ECSS-E-30 Part 1A
25 April 2000

EUROPEAN COOPERATION
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FOR SPACE STANDARDIZATION

Space engineering

Mechanical — Part 1: Thermal control

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Foreword

This Standard is one of the series of ECSS Standards intended to be applied together for the management, engineering and product assurance 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.

Requirements in this Standard are defined in terms of what shall be accomplished, rather than in terms of how to organize and perform the necessary work. This allows existing organizational structures and methods to be applied where they are effective, and for the structures and methods to evolve as necessary without rewriting the standards.

This Standard has been prepared by the ECSS Mechanical Engineering Standard Working Group, reviewed by the ECSS Technical Panel and approved by the ECSS Steering Board.

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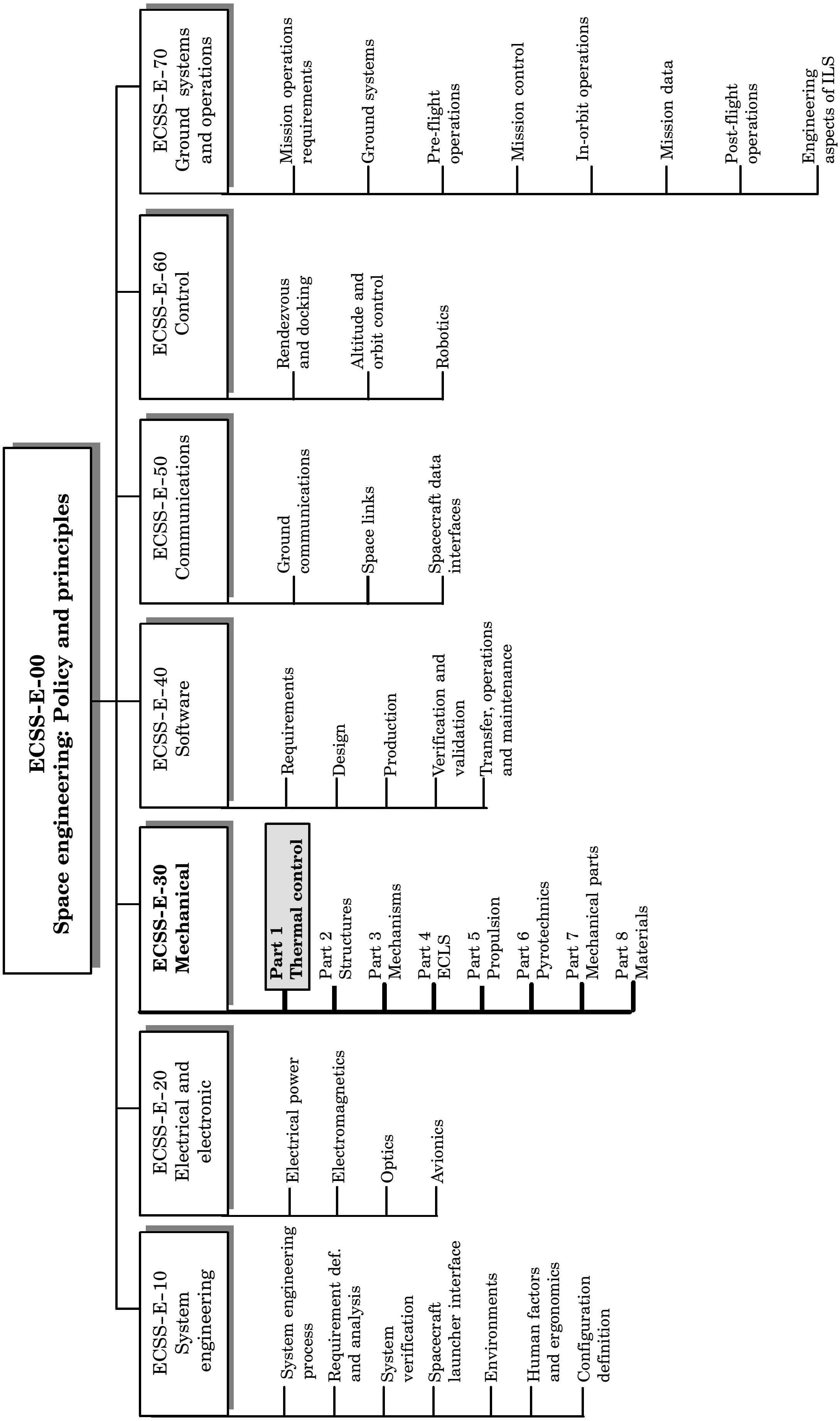

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Scope

Part 1 of ECSS-E-30 in the engineering branch of ECSS Standards defines requirements for the discipline of thermal engineering.

