INITIAL ASSESSMENT OF A RAPID METHOD OF CALCULATING CEV ENVIRONMENTAL HEATING

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ABSTRACT

An innovative method for rapidly calculating spacecraft environmental absorbed heats in planetary orbit is described. The method employs reading a pre-existing baseline database of orbital absorbed heats, calculated by Monte Carlo methods, and adjusting those heats for particular orbit parameters. The approach differs from traditional Monte Carlo methods that are orbit based with a planet centered coordinate system. The database is based on a spacecraft centered coordinate system where the range of all possible sun and planet look angles are evaluated. In an example case 37,044 orbit configurations were analyzed for average orbital heats on selected spacecraft surfaces. Calculation time was under 2 minutes while a comparable Monte Carlo evaluation would have taken an estimated 26 hours.

1.0 INTRODUCTION

For large complex spacecraft determining orbital heats as needed is often not practical due to excessive computation times. A solution to this problem has been to calculate databases of orbital heats in anticipation of needs. Typically these databases have been orbit based with a distribution of possible orbits and attitudes calculated. This approach results in very large databases that take a large amount of CPU time to make. Since these databases are orbit based there is close duplication of many planet and orbit vectors.

In this new approach the sun and planet are oriented in the spacecraft coordinate system. The range of all possible sun and planet look angles are accounted for in the database. There are no unnecessary duplication of vectors. A test database was built and a reading/analyzing routine was written.

The test database was built of separately computed solar, albedo and IR absorbed heats for a simplified Crew Exploration Vehicle (CEV) at 1134 uniformly distributed look angles using Monte Carlo ray tracing techniques in Thermal Desktop® (TD) [1]. The CEV model was constructed with 507 nodes. The absorbed heats were computed for a baseline set of planet radius, albedo, IR constants and altitude. An orbit generator (ORBGEN) routine was adapted to read the database and perform calculations. For an input orbit, ORBGEN will find database points closest to the orbit points, perform interpolation between points, modify the absorbed heat values for the actual planet parameters and the orbit altitude, and compute data for input queries.

The spacecraft oriented database Rapid Calculation Method (RCM) can greatly reduce computer time compared to calculating orbital heating using planet oriented coordinate methods. In a demonstration case, orbital minimums, maximums, and averages were obtained for a group of nodes for 37,044 orbit configurations. RCM took approximately 2 minutes to calculate. Using TD for each case would have taken about 26 hours.

2.0 MODELING ASSUMPTIONS

The database was constructed with these assumptions.

1. The planet is a diffuse emitter and reflector.
2. Only instantaneous direct and reflected environmental heating is calculated. There is no emitted radiation between vehicle surfaces due to surface temperature differences.
3. Planetary solar albedo flux is a function of the vehicle's sun zenith angle (angle from noon), and is constant over the vehicle's field of view.
4. Variation of planetary albedo and IR absorbed heats with altitude is assumed proportional to planet view factor on a surface facing the planet.

3.0 CONSTRUCTION OF DATABASE

The basis set of orbit and planetary parameters used to calculate the database is listed in Appendix A.

3.1 Uniformly Divided Sphere Used for Attitude Look Angles

The database, in order to anticipate all possible sun and planet look angles, was built with an isotropic sun and planet vector distribution. This uniform vector field was built by using an algorithm that places points uniformly on a sphere. The spacecraft is then considered to be at the center of the sphere (see Fig.1). Each point on the sphere results in a vector, heats were calculated for each vector by considering the planet and solar vectors to be anti-parallel. TD has a vector list option for input of solar and planet vectors.

