EUROPEAN COOPERATION

ECSS

FOR SPACE STANDARDIZATION

Space engineering

Thermal analysis handbook

Foreword

This Handbook is one document of the series of ECSS Documents intended to be used as supporting material for ECSS Standards in space projects and applications. ECSS is a cooperative effort of the European Space Agency, national space agencies and European industry associations for the purpose of developing and maintaining common standards.

The material in this Handbook is defined in terms of description and recommendation how to improve the thermal modelling and thermal analysis process for space applications.

This handbook has been prepared by the ECSS-E-HB-31-03A Working Group, reviewed by the ECSS Executive Secretariat and approved by the ECSS Technical Authority.

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Change log

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Scope

1.1 Objectives and intended audience

This handbook is dedicated to the subject of thermal analysis for space applications. Thermal analysis is an important method of verification during the development of space systems. The purpose of this handbook is to provide thermal analysts with practical guidelines which support efficient and high quality thermal modelling and analysis.

Specifically, the handbook aims to improve:

a. the general comprehension of the context, drivers and constraints for thermal analysis campaigns;

b. the general quality of thermal models through the use of a consistent process for thermal modelling;

c. the credibility of thermal model predictions by rigorous verification of model results and outputs;

d. long term maintainability of thermal models via better model management, administration and documentation;

e. the efficiency of inter-organisation collaboration by setting out best practice for model transfer and conversion.

The intended users of the document are people, working in the domain of space systems, who use thermal analysis as part of their work. These users can be in industry, in (inter)national agencies, or in academia. Moreover, the guidelines are designed to be useful to users working on products at every level of a space project – that is to say at system level, sub-system level, unit level etc.

In some cases a guideline could not be globally applicable (for example not relevant for very high temperature applications). In these cases the limitations are explicitly given in the text of the handbook.

1.2 Context

The use of computational analysis to support the development of products is standard in modern industry. Figure 1-1 illustrates the typical thermal modelling and analysis activities to be performed at each phase of the development of a space system.

> NOTE   More information about the project lifecycle can be found in ECSS-M-ST-10 [RD5].
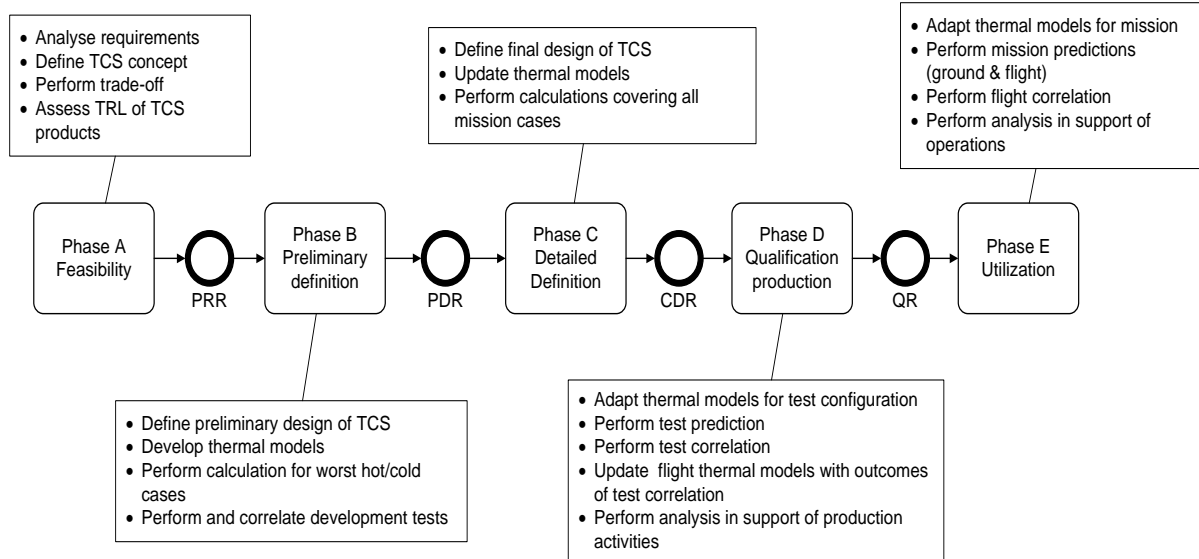
Figure 1-1: Thermal analysis in the context of a space project

It can be seen that thermal models are used during all phases of the space system development to support a large number of activities, ranging from conceptual design right through to final in-flight predictions.

Indeed, in some cases, thermal analysis is the only way that certain thermal requirements can be verified; as physical tests are either too expensive or unrealisable. It is therefore vital for the credibility of the predictions made that the quality of the models is as high as possible.

2
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3
Terms, definitions and abbreviated terms

3.1 Terms from other documents

a. For the purpose of this document, the terms and definitions from ECSS-ST-00-01 [RD6] apply, in particular for the following terms:

1. **validation**

    NOTE   Validation is the process of determining the degree to which a computational model is an accurate representation of the real world from the perspective of the intended uses of the model.

2. **verification**

    NOTE 1   Verification is the process of determining that a computational model accurately represents the underlying mathematical model and its solution

    NOTE 2   The topic of V&V is well known in the context of quality assurance and systems engineering (including software systems). There has also been some work in other domains such as Computational Fluid Dynamics (CFD) and structural mechanics to develop processes for V&V of simulation models. In the particular context of computational analysis the formal definitions usually apply [RD13].

    NOTE 3   More informally the following questions are often used to explain V&V in the context of computational analysis:

    - Verification "did we solve the equations correctly?"
    - Validation "did we solve the correct equations?"

b. For the purpose of this document, the terms and definitions from ECSS-E-ST-31 apply, in particular for the following terms:

1. **geometrical mathematical model**

    mathematical model in which an item and its surroundings are represented by radiation exchanging surfaces characterised by their thermo-optical properties

2. **thermal mathematical model**

    numerical representation of an item and its surroundings represented by concentrated thermal capacitance nodes or elements, coupled by a network made of thermal conductors (radiative, conductive and convective)

    NOTE   The current trend is towards integrated thermal modelling tools, in which case the distinction between Geometrical Mathematical

Model (GMM) and Thermal Mathematical Model (TMM) becomes ill-defined. Nonetheless the terms GMM and TMM are still used in the everyday language of thermal engineers and so the terms are retained in this document.

3. **thermal node**

representation of a specific volume of an item with a representative temperature, representative material properties and representative pressure (diffusion node) used in a mathematical lumped parameter approach

NOTE   The current document is written to be, as far as possible, tool and method independent. It is therefore useful to generalise the concept of thermal node to cover other numerical methods (e.g. the finite element method). Mathematically speaking a thermal node represents a "degree of freedom" in the equation system. More practically, the purpose of a thermal node is to provide a temperature evaluation (and output) at a selected location.

4. **uncertainties**

inaccuracies in temperature calculations due to inaccurate physical, environmental and modelling parameters

NOTE   This definition of uncertainty refers specifically to temperature calculations. In the context of this document this is widened to calculations of other key model outputs such as heater power or duty cycle.

3.2   Terms specific to the present document

3.2.1   accuracy

degree of conformance between an output of a thermal analysis and the true value

NOTE   The true value is usually a measurement from a physical test, for example a thermal balance test. The purpose of the verification and validation effort is thus to improve and quantify modelling accuracy.

3.2.2   arithmetic thermal node

thermal node with zero thermal capacitance

NOTE 1   Arithmetic nodes are normally treated specially by thermal solvers and a quasi-steady state solution is obtained for them during transient runs. This is useful to avoid excessively small time steps when lightweight items need to be represented in large models.

NOTE 2   Additionally arithmetic nodes are often used to represent thermal interfaces or the edges of region

3.2.3   computational model

numerical implementation of a mathematical model

NOTE 1   This is usually comprises numerical discretisation, solution algorithm, and convergence criteria.

NOTE 2   This definition is taken from RD11, where a more detailed discussion of the relationship between mathematical and computation models can be found.

3.2.4   CSG

ratio of capacitance to sum of connected conductances for a thermal node

NOTE   No specific acronym is available for CSG, most likely the C represents capacitance, the S represents the sum, and the G represents the conductors.

3.2.5   error

<CONTEXT: thermal analysis> difference between an output of a thermal analysis and the true value

NOTE 1   High accuracy analyses therefore produce outputs with small associated errors.

NOTE 2   This is a typical dictionary definition of error and generic. More specific and formal definitions occur in a number of other sources, for example ASME [RD13].

3.2.6   key model output(s)

output(s) from the thermal model having high level of importance

NOTE   Examples of key model outputs are TRP temperatures, heater duty cycles, and any other output form the model with special significance for the verification of the TCS.

3.2.7   radiative cavity

collection of radiative surfaces of the thermal-radiative model, having the property that its surfaces cannot exchange heat through thermal radiation with the surfaces belonging to another cavity

NOTE   This term is synonymous with "radiative enclosure".

3.2.8   radiative enclosure

See "**radiative cavity**".

3.3   Abbreviated terms

For the purpose of this document, the abbreviated terms from ECSS-S-ST-00-01 and the following apply:

Abbreviation	Meaning
BOL	beginning-of-life
CCHP	constant conductance heat pipe
CFD	computational fluid dynamics
CLA	coupled launcher analysis
CNES	Centre National d'Etudes Spatiales
COTS	commercial off-the-shelf

Abbreviation	Meaning
DGMM	detailed geometrical mathematical model
DRD	document requirements definition
DTMM	detailed thermal mathematical model
EEE	electrical, electronic and electromechanical
EOL	end-of-life
ESATAN	thermal/fluid analyser from ITP Engines
FEM	finite element method
GMM	geometrical mathematical model
HP	heat pipe
HTC	heat transfer coefficient
I/O	input / output
ICD	interface control document
ICES	International Conference on Environmental Systems
IR	infrared
KMO	key model output(s)
LHP	loop heat pipe
LP	lumped parameter
MCRT	Monte Carlo ray tracing
MLI	multi-layer insulation
OS	open source
PCB	printed circuit board
PID	proportional integral derivative
PLM	product lifecycle management
REF	radiation exchange factor
RGMM	reduced geometrical mathematical model
RTMM	reduced thermal mathematical model
S/C	spacecraft
SDM	simulation data management
SINDA	thermal/fluid analyser from C&R technologies
SVD	singular value decomposition
TB	thermal balance
TCS	thermal control system
TMG	thermal/fluid analyser from MAYA HTT Engineering Software Solutions
TMM	thermal mathematical model
TMRT	thermal model reduction tool
TRL	technology readiness level

Abbreviation	Meaning
TRP	temperature reference point
V&V	verification and validation
VCHP	variable conductance heat pipe

4
Modelling guidelines

4.1 Model management

The observed trend towards larger and more complex thermal models - coupled with an increase in the number of analysis cases to respond to challenging customer requirements - means that proper model management is essential.

Most thermal analysis campaigns have become an intricate series of activities that provide results in different scenarios and which can be a combination of a huge number of factors. This complexity calls for strategy and thoroughness and a key tool is the "TCS mathematical model specification" DRD in ECSS-E-ST-31. This DRD specifies the requirements for development and delivery of mathematical models to be used for thermal analysis.

Beyond this TCS mathematical model specification it is important to consider the analysis in the wider context of a project. A number of general considerations are listed below, some of which are covered in more detail in this document (as indicated). These points can be considered by thermal engineers when planning an analysis campaign.

a. management:

1. adequate computing resources;

2. sufficient and trained manpower;

3. availability of analysis tool licenses.

b. software tools:

1. the features of the analysis tools with respect to the intended use.

c. administration and configuration: (see section 4.2)

1. configuration control system;

2. architecture of data and files repository;

3. physical configuration of the system of interest;

4. management of the different thermal cases;

5. way to ensure a robust link between TMM and GMM.

d. model transfer and results distribution (see section 7.1):

1. thermal analysis tools used by different stakeholders (e.g. is a format conversions required?);

2. which models are deliverable and with what level of fidelity (e.g. detailed, reduced).

4.2 Model configuration and version control

Most thermal models of spacecraft are under some form of version control. However, this is often implemented as plain text headers at the top of analysis files and manual incrementing of version numbers in file names. At present there are number of options to support configuration control, ranging from software configuration control tools (e.g. subversion, git), to full Product Lifecycle Management (PLM) solutions.

These environments can be directly applied to thermal model configuration control, especially for ASCII formats. Moreover, many binary formats for documentation are also supported (e.g. .doc, .pdf). The use of such configuration control tools is not a burden and actually improves the efficiency and productivity of the analysts. In addition to this, the maintainability of models over a number of years is improved via the use of formal version control.

Guideline 4-1

Place thermal models under configuration control using a system that supports:

a.   tracking of model changes with informative remarks

b.   tracking of the engineer and organisation making the changes (author ,editor etc.)

c.   comparison (differencing) between distinct versions of the model in the repository

d.   tagging of model releases at critical milestones (e.g. PDR, CDR)

Guideline 4-2

Ensure results of all production runs are traceable to a specific version of the model inside the configuration control repository.

Guideline 4-3:

Where a multiple GMMs and TMMs are used ensure the link between the two is tracked in the configuration control environment (i.e. the GMM required as input to a given TMM)

As indicated in Guideline 4-3 above, often multiple models are needed in order to cover all of the different cases and scenarios to be simulated, for example: thermal test scenarios, stowed and deployed configurations. Additionally multiple GMMs are often used to represent distinct cavities (see section 4.7.6). It is therefore important to clearly configure the relations ship between the different models (and version of those model) in the configuration control environment.

4.3 Modelling process

As the analysis tools and methods used by thermal engineers evolve, so the modelling process evolves accordingly. For example, historically the analysis process typically started with the construction of a GMM which was used to compute the radiative couplings and environmental heat exchanges, which drive the thermal behaviour of a spacecraft. The results of the radiative analysis computed with the GMM were then fed into the TMM which was used to compute temperatures and heat flows. This process is shown in Figure 4-1.

