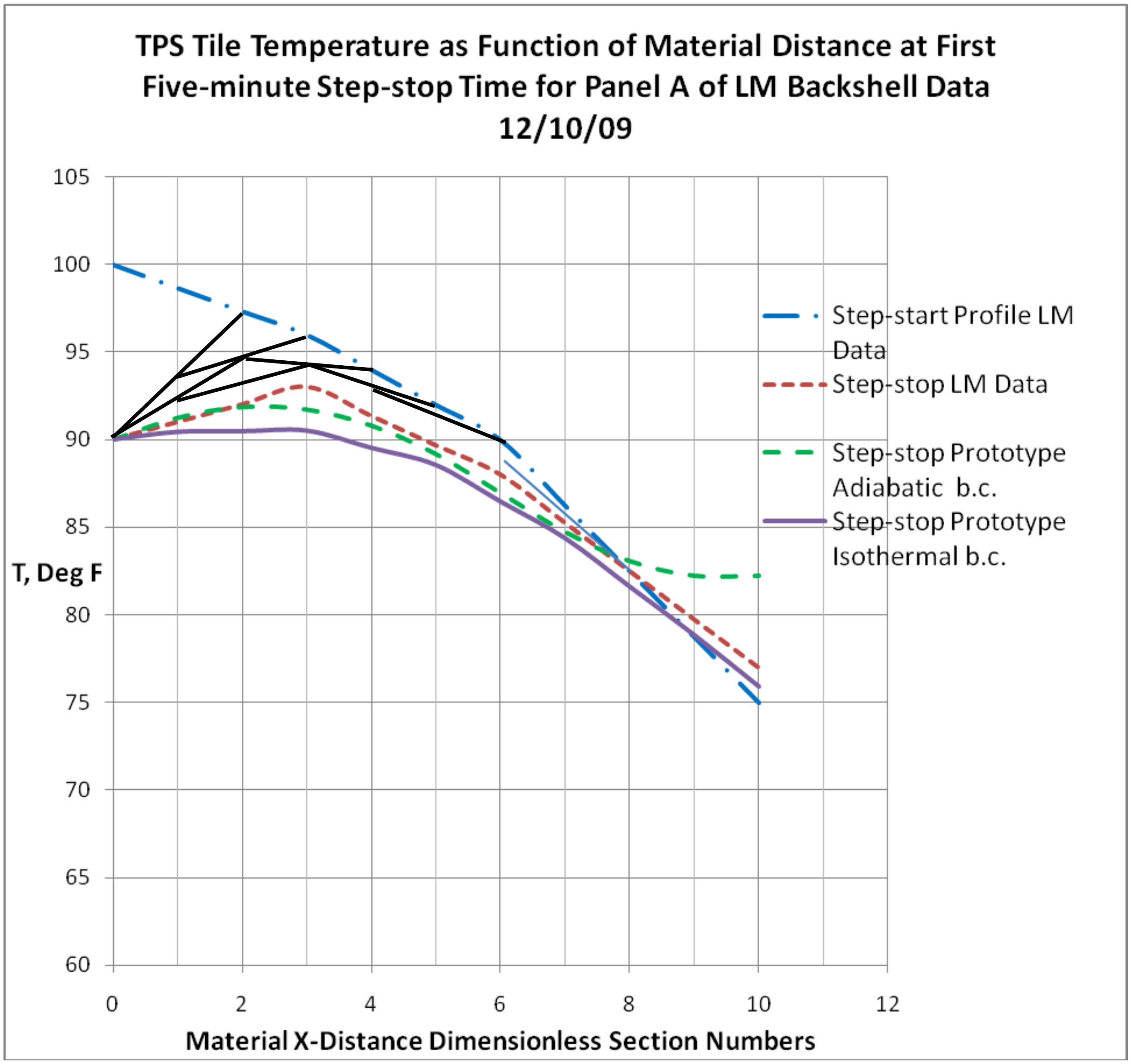


Figure 11: Prototype Output Results and Design-model Verification Data

Application of the Schmidt-plot technique for the tile-substrate composite material with heating only on the tile external surface produced satisfactory results as indicated in the previous figures. These results were based on Panel A, with orbit time-steps that produced normal values of incident heat rates upon the tile surface. It was initially proposed that since the rate of heat transfer to or from the pressure vessel to the interior substrate surface is generally much lower than the solar and earth albedo heat rate on tile external surfaces, that the substrate-to-pressure vessel heat effects could be included by only applying the pressure-vessel boundary condition temperature. In examining other bond-line locations and orbit phases in which the incident heat rates upon tile surfaces are low, approaching zero for eclipse parts of orbits, it became apparent that the calculation of a temperature profile by the technique shown graphically in Figures 7 – 10, needed to be applied to the substrate inner surface as well as to the tile external surface. The result is a final, integrated Schmidt-plot sequence that involves calculation of the temperature profile at section points by proceeding from both exterior sides of the material, simultaneously in the algorithm. This is shown graphically in Figures 12 and 13.

Schmidt-plot Method Applied to Two-surface Heat Conduction in Composite Material

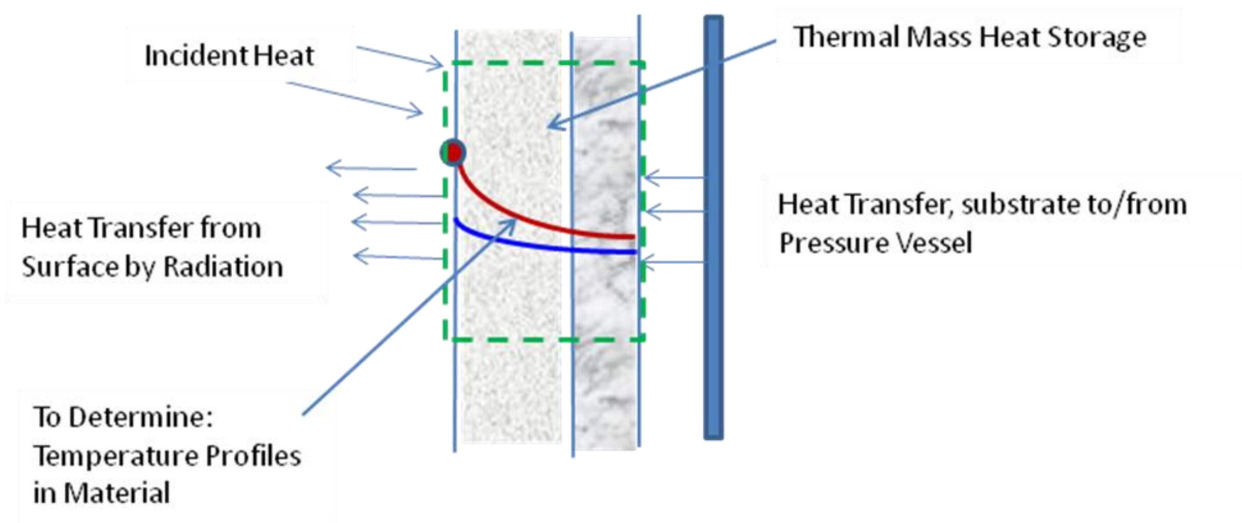


Figure 12: Two-sided Heat Transfer Configuration

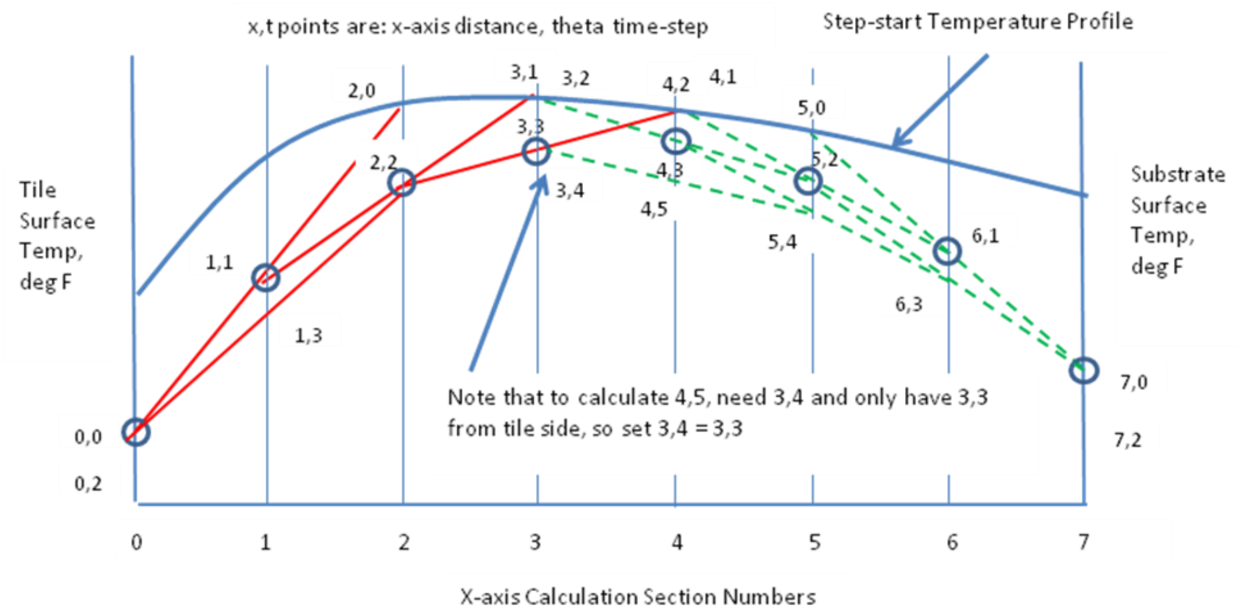


Figure 13: Temperature Profile Calculation from Two Sides of Material

The calculation sequence starts at x=0 and x=7, and proceeds from each external surface of the material to the first section past the midpoint. The sequence includes adjustments so the values needed by the steps from one surface inward are available from the calculation steps that proceed to the center from the opposite direction. Initial values for the calculation sequence are the step-start profile shown in Figure 13, and the Theta-time-zero step-stop surface temperatures. The output parameter, step-stop temperature profile is formed during the calculations as shown by the circles at the x-axis section lines.

As a result of the prototype development to this point, it was concluded that the major initial feasibility question objective of the prototype research had been answered favorably; the Schmidt-plot technique for direct, step-wise calculation of unsteady-state temperature profiles in the tile-substrate material could be incorporated into an algorithm that would produce adequately accurate temperatures.

Producing a complete application to use this method of calculating temperature profiles for the environment of spacecraft components in orbit requires the major additional capability of determining tile surface temperatures at successive orbit time-steps. Developing that part of the application is described in the following section.

DETERMINATION OF TILE SURFACE TEMPERATURE AT ORBIT STEP-STOP TIMES

Prior to calculating a temperature profile through the material as described in the preceding section, a step-increase or decrease in the tile surface temperature must be assigned as a starting-point for the process. This is the step-stop surface temperature that the material will be experiencing during the pseudo-steady-state short period of time of the orbit time-step, to the end of that time-step. The nature of this step-change in surface temperature is determined by the average incident heat rate, the outflow radiation heat rate, and the amount of heat stored in the thermal mass of the material during the time-step.

Since the radiation heat outflow and the thermal mass heat storage quantities are dependent on step-stop surface and interior temperatures which are being determined, the calculation must involve either an iteration process employing an assumed surface temperature, or a separate relationship by which the step-stop surface temperature can be determined. Three possible methods for determining this step-stop temperature and the overall process of heat transfer during the orbit time-step have been examined and are discussed in the remaining parts of this section.

a. Step-stop Surface Temperature Based on the Heat-balance Method

Overall program flow using the heat-balance method was initially planned to incorporate the iteration process based on tile and substrate energy balance parameters shown in Figure 12 and described as follows:

1. Assume a step-stop temperature is assumed, based for example on assuming that the heat loss by radiation is the same as during prior orbit step.
2. Using the given step-start temperatures and the assumed surface step-stop temperature, calculate the radiation heat rate and the thermal-mass heat storage.
3. From an energy balance, determine the error between total heat input and heat output plus heat storage, using the following equations:

   Qincident + Qpv-to-substrate = Qtile-radiation + Qthermal-mass
   Qerror = Qincident + Qpv-to-substrate - Qtile-radiation - Qthermal-mass

4. Assume a different step-stop surface temperature and repeat the steps to find another heat-balance error.
5. Using a Newton-Raphson technique and the rate of change of error as function of the assumed surface temperatures, find the actual step-stop surface temperature that gives a satisfactory energy balance.

Difficulty was encountered in applying this heat-balance method for finding surface temperatures, so alternative techniques for finding the orbit step-stop surface temperatures were examined as described in subsequent subsections. As shown in Figure 14, the energy balance error varied with orbit time and reflected a relationship to surface temperature change-rate. This discussion relates only to the Panel A bond-line location, but similar results were found for Panel B and Panel E.

(Reference: Orion EECOM PTCS App Rev N 050510.xls Verif Calcs 022810 Sheet, Cell CS19)

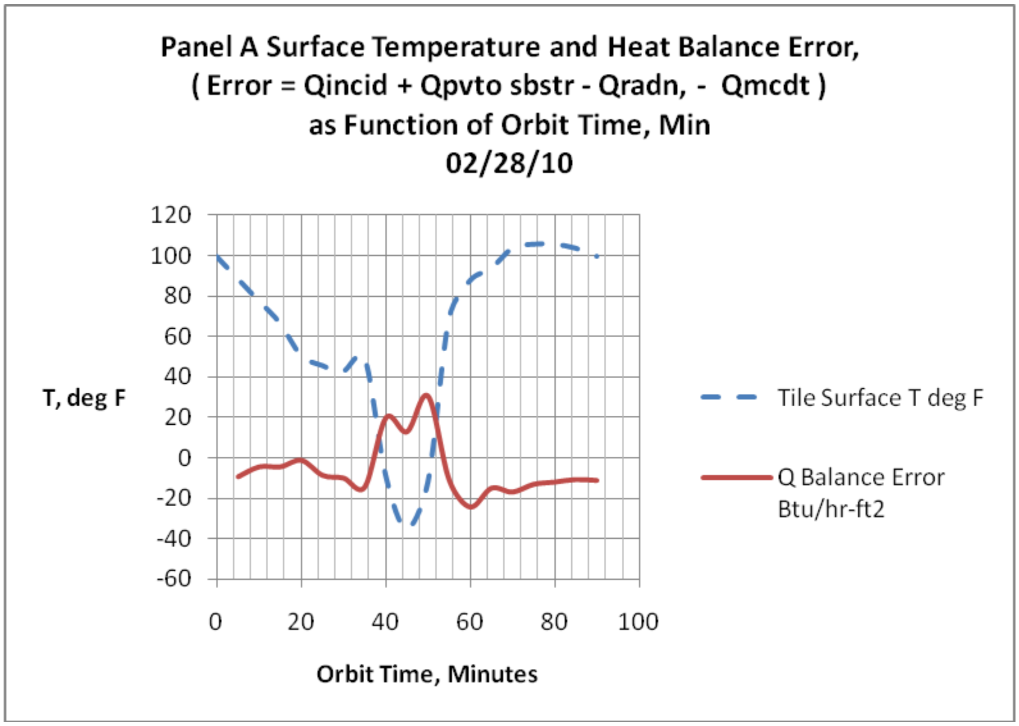


Figure 14: Panel A Heat Balance Error and Tile Surface Temperature

It is important to note that this question regarding energy balance was discovered during preparation of data from the detailed model output information for Panel A, not as a result of output from the prototype development; consequently, this is not due to simplifying assumptions made in the design of the prototype calculation approach. The source data of given incident heat rate and tile and substrate temperatures for Panel A are shown in Table 1.

In addition, and as part of the research into possible source of this error, an early examination was made to determine if some variation of heat transfer or temperature at the substrate-to-pressure vessel could account for this. As shown in Figures 15 and 16, the amount and nature of the variation that would be needed, as compared to the magnitude of heat transfer and temperatures at that location, indicate that this is not the source of heat-balance error.