This Standard defines the requirements for the definition, analysis, design, manufacture, verification and in-service operation of thermal control subsystems of spacecraft and other space products.

This Standard applies to the thermal engineering activities of all spacecraft and space related products for all thermal aspects and temperature levels for space products.

For this Standard, the complete temperature scale is divided into 3 ranges defined as follows:

- Cryogenic temperature range, below 120 K;
- Conventional temperature range, between 120 K and 420 K;
- High temperature range, above 420 K.

The core part of this Standard concerns the conventional temperature range; complementary information, requirements and definitions for the cryogenic and high temperature range respectively are provided in annexes B and C.

When viewed from the perspective of a specific project context, the requirements defined in this Standard should be tailored to match the genuine requirements of a particular profile and circumstances of a project.

NOTE Tailoring is a process by which individual requirements of specifications, standards and related documents are evaluated, and made applicable to a specific project by selection, and in some exceptional cases, modification of existing or addition of new requirements.

This Standard is applicable to:

a. thermal engineering activities of all space and space related products, covering all thermal engineering aspects involved in the achievement of the required thermal performance, particularly: design, verification, manufacturing and in service operations;

b. thermal control subsystem and to relevant parts of all space products.

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Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this ECSS Standard. For dated references, subsequent amendments to, or revisions of any of these publications do not apply. However, parties to agreements based on this ECSS Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references the latest edition of the publication referred to applies.

ECSS-P-001	Glossary of terms
ECSS-Q-20	Space product assurance — Quality assurance
ECSS-Q-40	Space product assurance — Safety
ECSS-Q-70	Space product assurance — Materials, mechanical parts and processes
ISO 128:1982	Technical drawings — General principles of presentation

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Terms, definitions and abbreviated terms

3.1 Terms and definitions

The following terms and definitions are specific to this Standard in the sense that they are complementary or additional with respect to those contained in ECSS-P-001.

3.1.1
acceptance margin
contingency agreed between system authority and TCS to account for unpredictable TCS-related events (see Figure 1)

NOTE The acceptance margin is the difference between the upper or lower acceptance temperature and the upper or lower design temperature (for both operating and non-operating mode).