Fundamentally the sequence of this process has not changed – radiation is still of fundamental interest and a geometrical representation is essential for radiative computations. However, as the tools develop, the tendency is towards integrated modelling environments where the TMM and GMM merge into a single entity; with most thermal couplings generated automatically by the tool. Thus the construction of the GMM/TMM becomes a single activity; although the actual analysis sequence necessarily starts with the radiative part, before running the thermal solution.
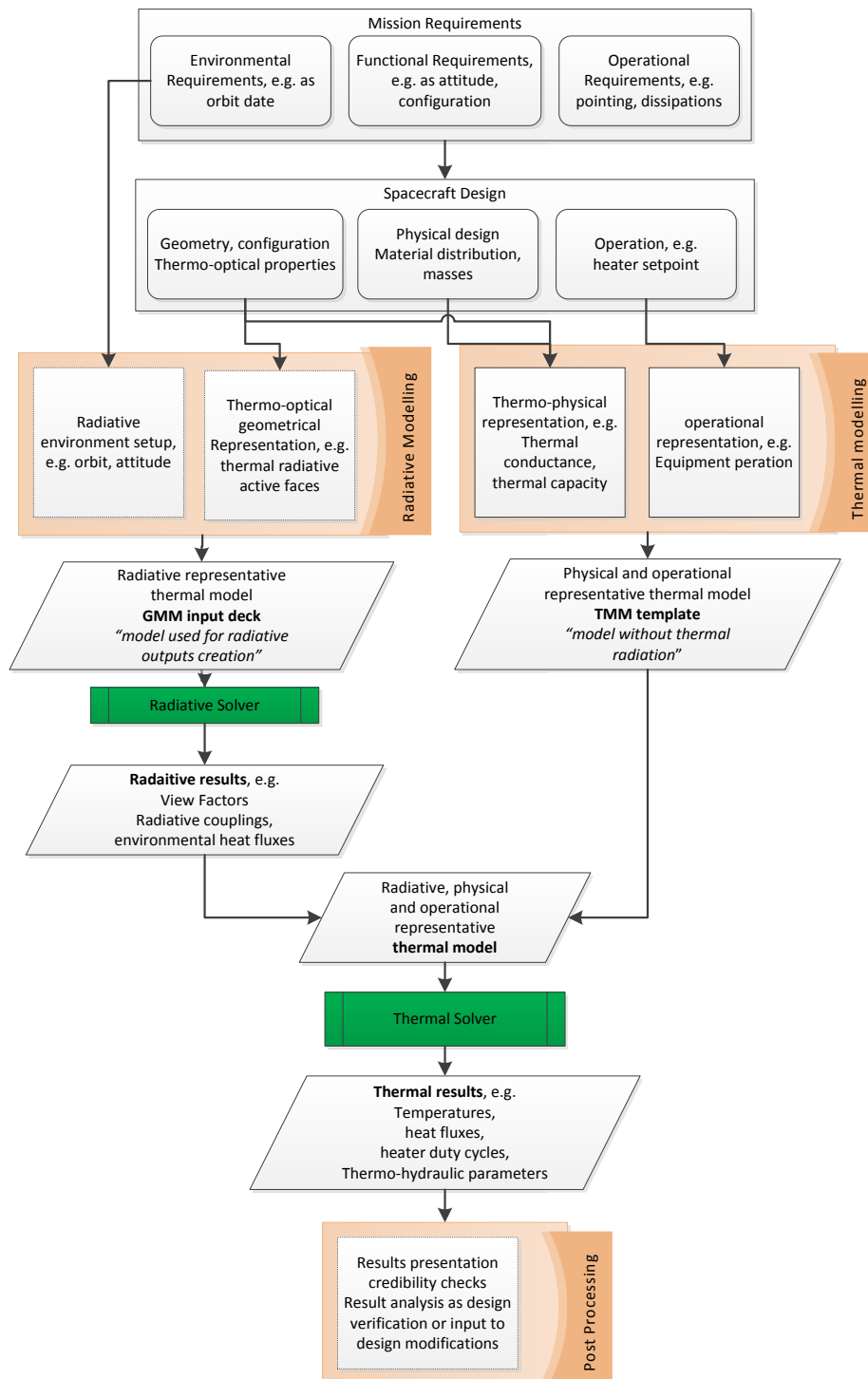
Figure 4-1: Modelling process

4.4　Modularity and decomposition approach

In order to manage model complexity, and to take into account the possible distribution of responsibilities over different partners/providers/suppliers, it is important to break down the overall system into individual modules. A module represents an element, sub-system or equipment which can be treated as a separate entity. From the perspective of the thermal engineer the module has its own thermal control requirements and likely its own TCS, with a clearly defined thermal interface. These thermal interfaces often correspond to mechanical interfaces but can also be defined through radiative exchanges, for instance using sink temperatures [RD21].

Guideline 4-4:

Break thermal models of complex items down into separate modules.

For the thermal analyst the decomposition of the model into modules can be facilitated by features of the analysis software, such as sub-models or predefined external elements. This brings significant benefits such as:

a.　it creates an opportunity to speed up the modelling process allowing parallel developments and verification of the different modules;

b.　it is a means to secure the whole process by confining the intrinsic risks of model development to local areas;

c.　it helps the management of the different spacecraft configurations - or even failure cases - and their impact at the interfaces level.

Guideline 4-5

Use groups to organise thermal models.

The use of groups (sometimes also called sets, depending upon the terminology of the analysis tool) is useful in order to organise the model. It is recommended to use groups from the very start of the modelling and analysis activities.

The use of groups also facilitates the verification of the model using features such as heat flow reports etc. These groups can be defined using features of the tools, but node labelling or node numbering can also be used if this is convenient.

4.5　Discretisation

4.5.1　Overview

Aside from the simplest analytical models, the usual modelling process involves a spatial discretisation, a temporal discretisation and most probably a discretisation of input parameters (e.g. time or temperature dependent properties). The discretisation approach that is taken has major implications for the quality of the analysis predictions: it is important that the layout and configuration of the physical hardware is properly captured and also that the expected heat paths can be adequately resolved in the model.

4.5.2 Spatial discretisation and mesh independence

Guideline 4-6

Make sure that the spatial discretisation used for thermal models is fine enough that key model outputs are no longer dependent upon it within an acceptable range.

For many years the predominant discretisation method for space thermal models has been the lumped parameter method. The basic justification for this spatial discretisation is the *isothermal assumption*; meaning that each node can be reasonably considered as isothermal and temperature gradients within it are limited to a given value. Thus in regions with large spatial temperature gradients, more nodes are needed for this isothermal assumption to be valid.

More generally when other spatial discretisation methods are considered (e.g. finite element, finite volume) this concept is usually referred to as *mesh independence*. Therefore in the fields of computational fluid dynamics, or stress analysis, a mesh sensitivity study can be carried out to determine how fine the mesh needs to be to achieve a given accuracy.

Irrespective of the method being used the conclusion is the same: the spatial discretisation needs to be assessed with respect to the targeted accuracy for the analysis. It is difficult to put a figure on the acceptable variation in key model outputs due to changes discretisation, but it is ideally much less than the uncertainty applied to the calculated values (typically 5-10 times less).

Beyond this objective, a finer discretisation is counterproductive, as:

- it implies a useless increase of the amount of data to be processed, (e.g. the number of conductive and radiative couplings) which incur penalties in terms of performance, runtime and storage;

- it means more risk for errors, more effort and time for debugging, maintenance and verification purposes;

- it brings most of all an illusion of better accuracy, as inaccuracies on input parameters cannot be recovered by a finer meshing.

Another consideration concerning the spatial discretisation is that the convergence of some common transient solvers can be disturbed, or the run completion drastically slowed down, when a large dispersion exists in the magnitude or nodal couplings (typically a factor 1000). Meeting this criterion can demand an appropriate grid.

As an additional remark on spatial discretisation, there are situations where a much coarser representation of the geometry is used. For example during the conceptual design of a spacecraft when the configuration is unclear and geometrical details are unavailable. In these case more simplified lumped parameter models can be appropriate and different considerations apply, such as introducing heat spreading conductors – based on a circular heat path - to account for the reduced mesh density.

4.5.3 Observability

When setting up a thermal model it is essential to account for the necessary observables. In particular TRPs need to be properly resolved in the thermal model breakdown. This allows a straightforward assessment of the interface requirements and facilitates the correlation exercise against test or flight measurements.

Additionally, if performance requirements need to be properly assessed then local refinements can be further instigated, for instance:

- ensure nodes fall at both end points of regions where a temperature gradient is to be verified, such to allow actual conductance computation;

- from a thermal control perspective, meshing can normally be coarse in high thermal conductivity areas but if a detailed temperature map is required – for example feeding into a thermo-elastic analysis – then the meshing can be reconsidered.

4.5.4   Time discretisation

Transient solution routines use a step-by-step approach to approximate the evolution of temperatures with time, starting from initial conditions and accounting for the time-varying parameters (e.g. boundary conditions, thermal loads).

Guideline 4-7

Evaluate the sensitivity of key model outputs to transient solver criteria and agree upon appropriate limits for the model.

Evaluate the following criteria:

a.   Primary convergence criteria for iterative solutions

b.   Transient time step

Guideline 4-8

Use a time step smaller than the CSG limit for transient runs that use explicit solvers.

> NOTE   Even when using Crank-Nicolson solvers the CSG limit can still give a useful indication about the time step to use in the model.

The previous guideline concerning the CSG limit is necessary to ensure the stability of explicit solvers. Whilst this is a well-known constraint from the theory of transient solvers, the use of explicit solvers is not common for space thermal analysis. Therefore checking the sensitivity of KMOs to time step is more important when using implicit and Crank–Nicolson type solvers. There is an intrinsic inter-relation between convergence criteria and time step, and it is important to find a balance such that the truncation and convergence errors are minimised. Ideally the model outputs are independent of the transient solver criteria although, in practice, the objective is to reduce these errors to acceptable levels.

For transient simulations, it is important to take care in modelling the thermal capacity of sensitive items like low thermal capacity instruments, cryogenic radiators, lightweight deployable systems, or in general low capacity, high surface area uninsulated items mounted externally or with view to the space.

If the local time constants are very short then it can be advantageous to use arithmetic nodes for the lowest capacity elements in the model in order to increase the time step. Alternatively, in some tools, the use of local sub-stepping is possible, whereby the items with different thermal capacities use a different time step than the rest of the model.

The resolution of model inputs is also an important consideration when choosing the time discretisation.

Guideline 4-9

Choose the transient time step such that the effects of imposed loads and boundary conditions are adequately resolved.

Other possible examples where choosing an adequate time step is important are:

a. the model is subject to a short pulse of imposed heat input: in this case the time step needs to be small enough to resolve the resulting temperature changes in the model.

b. the model includes active control (e.g. PID): in this case, a certain time step is necessary to ensure controller stability, or to reproduce flight input/output response.

c. a requirement involves thermal stability: in this case the time step dictates the maximum frequency that can be resolved.

4.5.5   Input parameters

Many of the input parameters to thermal models are approximated at discrete points in the region of interest. For example:

a. temperature dependant properties defined through a look-up table with a finite numbers of values.

> NOTE   Note that generally all material property data is temperature dependent, but it is often possible to assume a constant value over a limited range of applicability.

b. the orbital fluxes or variable radiative couplings are generally only computed at certain positions along the orbit. It is important to select these positions carefully in order to capture potential local transient phenomena that can drive the performances of a system element;

c. in a few cases, namely when high accuracy is at stake, computations led with single precision real values entail a numerical behaviour that can be considered by analogy as a loss of continuity. Similarly, in extreme cases, the rounding of initial temperatures translates into an alteration of the energy distribution in the model creating a so-called numerical drift when starting transient solution.

Guideline 4-10

After an analysis cycle assess the discretisation of input parameters against the region of the obtained solution.

For example: assert that obtained temperatures lie within the applicable range of material property data, check that environmental heat fluxes are not truncated due to discretisation of the orbital arc etc.

4.6   Transient analysis cases

The use of transient thermal analysis to produce flight temperature predictions for spacecraft is standard. However, the transient analysis, in the way it is used by thermal engineers, is also quite different from the types of analysis carried out in other computational domains. For example, a low-Earth orbit can have a period of 100 minutes, and an analysis duration of several orbits is usually required to reach a quasi-stabilised condition. This calls for long transient runs which are computational demanding. It is the job of the thermal analyst to balance the computational effort against the accuracy of the model predictions.

Guideline 4-11

Choose the time range over which model results are observed based on the model dynamic behaviour (either induced by the environment variations or by the thermal control operation) or the simulated mission sequence.

Guideline 4-12

Assess the cyclic convergence between successive time ranges on the basis of criteria agreed with the customer that can address temperature differences and heating budget stability.

The topic of cyclic solution routines is a difficult one because in some cases a convergence is impossible to achieve. For example when the heater cycling period is of the same order as the orbit (or repeats the analysis period) then assessment of the heater duty and budgets can become difficult and it is better to perform it on the appropriate cycle defined by a certain number of orbits.

Another interesting topic associated with transient analysis cases is timeline management – for example the switching of operational modes through a transient run. Typically this is handled via "user logic" manually introduced, or sometimes via interpolation tables. The use of such logic does, however, introduce some risk and it can happen that an event is just ignored because it is not properly coded. So it is important to properly verify this user logic.

Some tools provide an inbuilt "events" mechanism to handle timeline management and this is recommended where possible.

4.7   Modelling thermal radiation

4.7.1   Introduction to thermal radiation

The use of tools to analyse thermal radiation exchange is essential for almost all space projects. Indeed it is the importance of radiation that most clearly differentiates space thermal analysis compared with other domains or terrestrial computational heat transfer.

This section contains some considerations regarding the development of models for radiative analysis. Traditionally the terms "radiative model" and "GMM" can be interchanged quite freely. However, with recent developments in the tools the geometric modeller can be used to generate much more than just the radiative aspects of the model, in particular conductive terms. Nonetheless one of the primary objectives of developing a geometric model is performing the radiative analysis (see Figure 4-1) and, as such, considerations on geometrical modelling and radiative analysis are strongly linked and therefore covered together in this section.

4.7.2 Radiative environment

When modelling an open cavity of a space system, it is important to consider the external radiative fluxes. When orbiting around a body such as a planet or a moon, these fluxes are divided into three types:

- the solar flux, that is the flux directly coming from the sun;

- the IR flux, that is the flux directly emitted by the body;

- the albedo flux, that is the part of solar flux reflected by the body around which the modelled system orbits.