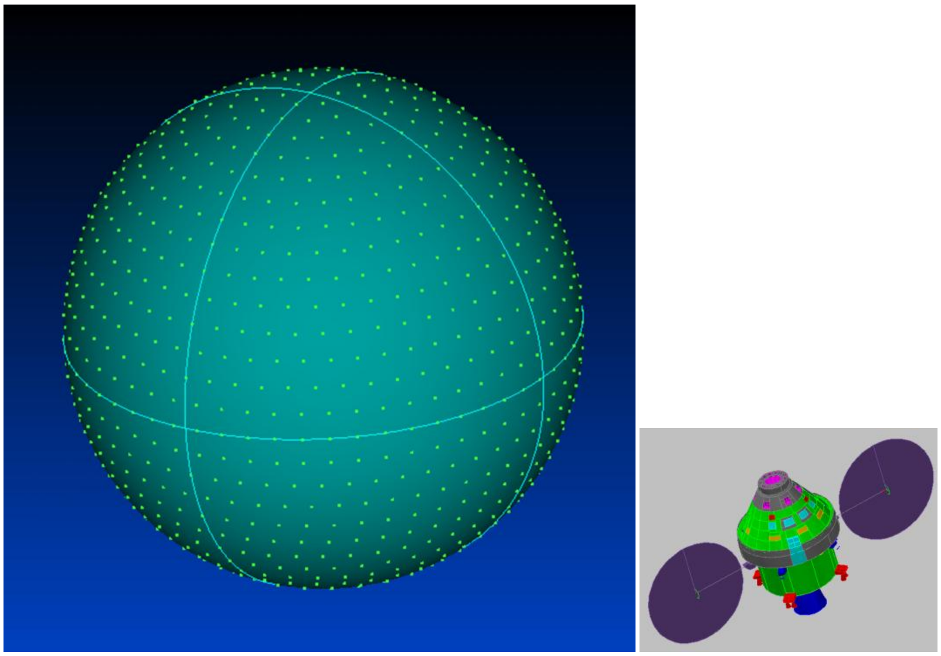

Figure 1 Sphere with 1134 equally spaced vector directions. The CEV is considered to be at the center of the sphere with sun and planet located at vector directions. The angle between adjacent vectors is about 6^{o}.

3.2 Writing the Database

After the model has run for all the vectors (look angles) in the vector list, TD outputs the nodal absorbed heats into a text file (SINDA.HRa). The text file has separate listings for solar, albedo, and IR heats for each node for each vector. A Fortran program was written to read this text file and construct a binary database. Future enhancements could include reading the absorbed heat data directly from TD without the intermediate text file. There is a record for each vector in the binary database. The record format is:

j, PlanetFlag, theta, phis, Qs(j,1:Nnode), Qa(j,1:Nnode), Qp(j,1:Nnode)

where

j	vector number, record number
PlanetFlag	planet indicator- not used
theta	Inclination (cone) angle
phis	azimuthal (clock) angle
Qs(j1:Nnode)	nodal solar absorbed heats
Qa(j1:Nnode)	nodal albedo absorbed heats
Qp(j1:Nnode)	nodal planetary absorbed IR
Nnode	Nodes in the model

At a particular orbit location ORBGEN will search the database for solar and planet look angles that are closest to the actual angles.

The present database was constructed for 1134 vectors with 5000 rays per node and 507 nodes in the model. Run time took about 2.7 hrs on a 2.5 GHz PC computer. The database size is 6.7 MB. The current model was not optimized for reduction of runtime or reduction of error.

4.0 ESTIMATION OF COMPUTATION TIME AND DATABASE SIZE IF CORRECTION METHODS ARE NOT USED

If correction methods are not employed, the number of cases to be computed can be very large. As an example database consider:

Case = position in space with a heat calculation

A_n = angles, a = altitudes, N_s = off sub-solar angles,

If A_n = 10270 (vectors spaced 2^o apart), a = 30, N_s = 18 (every 10°, axially symmetric)

For 2 planets with albedo and IR plus solar heats

Cases = $4*A_n*a*N_s + A_n$

Cases > 22,000,000

With 507 nodes in the spacecraft and 5000 rays per node and each ray taking a µsec, CPU time would be about 650 days. The database size would be more than 40GB. (On a dual core 2.53 GHz machine it takes about 1 µsec for a ray computation. The runtime could be reduced by running TD in batch mode on several machines after hours. This would require COM language programming, see Appendix B.)

5.0 USING ORBGEN WITH THE DATABASE

ORBGEN assumes circular orbits, and the vehicle is oriented relative to a planet-oriented coordinate system in the current version. Orbit parameters are entered into a text file. If specific node groups are of interest they can be entered into another text file, e.g. one wishes to find the orbital minimum, maximum and average absorbed heats for the radiators. The executable is run and results are output in a text file.