Table 1. Panel A LM Source Data for Energy Balance Calculations

Time, Min	Incident Q, btu/hr-ft2	Tile temps: Outer Surf T deg F	TPS Middle deg F	Inner bond-line deg F	Substrate Inner Face T deg F
0	134.6	100.0	96.0	90.0	75
5	116.0	89.0	93.0	88.0	77
10	103.0	78.0	85.0	83.0	78
15	91.0	67.0	77.0	78.0	78
20	77.0	51.0	72.0	73.0	73
25	74.0	46.0	66.0	70.0	74
30	74.0	43.0	60.0	67.0	73
35	85.0	50.0	58.0	66.0	71
40	12.0	-8.0	45.0	55.0	69
45	12.0	-35.0	25.0	48.0	66
50	90.0	-12.0	12.0	38.0	60
55	131.0	69.0	28.0	42.0	55
60	143.0	88.0	52.0	50.0	52
65	153.0	94.0	72.0	60.0	53
70	156.0	104.0	86.0	73.0	55
75	156.0	106.0	92.0	82.0	62
80	151.0	106.0	97.0	87.0	68
85	141.0	104.0	96.0	90.0	72
90	134.6	100.0	95.0	90.0	75

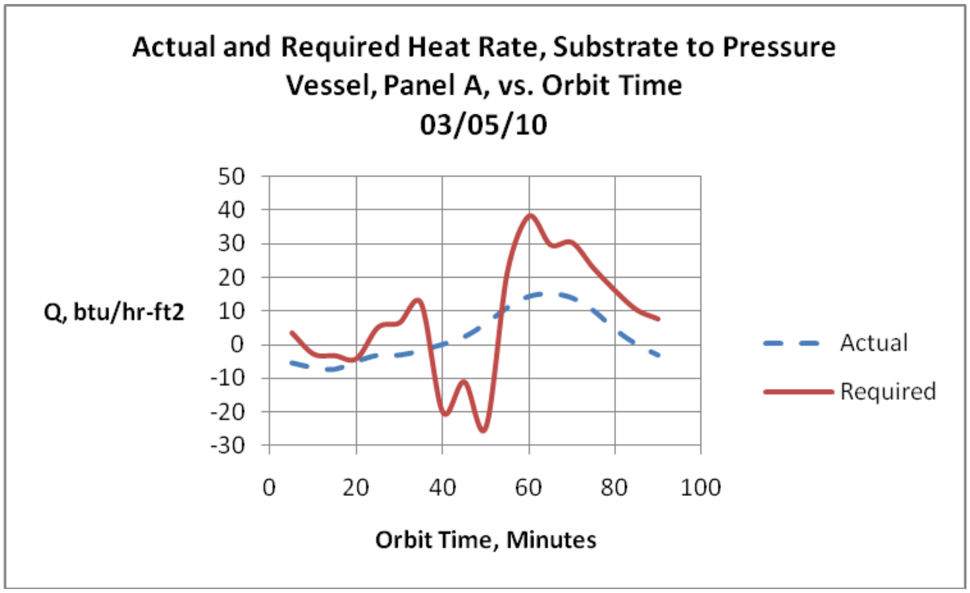


Figure 15: Actual and Required Heat Transfer Rate, Pressure-vessel-to/from-Substrate, for Heat Balance to be Correct

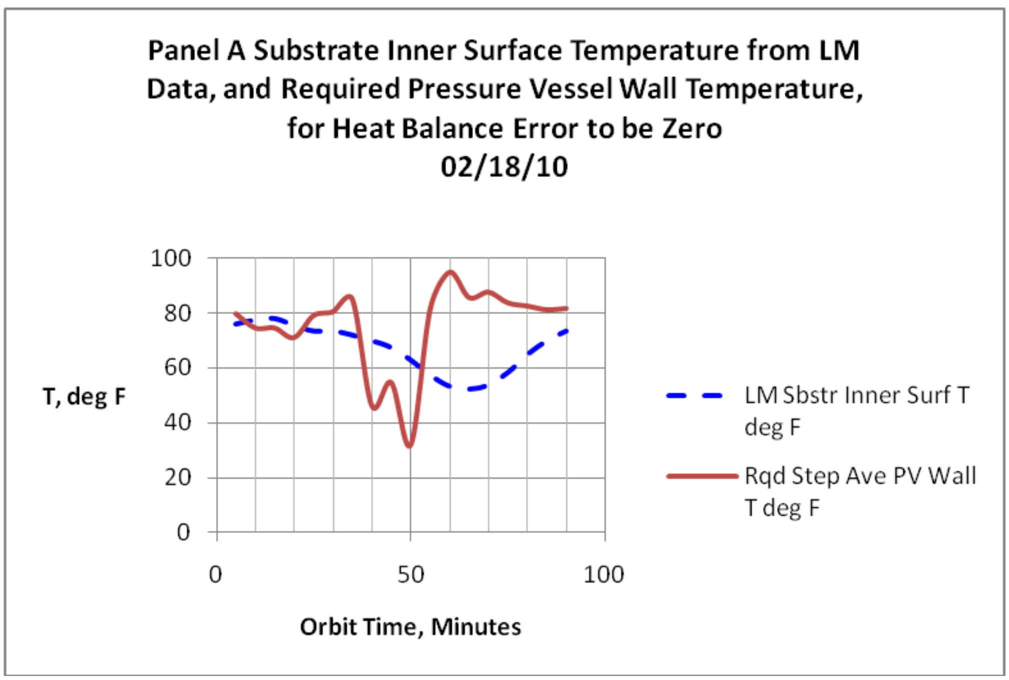


Figure 16: Actual and Required Substrate Inner Surface Temperature, for Heat Balance to be Correct

As shown in Figure 17, thermal mass is present between the substrate and pressure vessel in the form of longerons and other components and structure, and these unknown thermal masses are not included in the heat-balance calculations based only on tile and substrate temperatures and thermal mass.

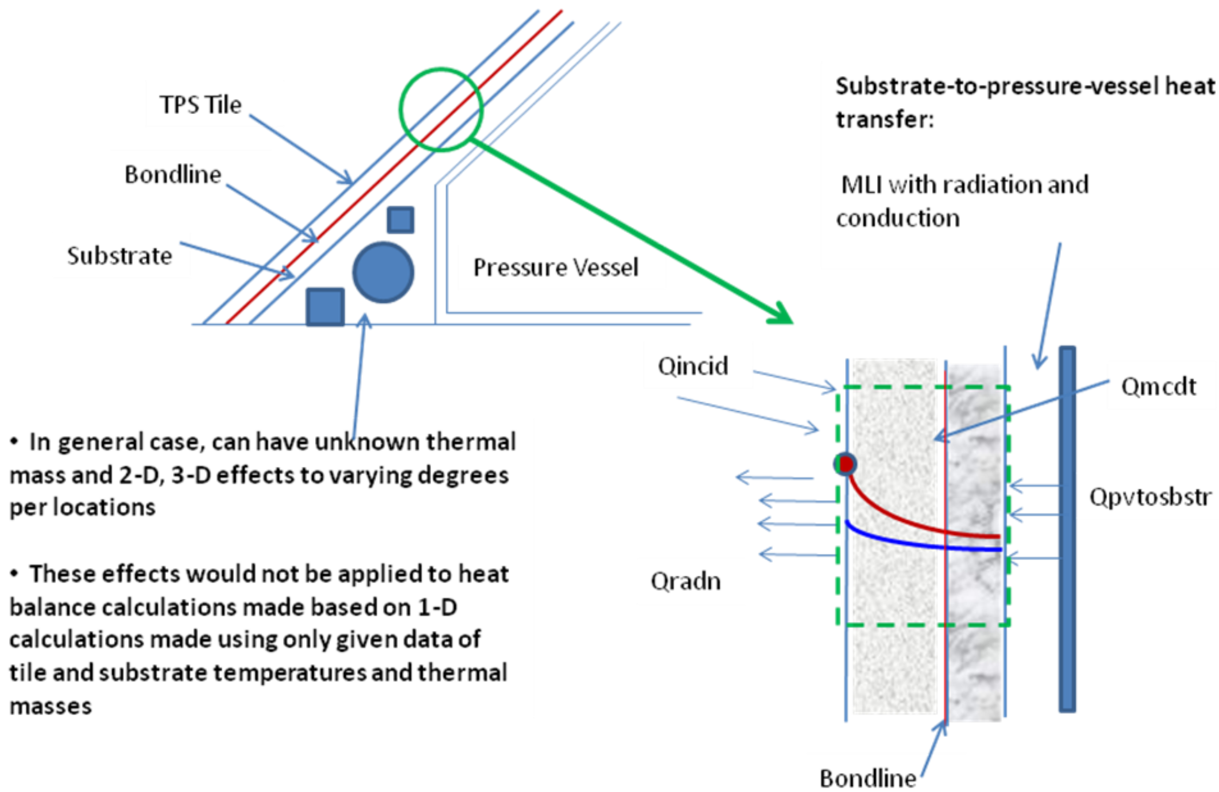


Figure 17: Configuration of Tile, Substrate and Pressure Vessel, Related To Thermal Mass and Heat-balance Effects

The initial approach to account for and to incorporate this effect, involved calculation of the equivalent, unexplained thermal mass that would be needed if the heat-balance error were to be reduced to zero. A typical example of the nature of this required unknown thermal mass is shown in Figure 18.

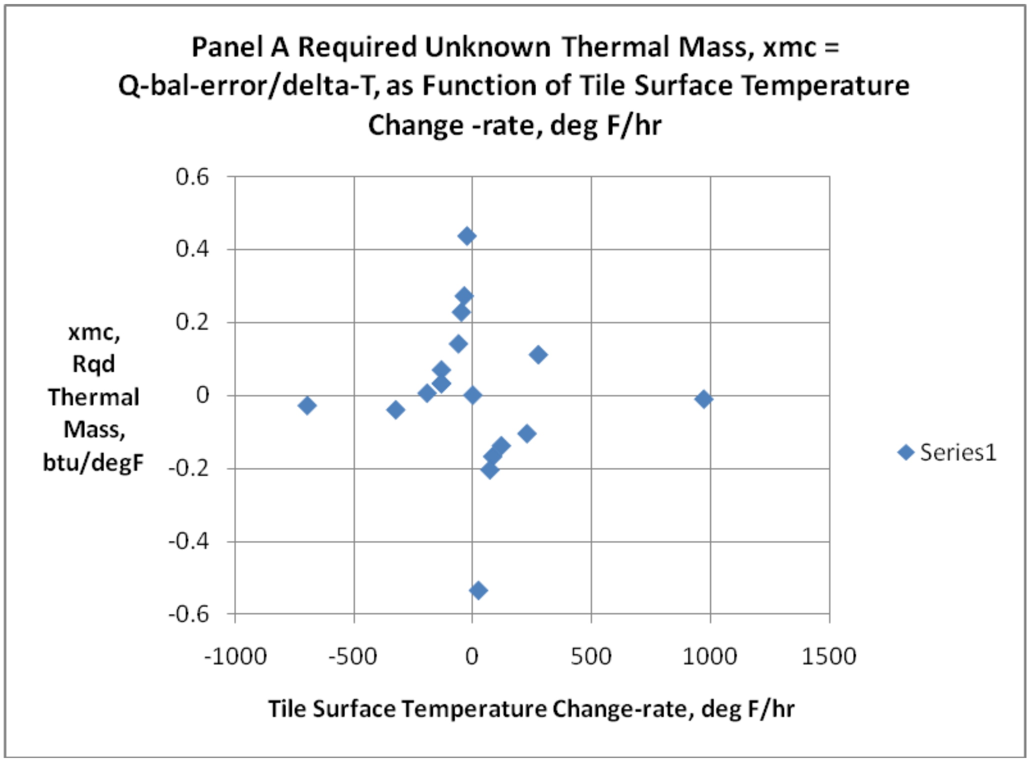


Figure 18: Required Unknown Thermal Mass as Function of Tile Surface Temperature Change-rate

It can be seen that the required amount of thermal mass is generally in the form of dual exponential curves, and that it varies in a way that could be expected for thermal mass in the region between the substrate and the pressure vessel as indicated in Figure 17. When the surface temperature changes slowly (Low x-value region near center of the plot), the thermal mass effect has more influence on heat balance and would have to be of larger values to compensate for the error. When the surface temperature changes at higher rates, the needed unknown thermal mass is smaller, as it does not have time for heat-soak from unknown mass into tile-substrate material, to influence the heat balance to a large degree.

Various examinations were made regarding the relationships between the unknown thermal mass, surface temperature, surface temperature rates and incident heat rate, in an effort to find a curve-fit equation that would adequately represent the unknown thermal mass in the subroutine calculations. The most accurate and appropriate representation of unknown thermal mass is as shown in Figure 19.

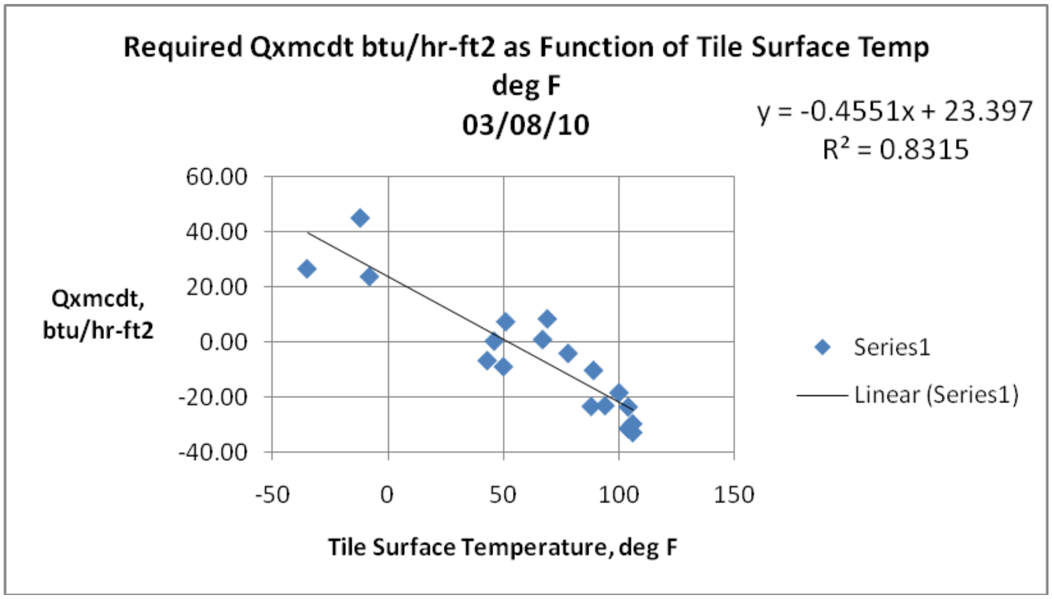


Figure 19: Required Unknown Thermal Mass as Function of Tile Surface Temperature

When the unknown thermal mass is represented by the equation shown in Figure 19 and applied back into the calculation of heat-balance error for all orbit time-steps of one orbit, the result is as shown in Table 2.

Table 2. Panel A Heat-balance Error if Unknown Thermal Mass is Represented by Equation Based on Tile Surface Temperature

Time, Min	Outer Surf T deg F	Required Qxmcdt btu/hr-ft2	y = -0.4551x + 23.397 Chk-calc this: Calcd Qxmcdt btu/hr-ft2	Error, % of range 70
0	100			
5	89	-10.14	-17.11	9.95
10	78	-3.98	-12.10	11.60
15	67	1.03	-7.09	11.61
20	51	7.49	0.19	10.44
25	46	0.47	2.46	2.85
30	43	-6.61	3.83	14.91
35	50	-8.81	0.64	13.50
40	-8	23.89	27.04	4.50
45	-35	26.69	39.33	18.05
50	-12	45.15	28.86	23.27
55	69	8.54	-8.00	23.64
60	88	-23.23	-16.65	9.39
65	94	-22.94	-19.38	5.09
70	104	-31.26	-23.93	10.47
75	106	-32.71	-24.84	11.24
80	106	-29.54	-24.84	6.71
85	104	-23.41	-23.93	0.74
90	100	-18.28	-22.11	5.48
		Ave Error, %		10.75

In view of the complications of representing the thermal mass by equations when the dual-sided heat transfer and the preparation steps of examining given design data or flight data are considered, a search was made for a more practical method of determining step-stop surface temperature. The applicable fundamental physical phenomenon is the relationship between incident heat rate and tile surface temperature. These are the basic input-output variables of the process during an orbit time-step, and the intermediate effects of radiation heat transfer, and of thermal mass of tile, substrate and unknown thermal mass, are all inherently represented in the relationship between incident heat and surface temperature.

Alternatives are based on the relationship between incident heat rates on tile surfaces and the surface temperature plots, and on the incorporation of surface boundary conditions within the Schmidt-plot graphical technique, directly. These approaches are described in the subsections below.

b. <u>Step-stop Temperature Based on Curve-fit of Relationship Between Incident Heat Rate and Tile Surface Temperature</u>

As shown in Figure 20, a simple plot of incident heat and tile surface temperature as function of orbit time shows a skewing of the surface temperature as compared to the incident heat rate curve. Lag between a time of application of incident heat and the time of evidence of that heat in the surface temperature can be expected by thermal-mass effects. It can intuitively be proposed that the surface temperature may more accurately be represented in relation to the time-step-average incident heat, rather than to instantaneous incident heat rate. This was examined and was found to be true as shown also in Figure 20, and for the three bond-lines of this study. The tile surface temperature more accurately matches the average incident heat rate curve than the instantaneous heat rate curve.

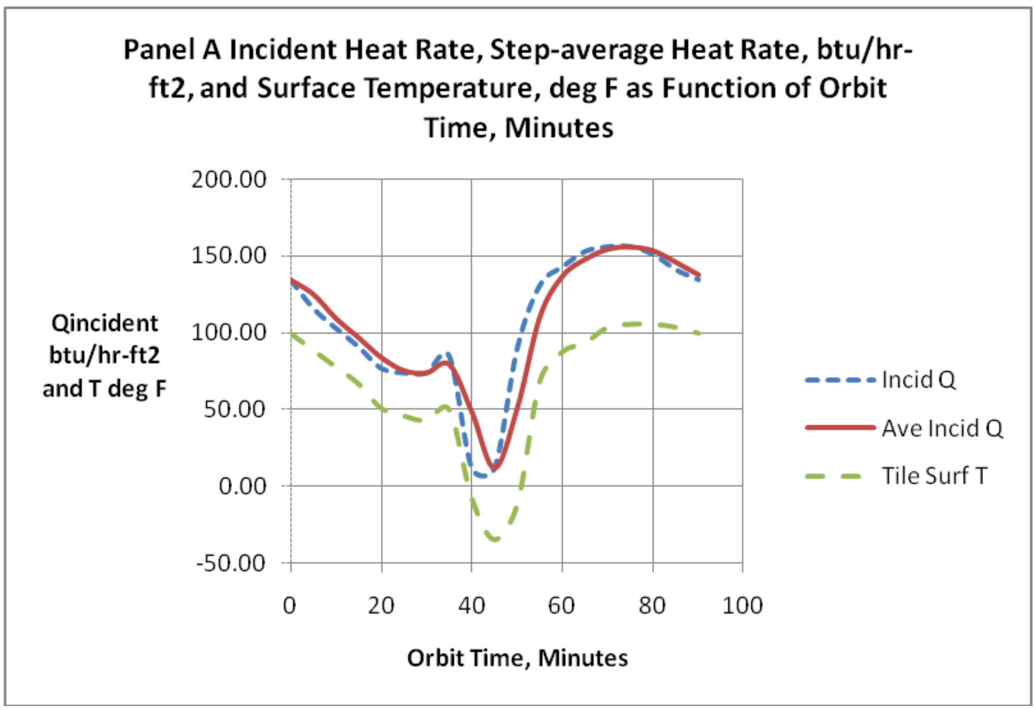


Figure 20: Panel A Incident Heat Rates and Surface Temperature

Reference Verif Calcs 022810 RH68

A curve-fit equation was derived to determine step-stop temperature as a function of step-average incident heat rate upon the tile exterior surface, as shown in Figure 21. The relationship shows a reasonable correlation for accurate use, and this is verified in the display of calculated step-stop values shown in Table 3.