Classically the radiative environment for a S/C orbiting a planet is adequately represented by assuming:

- IR fluxes: the planet is a grey emitter with constant temperature and emissivity (i.e. independent of longitude and latitude);

- Albedo: the planet is a diffuse reflector with constant reflectivity (i.e. independent of longitude and latitude, and other factors such as local weather conditions, including presence of clouds).

In some cases, however, these assumptions are not valid, examples are:

- orbits around Mercury where the IR behaviour of the planet varies considerably around the planet;

- polar orbits around Earth where Albedo reflectivity can increase around the polar ice caps;

- orbits around the Earth's moon where the albedo reflectivity is non-diffuse and has a significant directional contribution (e.g. retro reflectivity);

- low Earth orbits for external equipment with low thermal inertia that can be sensitive to IR fluxes and Albedo variation.

Guideline 4-13

For orbits in which the thermal properties of the central body vary with anomaly, assess the sensitivity of key model outputs to this. If necessary, include the variation of the planet properties in the model.

It is the job of the engineer to critically assess the underlying assumptions and determine if they are valid. In some cases special modelling can be required. For example in some tools there already exists functionality to provide planet temperature or emissivity maps. Alternatively the orbit can be broken into arcs with different planet properties.

Guideline 4-14

For external flux calculation, choose the calculations points with care. In particular, capture the flux discontinuities (e.g. eclipse entrance and exit).

In any case, it is recommended that the sensitivity of key model outputs to the number of orbital positions is evaluated and that there is agreement on the appropriate limits for the model.

To define the numerical values to be used for the environment some useful references are available:

- NASA Technical Memorandum 4527, "Natural Orbital Environment Guidelines for Use in Aerospace Vehicle Development" [RD8].

- NASA Technical Memorandum 2001-211221, "Guidelines for the Selection of Near-Earth Thermal Environmental Parameters for Spacecraft Design" [RD9].

- Anderson et al, 2001-211222, "Simple Thermal Environment Model (STEM) User's Guide [RD10]

- Gilmore, "Spacecraft Thermal Control Handbook – Volume 1: Fundamental Technologies" [RD7].

It is also important to ensure that the orbital fluxes computed are correct with respect to the Equation of Time. The Equation of Time is the expression of the error made for orbit-related computations by using mean solar time instead of true solar time. The maximum deviation is around 16 minutes. As far as thermal aspects are concerned this deviation is not significant for most missions. But, in the case of sun-synchronous orbits with stringent thermal requirements it can be relevant. A more detailed discussion is given in [RD11].

4.7.3   Thermo-optical properties

Guideline 4-15

Choose the optical properties on the basis of the analysis case, for example to reflect Beginning of Life (BOL) and End of Life (EOL) properties.

Typically EOL conditions are used for hot case predictions due to the general trend of solar absorptivity increasing with exposure to the space environment (e.g. UV radiation, atomic oxygen, plume impingement). EOL properties need to be assessed and justified based on the space environment specific to each mission. A useful resource showing the ageing of optical surfaces is the THERME experiment [RD14].

Guideline 4-16

For models containing surfaces with non-zero specular reflectivity, use an appropriate method, for example Monte Carlo Ray Tracing.

Additionally when setting up a GMM it is important to consider the real effects introduced by items which could not be present in the reference CAD model. For example the presence of harness or non-planar features on internal panels could lead to a higher effective emissivity of the surface. If these complex surface are not modelled geometrically, it can be appropriate to use effective optical properties in order to approximate the radiation exchange.

> NOTE   This is only appropriate for internal cavities with no exposure to environmental heat fluxes.

4.7.4 Transparency and optical elements

Guideline 4-17

Use MCRT based tools when modelling partially transparent elements.

The common thermal modelling tools usually do not have volume radiation modules, and only surface radiation can be considered: thus only elements which thickness is small compared to other dimensions can be modelled. The global transmissivity over the thickness is then specified to the tool.

4.7.5 Spectral dependency

Traditionally space thermal-radiative analysis models use the idealisation of "semi-grey bodies", which means that the thermo-optical properties of all surfaces are regarded to be invariant with respect to the wavelength of the radiation within two main spectral bands: the solar spectrum and the infra-red spectrum. In the solar spectrum only incident and absorbed solar and albedo flux (possibly after multiple reflections) is considered. All thermal-radiative emission from the system of interest is considered to take place in the infra-red spectrum. The infra-red wavelength range is roughly taken to be 1 μm to 1000 μm.

> NOTE   For most applications values are derived for a range from about 2,5 μm to 30 μm. For high-temperature applications this can be extended towards the lower side; for low-temperature applications extended on the upper side.

However, for systems with parts at very different temperature ranges and with thermo-optical properties that do depend on wavelength and/or temperature, the "semi-grey body" idealisation is no longer correct and can cause significant discrepancies between analysis predictions and observed thermal behaviour. Examples are:

- spacecraft with infra-red instruments in the cryogenics range, where some parts operate at room temperature and other at very low temperatures;

- operating rocket nozzles, re-entry vehicles or spacecraft flying close to the sun, with some parts at room temperature and other at very high temperatures;

- thermal tests where cryogenic shrouds are present in the test facilities, in this case infra-red emissivity values of the shrouds, measured at room temperature, often differs significantly from the emissivity/absorptivity of the operating shrouds.

In such situations extended non-grey body thermal analysis capabilities are needed to properly model the wavelength-dependent thermal radiation.

Guideline 4-18

During the development of the radiative model, assess the standard grey two-band approach classically used for space thermal analysis. A full wavelength dependent radiative analysis can be necessary in certain cases.

4.7.6 Radiative cavities

A radiative cavity is a collection of radiative surfaces - typically a subset of the total number of surface of the thermal-radiative model. By definition, it is impossible for the surfaces in one cavity to exchange heat through thermal radiation with surfaces in another cavity. The terms *radiative cavity* and *radiative enclosure* are equivalent and different terminology is used by different tool vendors.

The use of external and internal cavities is the most common example of radiative cavities. This is recommended to avoid small but spurious radiative heat exchange - caused by a gap due to model or solver uncertainties - between a S/C internal part and deep space. If a single cavity is used for both internal and external surfaces, then it is good practice to verify that no REFs exist between internal surfaces and space, and that no environmental fluxes appear in the energy balances of the purely internal nodes. Setting up an *internal group* for this sanity check can be useful.
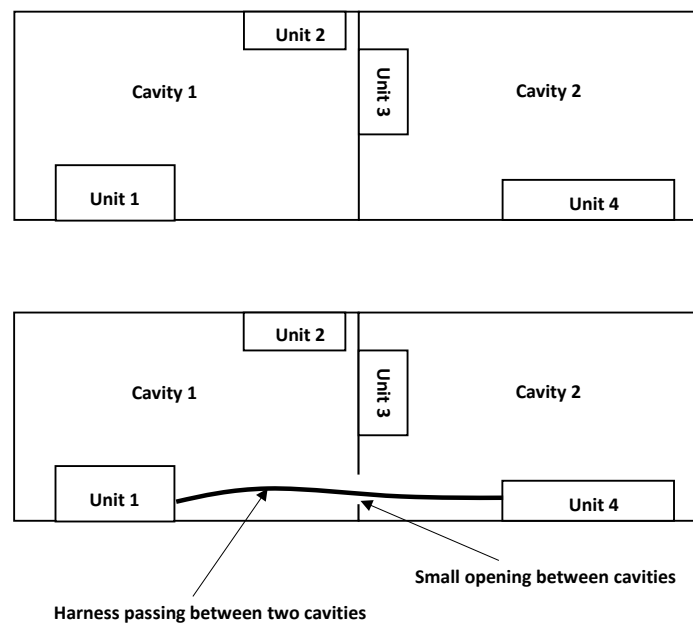
Figure 4-2: Examples of cavities: top showing two completely closed cavities, bottom showing two almost separated cavities with a small opening

The computational effort necessary to calculate radiative exchange factors is typically nearly proportional to the square of the number of surfaces involved. Therefore, if possible, splitting the thermal radiative model into cavities is desirable, since usually more efficient. Additionally splitting up the thermal model into an external and internal model can speed up the analysis time significantly if time dependent REFs are required for external parts (e.g. due to a moving solar array) while all internal REFs are constant. Additional there is no orbital analysis required by modification of the internal radiative cavity.

Cavities are also used to partition the model in terms of the relevant physics, for example external cavities where visible and IR radiation exchange play a role, and internal cavities where radiation exchanges are limited to the IR. Another example is a cavity for an optical payload where wavelength dependence of IR radiation exchanges is important, and another cavity for the service module where classical single band radiation exchanges are sufficient.

In some cases "almost separated" cavities (e.g. Figure 4-2 bottom) can be split up if the radiative exchange between them is small enough compared to other heat exchanges to be neglected. As for any modelling choices, this assumption is justified by the modeller based on an estimate of the heat exchanges.

4.7.7　Geometrical modelling

When building a geometrical model for radiative analysis it is usually bad practice to place two surfaces coincident with each other in the same cavity; for example two overlapping co-planar rectangles. This is because:

- when using ray tracing tools, ambiguous ray tracing intersections and resulting REFs can be produced;

- when using analytical view factor computations, the zero distance between surfaces can lead to numerical singularities.

It is generally better to leave a small gap between surfaces which are in "contact". This gap helps to enforce the correct topological connectivity of the geometry. Appropriate values for the gap need to be assessed on a case-by-case basis because they depend on the overall length scale of the system being modelled.

> NOTE In this example, if an interface filler or gasket is used between the box baseplate and its mounting surface, the appropriateness of a radiative coupling between the box and base plate can be questioned, anyway the radiative coupling becomes irrelevant because the coupling is dominated by the filler. The example is used only to illustrate the basic principle.

Guideline 4-19

Avoid the use of coincident surfaces in radiative geometrical models

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Guideline 4-20

Do not place the edges of the Boolean cutting tools to be too close to the edges of the source surface: this can lead to numerical difficulties in the geometrical engine.

> NOTE For clarity, in the previous guidelines for a Boolean operation
> $c = u - t$
> where:
> u　is the source surface
> t　is the cutting tool
> c　is the final cut shape

Guideline 4-21

Minimize the area fraction of the source surface to be removed. Internally even the "cut" area can be used in ray-tracing computations and can create a significant increase in run time for ray-tracing.

> NOTE If u has an area A_u and the final cut surface has an area A_c then the area fraction to be removed is defined as $(A_u - A_c) / A_u$

4.8　Considerations for non-vacuum environments

4.8.1　General

One of the specificities of space projects is the vacuum environment which implies that no heat transfer with fluids. However, in some applications, or during certain phases of a product's life, this kind of heat transfer can be important. Examples are as follows:

- external heat fluxes on launchers during ascent phases;

- external heat fluxes on spacecraft during landing phases, on Earth or other celestial bodies (e.g. Mars);

- exceptionally low orbits where molecular heating can occur;

- fluxes in fluid lines for propulsive devices;

- fluxes in internal pressurised cavities, with or without venting devices;

- thermal control devices (heat pipes, fluid loops, etc.);

- heat fluxes associated with charge or discharge of gas inside gas tanks and lines;

- heat exchange of spacecraft with air in ambient conditions.

This document only deals in details with the heat pipes (see A.2) but some generic considerations are presented in sections 4.8.2 to 4.8.5.

4.8.2　Specific regimes

In some specific cases, the heat transfer phenomena can have very high coefficient, and special attention is necessary. In particular, the following applications need dedicated modelling:

- biphasic heat transfer;

- high speed flows, especially external fluxes on launchers and re-entry bodies;

- plume impingement from thrusters on external surfaces.

Re-entry vehicles typically require a thermal protection system to withstand the harsh aero-thermal entry environment. In particular in the case of ablative thermal protection materials additional effects like pyrolysis, gas production & transfer and surface recession need to be taken into account. Dedicated software tools are available for this kind of analysis, however, these specific applications are not covered by this document.

4.8.3　Conduction or convection

An important point is the absence of free convection for orbital applications: as apparent gravity is negligible, no fluid flow occurs without an external driving force (pumping, venting, etc.). In this case, the modeller can decide that only conduction is considered in the fluid.

For gaseous phases, the conductivity and thermal capacity values are usually very low compared to those of solids, and their impact on the system is negligible, unless high pressurization is involved.

The modeller only needs to consider these fluids when the thermal thickness is low enough to induce appreciable couplings (for example small air gaps). It can be an important parameter for contact modelling. Additionally within an MLI (which is typically designed for use in a high vacuum) even a very low gas pressure (e.g. during ascent or atmospheric re-entry & descent) can significantly impact

the insulation performance. Another example are fibrous insulation systems which can e.g. be used underneath a hot structure of a re-entry vehicle. Here the total heat transfer is composed of three parts, i.e. fibre conduction, radiation from fibre to fibre and gas conduction. In the analysis it needs to be considered that while the radiation is strongly temperature-dependant, the gas conduction is pressure-dependant.

For applications where gravity is present, but a gravitational acceleration different to 1 g exists, then the relevant non-dimensional parameters (e.g. Rayleigh number) needs to be considered carefully. For example in reduced gravity applications (e.g. Mars) then inside cavities with a small length scale it can be possible to neglect free convection – indeed gas gaps can be used as an effective thermal insulation.

4.8.4 Heat transfer coefficient correlation

For nominal cases (apart from those specified previously), the calculation of wall heat transfer coefficient often relies on empirical correlations. A large collection of references exist for this purpose but it is important to assess their relevance in terms of geometry, flow conditions, fluid properties, gravity, etc. When several correlations are available for a given case, then they can be compared to check consistency.

4.8.5 Charge/discharge of gas inside pressurised systems

During propulsion or gas delivery system operations, the phenomena of gas charge (during ground operation) or gas discharge (during flight operations) generate or absorb a certain amount of heat inside the pressurised system (e.g. tanks, tubing, valves, pressure regulator). These phenomena can have an impact on both local and global thermal behaviour of a vehicle and need to be managed with special care especially, concerning the risk of condensation and freezing.

The modelling of this specific thermodynamic behaviour can be complex (single or multiple fluids, single or multiple phases) and is not covered by this document.

5
Model verification

5.1 Introduction to model verification

This section aims to cover the topic of thermal model checks and numerical verification, or, using the informal definitions provided in section 3.1, "did we solve the equations correctly?"