5.1 Computation of Orbital Absorbed Heats

In order to limit the number of cases that must be computed in TD, adjustment methods were used to compute absorbed heats for orbits with different parameters than the basis set tabulated in Appendix A. Orbits with different altitudes and planet radius are scaled according to view factors. Solar, albedo and IR constants were also scaled. These methods are discussed below.

5.2 Correction of Heats Due to Altitude, Albedo and IR Constants

For surfaces that have a full view of the planet, the view factor to the planet is proportional to

$$\frac{1}{\left(1+\frac{a}{r}\right)^2}$$

Eq. 1

where a is the altitude and r the planet radius. Absorbed heats for different radii and altitudes are computed by multiplying the database heat value by the ratio of the actual view factor and database basis view factor. Absorbed heats for solar, albedo, and IR constants differing from the basis set are likewise adjusted.

5.3 Calculation of Lunar and Earth Albedo and Lunar IR

All planetary heat sources are considered to be diffuse. However only the earth IR can be assumed to be uniform, while lunar and earth albedo and lunar IR depend on orbit position, specifically the angular distance from the planet sub-solar axis.

5.3.1 Calculation of Lunar IR

If one assumes an adiabatic regolith, that all sunshine not reflected is radiated as diffuse IR, then the IR radiosity is given by:

Eq. 2

where S is the solar constant, ρ is the solar reflectivity, and is the inclination angle from sub-solar axis to the spacecraft orbit position. See Fig. 2.

5.3.2 Calculation of Planetary Reflected Solar

Assuming diffuse reflection the planetary reflected solar flux is given by

Eq. 3

where is the solar constant, is reflectivity and is the angle from the sub-solar axis. The current absorbed heat calculation algorithm uses the IR or A values from Eq. 2 and Eq. 3 above for scaling. There is an error involved in using a constant radiosity value for all the planet surfaces in view of the spacecraft, see Fig. 2. TD does not correct for this error; it uses a constant value for all the planet surfaces within view of the spacecraft. This error is discussed in Section 8.7.

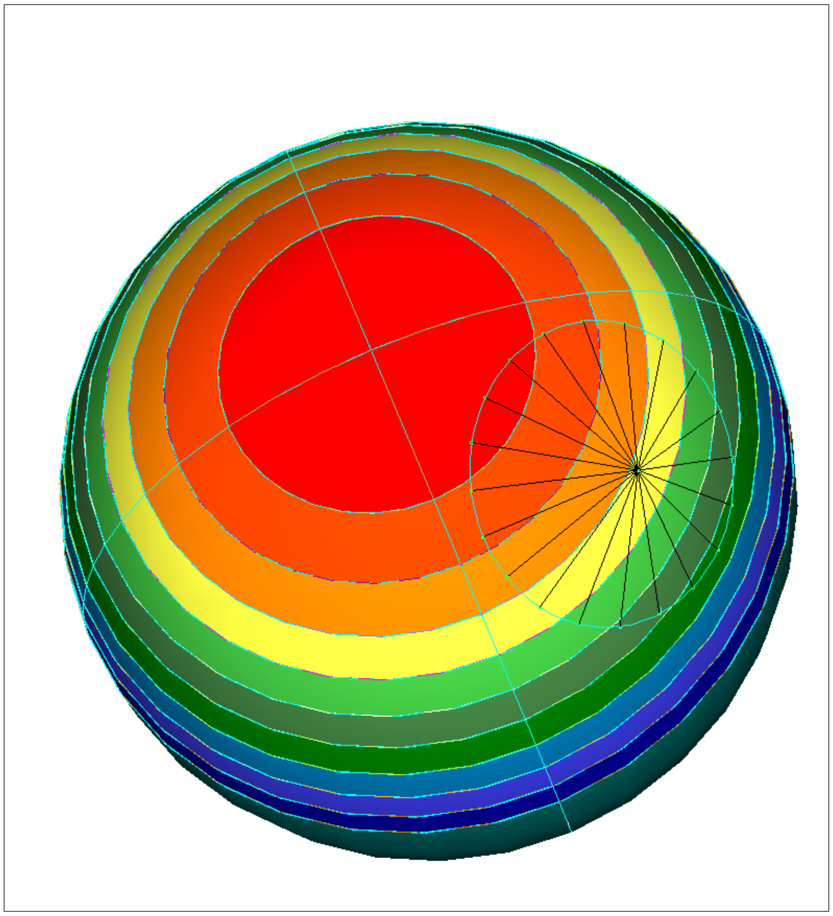

Figure 2 **A spacecraft view cone over planetary albedo or IR radiosity field. The fields vary with cosine of angular distance from the sub-solar axis. Contour lines are equidistant, scale is arbitrary. A spacecraft surface will receive energy from areas with possible large variations in radiosity. TD does not account for this variation; it uses a constant radiosity value for the planet surface in view of the spacecraft.**