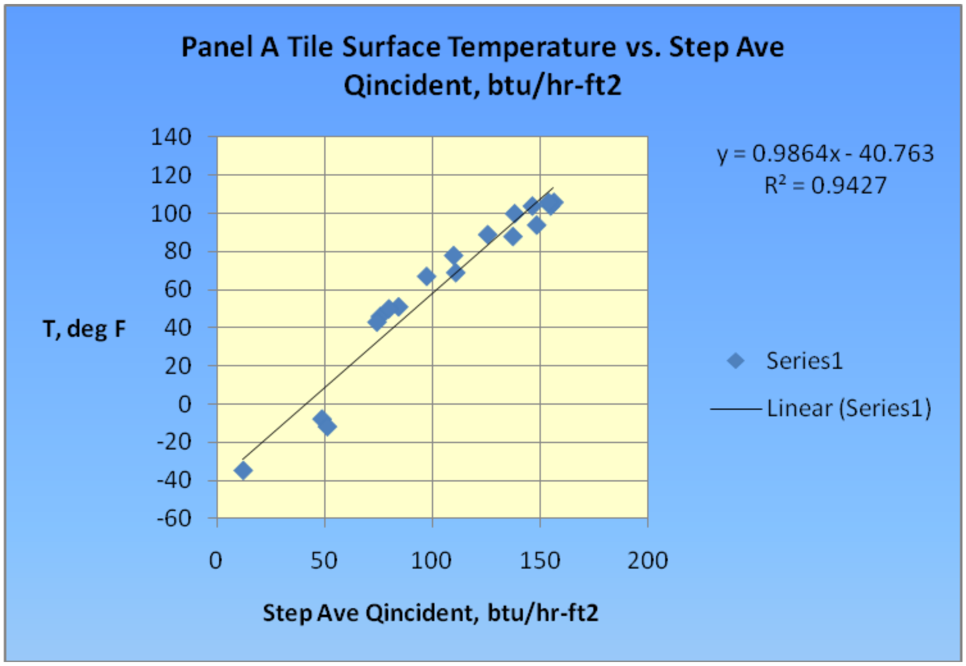


Figure 21: Curve-fit Equation for Panel A Surface Temperature As Function of Step Average Incident Heat Rate

Table 3. Panel A Surface Temperature Error, Using Step-Ave Qincident

Step ave Qincident

Panel A y = 0.99657x - 40.94322

	LM Data				Error abs
	Qincid BHF2	step-start-stop ave	LM	Calcd	pct of 150 deg F temp range
	103	Qincid	Surf T	Surf T	%
	116.00	BHF2	deg F	deg F	
0	134.57	125.29	100.00		
5	116.00	125.29	89.00	83.91	3.39
10	103.00	109.50	78.00	68.18	6.55
15	91.00	97.00	67.00	55.72	7.52
20	77.00	84.00	51.00	42.77	5.49
25	74.00	75.50	46.00	34.30	7.80
30	74.00	74.00	43.00	32.80	6.80
35	85.00	79.50	50.00	38.28	7.81
40	12.00	48.50	-8.00	7.39	10.26
45	12.00	12.00	-35.00	-28.98	4.01
50	90.00	51.00	-12.00	9.88	14.59
55	131.00	110.50	69.00	69.18	0.12
60	143.00	137.00	88.00	95.59	5.06
65	153.00	148.00	94.00	106.55	8.37
70	156.00	154.50	104.00	113.03	6.02
75	156.00	156.00	106.00	114.52	5.68
80	151.00	153.50	106.00	112.03	4.02
85	141.00	146.00	104.00	104.56	0.37
90	134.57	137.79	100.00	96.37	2.42
	116.00			**5.90**	

Reference: Excel Verif Calcs Update 022810 AFO18

Similar equations were developed for the three active panels of this study, as follows:

Panel A y = 0.99657x - 40.94322
'Panel B y = 1.8774492x - 103.9863429
Panel E y = 0.78029x - 3.84233

where x = ave Qincid, 2-step, the average of step-start and step-stop Qincident, btu/hr-ft2,
and y = calculated step-stop tile surface temperature, deg F

Reference: Excel Verif Calcs Update 022810 AFQ25, AGZ25 and AJH25

Coefficients are placed in an appropriate worksheet location for use by the application, so a general equation for basic step-stop tile surface temperature calculation can be used in the subroutine for all bond-lines:

This gives accuracy of step-stop temps of 5.9% and plot as shown in Figure 22

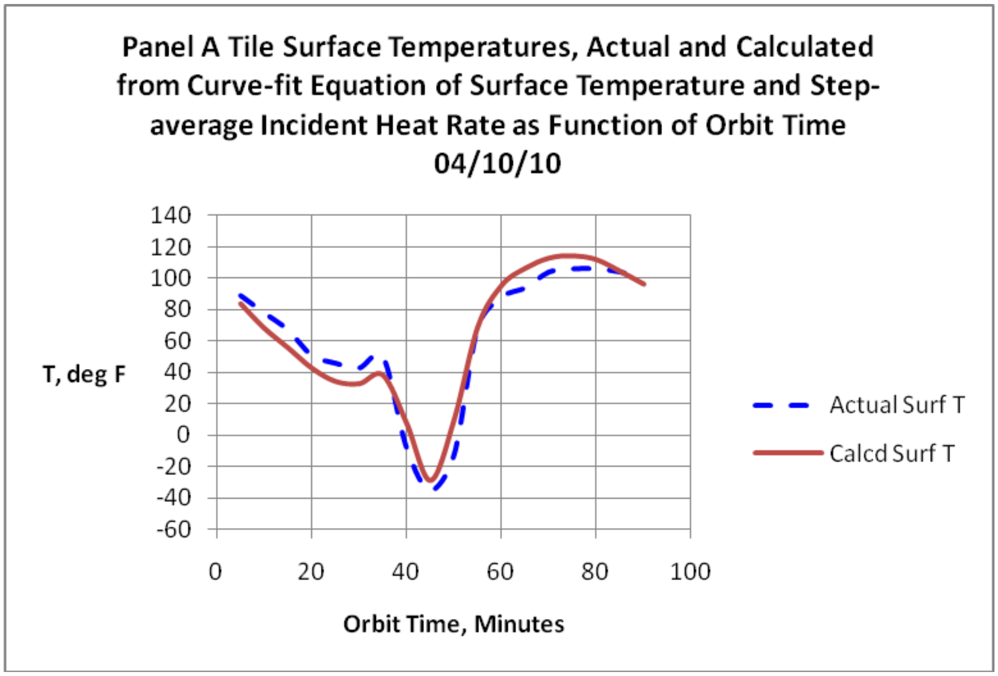


Figure 22: Panel A Actual and Calculated Surface Temperatures, Using Equation Based on Incident Heat Rate

Reference: Excel Verif Calcs Update 022810 AGB70

It was observed that an error existed between actual and calculated step-stop surface temperatures by this method as shown in Figure 22, and that this error could be correlated to rate of change of surface temperature. An equation was developed for this correction, and when it was applied, the result is as shown in the Verification and Results section of this paper, with an average error between actual and calculated step-stop temperatures of 3.9%.

Additional evaluation is needed to verify that the improved accuracy obtained by use of the correction has benefit worth the cost of added data-preparation needed prior to mission analysis test-runs. This is provided to indicate the potential accuracy of this method as it was observed in this one bond-line, and generally for the three bond-lines of this study. The correction factors are incorporated for the three panels by use of a case-statement and specific subroutines for each bond-line location.

Reference: Excel Verif Calcs Update 022810 Cell AGQ46

At this point, the two essential aspects of the temperature profile and bond-line temperature determination – ability to calculate an unsteady-state temperature profile from a given prior-step profile plus a new step-stop surface temperature, and ability to predict new step-stop temperatures for the tile surface – have been developed and verified to be of sufficient accuracy.

It is important to note that this sequence of calculating step-stop surface temperatures from given incident heat rates, only functions correctly for orbit time-steps in which the incident heat rate is above certain absolute values. For cases in which the incident heat rate is near zero, a modified form of the heat-balance method is used, as is described briefly in the subsequent section summarizing the functional flow of the code.

c. <u>Step-stop Temperature Based on Integrated Schmidt-plot Boundary Condition Graphics</u>

The third method of determining step-stop surface temperature is a common one described in the literature related to the Schmidt Plot use. This is particularly true for the configuration of a fluid with a convective heat transfer coefficient, h_c, adjacent to the exterior surface of material in which the temperature profile is to be calculated. As shown in Figure 23, a Schmidt-plot x-axis distance can be assigned that represents the relationship between h_c and thermal conductivity of the material, and the effective boundary condition can be incorporated automatically within the usual temperature-profile calculation sequence.

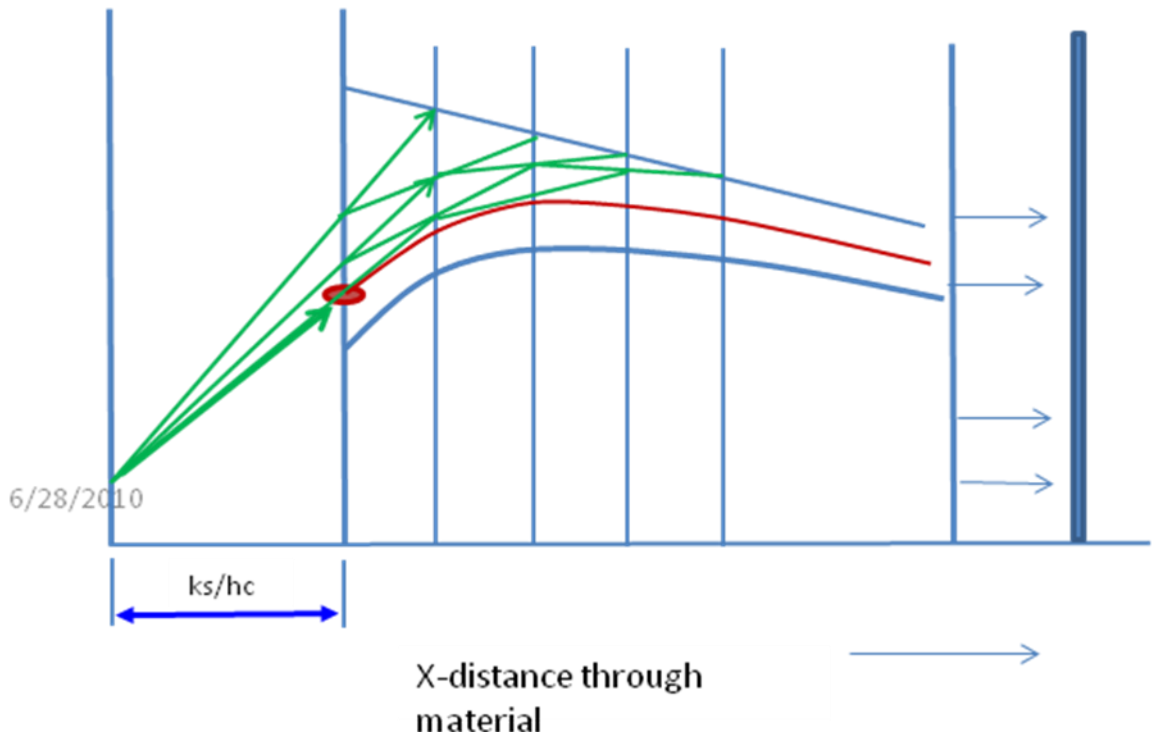


Figure 23: Graphical Representation of Finding Step-stop Surface Temperature Directly from Schmidt Plot Boundary Condition Calculations.

As shown in the comparison of equations shown below, however, radiation heat transfer from the surface, rather than convection, presents complexity for use of this method for calculating temperatures in passive thermal components of spacecraft. With radiation rather than convection acting externally, the heat transfer to or from the surface is a function of the surface temperature, so this method also becomes one in which an estimation and/or iteration process is needed. This method is shown briefly for background documentation of possible applicable techniques, but is not used in the prototype algorithm.

Convection: q = hcA(Tsurf – Tfluid) Distance = ks/hc

Conduction: q = (Akext/Lext)(Th – Tc) Distance = ks/(kext/Lext)

Radiation: q = Kr (T1 – T2') where
Kr = sigma*A*F*(T1^4 – T2^4)/(T1 – T2')
and Distance = ks/Kr

With the essential elements of the calculation process presented in the previous sections of this report, the next phase of description of the prototype is a summary of the major functional sequences in the subroutines.

APPPLICATION FUNCTIONAL FLOW SUMMARY

In addition to the need to predict step-stop temperatures and temperature profiles in the materials as previously described, other challenges were encountered by the configuration to which this thermal analysis approach was applied. Those challenges related to the need to represent temperature-dependent specific heat and thermal conductivity, the need to compute properties of the honeycomb substrate, and the attempt to represent the complex three-dimensional geometry of the Orion tile, substrate and pressure vessel configuration by a one-dimensional heat transfer model.

The ways in which these challenges are met and accomplished in the prototype are described in this section in the form of a summary of the major subroutines and functions of the prototype code.

PRELIMINARY PREPARATION STEPS EXTERNAL TO MAIN APPLICATION

a. Temperature-dependent Properties

The first data-preparation step is accomplished one time for any given set of materials of the component to be modeled, and is maintained within the code. This step consists of the preparation of curve-fit equations of specific heat (cp), mass-times-specific-heat (mcp) and thermal conductivity (k). Available data for cp and k of materials are from the LM detailed-model data for Orion TPS tile and substrate [4]. These material properties are used to determine curve-fit equations in a separate workbook used for the initialization calculations, as shown in Appendix A.

Formats of the cp and k equations are arranged to be the same for given properties of all active bond-line locations to be used in the application. The coefficients are then arranged in a table within Excel as shown in Table 4, for access by the subroutine, GetInputs().

Table 4. Panel A Surface Temperature Error, Using Step-Ave Qincident

Bond-line #	1	2	3
Panel	A	B	E
cpTileSqCoeff	-0.0000001460472500	-0.00000014604725	-0.00000014604725
cpTileLinCoeff	0.0002771678000000	0.00027716780000	0.00027716780000
cpTileConst	0.1499062875000000	0.14990628750000	0.14990628750000
mcpTileSqCoeff	-0.0000000963911850	-0.00000009639119	-0.00000009639119
mcpTileLinCoeff	0.0001829307480000	0.00018293074800	0.00018293074800
mcpTileConst	0.0989381497500000	0.09893814975000	0.09893814975000
kTileLinCoeff	0.0000207429000000	0.00002074290000	0.00002074290000
kTileConst	0.0197853029000000	0.01978530290000	0.01978530290000
mcpSbstrLinCoeff	0.0003127860000000	0.00031278600000	0.00031278600000
mcpSbstrConst	0.1413752628000000	0.14137526280000	0.14137526280000
kSbstrLinCoeff()	0.000065929166	0.000065929166	0.000065929166
kSbstrConst()	0.077884320530	0.077884320530	0.077884320530

b. Mission-dependent Properties

Remaining data-preparation steps external to the main application are accomplished for analysis of given missions or mission phases. These steps pertain to the determination of curve-fit equations for step-stop tile surface temperature as functions of step-average incident heat rate. These are planned to be a routine, expedited steps of obtaining a given format of design-model output data in coordination with Engineering or contractor support through the MER interface, or to be based on a similar format of selected prior-flight data.

An example of the required input data for this calculation of mission-dependent properties is provided in Table 5, using the given LM data for Panel A [4].

Table 5. Panel A Example of Mission-dependent Input Data

Panel A

LM Data	**1/19/2010**		Tile temperatures			Substrate
			Outer	TPS	Inner bond-	Inner Face
Time,	Time,	Incident Q, btu/hr-ft2	Surf T	Middle	line	T
Min	Hrs		deg F	deg F	deg F	deg F
0	0	134.57	100	96	90	75
5	0.08333333	116.00	89	93	88	77
10	0.16666667	103.00	78	85	83	78
15	0.25	91.00	67	77	78	78
20	0.33333333	77.00	51	72	73	73
25	0.41666667	74.00	46	66	70	74
30	0.5	74.00	43	60	67	73
35	0.58333333	85.00	50	58	66	71
40	0.66666667	12.00	-8	45	55	69
45	0.75	12.00	-35	25	48	66
50	0.83333333	90.00	-12	12	38	60
55	0.91666667	131.00	69	28	42	55
60	1	143.00	88	52	50	52
65	1.08333333	153.00	94	72	60	53
70	1.16666667	156.00	104	86	73	55
75	1.25	156.00	106	92	82	62
80	1.33333333	151.00	106	97	87	68
85	1.41666667	141.00	104	96	90	72
90	1.5	134.57	100	95	90	75

These sets of input data, one for each bond-line location, are used to produce curve-fit equations as shown in Figure 22 and Table 3.

The basic set of mission input data will also be used to produce any required accuracy adjustment as described with reference to Figure 24. It is expected that the use of such data sets one time for typical, normal conditions and vehicle attitudes in orbital missions in low earth orbit will be satisfactory for many similar mission phases and entire missions. As experience and flight data are gained in the use of this passive thermal analysis application, it may be that worst-case, a data set of this type may be needed for specific phases of a mission. In either case, it is planned that an auxiliary, off-line part of this application will be established and used to automate and expedite the process of proceeding from the input of basic data as shown in Table 5, to the curve-fit equations for step-stop temperature calculations ready to be used within the main application.