Typically the verification of computational models is split into code verification and calculation verification [RD13]. Throughout the following discussion it is assumed that the code verification is carried out by the software vendors. Therefore, the users of the thermal analysis tools are only concerned with calculation verification.

As far as possible the guidelines introduced in this section 5 have been kept tool neutral.

5.2 Topology checks

Many problems with thermal models can be attributed to ill-defined node/conductor topology in the model. It is recommended as a minimum to adhere to the following guidelines.

Guideline 5-1

Identify and justify isolated nodes.

> NOTE   Isolated nodes are understood to be thermal nodes with no attached conductors. Generally speaking isolated nodes need to be inactive unless there is a clear justification otherwise.

Guideline 5-2

Identify and justify isolated groups of nodes.

Guideline 5-3

Identify and justify parallel conductors of the same type.

> NOTE   The qualification "of the same type" in the guideline means for example, parallel linear or parallel radiative conductors. The use of parallel linear and radiative couplings is common, for example when modelling MLI (see Annex A.1).

Guideline 5-4

Identify and justify negative or null valued conductors.

> NOTE   Possibly identify conductors with an unusually high value because these can lead to convergence problems (see section 4.5.2).

Guideline 5-5

Identify and justify negative or null nodal thermal capacities.

Concerning the previous guidelines, it could not be necessary to justify every occurrence individually in the model. For example, if using an automatic model reduction routine, then negative valued linear conductors can be generated. In this case it is sufficient to justify the negative couplings for each block where they occur. Likewise if arithmetic nodes are used to model MLI (where appropriate) then a single justification for the model can suffice (see Annex A.1 for discussion of MLI modelling).

Additionally, concerning the use of arithmetic nodes, it is important to keep track of the overall mass represented in the thermal model and to ensure that this does not differ significantly from the overall system mass captured (normally captured in the system budgets).

5.3   Steady state analysis

The adequate convergence of steady state analyses is a critical factor in ensuring the credibility of the model predictions. Unfortunately, and especially for large models, the computational time necessary to achieve adequate convergence can be significant. The temptation is thus to relax the convergence requirements in order to reduce computation time.

Guideline 5-6

Evaluate the sensitivity of key model outputs to convergence criteria. Evaluate the following criteria:

a.   Primary convergence criterion for iterative solutions, and

b.   Energy balance.

Guideline 5-7

Ensure that steady state production runs are converged - in the sense the effect of convergence criteria on the key model output is negligible.

In the previous guidelines it is proposed that the term *key model outputs* are temperatures, heat flows, heater powers or any other important model variables. Essentially, in a well converged model, the key model outputs are independent of any further tightening of the convergence criteria.

The so called *primary convergence criterion* depends upon the analysis tool used, but it is often the maximum temperature change for any node in the model between two successive iterations of the steady state solver.

In reality the actual value of the convergence criteria is highly model dependent and therefore hard numerical guidelines cannot easily be established. For example, the appropriate convergence criteria for a telecommunications platform model and a cryogenic instrument can be entirely different.

One of the key elements to understanding thermal models is to examine the heat flow network of the steady-state result. For larger models, grouping nodes in functional blocks (see section 4.1) and analysing the heat flows within and between these blocks allows checking for plausibility and can thus reveal erroneous conductors. It is recommended to separately analyse radiative and conductive heat exchanges.

Guideline 5-8

For a steady-state solution, establish heat flow charts between nodes or groups of nodes, and check for plausibility of the results.

5.4 Finite element models

Finite elements are becoming more used by thermal engineers, both inside classical thermal models, but also for detailed local analyses, for example calculation of conductive couplings between complex 3D parts for later usage in lumped parameter models. The use of finite element methods leads to some specific best practices which are quite generic for all finite element models across application domains.

The actual safe limits used for topology checks can probably be less restrictive for thermal models compared with, for example, structural models: in other words "worse" elements can probably be used in thermal models. Nonetheless the following guidelines are useful to ensure the quality of finite element meshes.

Guideline 5-9

Check the geometrical adequacy of finite elements to be within the limits recommended by the analysis tool. Check the following criteria as a minimum:

a.   warp,

b.   skew,

c.   interior angle, and

d.   aspect ratio.

NOTE   ECSS standard ECSS-E-ST-32-03 "Structural finite element models" [RD2] provides some preliminary numbers for element quality checks.

Guideline 5-10

Justify duplicate or overlapping elements.

Guideline 5-11

Justify duplicate finite element nodes.

Guideline 5-12

Check the topological connectivity of finite element meshes using the following utilities:

1. Free edges (for 2D and 3D elements), and

2. Free faces (for 3D elements).

5.5 Verification of radiative computations

The following guidelines are, where possible, generally applicable and tool independent. However, most of the major tools for space thermal analysis today use the Monte Carlo Ray Tracing (MCRT) method and as such the guidelines are clearly focussed towards these tools.

Guideline 5-13

For MCRT computations, evaluate the sensitivity of key model outputs to input parameters of the ray-tracing algorithm.

Consider in the sensitivity analysis:

a.   both radiative couplings and heat fluxes.

b.   measures of statistical convergence such as:

    1.   energy conservation for REFs (sometimes called "line accuracy" or "line sum"),

    2.   reciprocity for REFs, and

    3.   variation of random number seeds and/or number of rays.

Concerning the sensitivity analyses discussed in the previous guideline, it is best to consider end-to-end results from the thermal solution (e.g. temperature, heat flows etc.) due to ray-tracing parameters.

Note that for radiative solvers using MCRT, the conservation of REFs is normally ensured by design, however, the results are often adjusted to enforce reciprocity at the expense of energy conservation. Therefore the energy conservation (often called line sum or line accuracy) often becomes the measure of statistical convergence.

Guideline 5-14

Evaluate the sensitivity of key model outputs to the filtering of radiative couplings. Consider with extra care the filtering of radiative couplings involving the environment (e.g. space).

Different types of filtering of radiative couplings are available in different thermal tools. Experience shows that often the default values for the tool are used, which could or could not be appropriate depending on the applications. For critical situations some variation of the filtering parameters needs to be done in order to ensure the KMOs are not dependent on it within acceptable limits (to be defined on a case by case basis).

Guideline 5-15

Ensure that for a given face, the REFs to inactive surfaces are thermally negligible.

6
Uncertainty analysis

6.1   Uncertainty philosophy

In the analytical process of temperature prediction with a thermal mathematical model, a number of inaccuracies due to the depth of modelling, available physical data and lack of precise definition of the item and its environment are present. In case a test is performed additional inaccuracies due to test set-up, and test instrumentation are also considered.

All these different inaccuracies lead to temperature uncertainties which are considered on top of the calculated temperature range. The calculated temperatures, increased or decreased by the appropriately assessed uncertainties, form the "predicted temperatures," which are compared against the TCS design temperatures (see ECSS-E-ST-31 Figure 3.1 [RD1]).

> NOTE   The term "uncertainties" is defined in ECSS-E-ST-31 [RD1].

The uncertainty of a temperature prediction depends on several factors, such as the type of model (e.g. overall spacecraft, local and equipment model) and the uncertainty associated with physical parameters.

Generally the uncertainties reduce during the course of a project as a consequence of the use of more detailed models and improved knowledge of the properties (usually obtained by tests. However, it is important to note that thermal tests do not always result in a reduction of uncertainties. For example after the spacecraft thermal balance test, a poor thermal model correlation can be obtained that actually leads to an increase in some uncertainties.

Good practice would be to re-assess the remaining uncertainty using the individual deviation between measured and correlated temperature at end of thermal model correlation plus the uncertainty related to the parameters that were not correlated during the TVAC, mainly environmental parameters, EOL properties and possibly thermal capacitances.

Typical temperature uncertainty values - useful for the classical temperature range of 200 K – 470 K as defined in [RD1] - together with a short definition of the TCS activities and models relevant to the various phases are:

a.   Phase A:

　　1.   TCS feasibility study and assistance to configuration definition, using coarse overall spacecraft TMM, where most items are not modelled explicitly, but are lumped with structure.

　　2.   Typical uncertainty: ± 15 K.

b.   Phase B:

　　1.   TCS coarse design, with overall spacecraft TMM where critical items are modelled explicitly.

2. Typical uncertainty: ± 10 K.

c. Phase C and D:

   1. TCS detailed design with detailed overall TMM, where all items are modelled explicitly.

   2. Typical uncertainty: ± 8 K before thermal balance tests.

   3. Typical uncertainty: ± 5 K after thermal balance test and TMM correlation.

The uncertainty values provided in the aforementioned bullet points are only indicative of a typical project. The actual uncertainty values used are the result of a thorough sensitivity analysis and uncertainty derivation.

In case of a feed-back controlled thermal design (e.g. VCHP, regulation heaters, fluid loops), the *temperature* uncertainty from the model is likely to be quite small. In this case it is more appropriate to select a different parameter to consider in the uncertainty analysis - for example the heater power or duty cycle. A clarification on temperature controlled items is provided in section 6.6.

6.2   Sources of uncertainties

6.2.1   General

Uncertainties on spacecraft temperature predictions are caused by inaccuracies in the following categories of data:

- environmental parameters,

- physical parameters,

- modelling parameters, and

- test facility parameters.

In many cases these uncertainties are out of the control of the thermal engineer, for example workmanship variations. Typical inaccuracy values for these parameters are provided in section 6.5.

6.2.2   Environmental parameters

As far as appropriate, the uncertainty can account for inaccuracies in the following parameters:

- solar and planetary radiation,

- orbital and attitude parameters,

- aero-thermal and plume radiative fluxes.

The choice of these environmental parameters as inputs to an uncertainty analysis can be critically assessed. This is because in many situations worst case values are often used – typically for hot/cold sizing analysis cases. In these situations varying these parameters can be inappropriate or overly conservative.

In other situations, however, the figures used during the nominal thermal analysis for the solar, planetary albedo and planetary infrared radiation do not reflect necessarily the extreme values which an item can be subjected to during its lifetime. If this is the case, sensible variations around the nominal values are applied to these parameters. This is particularly relevant for items with low time constants.

6.2.3 Physical parameters

The temperatures of an item are controlled through conductive and radiative (and, in some cases, convective) heat transfer paths. The parameters which describe such paths are subject to inaccuracies which are due to measurement tolerances, manufacturing tolerances and in most cases a combination of both. The parameters which are considered pertain to:

- bulk and surface material properties,

- inter-material contact characteristics,

- dimensions,

- heat dissipations of units,

- control logic set-points (e.g. hysteresis of thermal switch), and

- sensor inaccuracy (in particular for temperature controlled items).

6.2.4 Modelling parameters

The process of modelling an item and its external environment, as well as defining in mathematical terms the scenarios to be applied to this system, is necessarily based on approximations in order to get a set of equations that can be solved by existing thermal software packages. These approximations lead to discretisation errors, in particular:

- Spatial discretisation, with the physical reality discretised into finite isothermal elements in order to get a set of ordinary differential equations;

- Time discretisation, with continuous time being represented by finite time steps.

Some attempt can be made to quantify and minimise these discretisation error using mesh and time step refinement methods as presented in section 4.5.

Beyond these discretisation errors there are also more subtle and inherent inaccuracies introduced by modelling actual geometry represented by idealisations. Some loss of geometric correctness is inevitable, for example with thin structures being represented by zero-thickness shells. These types of errors can become particularly important at locations such as joints or where loads/boundary conditions are applied. The effects of geometric idealisations are more difficult to quantify. For example it can oblige changing from a 2D model to a full 3D model to see this effect.

6.2.5 Test facility parameters

Inaccuracies for a special set of parameters are allocated to account for test conditions during TB testing used for the correlation of the thermal mathematical model of an item. These are mainly the result of assumptions to be made for:

- shroud and its thermo-optical properties;

- solar simulation characteristics (including spectrum, decollimation angle, flux uniformity);

- temperature measurements;

- thermal node or temperature sensor position error.

6.3 Classical uncertainty analysis

In a classical uncertainty analysis there are essentially two steps:

1.   sensitivity analysis

2.   combination of sensitivity analysis results to yield uncertainties

In the first step the impact of the applicable inaccuracies (see section 6.5) on the key model outputs are assessed via sensitivity analyses. Based on the TMM used for nominal temperature predictions, such sensitivity analyses are performed by replacing nominal input parameter values by values including the expected or assumed inaccuracy.

It is usually not needed, nor suitable to carry out as many analysis runs as individual parameters exist. After proper assessment some parameters can be grouped and handled together.

The result of such an analysis run provides a specific uncertainty (i.e. difference between actual KMO and nominal KMO) either as a function of one parameter or of a group of parameters.

Following this sensitivity analysis the next step is to combine the results into combined uncertainties on KMOs. The specific uncertainties are combined as follows:

a.   specific uncertainties due to inaccuracies in environmental, physical and test facility parameters (if applicable) are assumed to be of statistical nature and summed as root sum squared (sometimes referred to as "combining in quadrature").

> NOTE   If any of these specific uncertainties can be clearly shown to be of systematic nature, they are added algebraically.

b.   specific uncertainties due to inaccuracies on modelling parameters or due to the modelling method are either of systematic nature and are, in this case, added algebraically or of statistical nature and are in this case summed up as root sum squared.

To summarize, the formula is:

$$\Delta\phi_i = \sqrt{\sum_{j=1}^{n_s}\left(\Delta\phi_{r,j}\right)_i^2 + \left(\Delta\phi_s\right)_i}$$	**[6-1]**
• $\Delta\phi_i$ overall uncertainty on model output i • $\left(\Delta\phi_{r,j}\right)_i$ uncertainty due to statistical parameters j on model output i • $\left(\Delta\phi_s\right)_i$ systematic uncertainty on model output i	

The approach of combining statistical parameters together using a root sum square is based on a number of assumptions. Notably it assumes that the statistical parameters j are uncorrelated independent variables. Although this assumption is often not strictly true, experience has shown the approach to be generally appropriate for space thermal analysis. In the case that this approach seems to be clearly invalid then it can be challenged and other methods used (for example the stochastic approach, see section 6.4).

Additionally two further observations can be made about this type of uncertainty analysis:

•   this type of uncertainty analysis can never account for severe modelling errors. These errors are usually only picked up by: review of a model, by comparison with previous projects, or during test correlation;

•   if using this type of uncertainty leads to drastically different uncertainties than those typical values listed in section 6.1, then the validity of the approach and the choice of input parameters and ranges need to be critically assessed.