6.0 RESULTS

RCM demonstration cases were run. In one example, with an altitude of 150 miles, the beta angle was varied in 15^o increments while yaw, pitch and roll were varied in 5^o increments. A total of 37,044 orbit configurations were analyzed and the average absorbed heat flux was computed for a group of nodes. Calculation time was approximately two minutes. A partial list of the data is shown below.

LIDS ELECTRICAL BOXES							
Average Group Absorbed Fluxes - W/M2**							
beta	**yaw**	**pitch**	**roll**	**Qs**	**Qa**	**Qp**	**Qtotal**
0	5	5	5	87.97	30.39	168.4	286.8
0	15	0	0	83.40	26.02	154.4	263.8
30	-15	-5	5	102.15	19.43	144.9	266.5
60	10	15	0	83.97	19.85	196.2	300.1
75	15	15	0	94.74	10.17	196.2	301.2

7.0 FUTURE WORK

7.1 COM Language Implementation

TD allows automation of models runs through an Excel interface using Microsoft COM language (See Appendix B). COM scripts were investigated to modify model parameters. COM can be used to build the vector list, input planet parameters, set ray numbers etc. Multiple machines could be utilized to run TD by scheduling runs after hours. COM scripting will no doubt have to be implemented if the number of data points to be computed becomes very large.

7.2 Oct-Cell Optimization

Oct-cells are a way TD subdivides the model space to reduce Monte Carlo runtimes. Without oct-cells, when a ray is cast, every surface in the model has to be checked for intersection. By dividing the model space into oct-cells, only those surfaces within the cell must be checked. There is an optimum number of cells for any model that will produce the shortest runtimes. This has not been thoroughly investigated.

7.3 Flux Cubes

Flux cube calculations could be added to the database for given points about the spacecraft. Previously, use of the flux cube technique involved placing a physical cube at the location and tracking orbital thermal radiation impinging on the surfaces of the cube [2]. The cube acted as a probe in the model but it affected the results because it blocked the radiation flux. A proposed enhancement would be to incorporate the concept of transparent flux cubes. The rays that encounter a cube face would pass through unaffected but the ray would be counted.

7.4 Investigate Error Size for Each Surface

The reflected error for a large surface to a small surface can be significant. The error is given by Eq. 4.

$$\varepsilon_{ij} = 1.645\sqrt{\frac{1 - B_{ij}}{n_i B_{ij}}} \qquad \text{Eq. 4}$$

where n_i is the number of rays cast from surface i, B_{ij} is the energy exchange factor, the fraction of energy emitted from surface i that is absorbed on surface j. The error increases for decreasing B_{ij}.

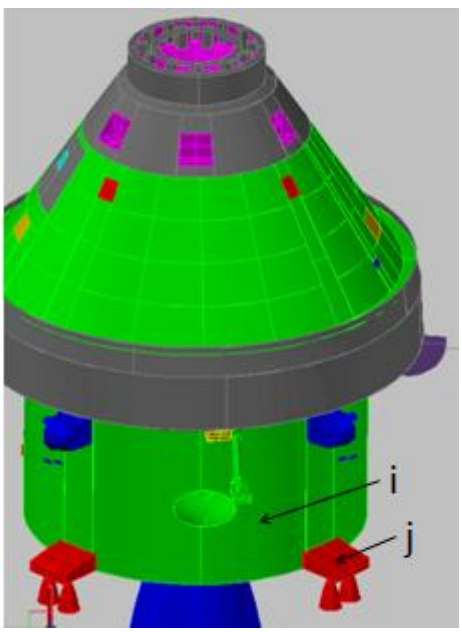

Figure 3 The indirect energy from surface i impinging surface j may be a large fraction of all energy received at j. The error in this energy calculation may be large.