MISSION ANALYSIS SETUP AND OBTAINING USER-INPUT DATA

Following the establishment of temperature-dependent and mission-dependent properties in prescribed tables referenced for use by the application, the control panel is used to setup and initiate the mission analysis case-run. A graphical user interface control panel for input-data category selection is part of the requirements for the final application, with a conceptual design as shown in Figure 26. Upon selection of each category by the user, popup dialog boxes are to be displayed for complete set-up and definition of analysis run-cases. The categories for user inputs are as follows

Update Material Properties
Setup Analysis Case Mission
Specify Initial Conditions
Define Orbit
Select Attitude Timeline
Define Output Tables and Plots
Incorporate Flight Data

Main categories for routine analysis case setup and operation are contained within the central part of the control panel. Linkage into the planned pre-analysis data preparation and automated, auxiliary application noted earlier is planned to be accomplished by selections to be available in the Background and Flight Data Verification section at the lower part of the control panel.

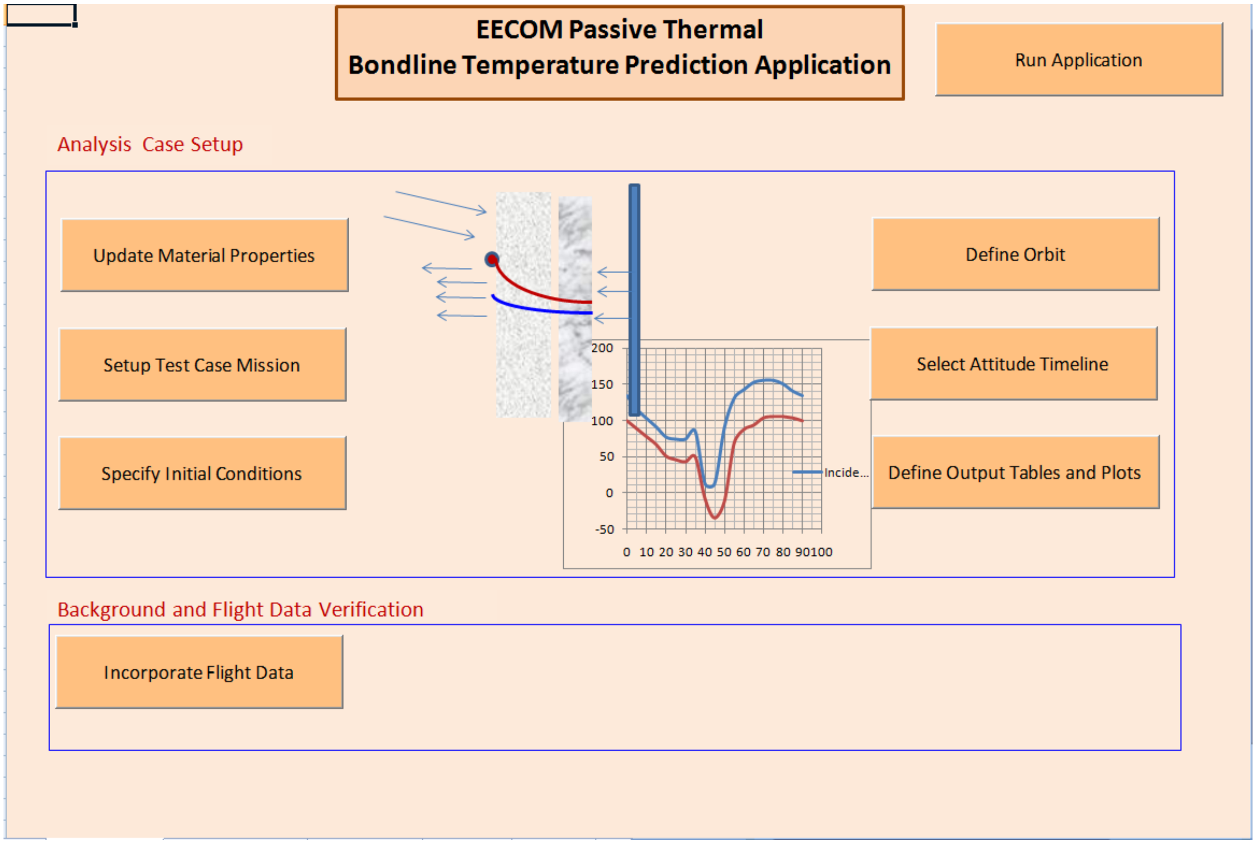


Figure 24: Graphical User Interface Control Panel Planning Example

Functions similar to those indicated for the planned final application control panel are accomplished in the spreadsheet and dialog boxes of the Excel/VBA prototype, although the format of the user interface is different from the design shown in Figure 26 for the final application.

Features provided in the current prototype are described in terms of a functional flow summary of major steps of the subroutine calculation sequences. The detailed presentation of prototype subroutine steps is provided in Appendix B. Major sequences and brief descriptions of essential aspects of prototype Excel/VBA coding are provided in the following section.

PROTOTYPE FUNCTIONAL SUMMARY

a. Control Panel Input Categories

Control panel categories are as follows:

Initial conditions, analysis case setup, orbit definition, attitude timeline, active bond-lines and number of bond-lines selection, and output data selections.

Inputs from the control panel are applied into the application operating code by subroutines The overall management subroutine, OverallMacro(), corresponds to a Main function of C-Language code, and contains the sequence of operating subroutines in the Excel/VBA prototype.

b. Popup Dialog Boxes

Popup dialog boxes are provided in sequence after the user initiates the mission-analysis case. These dialog boxes are used to obtain user-selected options that are specific within a given analysis case activity. These options include the following aspects:

Option to display or not display tables of intermediate values of all calculations, for diagnostic work during development

Selection of bond-line number and orbit time-step to be used for the display of intermediate values

Selection of bond-line number and orbit time-step for routine display of two temperature profiles for step-to-step comparison and evaluation

Selection of option for substrate inner surface boundary conditions

c. Pre-loop Calculations

OverallMacro() operation accomplishes standard pre-loop preparatory calculations prior to the main orbit time-step loop. These pre-loop calculations include the following items:

Initialize orbit time-step, orbit and bond-line loops, and cycle-control parameters

Select type of incident heating to be applied to the TPS tile exterior surface: Simulated solar heat flux, table of incident heating values or single step-function test-case of incident heat rates.

Clear the output data tables that are used to display intermediate values

Cycle through all bond-lines, and initialize parameters

Calculate temperature-dependent specific heat and thermal conductivity, pre-loop, using curve-fit equations

Calculate the Schmidt-plot parameters, using specific heat and thermal conductivity:
Generic material section thickness and Theta time-steps

Set dynamic array variables for the Schmidt-process-calculated temperature

Calculate initial stepStartProfileTDegF() using given starting data and linear slopes.

d. Main Program Loop of Orbit Time-steps

Orbit Time-step Loop:
This primary Do-while loop of the application steps through the orbit time-steps for the amount of time selected for the mission analysis case.

Main calculation loop for selected bond-lines:
This loop contains the subroutines and calculation sequences that accomplish the core calculation of material temperatures for each bond-line at each orbit time-step. The major steps of this bond-line calculation loop are as follows:

Calculate incident heat rate

Determine if to calculate temperature-dependent variables, based on the rate of change of incident heating compared to a threshold value
To save run-time, the temperature-dependent variables are not re-calculated if incident heat rate is not changing by an appreciable amount.

Assign local variables

Run subroutine PassiveThermalCalcSeq() to accomplish the core unsteady-state temperature calculations
Steps of the PassiveThermalCalcSeq() are as follows:

Step-stop Surface Temperature Method Determination:
Evaluate major if-statement option to determine if the incident heat rate upon the bond-line location tile surface is changing at a normal rate so the method of finding step-stop temperature based on incident heat rate can be used. The alternative, if the incident heat rate is not changing as in the case of eclipse orbit periods, is to calculate step-stop temperature based on the heat balance of tile

and substrate.

.

Normal incident heat-rate case calculations:
Calculate step-stop temperature using curve-fit equations.
Also, calculate a delta surface temperature accuracy correction based on rate of change of surface temperature.
Calculate step overall average tile and substrate temperatures, and use these temperatures to calculate the temperature-dependent specific heat and thermal conductivity, and the Schmidt-plot parameters.
Since the basic Schmidt-plot generic x-axis steps are a function of the temperature-dependent parameters, re-scale that plot axis.

Low incident heat-rate case calculations:
Calculate tile step-delta temperature based on step net incident heat applied to the tile minus step outflow radiation heat rate,. and the apparent mass-times-specific-heat value of tile.
This uses specific-heat and thermal-conductivity values, plus the resulting Schmidt parameters, from pre-loop calculations or from the previous orbit time-step.

Calculate the starting temperature profile:
This temperature profile, iterStartProfileTDegF(n, NumGenDelx) is established using the stepStartProfile plus the value of step-stop temperature at the tile surface, and the value of temperature at the substrate inner surface.

At this point, we have a starting-point temperature profile and a step-function change of a surface step-stop temperature at both the tile surface and the substrate surface. These are the essential components needed to operate the core unsteady-state temperature profile-determining subroutine, IntegSchmidtPlotCalc().

Run IntegSchnidtPlotCalc()
This subroutine accomplishes the Schmidt-plot calculations simultaneously from both sides of the composite material to determine a new, step-stop temperature profile, as depicted graphically in Figure 14.
The sequence involves use of appropriately arranged nested and successive Do-while loops.
Details of the cycles of calculating the successive profiles of temperature values at the x-axis distances and at the Theta-time steps of calculation time are provided in Appendix B.
The step-stop temperature profile that results from this sequence is extracted from the subroutine when the total of small calculation

step time intervals is equal to the orbit time-step value.

PassiveThermalCalcSeq(), Continued:
Output Data:
Output values of the various step-stop temperatures and heat changes of the thermal masses are assigned to appropriate array variables and saved as recorded results.
The primary output parameters of interest, tile surface temperature, bond-line temperature, and substrate inner surface temperature are assigned and saved as array variables at this point.

The current step-stop temperature profile data for this orbit time-step and bond-line are saved in array variables for use in the
display of temperature profiles of the material, in subroutines that
display

this information at the end of the mission-case analysis.
These output profiles of temperature provide a graphical comparison between given LM design-model data and prototype output data.

Output of PassiveThermalCalcSeq() also includes data for displaying two temperature profiles through material at bond-line locations and orbit time-steps selected by the user during initialization of a mission analysis case.

This point constitutes the end of PassiveThermalCalcSeq(), and end of both the main bond-line loop and the main orbit time-step loop

e. Continue to the End of OverallMacro(), Displaying Output Data

Completion of the OverallMacro() management sequence for the current mission analysis case is accomplished by running subroutines that organize and display the complete set of output data as specified by the user for the mission analysis case. These subroutines include the following:

DisplayBLProfilesRoutine()
CalcLMTempProfiles()
DisplayOneOrbProfiles()
PrintAllOutputData()
PrintBLandSurfTTable()

VERIFICATION AND RESULTS

Feasibility and accuracy of the prototype have been verified by comparing output data of the prototype to design-engineering data for incident heating and selected bond-line temperatures of the Orion Crew Module. This has been accomplished in detail throughout the development process for all calculations and is described in this section for both of the following major functions of the application, determining orbit time-step surface temperatures and calculating unsteady-state temperature profiles within the material. Prototype run-time and extrapolated final application run-time are also described in this section.

DETERMINING ORBIT TIME-STEP TILE SURFACE TEMPERATURE

Initial verification of prototype step-stop surface temperature calculation was accomplished as noted earlier in the data of Table 3. Additional verification of accuracy and feasibility of the approach developed in the prototype for calculating step-stop temperature is provided in this section as shown in Figure 25. The accuracy of prototype methods of calculating step-stop surface temperatures is demonstrated to be sufficient for planned use of an application based on techniques developed within the prototype.

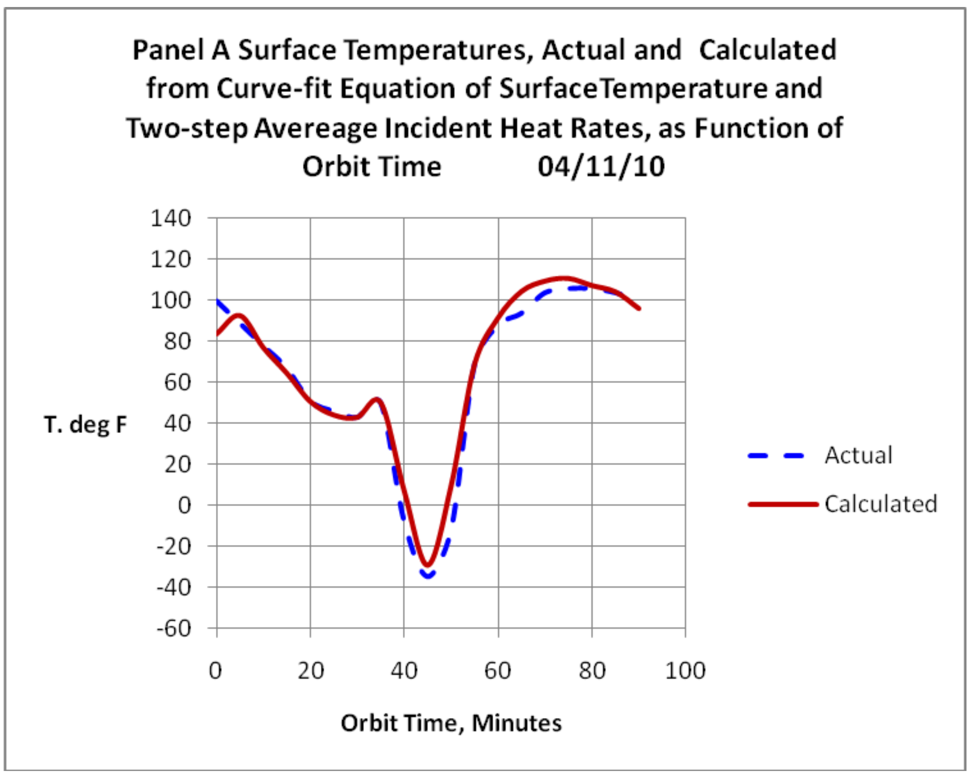


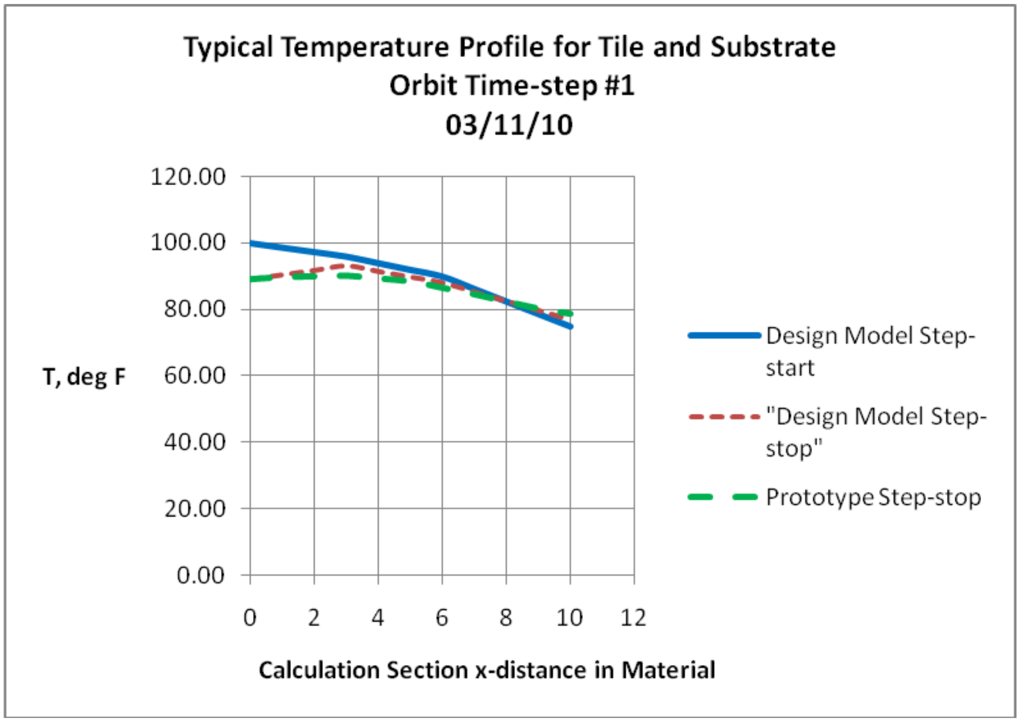
Figure 25: Panel A Actual and Calculated Surface Temperatures, Using Equation Based on Incident Heat Rate and Correction Factor Based on Surface Temperature Change-rate

USING STEP-STOP SURFACE TEMPERATURES WITH THE SCHMIDT-PLOT TECHNIQUE FOR CALCULATING TEMPERATURE PROFILES

Verification of capability of the prototype to determine unsteady-state temperature profiles was indicated in Figure 11. Additional verification of the accuracy by which the prototype technique can produce temperature profiles for the three bond-line locations has been accomplished for many orbit time-step cases. Subroutines of the prototype which display output data are designed to routinely produce tables and plots of temperature profiles for the eighteen orbit time-steps of the first orbit of mission analysis cases. Examples of these temperature-profile plots for Panel A are shown in Figure 26, indicating good agreement between given and calculated step-stop internal material temperature profiles. These temperature profiles were produced by the prototype version that accomplished the Schmidt-plot sequence from only the tile exterior surface inward, and used the relationship between step-average incident heat rate and surface temperature to find step-stop surface temperature values.