The classification of input parameters as statistical or systematic is also subjective and can depend on how input parameters have been grouped together. For example, if a global "contact conductance" parameter is used throughout a model - to couple all equipment to panels - then this can be treated as one of the statistical parameters. However, if these contact conductance parameters are varied *per item of equipment* (e.g. *n* input parameters to be varied for *n* items of equipment), and they are all based on the same physical hypothesis, then they can reasonably be considered as systematic. This is because an error in one parameter is also likely to be present in all the other ones.

Another observation is that equation [6-1] makes no distinction between negative and positive uncertainties, because they are squared at some point. Thus, the contributions of a parameter varied in both directions (e.g. +10 % / -10 % of dissipation) end up to be summed up in the same uncertainty, this can be over-conservative. In some cases the approach taken is to group all "positive" contributors so as to get a positive uncertainty, and similarly to group all "negative" contributors.

6.4 Stochastic uncertainty analysis

The use of stochastic analysis, based on Monte Carlo methods, to derive uncertainty values can bring a number of benefits compared with the classical approach. In particular the use of probability distributions to describe the spread of input parameters offers an opportunity to reduce over-design.

A detailed study into the use of the stochastic method for space thermal analysis was carried out in 2004 and the results, including guidelines for use, are available online [RD12].

6.5 Typical parameter inaccuracies

Depending on the project status, the parameter inaccuracies to be taken into account can vary. At early project stages (typically pre-phase A and phase B), the values shown in Table 6-1 are typically considered.

> NOTE   Typical parameter inaccuracies for cryogenic applications are functions of the temperature regime (sub-kelvin, 10 K, 100 K) and the method used (radiative, cryocooler, cryogen). Values are strongly dependent upon the actual project requirements.

Table 6-1: Typical parameter inaccuracies (pre-phase A and phase B)

Parameter	Inaccuracy
Effective MLI performance (both radiative and conductive) [1]	± 50 %
External radiative couplings	± 20 %
Internal radiative couplings	± 10 %
Linear couplings	± 50 %
External heat loads	± 20 %
Internal heat loads (large values)	± 20 %
Internal heat loads (small values)	± 40 %
[1] For very complex MLI an inaccuracy of +100 %, -50 % can be considered.	

For later, more advanced project stages (typically phase B and phase C/D), the following inaccuracies, shown in Table 6-2, are typical. It is worth noting that the proposed figures are a set of values which broadly represent the experience of thermal engineers from past space projects (indeed they are taken from a previous version of the ECSS thermal standard). The values themselves are roughly consistent

with a 2-sigma confidence interval, however, there is no rigorous set of characterisation tests underpinning these values. It is important to recognise this and to treat these values as a starting point; for specific cases these values need to be challenged and additional uncertainties contributions need to be added.

Table 6-2: Typical parameter inaccuracies (phase B and phase C/D)

Class	Parameter	Inaccuracy
Environmental [1]	Solar intensity	± 21 W/m²
	Earth radiation	± 65 W/m²
	Albedo factor	± 0,1
Physical	Absorptivity	± 0,1
	Absorptivity (<0,2)	± 0,03
	Emissivity	± 0,03
	Emissivity (< 0,2)	± 0,02
	Specularity ratio	± 50 %
	Radiating area (effective)	± 5 %
	Effective MLI performance (both radiative and conductive)	± 50 %
	Thermal conductivity (homogeneous materials)	± 10 %
	Thermal conductivity (composites)	± 30 %
	Contact resistance unit-structure (by similarity)	± 50 %
	Contact resistance for units supported by conductance tests	± 25 %
	Dissipation (for absolute value <10 W)	± 10 %
	Dissipation (for absolute value >10 W)	± 5 %
	Thermal capacity (equipment)	± 25 %
	Thermal capacity (structures)	± 15 %
Geometrical	Shape (view) factors (simple geometry)	± 10 %
	Shape (view) factors (complex geometry)	± 50 %
Test Facility	Chamber wall temperature	± 10 °C
	Chamber wall emittance	± 0,03
	Test adaptor temperature	± 2 °C
	Test adaptor IF conductance	± 50 %
	Solar intensity distribution and spectrum	± 3 %
	Test configuration and hardware [2]	± 10 %
	Temperature sensor measurement accuracy	± 1,5 °C
	Nodal or sensor position error	± 3 °C

[1] Note that these environmental parameters are for Earth orbits. For interplanetary missions for surface missions (Mars, Earth's Moon) different uncertainties are needed, to be derived on a case by case basis.

[2] The test configuration and hardware could cover many uncertainties related to thermal testing, for example: heat leaks via harness, effect of test configuration such as test adapter or missing appendages such as solar arrays or antennae. Depending on the test configuration and the level of specific test related modelling these uncertainties are reviewed on a case by case basis.

[3] For very complex MLI an inaccuracy of +75 %, -50 % can be considered.

6.6   Uncertainty analysis for heater controlled items

The use of active heater control is widespread on almost all S/C, at least for some part of the mission lifetime. Therefore some dedicated discussion of uncertainty analysis for heater controlled items is deserved. As indicated in section 6.1 above, the heater power (or duty cycle) can be included in the classical uncertainty analysis by considering it as a key model output. In addition a commonly used approach is outlined here for information.

For *temperature* uncertainty on heater controlled items:

a.   If heater is deactivated or has a high duty cycle (e.g. 75 %), apply the normal modelling uncertainty,

b.   If heater is acting with less than the duty cycle used in 6.6a above, a reduced uncertainty can be used, defined on a case by case basis.

For *heater power* uncertainty on heater controlled items the set point of the heater can be increased by a given value (typically the modelling uncertainty in that area). The additional heater power required to maintain this increased set point is taken as heater power uncertainty.

7
Model transfer, conversion and reduction

7.1 Model transfer

7.1.1 Introduction to model transfer

The transfer of thermal models between parties is a task that occurs many times during the course of a typical space project. For example, models of equipment or subsystems are regularly provided by sub-contractors to customers for integration into a higher level model. Prime contractors also regularly provide system level models to customers (e.g. ESA) or reduced models to launch authorities for coupled analysis. Unfortunately, every time a model transfer occurs there is the potential for problems to arise.

Some examples of the kind of problems that can occur when exchanging models between parties are given in the following (non-exhaustive) list:

a.   corruption, or even loss, of electronic data;

b.   incomplete or incorrect deliveries meaning that the model cannot be executed (e.g. missing files);

c.   incomplete or inadequate documentation describing the model and how to execute it;

d.   portability problems such as the use of different operating systems (e.g. MS Windows, Linux);

e.   problems associated with supporting tools needed to execute an analysis (e.g. proprietary, obsolete or in-house tools, etc.).

The following guidelines aim to establish best practice for the transfer of thermal models between parties.

7.1.2 Analysis files and reference results

The fundamental items in any model delivery are the analysis files themselves; usually both geometrical models and thermal models are included. For a formal delivery, associated with a project milestone, there are also typically a number of scenarios which are delivered relating to worst cases, different operation models, different configurations (e.g. stowed, deployed) etc.

In order to make the transfer of thermal models as seamless as possible there is a minimum set of deliverable model files which are necessary.

Guideline 7-1

When preparing a formal model transfer, include all necessary components to execute a complete analysis run

When a thermal model is transferred between parties, it is important that the recipient is able to directly execute a complete analysis run and obtain results. In order for this to be possible it is essential that the delivery contains all of the necessary components to execute an end-to-end analysis. Here the term "components" can refer to:

a.   all of the analysis files.

> NOTE   The associated "include" files and "global" files are included.

b.   any external libraries or routines necessary to run the model.

> NOTE   For example externally linked FORTRAN routines for material properties or results processing.

c.   any supporting tools (such as run scripts, or EXCEL based tools) which are used to execute the analysis chain or needed to generate key model outputs. For example tools used to:

1.   extract radiative couplings or fluxes,

2.   set up analysis cases,

3.   create results directories, and

4.   carry out other pre- and post-processing.

Guideline 7-2

A complete formal model transfer contains, for each analysis case provided, a set of reference results to be used for verification of the delivery. Reference results are in raw data files in the same format as produced by the analysis process.

> NOTE   Normally a minimum of two analysis cases (the hot and cold cases) are provided as reference results, although for more complex missions a number of cases with different configurations is needed.

Guideline 7-3

On receipt of a formal model transfer, execute the provided reference analysis cases and verify that the output results are identical to those provided with the delivery.

Assuming that a complete set of analysis files is provided in-line with the previous guidelines, the recipient is able to directly execute the model and obtain results. The results can then be compared to those provided in the delivery. The purpose of this comparison is to ensure that the delivered files were not corrupted in any way, and that the recipient's tool-chain is capable of producing results consistent with the supplier's.

Ideally the recipient's results are numerically identical to the reference results, although some differences can be expected due to different computing architectures (32 or 64 bit) or different versions of the analysis software. For example, enhancements or bug fixes in the analysis software can lead to numerical differences. Generally speaking, however, this kind of numerical differences are expected to be several orders of magnitude lower than the uncertainty applied to the analysis predictions.

Often the thermal models delivered contain some sort of hard-coded file paths which can cause problems on the recipients file system. If the models need to be unpacked in a specific directory structure, or if certain file paths are required, then it is important to flag these constraints in the delivery documentation.

Guideline 7-4

Avoid the use of full file system paths inside thermal analysis files and supporting utilities.

7.1.3   Documentation

It is recommended that the formal transfer of thermal models is accompanied by supporting documentation that allows the recipient to install and use the models on their computing system. This can be a standalone document, a read-me file, or it can be part of the thermal model description document (see ECSS-E-ST-31 [RD1]). Nonetheless it is an essential part of any model delivery.

Guideline 7-5

Ensure that the documentation provided with a formal model transfer contains full end-to-end instructions on how to install and run the delivered analysis cases. This also includes:

- description and usage of any software utilities, in addition to the thermal analysis tools, required to run the analysis cases.

- description of any manual steps that are required to run the analysis cases.

Guideline 7-6

Ensure that documentation provided with a formal model transfer contains the following administrative information:

- versions of all thermal analysis software used to produce reference results.

- versions of all thermal models in the supplier's configuration control environment.

- computational architecture and platform used by the supplier and used to generate the reference results.

The provision of the information described in the previous guidelines is essential in order for the recipient to be able to execute the model with minimum effort. Moreover it is important to establish a traceable workflow from the model files to the reference results. This is especially important when the long lifetime of space projects, and the number of people who work on a given project, is considered.

7.1.4   Portability of thermal models

In order to improve the portability of thermal models between computing platforms (e.g. between Windows and Linux) the following guidelines are proposed:

Guideline 7-7

Limit file and directory names to the characters A-Z, a-z, 0-9, full stop, hyphen, and underscore.

Guideline 7-8

Do not use full stop in directory names.

When software utilities, additional to the thermal analysis tools, are required to execute a full analysis run, it is important to consider the portability of the tools. For example if the extraction of external heat fluxes, and processing for input to the TMM, is carried out using a Visual Basic program then it is difficult to execute the complete workflow on a Linux system. The same concern is applicable to in-house tools which cannot be distributed (for example for reasons of confidentiality).

Guideline 7-9

Use only supporting software utilities that are portable across computing platforms.

Guideline 7-10

Use only supporting software utilities that are not based on proprietary software which cannot be included in a thermal model delivery

7.2 Model conversion

7.2.1 Introduction to model conversion

The collaborative nature of most space projects implies that many different companies and organisations are involved in the thermal modelling tasks. Inevitably different analysis tools are used and this means that the transfer of thermal models is very often accompanied by the conversion of the model format. In some cases the source and destination tools even use different numerical methods, for example ESATAN is a lumped parameter based tool whilst TMG is a control volume tool.

Over the last decade the introduction of the STEP-TAS [RD19] standard for data exchange, along with supporting tools such as TASverter has improved the situation; especially where the conversion of GMMs is concerned. The STEP-TAS standard aims to provide an open neutral format for the exchange of space thermal models including the network model, results, thermal geometry and mission aspects. Almost all of the major space thermal analysis tools now have a STEP-TAS geometric model interface of some sort – although clearly there is work still to be done.

Nevertheless, despite the development of STEP-TAS, the conversion of thermal models between tools is still a major bottleneck for space product development. This is especially true for the TMMs, for which there is no industrially validated and robust data exchange standard or tool currently available. This situation is complicated further by possible conversions of physical units between the tools – notably between SI and imperial units when working in collaboration with partners in the USA.

The following guidelines provide some useful measures to ensure that the model conversion process is as efficient as possible, and, moreover, that the models have been converted properly.

7.2.2 Management of thermal model conversions

Very often model conversions are carried out under significant time pressure. This is because the primary focus of the analysis team is on building the thermal models and executing production runs to support the project. It is only after these runs are complete that attention is given to the delivery and possible conversion of the models for the customer. A classic example of this is the conversion of thermal models for Coupled Launch Analysis (CLA) which can come late in the project.

> NOTE   This conversion for CLA is often very restrictive in terms of format - often a simple spreadsheet based format - and model size implying both a model conversion and model reduction (see section 7.3) are necessary.

Whilst this situation is understandable to some extent, it is recommended to take a proactive approach and to identify possible conversions at the start of the project. If it is known early in the project that different teams will be using different tool-chains then steps can be taken to mitigate risk and ensure that any conversions are as easy as possible. For example any project involving US/European collaboration almost certainly involves a model conversion at some point. This is usually clear from an early stage and needs to be planned for accordingly.

Guideline 7-11

During the writing of the thermal modelling specification it is important that the prime contractor identifies any anticipated conversion tasks and defines in advance the approach to be taken to complete them, clarifying in particular the following topics:

a.   identification of responsibility for conversion tasks,

> NOTE   The conversion in principle can be carried out by the model developer, the customer or by another entity (such as an agency).

b.   assessment of available conversion methods and best conversion strategy, and

c.   specific modelling rules or constraints to facilitate conversion.

It is important that there is a clear agreement between the model developer and the customer regarding the responsibility for the conversion work and associated allocation of resources.