Consider surfaces i and j shown in Fig. 3. At some look angles j could receive a significant amount of indirect radiation from i. If an insufficient number of rays are cast from i the error in energy exchange from i to j could be significant since the amount of radiation leaving i and impinging j is a small fraction of all the energy emitted by i. TD allows automatic error criteria to be used in determining the number of rays cast from a surface. This method was not used. Future work would involve determining acceptable error levels for each surface without unduly increasing runtimes.

7.5 Corrections for Articulating Surfaces

The database was constructed with solar and planetary vectors being anti-parallel; the solar arrays always tracking the sun as would be expected in an actual orbit. However in an actual orbit the solar and earth vectors will be at arbitrary angles and the solar arrays will not have the same orientation as calculated in the database. Test cases will have to be run to investigate the size and nature of this error. A method for correcting for this error has not been devised.

7.6 Investigate the Accuracy of View Factor Corrections for Surfaces That Only See Partial Planet View

The view factor for surfaces that see only part of the planet view cone does not have a simple altitude adjustment as given in Eq. 1.

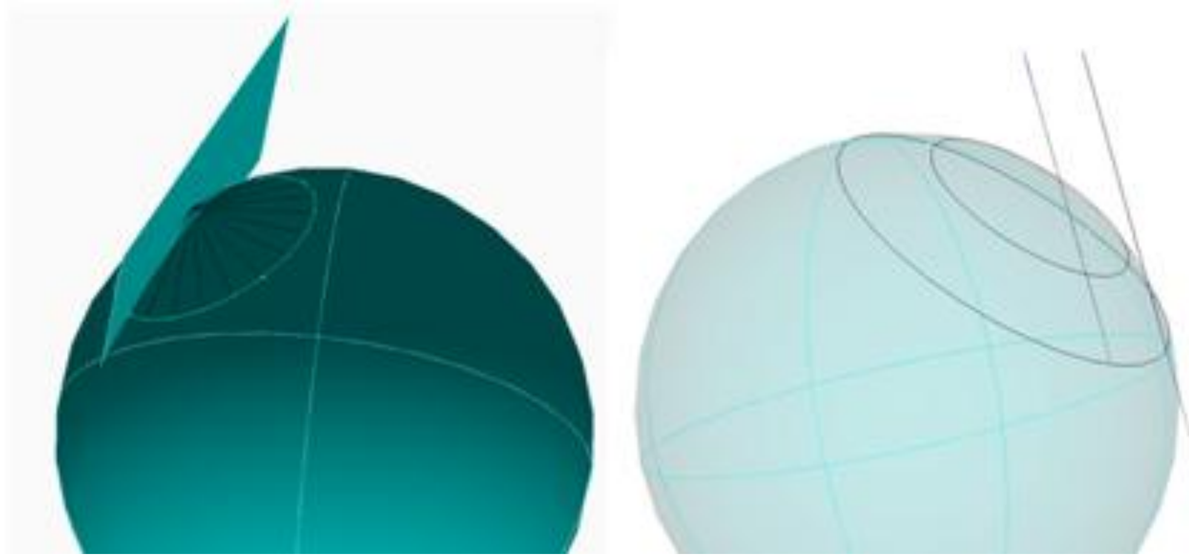

Figure 4 Some spacecraft surfaces with a normal that does not intersect the planet center will only have a partial view of the planet. The view cone will be truncated. The relative truncation of the view cone will not be the same for spacecraft surfaces at parallel orientations but different altitudes.

The nature of the error is due to the fact that, although the view cone scales with altitude and radius, the view angle that subtends the view cone does not remain constant, see Fig. 5. One possible approach would be to track surface normals and scale the heats according to view cone truncation along with view factor scaling. Another approach is to add altitudes to the database variables and interpolate between known altitudes. This approach would increase the size of the database.

7.7 Estimation of Error Due to Non-Uniform Planet Radiation Fields

As shown in Fig. 2 spacecraft surfaces receive radiation from a variation of radiation field intensities. Fig. 5 shows an example of heat flux computation using a constant radiosity value for all surfaces within the view cone and an exact integral calculation that takes into account the variation of radiosity over the planet's surface. The Fig. 5 altitude is half of the planet radius, greater than a typical orbit altitude. Relative magnitude of the error increases with altitude.