During development of the prototype and production of temperature-profile plots for Panel B and Panel E, examples of which are shown in Figure 27, it was discovered that improvements were needed in the calculation of step-stop temperatures and the Schmidt-plot sequence to adequately deal with instances of low incident heat rate. Indication of this need for improved accuracy can be seen in Figure 27 for the time-step-three example. The difference between prototype output and the given design-model data at Section 6, the x-distance of bond-lines, indicates the need for the improvements.

Changes were made to the step-stop surface temperature determination to use heat-balance methods for orbit times of low incident heat rates, and to the Schmidt-plot unsteady-state temperature calculation sequence to run the process from both external surfaces of tile-substrate combined material, as indicated by Figure 13. These improvements are showing success in more accurately determining the temperature profiles, but final evaluation and presentation of results remain to be completed.



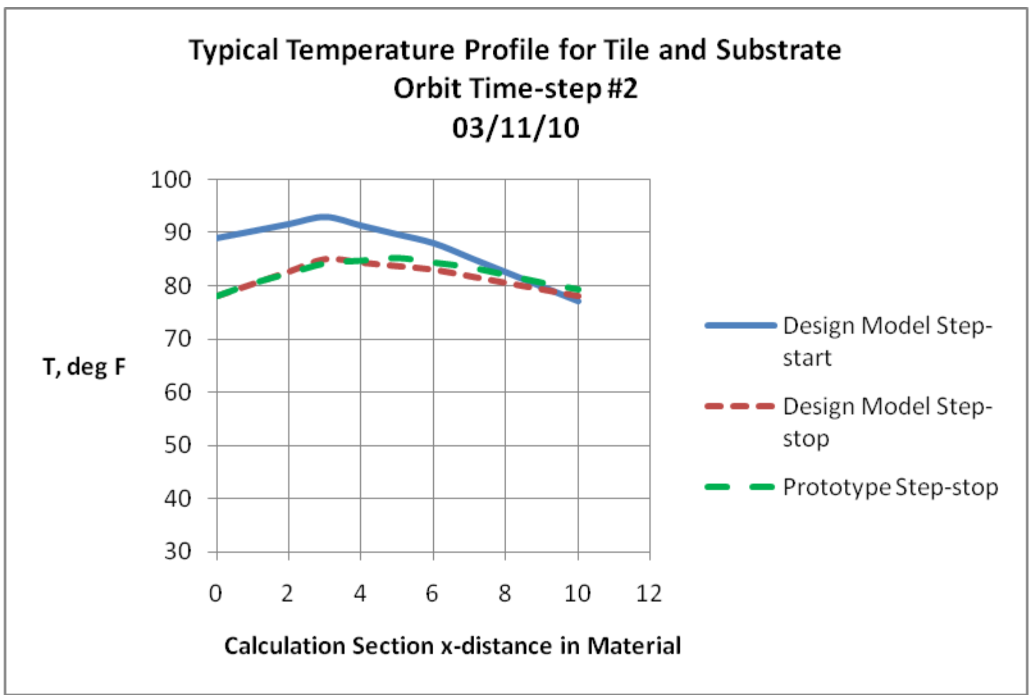
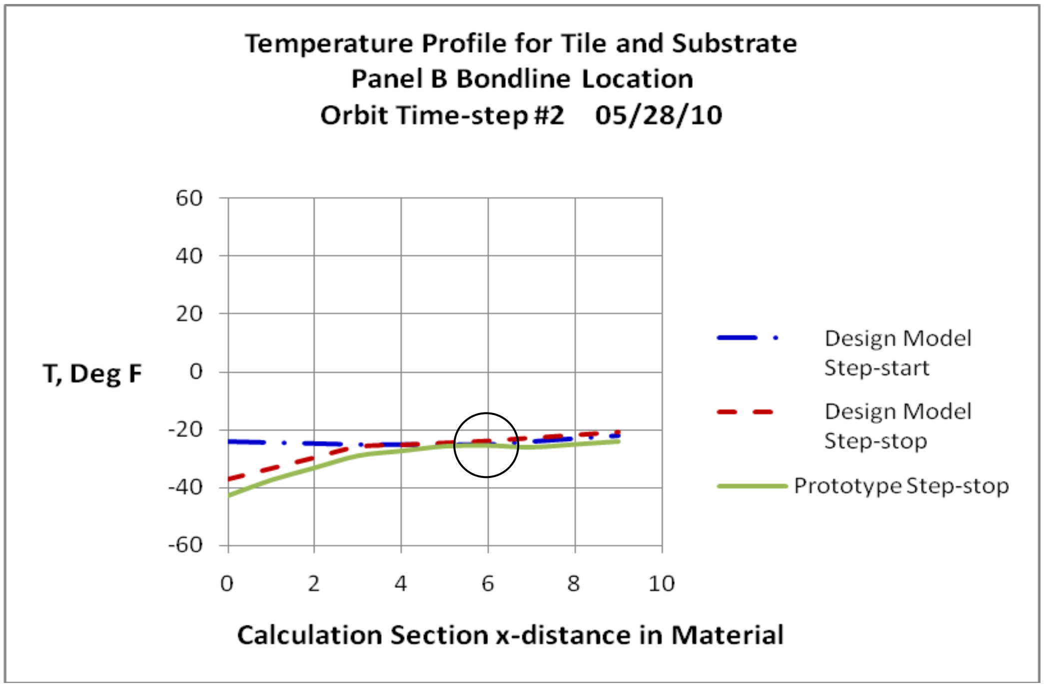


Figure 26: Examples of Prototype Temperature Profile Output Data, Panel A Bond-line Location #1 (Ref: Archived Data Workbook)



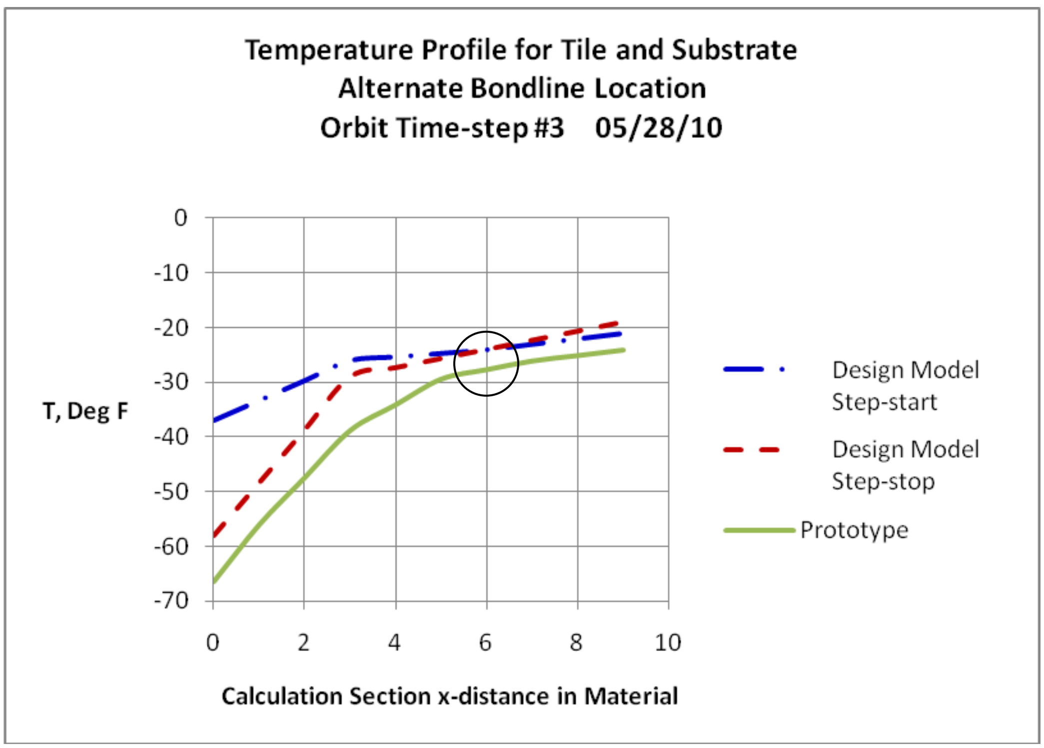


Figure 27: Examples of Prototype Temperature Profile Output Data,

Panel B Bond-line Location #2
(Ref: Archived Data 021010, Sheet Data 042810 AZ47)

DETERMINING BONDLINE TEMPERATURES OVER MULTIPLE ORBIT CYCLES AND MISSIONANALYSIS RUN-TIMES

A primary objective of prototype development is to evaluate the capability to produce values of surface and bond-line temperatures as functions of orbit time for multi-orbit mission analysis cases. To accomplish this, the prototype first produces step-stop temperature profiles throughout the material as shown in the previous section. Appropriate x-axis points are then selected for representation of the tile surface, bond-line and substrate inner surface, and these x-values are used in the stored step-stop temperature array variables to select the temperatures at each orbit time-step. These output temperatures of surfaces and bond-lines are displayed as functions of orbit time for the mission analysis case, as shown in Figure 28.

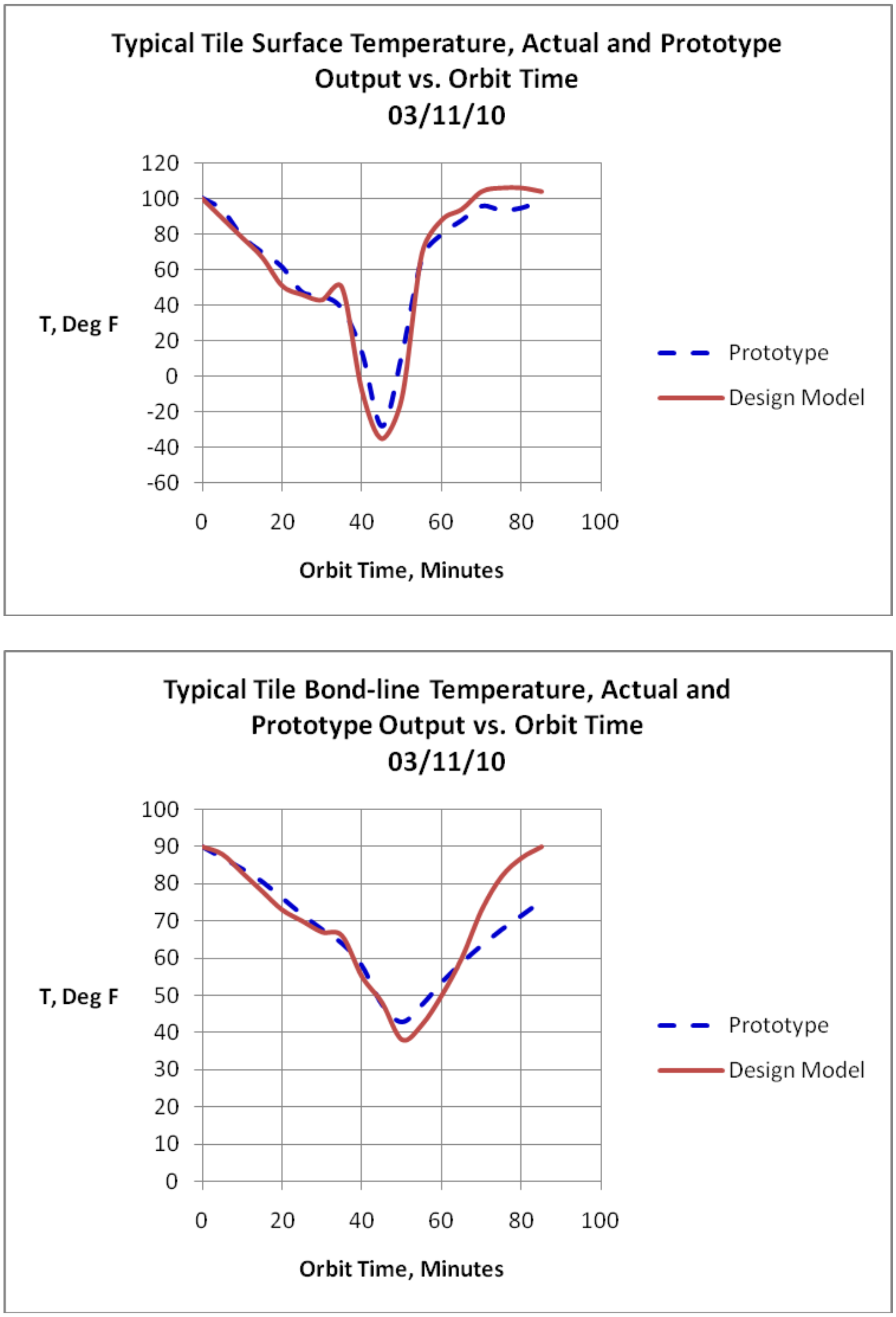


Figure 28: Tile Surface and Bond-line Temperature Output Data from Prototype for Single-orbit Mission Analysis Cases, Panel A Bond-line Location

Plots shown in Figure 28 are based on data produced by the earlier version of the prototype as described for the temperature-profile plots and Figure 27. Generally acceptable results, in terms of being able to model the orbit-cycling nature of temperature profiles and the temperatures of surfaces and bond-lines as functions of orbit time, are indicated by Figure 28 and similar data in more detail in prototype development documentation. The need for improvements in prototype operation for the periods of low incident heat and for two-sided heat transfer to or from the material, can be seen in the bond-line temperature plot of Figure 28. This is being accomplished as previously described.

PROTOTYPE OPERATING ANALYSIS RUN-TIME RESULTS

Run-time of the prototype was determined by timing various mission-analysis test-case durations for the current version that calculates temperatures for three bond-lines. The results are extrapolated to compare run-times with the generally required runtime desired at the initiation of the prototype development task. This general requirement is for a capability to calculate surface and bond-line temperatures for 20 bond-lines as function of orbit time for a 21-day mission analysis case, with a runtime on the order of five minutes.

Display of intermediate variables in the development version of the prototype requires numerous if-statements throughout the code to save and display values of parameters as they are being used. This feature extends run-time and would not be required in an operating version of the application to the extent that intermediate variables are examined in development versions. Consequently, an identical version of the Excel/VBA prototype, but without the option to display intermediate variables was used for a test of runtime of the prototype.

A test with three bond-lines and a five-day mission analysis duration gave a run-time of 90 seconds for the version that included display of intermediate variables. Extrapolating this to a prototype run-time for 20 bond-lines and a 21-day mission duration, gives a prototype run-time of 42 minutes.

Using the version of prototype without display of intermediate variables, the analysis runtime for three bond-lines and five-day mission analysis duration was 35 seconds. Extrapolating this to the configuration of 20 bond-lines and a 21-day mission duration, gives a projected runtime of the Excel/VBA prototype of 16.3 minutes. This is the projected actual runtime for analysis calculations, not including set-up time nor post-processing data display time.

For the given design-model data related to 14 bond-lines, and for an average desirable mission duration of 10 days for contingency attitude timeline evaluation that requires a rapid response, the prototype run-time would be 5.4 minutes in the Excel/VBA prototype.

Improvement in run-time can be expected if the Excel/VBA code is changed to use a C or C++ Dynamic Link Library (DLL) or if the final application is hosted on a Linux workstation rather than using Excel/VBA on a personal computer. The increase in speed should decrease the run-time by a factor of five to 10, so a reasonable expectation is to accomplish the 20-bondline, 21-day-mission case with a run-time of two to four minutes.

CONCLUSIONS

Exploration of the proposed analytical approach for an operations-oriented passive thermal model has shown that the method has the potential to perform within needed accuracy and run-time requirements. Study of this approach by development of the Excel/VBA prototype application has provided valuable insight into both the advantages and unexpected complexities of using the techniques based on Schmidt-plot calculation sequences to predict TPS tile and substrate temperatures.

Positive aspects and beneficial results have been demonstrated toward the goal of meeting constraints that are typical for Mission Operations requirements for real-time applications. Feasibility of use of the proposed method has been demonstrated in terms of the orbit time-step calculation of tile surface temperatures exposed to orbital heating, and the use of those time-step surface temperatures to calculate unsteady-state temperature profiles within the TPS and substrate materials.

Experience from the prototype development is being applied to the writing of requirements for the final workstation application. By this development effort, it has been shown to be feasible to integrate major passive thermal analysis capabilities into a unified ATCS – PTCS application. These capabilities include providing user-selection of orbit definition and attitude timeline input data, calculating external incident heat rates, accomplishing thermal analysis to compute bond-line temperatures and internal heat rates, and presenting plots of selected output data.

Use in a final passive thermal application of the approach that has been developed in the prototype effort has been shown to offer advantages over the alternatives of adapting a numerical-analysis, design-oriented detailed model to the operations-driven requirements, or of applying state-of-the-art data-base techniques to the application. The final form of the prototype approach incorporates some beneficial aspects of the data-base approach of using archived design-model analysis results and flight data, by using data of this type to initialize some calculation aspects.

Features of ease of setup and initiation of mission analysis cases for contingency attitudes, ease of incorporating design-model data and flight data in a data-base oriented accompanying resource and processing sequence, adequate accuracy and acceptable run-times have been demonstrated and indicated by the prototype development task.

Unexpected complexity was encountered in the aspects of prototype development related to use of tile-substrate energy balance and thermal-mass heat storage as a basis for calculating subsequent time-step surface temperatures of tile. Evidence from prototype development indicates that this is due to use of the one-dimensional analysis related only to the tile, substrate and pressure vessel, in configurations in which other thermal mass effects and multi-dimensional effects of structure and components are present between the substrate and the pressure vessel. Two methods of compensating for these effects, the use of correlation between incident heat and tile surface temperature and the use of correlated unknown-thermal-mass effects, have been examined and used. Final determination of the appropriate instances and ways in which to apply these methods remains to be accomplished.