Moreover, if certain conversions are anticipated then these can be eased by applying rules and constraints on the modelling approach. For example, if a conversion from "Tool A" to "Tool B" is envisaged, and a feature of "Tool A" is not supported in "Tool B", then some modelling rules to avoid the use of this feature could be considered. A well know example of this is the use of Boolean cutting operations. Boolean cutting operations have different levels of support, and different implementations, in different tools. Another example is the use of finite elements which are supported in some, but not all of the thermal tools. It can therefore be practical to impose modelling rules in order to avoid model conversion problems later on. It is worth noting that the features available in the tools evolve and as such modelling rules could need to be updated throughout the project.

> NOTE   This document aims to be tool neutral so specific modelling rules for given tools are not provided here. Specific cases need to be treated on a case by case basis, possibly involving tool vendors.

Finally, it is important that formal model conversions are adequately documented.

Guideline 7-12

Provide suitable documentation of the formal model conversion.

Provide the documentation with the model delivery, including the following items as a minimum:

- description of conversion approach and any issues encountered;

- description of any unit conversion and associated conversion factors;

- discussion of verification of the conversion and verification status.

7.2.3   Model conversion workflow

Ideally, when a model is converted, the party doing the conversion has access to both the source and destination tools. This enables an end-to-end verification of the model conversion process to be carried out via comparison of the results/outputs from both models. Such a work flow is depicted in Figure 7-1.
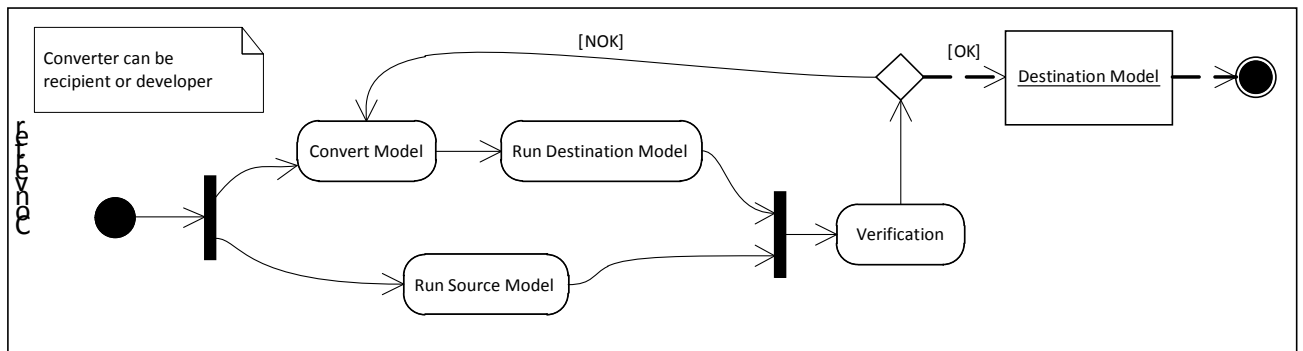

Figure 7-1: Diagram for the ideal model conversion workflow

Unfortunately, it is very often the case that the party doing the conversion has only one of the tools is available. This means that for a thorough verification to be carried out the work is necessarily split between parties, significantly adding complexity and effort to the task. Two common workflows are shown in Figure 7-2 and Figure 7-3 in order to support the following discussion (although other scenarios can be envisaged).
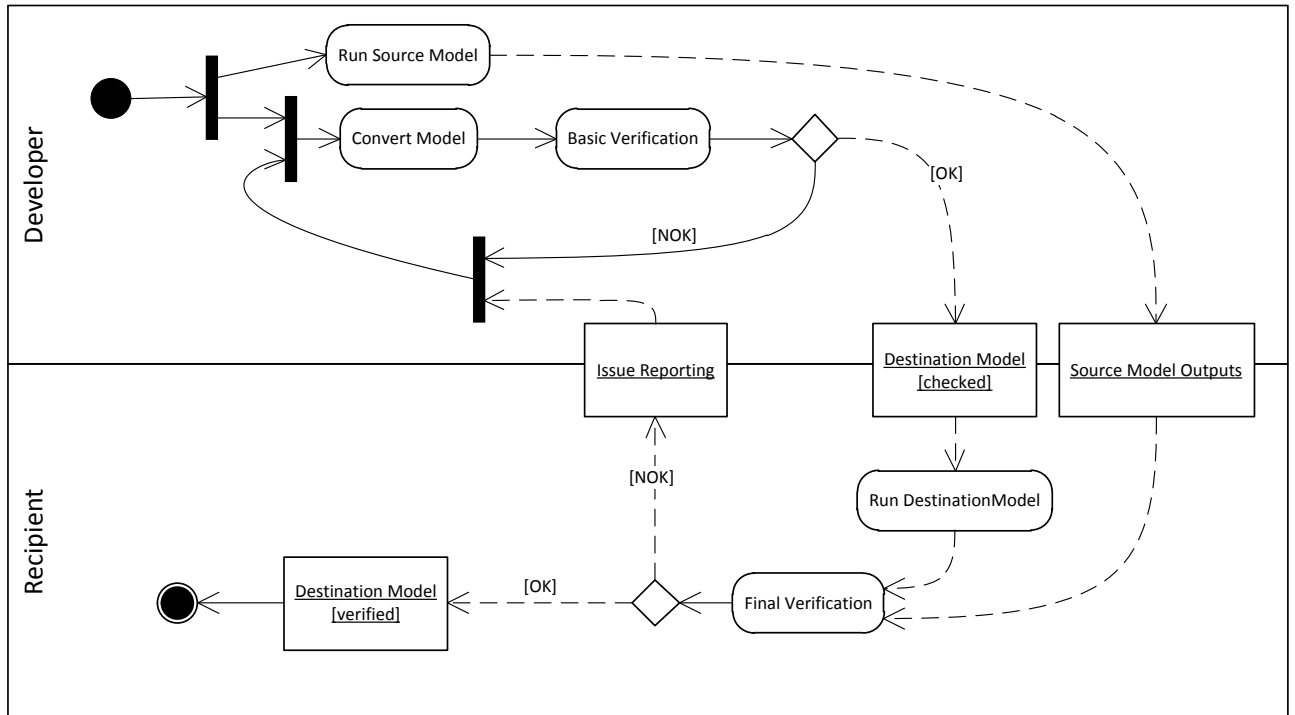
Figure 7-2: Activity diagram for conversion workflow - Conversion done by developer.
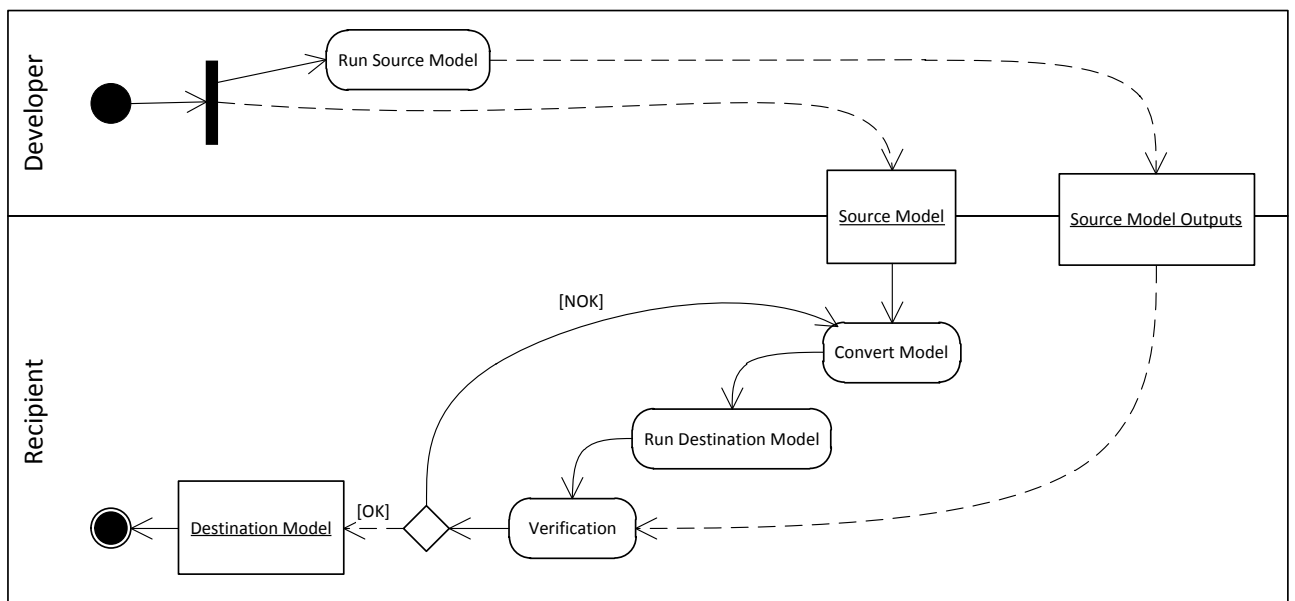

Figure 7-3: Activity diagram for conversion workflow - Conversion done by recipient.

In Figure 7-2 and Figure 7-3 it can clearly be seen that for conversions where the work is split between parties then the workflow is considerably more complex. For a proper verification to be done, several iterations between the model developer and recipient can be necessary, entailing several deliveries of models and data. Therefore, to have the best chance of a successful conversion at the first attempt it is important to ensure that the necessary data is provided for the verification; in particular concerning delivery of the source model and outputs from the developer to the recipient.

Guideline 7-13

When delivering a model for conversion by another party, apply the standard guidelines for model transfer (see section 7.1)

Guideline 7-14

When delivering a model for conversion, provide representative test cases that exercise all model elements.

Concerning exercising the model elements, an obvious example is thermostatically controlled heaters. If only a "hot" test case is provided then the heaters can never be cycling and any problems in the conversion can be missed.

In addition to the standard deliverable items, it is important to provide to the recipient additional model data which can aid in the conversion process and the verification of the converted model.

Guideline 7-15

To support an efficient conversion and thorough verification of the converted model, provide the following model data and outputs:

- full listing of radiative couplings and heat fluxes produced with GMM. Use a high number of rays and do not use filtering of couplings and fluxes;

- full listing of pertinent nodal entities during the TMM execution, including temperatures and heat inputs (environmental, dissipation and heater power);

- full listing of nodal capacitance and conductors for models containing user logic or time/temperature dependence.

Unless otherwise agreed between the parties this data is provided in an ASCII format which enables simple data processing (e.g. CSV format). The data provides enough numerical precision to allow for meaningful processing and comparison with converted results. Clearly this leads to a large amount of data, however, having a full overview of the model data is helpful when carrying out a model conversion – especially when differences emerge between the source and destination results. In this case it is necessary to debug the models and look in detail at all model parameters.

When delivering a model in converted form (as in the workflow shown in Figure 7-2) then the source models are useful for reference and can be delivered where appropriate.

7.2.4 Verification of radiative model conversions

It is essential that when a GMM is converted the outputs of the model are verified against the outputs of the source model. The primary outputs for comparison are, of course, radiative couplings and heat fluxes. Unfortunately, however, it is often difficult to carry out a direct comparison for a number of reasons:

- the stochastic nature of MCRT tools (e.g. ESATAN-TMS Radiative, RadCAD) means that differences in the coupling between a given nodal pair can emerge. This is especially true for small couplings and also for couplings between nodes with large difference in surface area where reciprocity is difficult to achieve.

- typically the radiative exchange matrix for a given enclosure is "full," meaning that every surface is radiatively linked to every other surface. This leads to a huge number of radiative couplings to be compared.

It is, however, possible to provide some measures which give some confidence about the conversion quality. Some possible approaches for comparing radiative couplings are the following guidelines.

Guideline 7-16

Carry out a qualitative check of the converted GMM. Where possible include a visual check of the model geometry. Carry out a basic check of the model file, for example looking at optical properties, number of surfaces, node numbers etc.

Guideline 7-17

When converting a GMM and only one of the source/destination tools is available, it is useful to perform a "round trip" check.

In this context, a "round trip" means converting to the destination format and then back to the source format. Although this cannot highlight some systematic errors in the conversion approach, it can provide a very useful check and identify many problems. It is also a relatively straightforward task if using a conversion tool (e.g. TASverter).

Guideline 7-18

After GMM conversion, carry out a check for "missing" radiative couplings- i.e. couplings that are present in either the source or destination models, but not both.

The "missing couplings" check is one of the most fundamental to carry out after a GMM conversion. Using MCRT solvers these missing couplings often occur when converting non-trivial GMMs.

To deal with missing couplings two approaches can be taken. Firstly, for MCRT solvers, more rays can be fired and secondly turn off filtering of couplings. This helps to ensure that as many couplings as possible are picked up. Normally such missing couplings are thermally negligible; however, it is important to check that there are no serious omissions.

Performing quantitative checks of the radiative couplings generated by the converted model is more difficult. In the simplest case a direct magnitude comparison can be carried out; i.e. for each node pair, to compare the magnitude of the coupling produced by both the source and destination models. A

percentage error term for each coupling can also be computed and the couplings "ranked" in terms of the percentage error. The main problem with this approach is that many of the small couplings exhibit very large percentage errors – especially when MCRT solvers are used. It is therefore difficult to identify any important erroneous couplings.

In order to overcome these difficulties a number of processing techniques can be carried out for the radiative coupling checks. For example, the couplings can be grouped by magnitude and the maximum percentage error per group evaluated. This can result in a plot as shown in Figure 7-4 which gives a quick overview of the conversion status. A useful addition to this approach is to treat all couplings with deep space in a separate group as these can have a major impact on the nodal temperatures and heat flows with the environment.
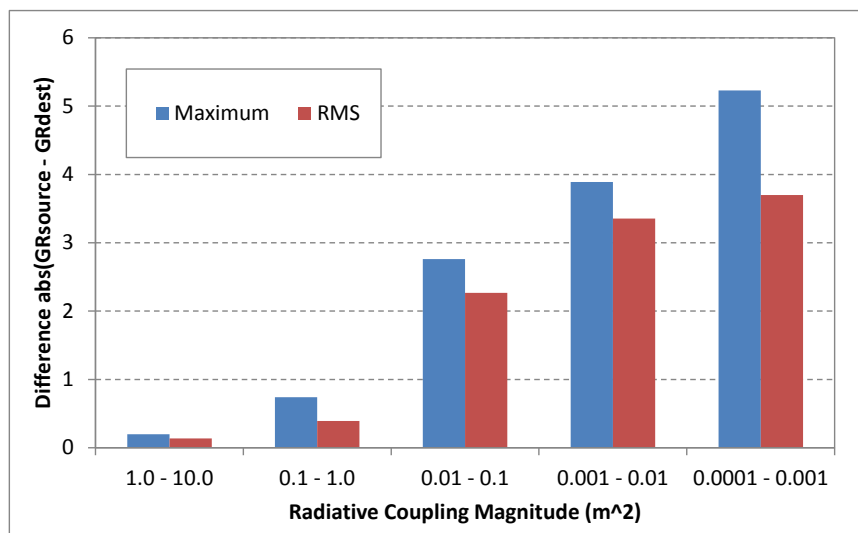

Figure 7-4: Comparison of converted GMM radiative couplings

Although checks on the coupling magnitude are useful, they are also difficult to interpret and critically evaluate. Ultimately, the best approach is to take the output of the converted GMM, integrate it in the TMM, and run a thermal solution. This enables a check on key model outputs such as temperature and heat flow to be compared.