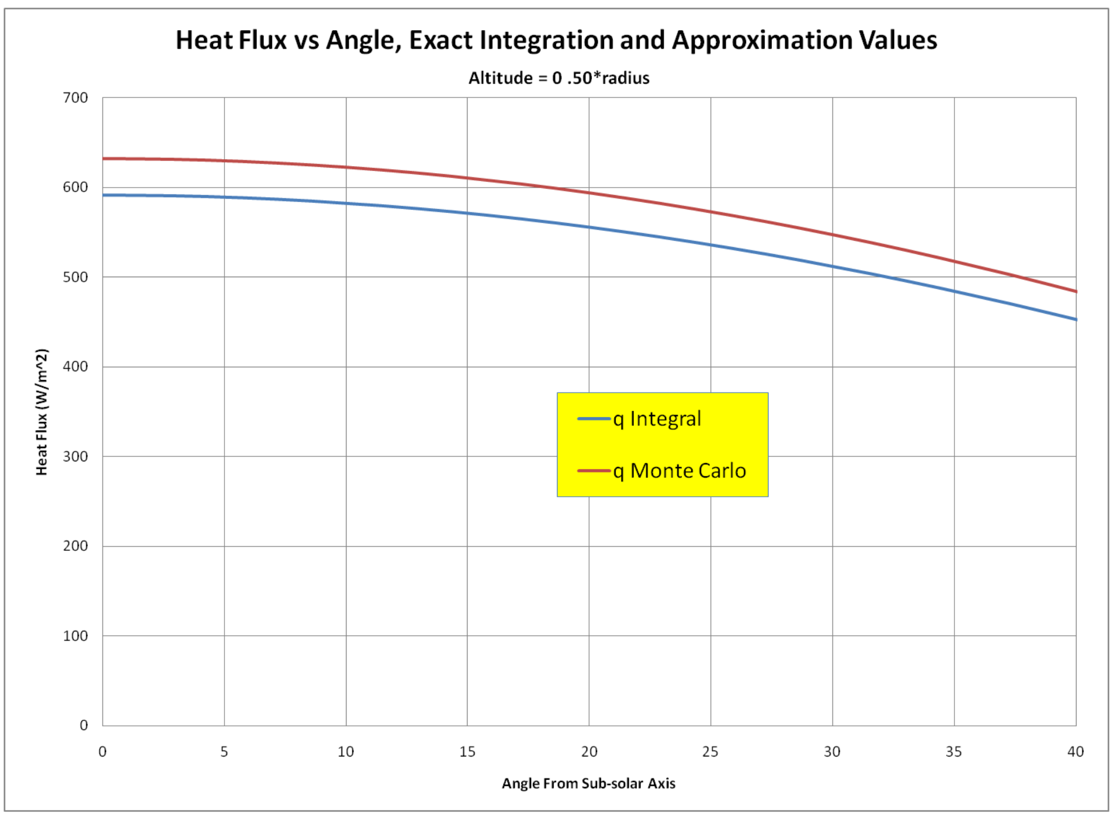

Figure 5 Heat flux calculated using the value of radiosity at sub spacecraft point and heat flux calculated from integration over view cone. Surface normal toward planet center. Exact integration used the integration formula discussed in Appendix C.

7.8 Using Exact Integration to Evaluate Error

An integral equation was formulated to calculate exact planetary reflected solar. The integral takes into account the cosine variation of radiosity fields as well as view cone truncation. The integral can be evaluated in MathCad [3]. The integral is applicable for flat surfaces with no shadowing but can be modified to accommodate curved surfaces. See Appendix C.

9.0 CONCLUSIONS

A method of rapidly calculating orbital heats on a spacecraft from database values was demonstrated. The method can calculate heats for an arbitrary orbit in minutes while a full Monte Carlo simulation may take hours. The method was demonstrated on CEV but is applicable to any spacecraft. Additional work is required to fully develop the method.