Current information from the prototype development task indicates that both the proven, Schmidt-plot-based calculation of unsteady-state temperature profiles and the less-developed companion methods of calculating time-step surface temperatures from heat-balance equations or correlations with incident heat rate, can form a basis for a useful passive-thermal application. Feasible characteristics of the application are demonstrated by the ability to accomplish bond-line temperature analyses for 10 - 20 bond-line locations at five-minute orbit time-step intervals for up to a 21-day mission, with projected run-times on the order of five minutes.

Development of the prototype operations-oriented passive thermal model for bond-line temperature prediction has provided positive opportunities for coordination and understanding between Mission Operations, JSC Engineering personnel, and Orion contractor personnel on many beneficial aspects of study and development of passive thermal analysis applications.

ACKNOWLEDGEMENTS

Appreciation is expressed to the following personnel and groups whose assistance has been essential for the successful conclusion of this work:
JSC Engineering Directorate, Thermal Design Branch ES3/Stephen Miller and others for providing overall guidance, recommendations and Thermal Desktop expedited intermediate model checks of aspects related to thermal capacitance of materials.
Lockheed Martin/Sam Lucas, Alex Walker and others who provided excellent examples of design-engineering numerical analysis results for panels of Orion TPS and substrate materials.
Other personnel within JSC Mission Operations and DS44 Environmental Systems Group for technical support and recommendations.

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NOMENCLATURE, ACRONYMS, ABBREVIATIONS

(Not Applicable)

APPENDICES

Appendix A Curve-Fit Equations for Specific Heat and Thermal Conductivity

Appendix B Prototype Functional Flow Summary

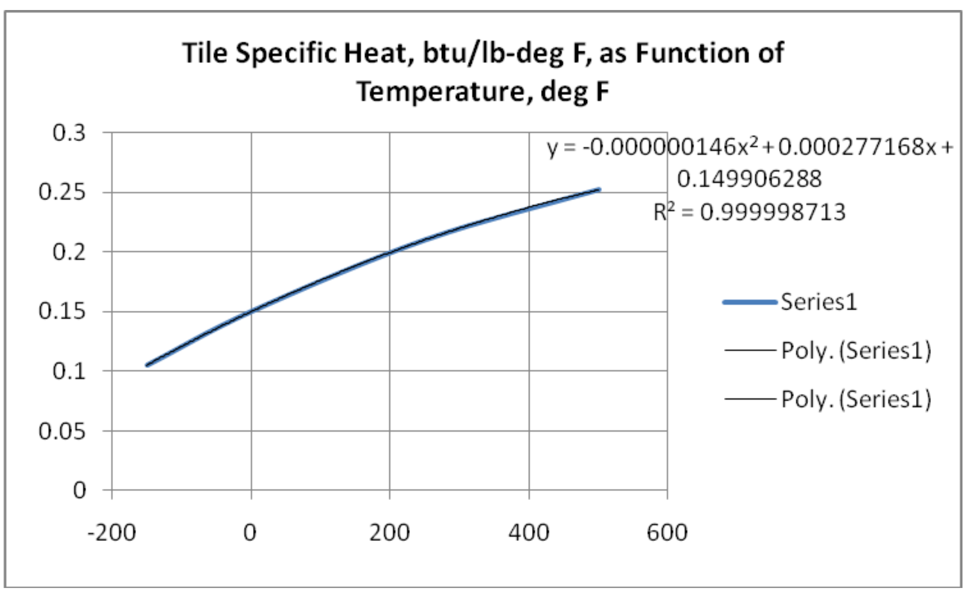
Appendix A

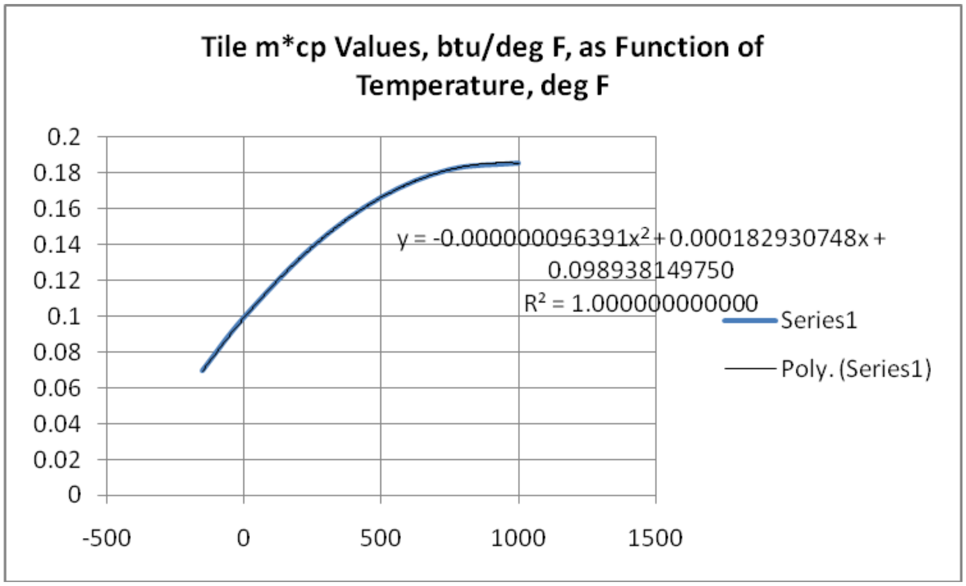
Curve-Fit Equations for Specific Heat and Thermal Conductivity

Reference: Initialization workbook

Calculation of Tile and Substrate Specific Heat as Function of Temperature
Ref: LM Data: Backshell Temperatures and Properties 10/22/2009
Ref: PTCS Model Rev F, Input-Output Data Cell A238
Tile: AETB-8 TPS cp

Temp deg F	Btu/lbm-F	cp, btu/lbm-degF	lbm/ft2		Tile m*cp	Eqn check tile m*cp
-150	0.105	0.10504505	0.66	-150	0.06932974	0.06933
0	0.15	0.14990629	0.66	0	0.09893815	0.098938
250	0.21	0.21007028	0.66	250	0.13864639	0.138646
500	0.252	0.25197838	0.66	500	0.16630573	0.166306
750	0.275	0.27563056	0.66	750	0.18191617	0.181916
1000	0.288	0.28102684	0.66	1000	0.18547771	0.185478





Tile cp = (-0.00000014604725*(TdegF^2)) + (0.0002771678*TdegF) + 0.1499062875

Tile m*cp = -0.000000096391185x2 + 0.000182930748000x + 0.098938149750000

Substrate

Tile		Panel	A	B	E
	Tile thickness	In.	0.99	1.45	0.99
		Ft	0.0825	0.1208	0.0825
	Density	lbm/ft3	8	8	8
	Wt of 1 Ft2	lbm	0.66	0.97	0.66
	k	btu/hr-ft-degF	0.0213	0.0213	0.0213
	cp	btu/lbm-degF	0.15	0.15	0.15
	Tile m*cp	btu/lb-dgF-ft2	0.099	0.145	0.099

Substrate:		Panel	A	B	E
Outer Facesheet Thickness,		In.	0.022	0.044	0.022
		ft	0.00183	0.00367	0.00183
	Density	lbm/ft3	98.50	98.50	98.50
	Wt of 1 Ft2	lbm	0.1806	0.3612	0.1806
	k	btu/hr-ft-degF	0.3758	0.3758	0.3758
	cp	btu/lbm-degF	0.2460	0.2460	0.2460
	Mass Fraction		0.2194	0.3599	0.2194
	k fraction: R = L/k for A 1 Ft2		0.0049	0.0098	0.0049
	cp fraction		0.0540	0.0885	0.0540

		Panel	A	B	E
Core Thickness		In.	0.75	0.75	0.75
		ft	0.06250	0.06250	0.06250
	Density	lbm/ft3	4.50	4.50	4.50
	Wt of 1 Ft2	lbm	0.2813	0.2813	0.2813
	k	btu/hr-ft-degF	0.0342	0.0342	0.0342
	cp	btu/lbm-degF	0.1250	0.1250	0.1250
	Mass Fraction		0.3417	0.2802	0.3417

k fraction: R = L/k for A 1 Ft2		1.8275	1.8275	1.8275
cp fraction		0.0427	0.0350	0.0427

	Panel	A	B	E
Inner Facesheet Thickness, In.	In.	0.044	0.044	0.044
	ft	0.0037	0.0037	0.0037
Density	lbm/ft3	98.50	98.50	98.50
Wt of 1 Ft2	lbm	0.3612	0.3612	0.3612
k	btu/hr-ft-degF	0.3758	0.3758	0.3758
cp	btu/lbm-degF	0.2460	0.2460	0.2460
Mass Fraction		0.4388	0.3599	0.4388
Total Sbstr Wt, 1 Ft2	lbm	0.8230	1.0036	0.8230
Tot Mass Fract Chk		1	1	1
k fraction: R = L/k for A 1 Ft2		0.0098	0.0098	0.0098
cp fraction		0.1080	0.0885	0.1080
total Sbstr R1+R2+R3	hr-degF/Btu	1.8421	1.8470	1.8421
UA = 1/(R1 + R2 + R3)		0.5429	0.5414	0.5429
Ltotal	ft	0.0680	0.0698	0.0680
kequiv = UA/A * Ltotal		0.0369	0.0378	0.0369
total Sbstr cp	btu/lbm-degF	0.2046	0.2121	0.2046
Bulk density Total wt/(L ft *1ft2)	lbm/ft3	12.1029	14.3711	12.1029

	Bond-line #	Approx, constant values:	1	-100	-50	0	50	
Tile		Panel	A					
Tile thickness		In.	0.99	0.99	0.99	0.99	0.99	
		Ft	0.0825	0.0825	0.0825	0.0825	0.0825	0
	Density	lbm/ft3	8	8	8	8	8	
	Wt of 1 Ft2	lbm	0.66	0.66	0.66	0.66	0.66	
	k	btu/hr-ft-degF	0.0213	0.01771 1	0.0187481 6	0.01978 5	0.02082 2	0.
	cp	btu/lbm-degF	0.15	0.1255	0.1355	0.1455	0.1555	0
	Tile m*cp =			0.08283	0.08943	0.09603	0.10263	0.
				Temperature, deg F:				
Substrate:		Panel	A	-100	-50	0	50	
		In.	0.0220	0.0220	0.0220	0.0220	0.0220	0
		ft	0.0018	0.0018	0.0018	0.0018	0.0018	0
	Density	lbm/ft3	98.5001	98.5001	98.5001	98.5001	98.5001	98
	Wt of 1 Ft2	lbm	0.1806	0.1806	0.1806	0.1806	0.1806	0
	k	btu/hr-ft-degF	0.3758	0.2937	0.3145	0.3353	0.3560	0
	cp	btu/lbm-degF	0.2460	0.1379	0.1666	0.1964	0.2262	0
	Mass Fraction		0.2194	0.2194	0.2194	0.2194	0.2194	0
	k fraction: R = L/k for A 1 Ft2		0.0049	0.0062	0.0058	0.0055	0.0051	0
	cp fraction		0.0540	0.0303	0.0365	0.0431	0.0496	0
		Panel	A					
		In.	0.7500	0.7500	0.7500	0.7500	0.7500	0
		ft	0.0625	0.0625	0.0625	0.0625	0.0625	0
	Density	lbm/ft3	4.5000	4.5000	4.5000	4.5000	4.5000	4
	Wt of 1 Ft2	lbm	0.2813	0.2813	0.2813	0.2813	0.2813	0

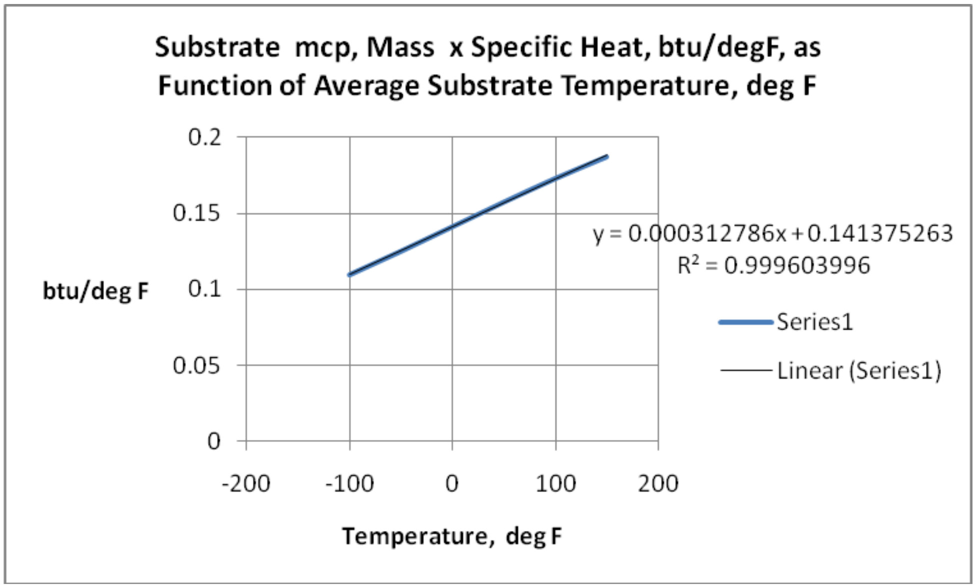
	k	btu/hr-ft-degF	0.0342	0.0668	0.0699	0.0730	0.0760
	cp	btu/lbm-degF	0.1250	0.1250	0.1250	0.1250	0.1250
	Mass Fraction		0.3417	0.3417	0.3417	0.3417	0.3417
	k fraction: R = L/k for A 1 Ft2		1.8275	0.9351	0.8942	0.8567	0.8222
	cp fraction		0.0427	0.0427	0.0427	0.0427	0.0427

		Panel	A				
		In.	0.0440	0.0440	0.0440	0.0440	0.0440
		ft	0.0037	0.0037	0.0037	0.0037	0.0037
	Density	lbm/ft3	98.5001	98.5001	98.5001	98.5001	98.5001
	Wt of 1 Ft2	lbm	0.3612	0.3612	0.3612	0.3612	0.3612
	k	btu/hr-ft-degF	0.3758	0.2937	0.3145	0.3353	0.3560
	cp	btu/lbm-degF	0.2460	0.1379	0.1666	0.1964	0.2262
	Mass Fraction		0.4388	0.4388	0.4388	0.4388	0.4388
Total Sbstr Wt, 1 Ft2		lbm	0.8230	0.8230	0.8230	0.8230	0.8230
	Tot Mass Fract Chk		1.0000	1.0000	1.0000	1.0000	1.0000
	k fraction: R = L/k for A 1 Ft2		0.0098	0.0125	0.0117	0.0109	0.0103
	cp fraction		0.1080	0.0605	0.0731	0.0862	0.0993
total Sbstr	R1+R2+R3	hr-degF/Btu	1.8421	0.9539	0.9117	0.8731	0.8376
UA = 1/(R1 + R2 + R3)			0.5429	1.0484	1.0969	1.1454	1.1939
	Ltotal	ft	0.0680	0.0680	0.0680	0.0680	0.0680
kequiv = UA/A * Ltotal			0.0369	0.0713	0.0746	0.0779	0.0812
total Sbstr cp		btu/lbm-degF	0.2046	0.1335	0.1524	0.1720	0.1916
mass-average							
Substrate total m*cp for 1 ft2			0.1684	0.1099	0.1254	0.1415	0.1577

For plot and equation of tot sbstr m*cp as function of temp:

Total composite sbstr m*cp: Sbstr m*cp = (0.000312786*TdegF) + 0.1413752628

-100	0.109885	0.110097
-50	0.125393	0.125736
0	0.141544	0.141375
50	0.157698	0.157015
100	0.17321	0.172654
150	0.187439	0.188293



Substrate Equivalent Overall Thermal Conductivity

T, deg F	btu/hr-ft-degF	y = 0.000070089641x + 0.077537613786
-100	0.069833	0.070529
-50	0.074588	0.074033
0	0.077886	0.077538
50	0.081182	0.081042
100	0.084477	0.084547
150	0.087772	0.088051

Note: This estimation of substrate thermal conductivity does not include radiation heat transfer effects in the honeycomb core. Additional evaluation is in-work, comparing prototype results with 1-D Thermal Desktop results, to determine the accuracy and effect of this estimation.

cpTile = (-0.00000014604725 * (stepTileAveTdegF ^ 2)) + (0.0002771678 * stepTileAveTdegF) + 0.1499062875

This needs: cpTileSqCoeff, cpTileLinCoeff, cpTileConst

mcpTileBtuDegF = (-0.000000096391185 * (stepTileAveTdegF ^ 2)) + (0.000182930748 * stepTileAveTdegF) + 0.09893814975

This needs: mcpTileSqCoeff, mcpTileLinCoeff, mcpTileConst

kcondTile = (0.0000207429 * stepTileAveTdegF) + 0.0197853029

This needs: kTileLinCoeff, kTileConst

akTile = kcondTile / (cpTile * densityTile)

cpSbstr = (0.000380055661 * stepSbstrAveTdegF) + 0.171780277476

This needs: cpSbstrLinCoeff, cpSbstrConst

mcpSbstrBtuDegF = (0.000312786 * stepSbstrAveTdegF) + 0.1413752628

This needs: mcpSbstrLinCoeff, mcpSbstrConst

kcondSbstr = (0.000070089641 * stepSbstrAveTdegF) + 0.077537613786

akSbstr = kcondSbstr / (cpSbstr * densitySbstr)

Appendix B

Prototype Functional Summary

a. Overview summary of control panel

This control panel for the prototype is a table section of the Input-Output Data worksheet, organized for rapid viewing, checking, changing of material properties and analysis case set-up parameters.

The categories are as follows:

Initial conditions, analysis case setup, orbit definition, attitude timeline, active bond-lines and number of bond-lines selection, and output data selections.