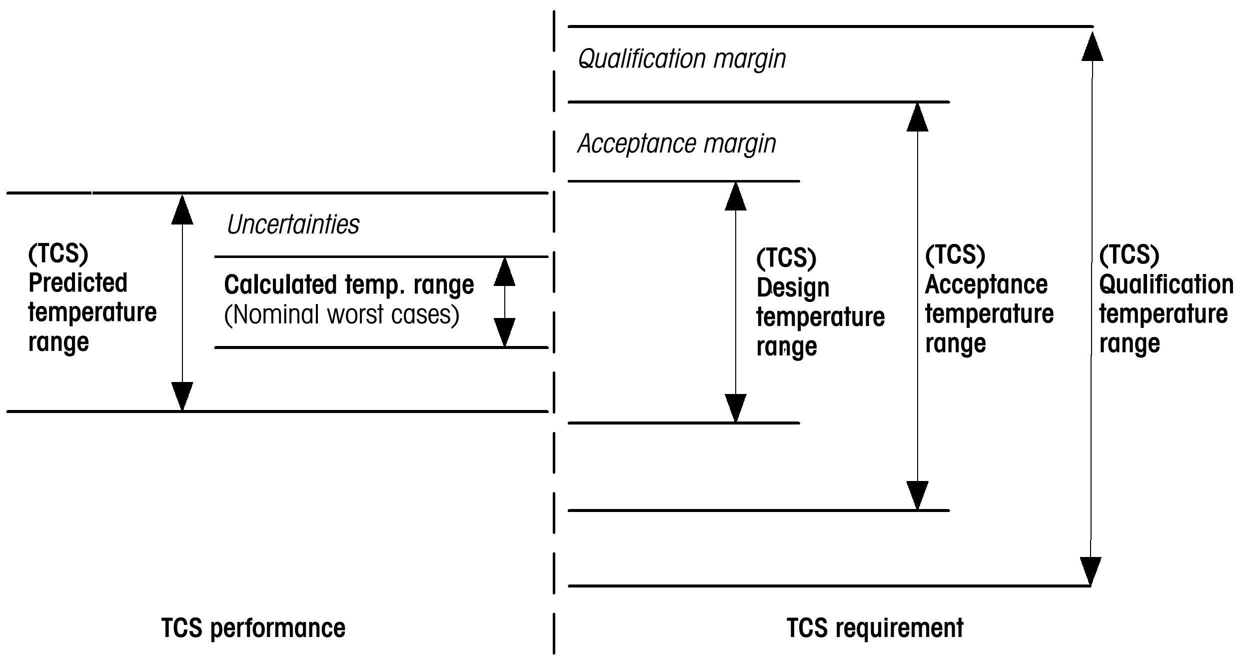

Figure 1: Temperature definitions for thermal control system (TCS)

3.1.2
acceptance temperature range
temperature range (see Figure 1) obtained from the relevant qualification temperature range after subtraction of suitable qualification margins specified for the operating and non-operating mode and the switch-on condition of a unit

NOTE The acceptance temperature range is the extreme temperature range that a unit can reach, but never exceeds, during all envisaged mission phases (based on worst case assumptions).

3.1.3
acceptance test (system level)
verification process that demonstrates that an item is acceptable for flight

NOTE During the acceptance test, the unit TRPs are exposed to temperatures within and not exceeding their acceptance temperature range.

3.1.4
assembly (thermal)
combination of parts, components and units which forms a functional entity

3.1.5
calculated temperature range
temperature range (see Figure 1) obtained by analysis or other means for the operating and non-operating mode and the minimum switch-on condition of a unit, based on worst case considerations (i.e. an appropriate combination of external fluxes, materials properties and unit dissipation profiles to describe hot and cold conditions) excluding failure cases

NOTE The calculated temperature range plus any uncertainties is limited to the specified design temperature range. During the course of a project these uncertainties change from initial estimates into a value determined by analysis.

3.1.6
climatic test
test conducted to demonstrate the capability of an item to operate satisfactorily or to survive without degradation under specific environmental conditions (e.g. pressure, humidity, composition of atmosphere) at predefined hot and cold temperatures

3.1.7
component (thermal)
piece of thermal hardware which by further subdivision looses its functionality, but is not necessarily destroyed

3.1.8
conductive interface temperature
temperature used to define the conductive heat exchange between an item and the supporting structure

NOTE 1 Depending on the degree of interaction between the item (via for example, its temperature, contact area, contact conductance) and the supporting structure, the conductive interface temperature, is reassessed in an iterative way during the course of a project.

NOTE 2 In case the expected conditions cannot be correctly simulated, the qualification process can include a flight demonstration (e.g. launchers, re-entry vehicles).

3.1.9
correlation
correspondence between analytical predictions and test results

3.1.10
design temperature range
temperature range (see Figure 1) specified for the operating and non-operating mode and the switch-on condition of a unit, obtained by subtracting suitable acceptance margins from the relevant acceptance temperature range

NOTE 1 This temperature range represents the requirements for the TCS design activities.

NOTE 2 The use of the term "operating temperature range" or "operational temperature range" to denominate the design temperature range, shall not be used.

3.1.11
geometrical mathematical model (GMM)
mathematical model in which an item and its surroundings are represented by radiation exchanging surfaces characterised by their thermo-optical properties

NOTE The GMM generates the absorbed environmental heat fluxes and the radiative couplings between the surfaces.