Guideline 7-19

Compare quantitatively the radiative couplings generated by the source and destination models; and assess the verification status of the converted model.

Finally it is recommended that also the environmental heat fluxes produced by the source and destination models are compared. The statistical difficulties associated with MCRT solvers are as relevant for heat fluxes as for radiative couplings. However, it is typically easier to compare heat fluxes and a comparison of heat flux magnitude for each node provides a good check of the conversion status.

Guideline 7-20

Compare quantitatively the environmental heat fluxes generated by the source and destination models; and assess the verification status of the converted model.

7.2.5 Verification of thermal model (TMM) conversions

Generally the conversion of TMMs is considered to be more difficult than GMMs. Despite the fact that the bulk of a TMM is comprised of easily convertible entities such as nodes and conductors, the difficulty lies in converting any user logic that can be present in the model. Moreover, subtle differences in the inner workings of the different tools mean that there are many pitfalls and a working knowledge of both the source and destination tool is necessary to carry out a proper conversion. As a simple example, the different ways that SINDA and ESATAN handle nodal heat inputs can cause many problems if the user is not aware of the differences.

The thorough verification of converted TMMs is therefore essential, however, compared with the verification of GMMs, it is also conceptually easier. Indeed once an appropriate set of test cases has been defined which properly exercises all model elements, it is simply a case of running the source and destination models and comparing the key model outputs.

Guideline 7-21

After TMM conversion, compare quantitatively the key model outputs with the source model outputs and assess the verification status of the converted model.

In this case the key model outputs can be temperatures and nodal heat inputs for simple models. For more complex models it can be necessary to compare other model entities (e.g. temperature dependent nodal capacities/conductors, user constants etc.) in order to gain full understanding of the model and to determine the verification status.

Sometimes large nodal temperature differences can be seen at a given output time, even though the models are well converted. For example, when thermostatically controlled heaters are present then the switching of a heater a few seconds earlier/later in one model can give an instantaneously large temperature difference. Nonetheless, in this case, the maximum and minimum temperatures over the orbit, the heater duty cycle as well as the general "form" of the results can be critically compared. The comparison of temperatures on 2D plots can be extremely useful in the conversion report.

7.3 Model reduction

7.3.1 Introduction to model reduction

Projects with system level thermal models built with contribution from different parties need to be kept under control to avoid excessive model size. Despite the increasing in computation capability, thermal analyses involve several runs for sensitivity analysis, test correlation and so on. As a rule of thumb, the run time effort for thermal analysis is proportional to n^m , where n is number of nodes in the model and m is a factor between 4 and 5 and depends on the solution algorithm selected (see [RD15]).

The objective of thermal model reduction is, for a given high order TMM, to find a low-order TMM such that the low-order TMM retains, or closely approximates, the input-output behaviour of the high order TMM.

In terms of computation resources the aim of model reduction is:

- to reduce run time, and

- to reduce storage needs (I/O files) and memory.

A usual side effect is the loss of accuracy. Nonetheless, the Reduced TMM (RTMM) are representative of the Detailed TMM thermal behaviour.

From the perspective of the recipient of a model of a S/C element, it is often not necessary to have a deep knowledge of temperature distribution, but only overall thermal behaviour at the interfaces. Further, physical meaning can be lost, depending on the approach selected by the user.

Detailed models can be LP or FEM based, however, reduced models are usually LP based and thus the reduction can involve a change in modelling method.

Some typical examples involving model reduction are:

- equipment or payload model to be delivered to subsystem/system;

- spacecraft reduced model for coupled analysis with the launcher.

7.3.2   Management

The TMM requirements (see ECSS-E-ST-31 clause A.2.1 [RD1]) already specify in the DRD what is documented concerning the reduced model. In order to make the process as seamless as possible the following are proposed.

Guideline 7-22

During the writing of the thermal modelling specification the prime contractor identifies any anticipated reduction tasks and defines in advance the approach to be taken to complete them, in particular addressing the following items:

a.   identification of responsibility for reduction tasks;

b.   specification of model reduction correlation success criteria;

c.   definition of specific modelling rules (e.g., specific nodes numbering) and constraints (e.g., number of nodes/model size, interface nodes).

Guideline 7-23

Document the formal model reduction, and provide the documentation with the model delivery, including as a minimum:

a.   listing of delivered files;

b.   assessment of available reduction methods, description of approach selected and any issue encountered;

c.   description of any unit reduction and associated factors;

d.   discussion of reduced TMM verification and verification status, including the list of physical parameters and associated deviations considered.

7.3.3   Model reduction guidelines

The RTMM is delivered according to the TCS Mathematical Modelling Specification (ECSS-E-ST-31, Annex A [RD1]). As such it is important for the customer to clearly specify the requirements for model reduction tasks.

The following guidelines can be considered when carrying out a model reduction.

Guideline 7-24

Use the same boundary nodes for both the reduced and detailed models, and in particular, consider that:

- additional boundary nodes are forbidden;

- grouping of similar boundary nodes can be accepted, but this is agreed with the customer and tracked;

- removal of boundary nodes is strongly discouraged.

Guideline 7-25

The imposed dissipation in the detailed and reduced models is equal for a given case.

Guideline 7-26

For equivalent surfaces, the imposed heat fluxes on reduced model are equal to those applied to detailed model

Guideline 7-27

If the reduced model is run for transient analyses, consider the same detailed model heat capacitance on equivalent elements.

7.3.4 Model reduction correlation success criteria

Representative test cases are needed for reduced model verification. Verification is performed by comparing the *reduced* model with the *detailed* one. The process is therefore somewhat similar to a test correlation in the sense that two different set of data with differing fidelity are compared. Thus the skeleton of ECCS-E-ST-31 clause 4.5.3.3 "Thermal balance test (TBT) [RD1], Correlation success criteria" can be used as inspiration to derive guidelines for model reduction.

Successfully correlated model meets the following criteria (Guideline 7-28 to Guideline 7-30), when the reduced and detailed models are compared considering the same conditions (i.e. environmental conditions and attitudes, boundaries and power dissipations). The correlation status needs to be checked for all relevant load cases.

Guideline 7-28

Perform reduced model correlation for both steady state and transient analysis cases

Guideline 7-29

Correlation for units is based on each TRP as defined in the ICD

Guideline 7-30

Successfully correlated reduced meet the following criteria:

a. Deviation between reduced model temperatures and weighted mean value of corresponding detailed model temperatures are within specification. Some examples are:

    1. equipment's and temperature controlled elements TRP:

        (a) average < 2 K

        (b) individual deviation at TRP <3 K

    2. external surfaces (no MLI) < 3 K

    3. structural elements (no MLI) < 3 K

    4. MLI < 15 K

b. The temperature standard deviation < 3K, 1σ taking into account all comparable model outputs

c. Deviations between heating/cooling powers are within specifications. Some examples are

    1. Conductive power at interfaces < 5 %

    2. Radiative power at interfaces < 5 %

    3. Heat flux to/from Spacecraft <10 %

    4. Heater power consumption <10 %

7.3.5 Model reduction approaches

7.3.5.1 Model reduction methods

The model reduction task is a continuously growing area and several methods are available and were presented over the years. A first classification is given of these methods based on top level procedure and collected in Table 7-1, with pros and cons.

Table 7-1: Model reduction methods

Method	Pros	Cons
Manual	Easy to implement No need for other tools	Slow: many interaction needed with the user intervention to converge Reduction depends on thermal engineer Not possible to recover temperature of detailed TMM
Direct Mathematical	Fast S/W tool available (TMRT)	Possible loss of physical interpretation (negative conductors) Cannot usually be adjusted, for example during a correlation.
Optimisation	Can be applied to reduce FEM to LP	Training necessary with S/W tool Multiple runs necessary (license and CPU demanding)

7.3.5.2 Manual method

This method is simple and intuitive since it mixes thermal analyst's experience with a physical approach and makes use of scaling parameters that can come from tests correlations, e.g., the "spreading effect factor", used for conductors between units and mounting panels, or introducing ad hoc parameters to recover somehow the loss of information intrinsic to the reduction process.

Model reduction starts with defining test cases (steady and transient) for the model reduction check and splitting the detailed TMM into following sets:

- <u>kept nodes:</u> detailed TMM nodes to be maintained for control and/or accuracy needs: interfaces, TRP, HP vapour nodes, temperature sensors locations, heated area, etc.;

- <u>Suppressed nodes:</u> nodes that have minor or no influence on thermal behaviour from the host TMM standpoint. Usually suppressed nodes do not involve radiative heat exchange;

- <u>Grouped or condensed nodes:</u> nodes set to be replaced with one node each.

Once these sets are defined, reduction activity starts and is implemented with a step by step approach, for which each modification is verified running test cases, before the next reduction is implemented.

It's worth noting that the major effort is in the definition of condensed nodes sets and properties, in particular thermal links between condensed nodes and other entities. Some general guidelines for nodes grouping are listed hereafter:

a. group nodes that can be considered isothermal, i.e., when detailed TMM temperature difference w.r.t. their mean value is between a specified accuracy;

b. avoid collapsing nodes with different optical properties when radiative heat transfer is relevant;

c. condensed node heat capacity is equal to the sum of detailed TMM single nodes contribution;

d. condensed node heat load is equal to the sum of detailed TMM single nodes contribution;

e. linear conductors involving collapsed nodes can be estimated at first iteration by considering the heat flow between groups computed with detailed TMM and their mean temperature.

> NOTE   For example, the first guess for a linear conductor between groups G1 and G2, with mean temperatures T_{G1} and T_{G2} (weighted by nodal capacitance), exchanging an heat flow $HF_{1,2}$ is $GL(1,2)=HF_{1,2}/|T_{G1}-T_{G2}|$. Modifications on computed GL try to recover the original heat flux $HF_{1,2}$

f. for internal cavities, where no GMM is delivered, a similar approach as in 7.3.5.2e can be used, starting from heat flux analysis and temperature weighted means.

7.3.5.3 Mathematical methods

Many approaches to model reduction exist in mathematical literature for large dynamic systems and are potentially applicable to thermal models as well. These include balanced model reduction, frequency-domain based approximation, moment matching methods, projection-based methods, singular value decomposition (SVD), Krylov subspace based techniques and so on.

One tool that uses a mathematical model reduction is the "Thermal Model Reduction Tool" which has been used on industrial models in a number of companies. More details can be found in [RD16] and [RD18].

Another mathematical approach which has been used before is the stochastic approach, for example presented in [RD17].

Annex A
Specific guidelines

A.1 Multilayer insulation

A.1.1 Introduction

Multilayer insulation (MLI) is a thermal control element composed of several stacked thin foils. These foils are separated (by embossing, crinkling or a spacer net) so that their contact area is small and the conductive path through the stack is minimised. The foils have low infrared emissivity, achieved by a deposition of thin metal layers such as aluminium and gold. This results in a very low overall radiative conductance through the stack.

The heat transfer through the MLI is composed of radiation between each foil and conduction through contact areas.

As MLI are complex structures and real conditions can strongly influence its characteristics. In particular the detailed design of MLI leads to areas of higher compression (fixations) and edges, seams etc. where the MLI performance is locally reduced. Therefore it is recommended that MLI characteristics values are considered with caution and suitable sensitivity analysis is carried out (see section 6).

A.1.2 Modelling principles

The thermal modelling of a MLI usually focuses on the through-thickness heat fluxes. It is recommended that the model accurately represents the following data:

- temperature of the external foils T_1 and T_2, and

- heat flux from one side to the other.

If the MLI is mounted flat on a surface, it is possible to avoid modelling the MLI foil in contact with the surface: in this case all couplings are between the MLI outer foil and the thermal node representing the surface.

Where possible, it is recommended that the nodal pattern of the MLI external matches the one of the underlying surface. This avoids artificial coupling between nodes and spurious thermal "shortcuts" which do not exist in practice.

The modeller is advised to check that in-plane phenomena can be neglected, especially for MLI with a small area.

A.1.3 Modelling patterns

The link between external temperatures and heat flux can be modelled with various detail level.

The most usual types of modelling only calculate the required data (that is T_1 and T_2, $\overline{q}$). The link between temperatures and flux is modelled with one or two couplings, which can be linear or radiative. The classical formulations are as follows:

a.   linear temperature dependent coupling : $\overline{q} = k^*(T_m)[T_2 - T_1]$ where T_m is the average of T_1 and T_2

b.   effective emittance : $\overline{q} = \sigma\varepsilon^*[T_2^4 - T_1^4]$

c.   parallel linear and radiative: $\overline{q} = k^*[T_2 - T_1] + \sigma\varepsilon^*[T_2^4 - T_1^4]$

As radiation is non-linear, the first formulation (a.) needs to be temperature dependent.

The second formulation (b.) can only be relevant on a short range of temperature because physical coupling is not purely radiative.

The third formulation (c.) can be relevant on a wide range of temperature.

It is worth noting that in the expressions above the coefficients k^* and ε^* are empirical and the values are normally obtained through dedicated characterisation tests.

In some case, it is possible to explicitly model the different foils of the MLI. It is recommended that the detailed composition and foil-to-foil coupling is known prior to any modelling. This kind of model is obviously expensive, and is only relevant if more details are needed. Examples are accurate in-plane flux calculation or MLI design optimisation.