Inputs from the control panel are applied into the application operating code by subroutines. Application operating begins when the user selects the button to initiate a mission case-run. The management subroutine that begins running, OverallMacro(), corresponds to a Main function of C-Language code, and contains the sequence of operating subroutines in the Excel/VBA prototype.

InitializeInputsTable() establishes default conditions and color-coding to indicate active parameters and values.

SelectActiveBondlines() applies the user-input selection for which bond-lines are to be analyzed for the case-run, at Input-Output Data Cell A76.

GetInputs() reads the input parameters from the control panel and uses these values to dimension the arrays, using parameters such as number of bond-lines and number of calculation sections of materials.

b. Popup Dialog Boxes

Popup dialog boxes are provided in sequence after the user initiates the mission-analysis case. These dialog boxes are used to obtain user-selected options that are specific within a given analysis case activity. These options include the following aspects:

Option to display or not display tables of intermediate values of all calculations, for diagnostic work during development. Based on status of DisplayIntermediate flag, an extensive system of optional display of all intermediate values of all calculations is contained within the prototype. This allows detailed examination of calculations during prototype development. Requirements may retain parts of this feature to be available to users of the final application.

Selection of bond-line number and orbit time-step to be used for the display of intermediate values

Selection of bond-line number and orbit time-step for routine display of two temperature profiles for step-to-step comparison and evaluation

Selection of option for substrate inner surface boundary conditions:
Option is provided for using a table of values for substrate inner surface boundary-condition temperature, or of using a value of pressure vessel temperature for each active bond-line as the boundary condition

c. Pre-loop Calculations

OverallMacro() operation continues to accomplish standard pre-loop preparatory calculations prior to the main orbit time-step loop. These pre-loop calculations include the following items:

Initialize orbit time-step, orbit and bond-line loops, and cycle-control parameters

Initialize parameters such as OrbTimeStepCount, OrbStepStartMin, etc.
ClearOutputDataTables() subroutine.
Initialize sun-to-y-axis angle to zero.

Select option of type of incident heating to be applied to the TPS tile exterior surface:

Based on user selection on control panel, the type of incident heating is based on one of these options:

(Note that this is still pre-loop, so the OrbTimeStepCount is set to be = 1)

If UseTestQ = 1, 2 or 3:

1. Use solar heat flux, calculated by stepping of the solar vector around the vehicle

Calculation of incident heat rate upon TPS tile exterior surfaces is accomplished in the prototype in a different manner than will be incorporated in the final application. This will be accomplished in the final application by use of orbit parameters and vehicle attitude timeline, plus vector calculations, to determine the solar vector, earth-view, earth albedo, and earth I.R. incident heat values on each bond-line location that is selected for analysis. This is similar to the operation of current applications within the Environmental Systems Group that determine orbital heating rates upon selected locations of radiators on the Orbiter. Since these are standard calculations accomplished by functions and classes that are readily available in the Operations applications development capabilities, these are not duplicated in this initial version of the passive thermal prototype.

To simulate some of the vector calculations that lead from definition of a solar vector to calculation of incident heat rates on each bond-line location for application design and run-time evaluation, the prototype uses a system of simulated solar vector calculations and incident heat values. These were developed from LM design model sink temperature tables for Orion vehicle radiator panels. The sink temperatures were used, along with assumptions for the portion of heating to be due to earth albedo and I.R, to find corresponding basic, total incident heat rates on all bond-line locations as functions of rotational distance around the vehicle.

If the option of using this simulated solar vector source of orbital heating is selected by the user, the subroutines calculate the resulting incident heat rate in terms of btu/hr-ft2 at each bond-line location for each five-minute orbital time-step, for the entire mission case-run.

For-next loops cycle through all active bond-lines, and accomplish this in the CalcIncidQ() subroutine.
Inputs: Bond-line number, n, SunYaxisAngleDeltaDeg and SolarAngStepDeg
Outputs: startBLSolAngDeg, stopBLSolAngDeg, startIncidQBtuHrFt2 and stopIncidQBtuHrFt2

2. Use table of test-oriented heat rates

This is used during development and testing to input a given sequence of heat-rate values upon the TPS surface, so prototype output can be compared with identical heat input values from the design-model data for verification.
Accomplished for 18 orbit time-steps of one orbit.

3. Use a step-function option of applying a heat value at a user-input initial value, and then providing one step-change to a different incident heat value

Used during early development testing

Clear the output data tables that are used to display intermediate values

This is accomplished if the DisplayIntermediate option is selected.

Pre-loop calcs continued: for all selected bond-lines, calculation of selected bond-line parameters

A loop is used to cycle through all bond-lines to calculate the following parameters for each bond-line:

Assign local variables to material properties of density, thickness, emissivity, mass per ft2, etc.
Calculate of pre-loop initial step-start and step-stop surface temps, using the incident-heat values:
Purpose of this is to find average tile and substrate temperatures to use to calculate temperature-depend cp and k, pre-loop, for Schmidt-plot parameters. Linear-average temperatures through the materials are used based on given inputs:
Given initial values of tile surface temperature, bond-line temperature, substrate temperature and average incident heat rate are organized and calculated
Surface temperature and bond-line array variables are initialized:
StepStartSurfTdegF(OrbTimeStepCount, n) = InitSurfTDegF(n)
StepStartBLIFTdegF(OrbTimeStepCount, n) = InitBLTDegF(n)

Initial substrate temperature, InitSbstrTDegF(n), is either from Input-Output Data is from the read-in of table of values.

These average temperatures are calculated by this, and are used to find initial temperature-dependent parameters

stepStartTileAveTDegF
stepStartSbstrAveTDegF

Step-start surface temperature is given, so step-start radiation heat rate, StepStartRadQBtuHrFt2() is calculated.

Step-stop surface temps are based on average step-start & step-stop Qincident values.

Since this step-stop surf temp is only used as part of finding temp-dependent cp and k, pre-loop at this step, we do not need the accuracy adjust that is used later in the main orbit loop.

If Qincident is changing normally, calc step-stop surf T from Ave Qincident.

If Qincident is not changing, set step-stop surf T = step start surf T:

For other step-stop values, assume step-stop bond-line and substrate inner surface temperatures are equal to step-start values.

End-result of this phase of pre-loop calculations is the determination of step overall average tile and substrate temperatures, to be used in the calculation of temperature-dependent specific heat and thermal conductivity.

Calculate temperature-dependent cp and k, pre-loop, using curve-fit equations:

Inputs for this are as follows: stepOvrlTileAveTDegF, stepOvrlSbstrAveTDegF, cpTile, mcpTileBtuDegF, kcondTile, akTile and the same for substrate

Preloop continued:

Calc the Schmidt-plot parameters,using cp and k:

Physical tile section thickness:

delXTileFt(n) = (thickTileIn(n) / 12) / NumSectionsTile   'ft

Generic, Schmidt-parameter tile section thickness:

genDelxFt(n) = delXTileFt(n) / kcondTile

The relationship for composite walls:

delXSbstrFt(n) = delXTileFt(n) / ((akTile / akSbstr) ^ 0.5)

NumSectionsSbstr(n) = 1 + ((thickSbstrIn(n) / 12) / delXSbstrFt(n))

NumSectionsTotal(OrbTimeStepCount, n) = NumSectionsTile + NumSectionsSbstr(n)

thickTotalSections(n) = (delXTileFt(n) * 12 * NumSectionsTile) +
(delXSbstrFt(n) * 12 * NumSectionsSbstr(n))
genDelThetaSec(n) = kcondTile * densityTile * cpTile * (genDelxFt(n) ^ 2) * 3600 / 2

Note that since the thermal properties can vary between orbit time-steps, the Schmidt-plot parameters such as generic x-axis delta-distance, genDelxFt(n) and the subsequent parameters can vary, so the total number of sections is a function of both the bond-line number and the OrbTimeStepCount, so this is stored in appropriate array variable.

Preparations are accomplished for setting the dynamic array variables for Schmidt-process-calculated temperature, Tx(delx,delTheta) in PassiveThermalCalcSeq() subroutine:
Set MaxNumGenDeltaTheta(n) and LgstMaxNumDelThetaLoop for ReDim of array variables

Pre-Orb loop calculation of stepStartProfileTDegF() using initial linear slopes.

stepStartProfileTDegF(n, 0) = InitSurfTDegF(n)
Result of this is: array variable, stepStartProfileTDegF(n, NumGenDelx)

End of Pre-loop calcs and pre-loop cycle through all bond-lines

d. Main Program Loop of Orbit Time-steps

This primary loop of the application is accomplished in the OverallMacro() subroutine.

Main program loop of time-steps:
Do While OrbStepStopHrs <= RunTimeMaxHrs
StepStopMinutes(OrbTimeStepCount)
OrbStepStopMin

'Use the startTestVerifStepCount and stopTestVerifStepCount for finding Qincid from the table values, and sbstr inner surface temp local values from array,also.
Use stopTestVerifStepCount to use the values of solar Q from a table, repeatedly for successive orbits.

Main calculation loop for selected bond-lines,
For n = 1 To NumBond-lines
Calculation of incident Q: In orb time-step loop

Based on user selection on control panel, the type of incident heating is based on one of these options described earlier:
If UseTestQ = 1, 2 or 3:

1. Use solar heat flux, calculated by stepping of the solar vector around the vehicle
   Cycle through all active bond-lines, and accomplish this:
   CalcIncidQ()
2. Use table of test-oriented heat rates
3. Use a step-function option of applying a heat value at a user-input initial value, and then

Calculate stepDelQincidBHF2pMin t be used later, during PassiveThermalCalcSeq()

For the determination of if to calc the temp-dependent variables:
'Note that MinNormAbsQincidStepBHF2pMin is set = 2 btu/hr-ft2 per step, or 0.4 BHF2 per min. Temporary change: MinNormAbsQincidStepBHF2pMin = 0.85
'Assign local variables:
densityTile = densTile(n)
densitySbstr = densSbstr(n)
tileThickInch = thickTileIn(n), etc.
'Set initial local variable sbstrInrBCTDegF for this bond-line and this orb time step, to be used for first cycle of IntegSchmidtPlotCalc(). The new, integrated part of
'sbstr-based Schmidt plot calc will re-calc or re-set this BC, based on sbstr
surf temp, each theta-cycle. The sbstrInrBCTDegF is temp that is set at Num Sections Total + 1, for the Schmidt plot calc cycles.

'

When option is selected to use a table of sbstr inner surf T values,
'sbstrStopInnerBCTdegF is based on
StepStopSbstrInrTdegF(OrbTimeStepCount, n)
'from the input-data table.
'If pv-wall-temp option is selected,
sbstrStopInnerBCTdegF is set to be = pv wall
'temperature. (Assumes effective conductivity sbstr to pv is = conductivity
'internal to substrate. May need to refine later)

If UseSbstrInrSurfTblFlag = 1 And UseTestQ = 2 Then
sbstrStopInnerBCTdegF =
StepStopSbstrInrTdegF(OrbTimeStepCount, n) + _

(stepStartProfileTDegF(n, NumGenDelx)
- _
stepStartProfileTDegF(n, (NumGenDelx
- 1)))

Now, within the OverallMacro and the main orbit time-step loop and
Cycling through each bond-line at each orbit time-step,
This subroutine is used for the core unsteady-state temperature profile calculations:
PassiveThermalCalcSeq()

PassiveThermalCalcSeq() subroutine accomplishes these tasks:

Major if-statement for option of main calculation sequence, to determine if the incident heat rate upon the bond-line location tile surface is changing at a normal rate so the method of finding step-stop temperature based on incident heat rate can be used. The alternative, if the incident heat rate is not changing as in the case of eclipse orbit periods, is to calculate step-stop temperature based on the heat balance of tile and substrate

.

```
If Abs(stepDelQincidBHF2pMin)  >=
                MinNormAbsQincidStepBHF2pMin Then
```

Normal Qincident calculations:

Calc StepStopSurfTdegF(OrbTimeStepCount, n)
using curve-fit equations for Surf Temp as function of step ave Qincident
Also, calculate a delta surf T accuracy correction based on stepDelRateQincidBHF2min and using subroutines that are specific for each bond-line

```
  Select Case n
        Case 1                   'Bond-line 1, Panel A
          SurfTAccuracyDelBL1
        Case 2                   'Bond-line 2, Panel B
          SurfTAccuracyDelBL2
        Case 3                   'Bond-line 3, Panel E
          'Input to this subroutine is:
      step-ave Qincident stepAveQincidBHF2
          SurfTAccuracyDelBL3
      End Select
  'Output of these subroutines is stepStopTCorrectionDegF
  StepStopSurfTdegF(OrbTimeStepCount, n) =
      StepStopSurfTdegF(OrbTimeStepCount, n) +
```

stepStopTCorrectionDegF

Also calculate:

stepStartRadnQBtuHrFt2
stepStopRadnQBtuHrFt2
stepAveRadnQBtuHrFt2
delSurfTdegF

For other step-stop values, for purposes of the
temp-dependent variable calcs
assume step-stop BLIFT and
Sbstr Inr T = step-start values.

stepStopTileAveTDegF
stepStopSbstrAveTDegF
stepOvrlTileAveTDegF
stepOvrlSbstrAveTDegF

calc of temp-dependent cp and k, tile and sbstr
Calc the Schmidt-plot parameters,using cp and k.

Note that based on the temperature-dependent parameters and the resulting calculation of Schmidt-plot variables, the number of sections of substrate and total material, can change as a function of orbit time-step. To appropriately record and use the profile temperature as a function of x-distance through the material, it is necessary to rescale the generic x-axis delta-step distances. This is accomplished by a special subroutine, RescaleNumGenDelx(). That subroutine uses a step-wise interpolation based in the array variables, and incorporates the previous number of sections, the available temperature profile based on that previous number of sections, and the new number of sections. The outputs of this subroutine are the new x-axis range of zero to total number of sections, and the new stepStartProfileTDegF(n, NumGenDelx)

This point of the main calculation loop also calculates the parameters thickTotalSections(n), genDelThetaSec(n), MaxNumGenDeltaThetaLoop(n) and LgstMaxNumDelThetaLoop

ElseIf Abs(stepDelQincidBHF2pMin) <
MinNormAbsQincidStepBHF2pMin Then

Low Qincident option

This finds a tileStepDeltaDegF based on step net Qincid - Qradn, and mcp tile apparent, to calculate StepStopSurfTdegF(OrbTimeStepCount, n).

This does not calculate new temperature-dependent uses temp-dependent variables, but uses the specific-heat and thermal-conductivity values, plus the resulting Schmidt parameters from pre-loop or from previous time-step.

Rather than iteration, for this estimated step-stop temperature, for finding step-stop Qradiation,this uses step-stop surf temp = previous step-stop surf T.

step-start T this cycle = step-stop T of last cycle
assumeStepStopSurfTDegF =
    StepStartSurfTdegF(OrbTimeStepCount, n)
stepStopRadnQBtuHrFt2
stepAveRadnQBtuHrFt2

Set mcTileApparent = 0.38, based on Verif Calcs 022810 Cell AHC112:

tileSurfTstepDelDegF = ((stepAveQincidBHF2 -
    stepAveRadnQBtuHrFt2) _
        * OrbTimeStepMin / 60) / mcTileApparent
StepStopSurfTdegF(OrbTimeStepCount, n) =
    StepStartSurfTdegF(OrbTimeStepCount, n) +
    tileSurfTstepDelDegF
stepStartRadnQBtuHrFt2
stepStopRadnQBtuHrFt2
stepAveRadnQBtuHrFt2
delSurfTdegF
Only the tile Qmcdt and tile surf Q are used to find tile surf stop temps
    for this Low Qincident Option, now:

PassiveThermalCalcSeq() Continued

Outcome at this point is calculation of iterStartProfile(n, NumGenDelx).

The initial temperature profile through the material at the star of the Schmidt-plot calc algorithm was planned to be an iteration step when The primary means of calculating involved the thermal mass and heat balance. Consequently, the Schmidt-process initializing profile was called iterStartProfileTDegF(n, NumGenDelx), a temperature profile being function of both the bond-line Number and the x-distance through the material.;

That iteration process is not primary now, but the nomenclature of the Array variable to contain the Schmidt-initiatiing profile is retained.

iterStartProfileTDegF array variable set for starting the Schmidt-plot calculations is established using the stepStartProfile plus the values of temperature at tile surface, stepStopSurfTdegF(OrbitTimeStepCount, n) determined as previously described using incident heat rates, and the value of temperature at the substrate inner surface. That substrate inner surface temperature and boundary condition are obtained either from a table of substrate temperatures vs. time from design-model data, or from a setting of the boundary condition to be equal to the pressure vessel wall external temperature

At this point, we have a starting-point temperature profile and a step-function change of a surface step-stop temperature at both the tile surface and the substrate surface. These are the essential components needed to operate the core unsteady-state temperature profile-determining subroutine, IntegSchmidtPlotCalc().

IntegSchnidtPlotCalc()

Description of this subroutine is based on Figure A-1, similar to Figure 13 in the body of the paper, but oriented here to variables and sequences used in the algorithm.