3.1.12
heat dissipation or heat flow rate
thermal energy (heat) divided by time, expressed in joules per second, or watts

3.1.13
heat flux or heat flow rate density
thermal energy (heat) divided by time and unit area perpendicular to the flow path, expressed in W/m^2

3.1.14
heat lift
transfer of a specified heat flow rate from a specified lower to a higher temperature (e.g. applicable to heat pumps)

3.1.15
heat storage
capability to store a specified amount of heat at a specified temperature, or over a specified temperature range

3.1.16
item (thermal)
term used in this Standard to designate, replace any or all of the following terms: part, component, unit, assembly, complete spacecraft

3.1.17
infrared test
thermal test method in which the solar and planetary radiation are simulated by locally heating the spacecraft surface to the predicted input level using infrared techniques (e.g. infrared lamps, heater mats)

3.1.18
minimum switch-on temperature
minimum temperature at which a unit can be switched from the non-operating mode to the operating mode and functions nominally when the unit temperature is brought back to the relevant operating mode temperatures

3.1.19
natural environment
set of environmental conditions defined by the external physical surrounding for a certain mission (e.g. the heat fluxes by the sun, the planets and satellites, the air pressure and density)

3.1.20
part (thermal)
smallest piece used in thermal hardware which, when subdivided any further, is destroyed (e.g. foils, thermal washers, bolt, pipe)

3.1.21
predicted temperature range
temperature range (see Figure 1) obtained from the calculated temperature range increased by the uncertainties

3.1.22
qualification margin
contingency defined by the system authority to account for any unexpected events (see Figure 1)

NOTE For temperatures, the qualification margin is the difference between the upper or lower qualification temperature and the upper or lower acceptance temperature (for operating and non-operating mode).

3.1.23
qualification temperature range
temperature range (see Figure 1) specified for the operating and non-operating mode and the switch-on condition of a unit, for which this unit is guaranteed to function nominally fulfilling all required performances with the required reliability

3.1.24
qualification tests (system level)
verification process that demonstrates that hardware functions within performance specification under simulated conditions more severe than those expected during the mission

NOTE During the qualification tests, unit temperature reference points (TRPs) are exposed to temperatures within but not exceeding the qualification temperature range.

3.1.25
radiative sink temperature
virtual black body radiation temperature used to define the equivalent radiative thermal load on an item

NOTE 1 The radiative sink temperature includes both the natural environment load (solar, planetary albedo and infrared fluxes) and the radiative exchanges with other items.

NOTE 2 The radiative sink temperature is typically used to provide a simplified interface for an item, to provide a means for parameter studies thus avoiding extensive calculations or to define adequate radiative boundary conditions for thermal tests.

NOTE 3 The sink temperature T_{Sink} of an item i with a temperature T_i in radiative exchange with n items j and submitted to external radiative environmental fluxes is calculated according to the formula:

$$T_{Sink,rad}(i) = \sqrt[4]{T_i^4 + \frac{\sum_{j=1}^{n} R_{ij}(T_j^4 - T_i^4)}{\epsilon A_i} + \frac{P_s}{\sigma\varepsilon A_i} + \frac{P_A}{\sigma\varepsilon A_i} + \frac{P_{IR}}{\sigma\varepsilon A_i}}$$

where

ε	emissivity of item i;
P_s	absorbed solar flux on item i (if applicable);
P_A	absorbed (planetary) albedo flux on item i (if applicable);
P_{IR}	absorbed infrared (planetary) flux on item i (if applicable);
R_{ij}	radiative coupling between item i and item j;
T_j	temperature of item j;
σ	Stefan-Boltzmann constant;
A_i	radiative exchange area of item i.

NOTE 4 The radiative sink temperature formula is applicable to steady-state conditions only. Depending on the degree of interaction between the item i (via its temperature, surface properties, dimensions, heat dissipation) and the radiative sink, the simplified approach using the radiative sink temperature is performed in an iterative way during the course of a project.

3.1.26
reference case
set of parameters (i.e. environmental, material properties, dissipation profiles) used for comparable analysis

NOTE A reference case can be a design case.