REFERENCES:

[1] Thermal Desktop User's Manual, Version 5.2, October 2008, C&R Technologies

[2] Lucas, G.W, ISS EVA Thermal Environments Databases and Search Routines (Rev H), September 30, 2004, MSAD-04-0336

[3] MathCad 14.0 MO3O, Parametric Technology Corporation, 140 Kendrick Street, Needham, MA 02494 USA

[4] http://www.microsoft.com/com/default.mspx

NOMENCLATURE

A	albedo
a	altitude
CEV	Crew Exploration Vehicle
COM	Component Object Model
F	view factor
IR	infra-red radiation
ORBGEN	Orbit generating, interpolation and heat calculation routine
Q_a	albedo heating
Q_p	planetary heating
Q_s	solar heating
r	radius
RCM	Rapid Calculation Method
S	solar constant
TD	Thermal Desktop
ρ	reflectivity

APPENDICES

APPENDIX A BASIS PARAMETERS

The basis values used to compute the database are listed in Table A.1

Parameter	Value
Planet Radius	6378.4 km
Altitude	637.84 km
Solar Constant	1354 W/m^2
IR Temperature	250 K
Albedo Constant	0.35

Table A.1 Parameters used in basisline database.

APPENDIX B COM TECHNOLOGY

From the Microsoft website [5]:

Microsoft COM (Component Object Model) technology in the Microsoft Windows-family of Operating Systems enables software components to communicate. COM is used by developers to create re-usable software components, link components together to build applications, and take advantage of Windows services. COM objects can be created with a variety of programming languages. Object-oriented languages, such as C++, provide programming mechanisms that simplify the implementation of COM objects. The family of COM technologies includes COM+, Distributed COM (DCOM) and ActiveX® Controls. COM is used in applications such as the Microsoft Office Family of products. For example COM OLE technology allows Word documents to dynamically link to data in Excel spreadsheets and COM Automation allows users to build scripts in their applications to perform repetitive tasks or control one application from another.

APPENDIX C INTEGRAL EQUATIONS FOR PLANETARY REFLECTED SOLAR

An integral equation was written that will calculate planetary heats exactly for unshadowed flat surfaces. It can be modified to accommodate curved surfaces.

$$q_{ji} = \frac{S}{A_i \cdot \pi} \int_0^{R_d} \int_0^{2\pi} \frac{n \cdot r_a(\alpha, R, t) \cdot r_a(\alpha, R, t) \cdot r(\alpha, R, t) \cdot (1 - \rho) \cdot z \cdot r(\alpha, R, t)}{P^2 \cdot \left| r_a(\alpha, R, t) \cdot r_a(\alpha, R, t) \right|^2} \cdot \frac{R}{\sqrt{1 - \left(\frac{R}{P}\right)^2}} \, dt \, dR$$

$$+$$

$$\frac{S}{A_i \cdot \pi} \int_{R_d}^{R_V} \int_{t_1(R)}^{t_2(R)} \frac{n \cdot r_a(\alpha, R, t) \cdot r_a(\alpha, R, t) \cdot r(\alpha, R, t) \cdot (1 - \rho) \cdot z \cdot r(\alpha, R, t)}{P^2 \cdot \left| r_a(\alpha, R, t) \cdot r_a(\alpha, R, t) \right|^2} \cdot \frac{R}{\sqrt{1 - \left(\frac{R}{P}\right)^2}} \, dt \, dR \qquad \text{Eq. C.1}$$

Symbol	Description
n	surface normal unit vector
P	planet radius
S	solar constant
z	solar unit vector
r_a	vector from planet surface to spacecraft surface
r	vector from planet center to differential planet surface area
R_V	radius of view cone
Rd	radius of partial view cone
t_1	angle 1 in truncation region
t_2	angle 2 in truncation region
ρ	reflectivity of planet
α	angle off sub-solar axis

The cosine variation of radiation is accounted for in z*r. The first integral is over the view cone in the non-truncated region; the second integral is over the truncation region.

If the surface normal intersects the planet center, then there is no truncation region and the integral formula simplifies:

$$q_{ji} = \frac{S}{A_i \cdot \pi} \int_0^{R_v} \int_0^{2\pi} \frac{n \cdot r_a(\alpha, R, t) \cdot r_a(\alpha, R, t) \cdot r(\alpha, R, t) \cdot (1 - \rho) \cdot z \cdot r(\alpha, R, t)}{P^2 \cdot \left| r_a(\alpha, R, t) \cdot r_a(\alpha, R, t) \right|^2} \cdot \frac{R}{\sqrt{1 - \left(\frac{R}{P}\right)^2}} \, dt \, dR$$

Eq. C.2