As a first approximation MLI is sometimes modelled by setting the external surface emissivity to the equivalent emissivity of the MLI outer layer in series with an ε^* value. It is recommended that this modelling is avoided for all but the simplest analyses (for example hand calculations) because neither external fluxes nor multi-reflection can be properly captured.

As MLIs are very lightweight, their capacitance is very small and can often be neglected (using "arithmetic nodes"). This can lead to convergence and time-step dependency problems (see section 4.6 about transient modelling).

NOTE   Exceptions can be MLI built with metallic foils with more significant thermal capacitance.

A.2   Heat pipes

A.2.1   Introduction

Heat Pipes (HPs), or more specifically Constant Conductance Heat Pipes (CCHPs), are a commonly used thermal control technology. CCHPs can be distinguished from the Variable Conductance Heat Pipe (VCHP) and the Loop Heat Pipe (LHP) which are not covered in this text. Several useful reference exist which provide an introduction to heat pipes. In particular the following references contain useful background information:

a.   Thermal design handbook ECSS-E-HB-31-01 Part 8 ("Heat Pipes") [RD4];

b.   Two-phase heat transport equipment ECSS-E-ST-31-02 [RD3];

c.   Spacecraft thermal control handbook [RD7].

Additionally there are many years of proceedings from conferences such as ICES and the International Heat Pipe conference which can be drawn upon. Another useful reference for the modelling of a heat pipe is "How to model a heat pipe"[RD20], which had been used as input to this section.

A.2.2 Modelling principles

In certain applications, such as telecommunication spacecraft, many tens of heat pipes can be used on a single panel to spread heat and create a uniform temperature field. In other applications a single heat pipe can be used, for example to transport heat over a distance with small temperature difference. These two applications can call for different modelling strategies. For example in a situation where many HPs are used then a simple increase of the overall panel conductivity is likely to be sufficient in a S/C level thermal model. On the contrary for HP sizing or verification a more detailed approach can be required.

A.2.3 Modelling patterns

The classical pattern for modelling a heat pipe is shown schematically in Figure A-1. Normally only the wall of the heat pipe is discretised in the axial direction. If an especially detailed model is required then circumferential discretisation, or the modelling of the heat pipe flanges, can be considered.
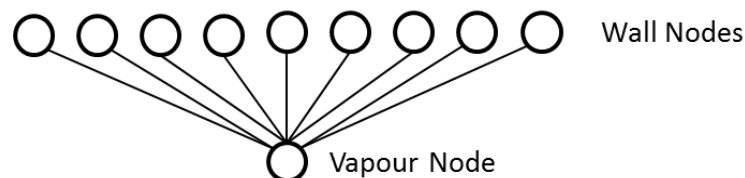

Figure A-1: Typical heat pipe nodal topology

The vapour inside the heat pipe is modelled by a single arithmetic node. The inside of the heat pipe wall/wick is thermal linked to the vapour node via appropriate boiling/condensation Heat Transfer Coefficients (HTC).

The advantage of this modelling pattern is that the nearly length independent conductance of a heat pipe is properly represented.

A simplified modelling approach involves modelling the heat pipe as a bar of high thermal conductivity. The disadvantage of this approach is that the heat pipe conductance becomes length dependent: the importance of this dependency is related to the specific application.

A.2.4 Design verification

As for any equipment the temperature is verified with respect to the appropriate design temperatures.

HP manufacturers usually provide curves of heat transfer capability vs. temperature in datasheets. It is usually verified by analysis that the design does not exceed this heat transfer capability.

An artificial example of computing this value is shown in Figure A-2. A single heat pipe is attached on the lower flange to a continuous radiator panel. On the top flange two items of dissipating equipment are mounted. The curve shown above the diagram shows the net heat transfer across the heat pipe boundary per unit length. Based on this curve the heat input can be integrated cumulatively along the heat pipe length as shown in the top curve. The extreme (furthest from zero) of this integrated curve

can be used to verify the heat transport capability, based on the manufacturer's data sheet at the appropriate temperature.
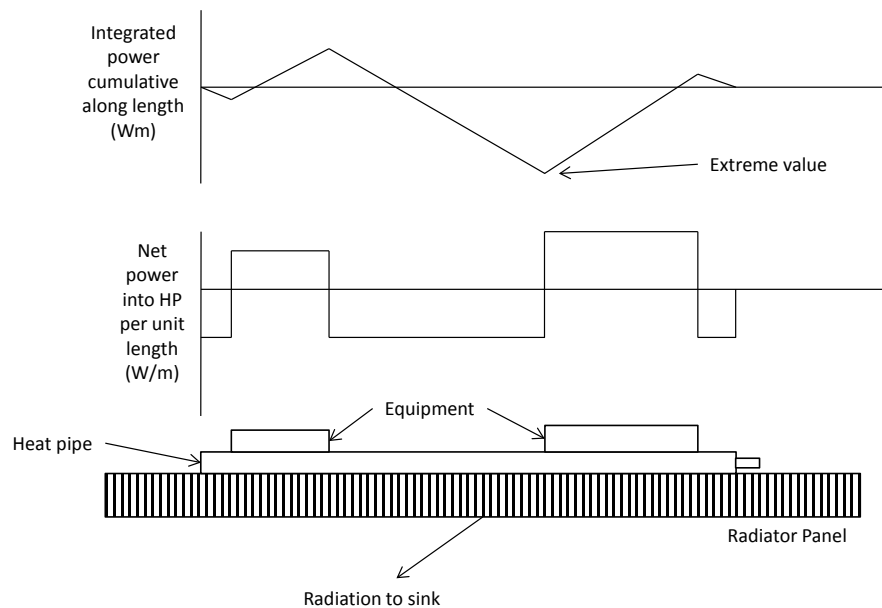

Figure A-2: Example of verifying heat pipe heat transport capability

A.2.5 Model verification

In order to properly compute the heat pipe the flanges are meshed in the axial direction. If this mesh is too coarse (too few nodes) then the peaks and troughs can be smeared out. Thus it is recommended that the meshing density of the flanges is assessed to ensure it provides enough resolution for the purpose of the model.

A.3 Layered materials

A.3.1 Modelling principles

The principle to be used is to consider a homogeneous material with thermal properties equivalent to the layer stack. This equivalent material property is usually orthotropic, as phenomena in the layer plane are different from those through the layer plane.

A.3.2 Modelling patterns

In the following discussion the nomenclature used is:

- k_i : conductivity of layer i (W.m^{-1}.K^{-1})

- t_i : thickness of layer i (m)

- ρ_i : density of layer i (kg.m^{-3})

- c_i : specific heat capacity of layer i (J.kg^{-1}.K^{-1})

- α_i : filling factor of layer i (dimensionless)

- g_j : interface conductance i (W.m^{-2}.K^{-1})

where the units of measurements are detailed in round brackets.

The simplest modelling pattern only considers full layers, and no interface resistance between layers. For the in-plane directions, conductivity is calculated with an arithmetic mean of the different layers:

$$k_{plane} = \frac{\sum_{i=1}^{n} t_i \cdot k_i}{\sum_{i=1}^{n} t_i} \qquad \text{[A-1]}$$

In the through thickness direction, conductivity is calculated with an harmonic mean of the different layers:

$$k_{thru} = \frac{\sum_{i=1}^{n} t_i}{\sum_{i=1}^{n} \frac{t_i}{k_i}} \qquad \text{[A-2]}$$

Density ρ and heat capacity c are also calculated with arithmetic means:

$$\rho = \frac{\sum_{i=1}^{n} \rho_i \cdot t_i}{\sum_{i=1}^{n} t_i} \qquad \text{[A-3]}$$

$$c = \frac{\sum_{i=1}^{n} c_i \cdot \rho_i \cdot t_i}{\sum_{i=1}^{n} \rho_i \cdot t_i} \qquad \text{[A-4]}$$

Where t_i is the thickness of layer i. k_i, ρ_i and c_i are respectively its thermal conductivity, density and heat capacity.

If some layers are not filled with material (e.g.: PCB trace layers), then, as a first approximation, their contribution can be considered by using a filling factor α:

$$k_{plane} = \frac{\sum_{i=1}^{n} \alpha_i \cdot t_i \cdot k_i}{\sum_{i=1}^{n} t_i} \qquad \text{[A-5]}$$

$$k_{thru} = \frac{\sum\limits_{i=1}^{n} t_i}{\sum\limits_{i=1}^{n} \dfrac{t_i}{\alpha_i \cdot k_i}}$$

[A-6]

$$\rho = \frac{\sum\limits_{i=1}^{n} \alpha_i \cdot \rho_i \cdot t_i}{\sum\limits_{i=1}^{n} t_i}$$

[A-7]

$$c = \frac{\sum\limits_{i=1}^{n} \alpha_i \cdot c_i \cdot \rho_i \cdot t_i}{\sum\limits_{i=1}^{n} \alpha_i \cdot \rho_i \cdot t_i}$$

[A-8]

If interface resistance between layers is considered, inter-layer conductivity is corrected as follows:

$$k_{thru} = \frac{\sum\limits_{i=1}^{n} t_i}{\sum\limits_{i=1}^{n} \dfrac{t_i}{k_i} + \sum\limits_{j=1}^{n} \dfrac{1}{g_j}}$$

[A-9]

A.4 Electronic units

A.4.1 Introduction

The thermal analyst in charge of an electronic unit is in the middle of the chain that connects the external environment to the internal components. Therefore it is important to agree the two frontiers that limit the responsibility in order to know exactly what is included in the model.
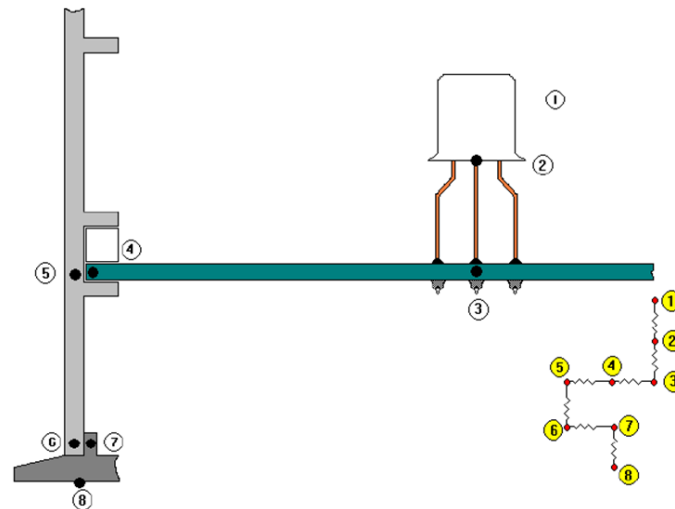

Figure A-3: Typical electronic unit thermal network

The sketch provided in Figure A-3 and the descriptions in the following lines help to describe the heat flows inside electronic units.

1. junction of the component (the term junction is used for semiconductors), it is not used for passive components like capacitors, resistances or inductors;

2. component case;

3. area of the Printed Circuit Board (PCB) just below the EEE and where the EEE is thermally coupled, it is the position where one individual EEE is mounted onto the PCB;

4. external limit of the board;

5. area of the external housing of the box wall where the wall is connected thermally with the Board;

6. area of the external housing of the box wall where the wall is connected thermally with the base plate;

7. area of the base plate where the base is thermally connected external wall plate;

8. Temperature Reference Point.

In Figure A-3, the nomenclature used to refer to these thermal resistances is done using a letter R followed by a sub-index with two numbers that indicate the two points connected by the resistance, for example the resistance between points 1 and 2 is written as R_{12}.

The thermal engineer of an electronic unit is responsible for the thermal path that runs from the TRP (point 8) to the component internal temperature (point 1). However, resistances R_{12} and R_{23} are imposed by the manufacturer and by the component assembly respectively. Practically this means that the resistances under the control of the unit analyst usually span from the TRP to the EEE (point 3).

> NOTE   For clarification, the point 3 can be a in a PCB or in a stiffener depending where the component is mounted.

R_{12}: thermal resistance due to the assembly of the component. The R_{12} is internal to the component and it is provided by the component manufacturer in datasheets.

R_{23}: thermal resistance due to the assembly of the component. The resistance R_{23} is fixed by the assembly of the component to PCB, this resistance depends on the materials used in the component assembly and its geometry. This assembly is usually qualified fulfilling the rules and validation criteria of applicable norms of the space agency, so typically these resistance (R_{23}) is imposed to thermal engineer and normally it is not included as part of the thermal model.

R_{34}: Thermal resistance between the point where the component is mounted and the external border of the board. The point can be a point in the PCB or in the stiffener; therefore the effective resistance R_{34} is typically complex to derive as it is the resultant of many others within the PCB, stiffeners etc. The PCB itself is full of discontinuities; it has copper that is an excellent thermal conductor but also dielectric materials (e.g. polyamide) with a low thermal conductivity. It is complex and time consuming to represent all of copper tracks and planes with the exact geometry in a model, so usually effective properties are used (see Annex A.3).

R_{45}: thermal contact between the PCB and the frame. The frame is typically made of aluminium and these joints can be realised using screws, clamping guides etc. Additionally a conductive interface material or filler such as glue or silicone can be used in this joint. It is important to consider all these materials in the calculation of this thermal resistance.

R_{56}: thermal resistance of the aluminium case; this part is normally a continuous and isotropic material and so classical methods for conductor generation are appropriate.

R_{67}: thermal resistance between two parts of the external housing of the electronic box. These parts of the housing are typically attached using screws and the contact conductivity depends on many factors like, size of the surface in contact, materials, pressure and contact surfaces quality (flatness & roughness).

R_{78}: thermal resistance of the base plate or the part where the TRP is located. Similarly as for R_{56} this resistance is usually straightforward to compute in a continuous and isotropic material.

A.4.2 Physical data and modelling advice

A.4.2.1 Modelling of discontinuities (R_{67}, R_{45})

The key to achieving good accuracy in the modelling of electronic units is the careful selection of the conductance values in the discontinuities. In the context of modelling electronic units the reader is directed in particular towards the following references where numbers can be found to use as a starting point in such analysis, for example see ECSS-E-HB-31-01 Part 4 [RD4].

A.4.2.2 Conductance inside a PCB (R_{34})

A PCB is a classic example of a layered material. The techniques discussed in Annex A.3 to derive equivalent properties are therefore appropriate.