3.1.27
solar simulation test
test method in which the intensity, spectral distribution, uniformity and collimation angle of the solar radiation are reproduced within acceptable limits

3.1.28
success criteria
predefined value or set of values, for one or several parameters (e.g. temperature, temperature gradient) which shall be achieved

NOTE Success criteria can be defined for analytical activities (i.e. correlation) or for testing activities.

3.1.29
system interface temperature point
physical point appropriately located on the structure of the system which can be used to evaluate the thermal conductive interaction between a unit and the spacecraft system

3.1.30
temperature
potential which governs the flow of energy, measured by the scale of absolute temperature, the kelvin scale (K)

NOTE Temperatures may also be expressed in degree celsius (°C).

3.1.31
temperature cycle
transition from some initial temperature condition to a predefined temperature (with stabilisation, if required) at one extreme and then to a predefined temperature (with stabilisation, if required) at the opposite extreme and returning to the initial temperature condition

3.1.32
temperature difference
difference in temperature of two points at a given time, expressed in K or °C

3.1.33
temperature gradient
vector whose direction at a given time and a given point is perpendicular to an isothermal surface at that point, and whose magnitude equals the rate of change of temperature in this direction, expressed in K/m

3.1.34
temperature reference point (TRP)
physical point located on a unit and unequivocally defined in the unit's ICD

NOTE 1 The TRP provides a simplified representation of the unit thermal status.

NOTE 2 Depending on the unit dimensions, more than one temperature reference point may be defined.

3.1.35
temperature stability
condition when the temperature variation is less than a defined (small) value for a given point

3.1.36
temperature uniformity
condition when the temperature difference or the temperature gradient at a given time is less than a defined (small) value for a given surface or a given body

3.1.37
temperature variation
change of temperature with respect to time for a given point, expressed in K/s

3.1.38
thermal balance test
test conducted to verify the adequacy of the thermal model and the adequacy of the thermal design

3.1.39
thermal design case
set of parameters (e.g. environmental, material properties, dissipation profiles) used for the detailed definition and sizing of the thermal control subsystem

3.1.40
thermal mathematical model (TMM)
lumped parameters model in which an item and its surroundings are represented by concentrated thermal capacitance nodes, each with one representative temperature, coupled by a network made of thermal conductors (radiative, conductive and, if applicable, convective)

NOTE 1 For thermo-hydraulic modelling enthalpy and fluidic conductors are specified.

NOTE 2 A TMM generates for all nodes a temperature history, an energy balance; in addition pressure drops and mass flow rates, if applicable.

3.1.41
thermal node
representation of a specific volume of an item with a representative temperature, representative material properties and, if applicable, representative pressure (diffusion node) used in a mathematical lumped parameter approach

NOTE Other nodes also used in a TMM include arithmetic or boundary nodes.

3.1.42
thermal vacuum test
test conducted to demonstrate the capability of the test item to operate satisfactorily or to survive without degradation in vacuum at predefined hot and cold temperatures

3.1.43
uncertainty
lack of certitude resulting from inaccuracies of input parameters, analysis process, or both (see Figure 1)

NOTE Temperature uncertainties are typically caused by inaccuracies in, for example, material properties, environmental data or modelling assumptions.

3.1.44
unit
finished product with a given internal design

NOTE 1 The only interaction between a unit and TCS is via the control of external means (e.g. surface coatings, mounting method) and temperature information is derived from the temperature at the unit temperature reference point(s).

NOTE 2 All data relevant for TCS are included in an Interface Control Document (ICD)

3.2 Definitions for unit internal thermal design

In addition to above thermal definitions, the following specific definitions are applicable to the internal thermal design of units and are illustrated in Figure 2.

3.2.1
unit acceptance test temperature range
extreme range which is used for unit acceptance at unit level (see Figure 2)

NOTE The unit acceptance temperature range is obtained from the (TCS) acceptance temperature range as defined in Figure 1 after the addition of a suitable value to account for test inaccuracies.