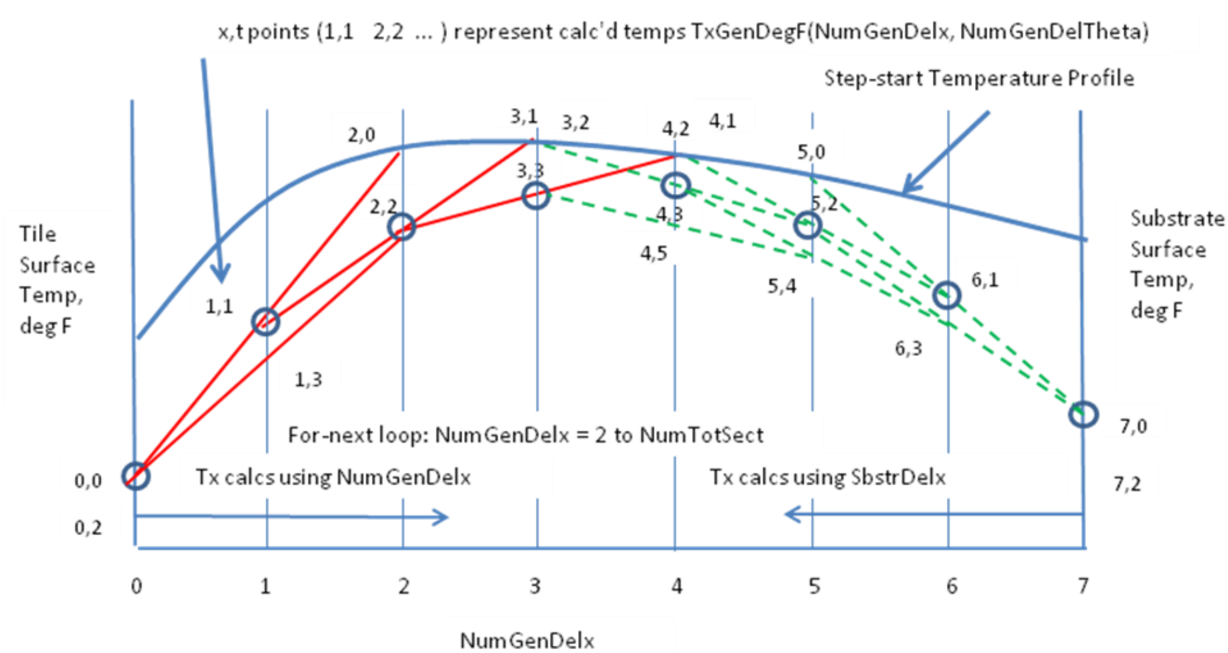


Figure B-1: Calculation Process in IntegSchmidtPlotCalc() Subroutine
Ref: Verif Calcs Update 022810 Cell ALZ250

Inputs to IntegSchmidtPlotCalc()

The Schmidt-plot parameters: NumGenDelx, NumSections, NumGenDelTheta etc

iterStartProfileTDegF(n, NumGenDelx) which is step-start profile with the step-function change of tile surface temperature and substrate inner surface temp.

Output: stepStopProfileTDegF(n, NumGenDelx)

Description:

Combined sequence is as described in Verif Calcs Update 022810 Cells approx AJV135, AKM204, AKL247.
See plots and discussion at that location of workbook for details

This description presents a summary of steps of the subroutine to indicate the approach and sequence of the calculations, but all details of the calculations are not duplicated here.

Reference also, the basic SchmidtPlotCalc() in Revs H – M and the IntegSchmidtPlotCalc() subroutine code.

NumTotSect = NumSectionsTotal(OrbTimeStepCount, n)

(1) Set the Tx temps on the iterStart profile line that are used to calculate the initial series

First, set the surface temperatures for all NumGenDelTheta:

TxGenDegF(0, NumGenDelTheta) =
iterStartProfileTDegF(n, 0)

Then: Set the Tx values that are on the iterStartProfile line:

```
For NumGenDelx = 2 To NumTotSect
        NumGenDelTheta = NumGenDelx - 2
        TxGenDegF(NumGenDelx, NumGenDelTheta) =
                iterStartProfileTDegF(n, NumGenDelx)
Next NumGenDelx
```

(2) First cycle of Tx calcs, x from 1 to total:

This calculates the first row of Tx points following along the iterStart profile (Points with circles in Figure A-1).

Run the calculations in from both sides to the mid-point,

```
MidGenDelx = Round(NumTotSect / 2)
For NumGenDelx = 1 To MidGenDelx
        NumGenDelTheta = NumGenDelx
        Calc TxGenDegF(NumGenDelx, NumGenDelTheta), basic
                Schmidt calc
        For the problem of needing next theta-value of Tx, from other
                direction:
                TxGenDegF(NumGenDelx, (NumGenDelTheta + 1)) =
                        TxGenDegF(NumGenDelx, NumGenDelTheta)
                Save the Tx value for output:
                TxFnlDegF(NumGenDelx) = TxGenDegF(NumGenDelx,
                        NumGenDelTheta)
                For the Schmidt calc from substrate surface;
                SbstrDelx = NumTotSect - NumGenDelx
                Calc TxGenDegF(SbstrDelx, NumGenDelTheta), basic
                        Schmidt calc
                TxGenDegF(SbstrDelx, (NumGenDelTheta + 1)) =
                        TxGenDegF(SbstrDelx, NumGenDelTheta)
                TxFnlDegF(SbstrDelx) = TxGenDegF(SbstrDelx,
                        NumGenDelTheta)
                CycleNum = CycleNum + 1
Next NumGenDelx
```

(3) Next cycles: A loop of theta-time cycles, and at each theta-time, run Tx calcs from tile surface to midpoint, and from substrate surface to midpoint.

```
Do While NumGenDelTheta <= MaxNumGenDeltaThetaLoop(n)
        'NumGenDelTheta = 3, 5, 7....
        NumGenDelx = 1
        CycleNum = 1
        Do While NumGenDelx < NumGenDelTheta And NumGenDelx
                <= MidGenDelx  'NumGenDelx = 1, 3, 5
                Calc TxGenDegF(NumGenDelx, NumGenDelTheta), basic
                        Schmidt calc
                TxFnlDegF and Tx for Theta+1, as before.
        Loop
        NumGenDelTheta = NumGenDelTheta + 1      NumGenDelTheta
                = 4, 6, 8
       NumGenDelx = 2
       CycleNum = 1
       Do While NumGenDelx < NumGenDelTheta And NumGenDelx
                <= MidGenDelx
                Calc TxGenDegF(NumGenDelx, NumGenDelTheta), basic
                        Schmidt calc
                TxFnlDegF and Tx for Theta+1, as before.
        Loop
Loop
Save the max used del-x and del-theta-time values:
        NumGenDelx = NumGenDelx – 2
        NumGenDelTheta = NumGenDelTheta – 1
        MaxUsedGenDelx = NumGenDelx
        MaxUsedNumGenTheta
Set the  output data of stepStopProfileTDegF(n, NumGenDelx):
        For NumGenDelx = 0 To MaxUsedGenDelx
                stepStopProfileTDegF(n, NumGenDelx) =
                        TxFnlDegF(NumGenDelx)
        Next NumGenDelx

 For the NumGenDelx from MaxUsedGenDelx + 1 to the
        NumSectionsTotal(OrbTimeStepCount, n), the step-stop
        profile is = the iterstart profile.
 If MaxUsedGenDelx < NumTotSect Then          'Fill in the remaining
        profile steps
       For NumGenDelx = (MaxUsedGenDelx + 1) To NumTotSect
          stepStopProfileTDegF(n, NumGenDelx) =
                iterStartProfileTDegF(n, NumGenDelx)
       Next NumGenDelx
 End If                 'End if for MaxUsedGenDelx <

 End Sub          'End IntegSchmidtPlotCalc()
```

Output of InegSchmidtPlotCalc(): stepStopProfileTDegF(n, NumGenDelx)

Output of PassiveThermalCalcSeq():

Near end of PassiveThermalCalcSeq():
Saves data in array variables for later display of normal two-temp profiles through material.
stepStopFirstProfileTDegF(NumGenDelx)
stepStopSecProfileTDegF(NumGenDelx)

End PassiveThermalCalcSeq()

Main bond-line loop, continued, in OverallMacro()

Call to CalcBLProfilesRoutine() here, because it is dependent on specific applicable bond-line and two orbit time-steps. Only the calculation steps for the routine display of two bond-line profiles' array values are here. The DisplayBLProfilesRoutine() subroutine used later is changed to only display, not calculate, the data, so it is called from the OverallMacro() after completion of the main orbit time-step loop.

```
If n = BLNumTProfile  And (OrbTimeStepCount =
        FirstProfileOrbStepCount _
        Or OrbTimeStepCount = SecProfileOrbStepCount) Then
                CalcBLProfilesRoutine to fill arrays for first and sec temp
                profiles
End If                  'End if-stmt for display first/sec BL profiles
```

'01/21/10: Updated to add the calc of tile and sbstr average temps, for use in calc of temp-dependent cp and k at top of loop next cycle:

```
stepStopTileAveTDegF = (StepStopSurfTdegF(OrbTimeStepCount, n) +
        StepStopBLIFTdegF(OrbTimeStepCount, n)) / 2
stepStopSbstrAveTDegF = (StepStopBLIFTdegF(OrbTimeStepCount, n)
        +  StepStopSbstrInrTdegF(OrbTimeStepCount, n)) / 2
stepOvrlTileAveTDegF = (stepStartTileAveTDegF +
stepStopTileAveTDegF) / 2
stepOvrlSbstrAveTDegF = (stepStartSbstrAveTDegF +
        stepStopSbstrAveTDegF) / 2
'>>>>>>>>>
'Set the new stepStartProfileTDegF(n, NumGenDelx) to be used at top of
        loop 'in next orb time-step count:
```

Note that at pre-loop calcs and at end of SchmidtQpvSbstrCalc, we have

stepStopProfile
to NumSectionsTotal(OrbTimeStepCount, n) + 1
For NumGenDelx = 0 To (NumSectionsTotal(OrbTimeStepCount, n) + 1)
stepStopProfileTDegF(n, NumGenDelx) =
stepStopProfileTDegF(n, NumGenDelx) + delTdegF
Next NumGenDelx 'End for-next NumGenDelx

For NumGenDelx = 0 To (NumSectionsTotal(OrbTimeStepCount, n) + 1)
stepStartProfileTDegF(n, NumGenDelx) =
stepStopProfileTDegF(n, NumGenDelx)
Next NumGenDelx 'End for-next NumGenDelx

Step-start values that are needed at top of loop, next cycle:
'These are needed:
'StepStartSurfTdegF(OrbTimeStepCount, n)
'StepStartBLIFTdegF(OrbTimeStepCount, n)
'StepStartSbstrInrTdegF(OrbTimeStepCount, n)
'stepStartTileAveTDegF
'stepStartSbstrAveTDegF
'stepOvrlTileAveTDegF
'stepOvrlSbstrAveTDegF
StepStartSurfTdegF((OrbTimeStepCount + 1), n) =
StepStopSurfTdegF(OrbTimeStepCount, n)
StepStartBLIFTdegF((OrbTimeStepCount + 1), n) =
StepStopBLIFTdegF(OrbTimeStepCount, n)
StepStartSbstrInrTdegF((OrbTimeStepCount + 1), n) =
StepStopSbstrInrTdegF(OrbTimeStepCount, n)

Next n 'End of main for-next loop for bond-lines, n, all calcs

Increment the angle, solar vector to y-axis:
SunYaxisAngleDeltaDeg = SunYaxisAngleDeltaDeg +
SolarAngStep

Loop 'End of main loop of stepping through orbit time-step

Section for display of output data tables and plots:
1. Place results in output data tables.
Results are stored in the 2-D arrays, so can print/display them anytime

Option to display tables of all output data or only the surface and bond-line temperatures

If DisplayAllOutputTables = 1 Then

Sheets("Input-Output Data").Select

PrintAllOutputData

Sheets("Input-Output Data").Select

Range("AR21").Select

This subroutine displays the following parameters in large tables that present the values for mission analysis duration and for all active bond-lines.

Some of these parameters were active only during the evaluation of unknown thermal mass, xmc.

StepStartBLSolAngDeg(ArrayOrbStepCount, n)
stepAveIncidQBtuHrFt2()
StepAveRadQBtuHrFt2(ArrayOrbStepCount, n)
StepStopSurfTdegF(OrbTimeStepCount, n)
StepStopBLIFTdegF(OrbTimeStepCount, n)
StepStopSbstrInrTdegF(OrbTimeStepCount, n)
stepTileDelQmcdtBtuHrFt2()
stepTileDelQmcdtBtuHrFt2()
stepSbstrDelQmcdtBtuHrFt2()
stepTotDelQmcdtBtuHrFt2()
stepXDelQmcdtBtuHrFt2()
stepDelQPVtoSbstrBtuHrFt2()
stepXmcBtuDegF(OrbTimeStepCount, n)

An example of the output results table, for the bond-line interface temperature is shown in Table B-1

Table B-1 Example Output Data Table

StepStopBLIFTdegF(OrbTimeStepCount , n)			1	2	3
0	0	0	90	-27	72
5	0.08	0.00	90.00	-25.30	72.00
10	0.17	0.01	91.25	-14.98	72.00
15	0.25	0.01	76.86	-34.29	72.00
20	0.33	0.01	64.65	-57.51	28.11
25	0.42	0.02	64.65	-57.51	55.31
30	0.50	0.02	64.65	-57.51	67.33
35	0.58	0.02	41.24	-57.51	82.89
40	0.67	0.03	28.47	-57.51	99.10
45	0.75	0.03	28.47	-57.51	99.10
50	0.83	0.03	-10.29	-57.51	55.25
55	0.92	0.04	-5.54	-111.26	65.51
60	1.00	0.04	56.85	-101.29	105.08
65	1.08	0.05	85.69	-81.97	108.26
70	1.17	0.05	85.69	-60.21	102.52
75	1.25	0.05	85.69	-29.74	92.25
80	1.33	0.06	102.78	-29.74	79.50
85	1.42	0.06	122.65	-29.74	65.51

```
ElseIf DisplayAllOutputTables = 0 Then
        PrintBLandSurfTTable
        Range("AR2645").Select
Else
End If
```

2. Display of material temp profiles for first orbit, for all three active bond-line:

These are plotted as function of NumGenDelx

Calculate the LM temp profiles from the LM given input data of tile surf temp, bond-line temp, etc., and display the total profile tables/plots for the first orbit for the three bond-lines at FV11 of Input-Output Data sheet.

This generates profile arrays from LM data.

CalcLMTempProfiles

This displays both the LM and subroutine profile data in tables and plots at FV11 of Input-Output Data:

DisplayOneOrbProfiles

Table B-2 Example of Output Data, Temperature Profiles Table
Ref: Normal is: Input-Output Data FV11
This example: Archived Data workbook,
Data 042810 C12

03/11/10 Based on LM Panel A data, and Schmidt-plot calcs
without Q pv to substrate, because substrate inner surface temp is given

1	OrbTCount	1	LM Start	LM Stop	Subroutine
	NumGenDelx		Profile T dg F	Profile T dg F	Stop Profile T
		0	100.00	89.00	89.00
		1	98.67	90.33	89.64
		2	97.33	91.67	89.86
		3	96.00	93.00	90.07
		4	94.00	91.33	89.22
		5	92.00	89.67	88.36
		6	90.00	88.00	86.41
		7	86.25	85.25	84.45
		8	82.50	82.50	82.28
		9	78.75	79.75	80.10
		10	75.00	77.00	78.55

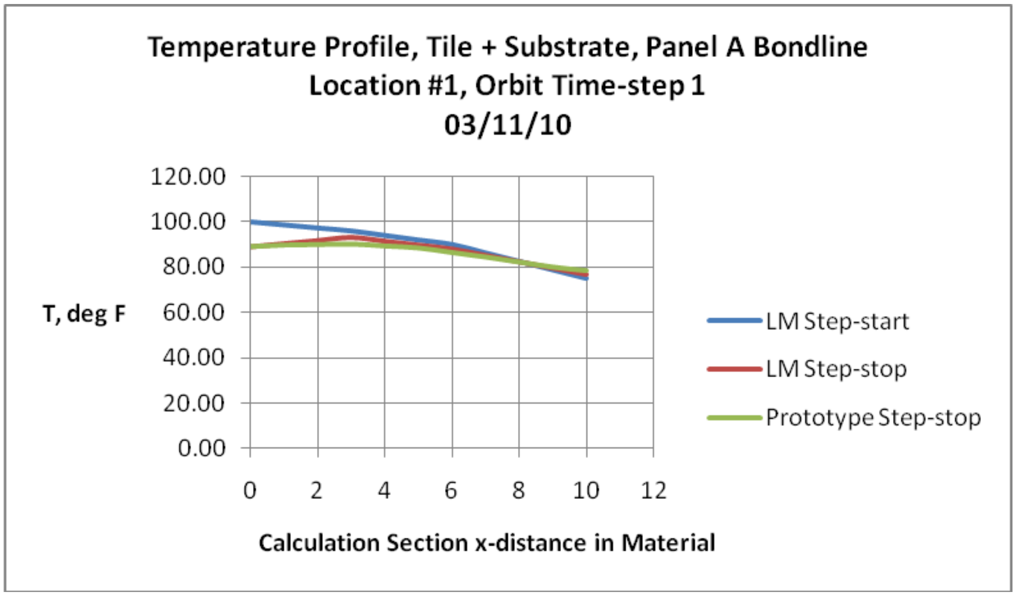


Figure B-2   Example of Output Data Temperature Profile Plots
Ref: Archived Data workbook, Data 042810 Sheet, I

3. Display of temperature profiles for the routine, selected two orbit cycles of one
bond-line.
DisplayBLProfilesRoutine

```
TotMaxNumTimeSteps = OrbTimeStepCount - 1
'TotNumMaxTimeSteps is used in print output data
```

4.   Place final OrbTimeStepCount and OrbStepStopDays in Output Data Table

```
Sheets("Input-Output Data").Select
Range("AO20").Select
ActiveCell.value = (TotMaxNumTimeSteps)
Range("AO21").Select
ActiveCell.value = OrbStepStopDays
Range("AO22").Select
ActiveCell.value = RunTimeMaxDays
Range("AO20").Select
MsgBox "Calculations and display of results are complete for this analysis case."
```

End Sub 'End OverallMacro()