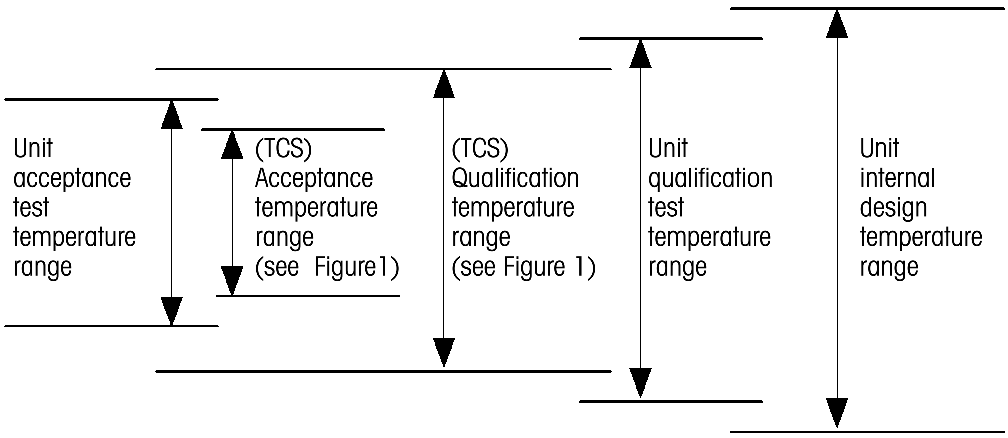

Figure 2: Temperature definitions for unit thermal design

3.2.2
unit internal design temperature range
extreme range for which components or parts are selected (see Figure 2)

NOTE These unit internal design temperatures are derived from unit thermal calculations including uncertainties and unit margins.

3.2.3
unit qualification test temperature range
extreme range used for unit qualification at unit level (see Figure 2)

NOTE The unit qualification temperature range is obtained from the qualification temperature range as defined in Figure 1 after addition of a suitable value to account for test inaccuracies.

3.3 Abbreviated terms

The following abbreviated terms are defined and used within this Standard.

Abbreviation	Meaning
ABM	apogee boost motor
AOCS	attitude and orbit control system
CCS	cryogenic cooling system
DRD	document requirements definition
DRL	document requirements list
EEE	electronic, electrical, electromechanical
EM	engineering model
EMC	electromagnetic compatibility
ESD	electrostatic discharge
FEM	finite element methods
FM	flight model
FOV	field of view
GMM	geometrical mathematical model
GSE	ground support equipment
H/W	hardware
ICD	interface control document

I/F	interface
LEO	low Earth orbit
LMP	lumped parameter method
MLI	multi layer insulation
OBDH	on-board data handling
PA	product assurance
PMP	parts, materials, process
QA	quality assurance
QM	qualification model
S/C	spacecraft
S/W	software
STM	structural thermal model
TB-Test	thermal balance test
TC	thermocouple
TCS	thermal control (sub)system
TM	thermal model
TMM	thermal mathematical model
TPS	thermal protection system
TRP	temperature reference point
TV-Test	thermal-vacuum test
VCHP	variable conductance heat pipe
w.r.t.	with respect to

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4

Requirements

4.1 Mission

4.1.1 General

a. The TCS shall consider every mission phase, up to the end of the operating lifetime.

b. For every phase, the specified environmental conditions (given typically in the system environmental specification) shall be taken into account.

4.1.2 Ground and pre-launch

a. The following conditions should be considered:

   1. integration and ground testing;
   2. storage, transport;
   3. functional check-out;
   4. waiting on launch pad.

b. Thermal constraints related to the ground and pre-launch phases shall be identified as early as possible in the programme.

c. Space vehicle design accommodation and auxiliary GSE shall be specified if adequate thermal conditioning is required.

   NOTE This includes, battery thermal conditioning, heat pipe panel levelling fixtures, auxiliary fluid cooling loops.

4.1.3 Launch and ascent

a. The following conditions shall be considered:

   1. launch time and season;
   2. external environment;
   3. requirements for special heat sinks during ascent;
   4. impact of depressurization and repressurization (if applicable);
   5. launch abort conditions (if applicable);
   6. spacecraft under fairing;
   7. phase between fairing jettison and separation;

8. ABM firing.

b. Thermal requirements related to the launch and ascent phases shall be identified as early as possible in the programme.

c. Space vehicle design accommodation and particular operational requirements shall be considered (e.g. need for auxiliary heating and cooling, opening and closure of apertures), for adequate thermal conditioning.

4.1.4 Planetary orbital phases

The planetary orbital phases cover transfer, drift, commissioning and operational orbits as applicable. The following parameters shall be taken into account as a minimum:

a. orbit radii (or heights) and eccentricity;

b. inclination;

c. ascending node angle and its evolution in time (if applicable);

d. maximum eclipse duration or argument of perigee and its evolution in time (if applicable);

e. spacecraft orientation, w.r.t. sun, planet;

f. relative movement of spacecraft items with respect to the main spacecraft body (e.g. solar array, antennae);

g. spacecraft attitude control type (e.g. 3 axes stabilized, spinning or free motion);

h. Planetary natural environment.

4.1.5 Interplanetary phases

The following parameters shall be considered:

a. spacecraft orientation w.r.t. external heat sources (e.g. sun, planets);

b. relative movement of spacecraft items with respect to the main spacecraft body (e.g. solar array, antennae);

c. natural environment.

4.1.6 Docking, docked and separation phases

The TCS shall take into account, if applicable, all mission requirements resulting from a docking or separation manoeuvre as well as from a docked phase.

Typical conditions are:

- spacecraft orientation;
- firing of thrusters;
- shadowing effects.

4.1.7 Descent, (re-)entry and landing

The TCS shall take into account the applicable heat fluxes as well as any transient phenomena during descent, (re)entry and landing.

Typical examples are:

- loss of MLI efficiency due to repressurization;
- heating and cooling effects due to the inlet of air and gas for repressurization;
- requirement for special heat sinks during descent.

4.1.8 Post-landing phases

a. The TCS shall conform to the environmental conditions occurring at the landing site for the specified duration.

b. The TCS shall define any means for thermal conditioning (e.g. via GSE), if required.

4.2 Performance

4.2.1 General

a. The TCS shall conform to the performance requirements (as applicable to the actual project) during all specified mission phases.

b. The mission phases shall be represented by a coherent set of thermal design cases to be proposed by the TCS, covering the extreme range of conditions experienced by an item during its lifetime.

c. As a minimum, a hot and a cold worst case shall be defined.

4.2.2 Temperatures

TCS shall derive a coherent set of design temperatures (minimum and maximum value), taking into account the acceptance temperature ranges provided by the system authority and on an agreed acceptance margin.

4.2.3 Functionality

The TCS shall conform to any functional requirement specified, e.g. the requirement to function in any orientation under any gravity environment.

4.2.4 Additional and other performance requirements

The TCS shall conform to the following additional performance requirements, if applicable:

a. temperature gradients;

b. temperature stability;

c. temperature uniformity;

d. heat flux;

e. heat storage;

f. heat lift.

4.3 Interfaces

4.3.1 General

a. The following interface requirements shall consider
   1. requirements from other subsystems affecting TCS, and
   2. requirements from TCS on other subsystems.

b. All interface requirements shall be controlled by the system authority.

4.3.2 Mechanical interface

a. The TCS shall take into account the overall spacecraft configuration and layout, together with the following information provided for each item from the applicable ICD:
   1. dimension and mass;
   2. materials and heat capacities;
   3. fixation and mounting techniques;
   4. contact area;
   5. surface characteristics, e.g. treatment, planarity, roughness;
   6. alignment requirements;

7. forbidden zones, e.g. FOV, operational range of mechanism;
8. connector locations;
9. available area for fixation of thermal hardware (e.g. heaters, MLI);
10. spacecraft harness.

b. The TCS shall conform to all mechanical loads during all relevant mission phases.

c. The TCS shall consider any specified stability requirement (e.g. exported vibrations by TCS units, microgravity disturbances).

d. The TCS shall define the TCS hardware configuration and layout and provide all necessary inputs for the ICD.

e. Any requirement concerning TCS-specific forbidden zones (e.g. unobstructed radiation to space, radiator deployment range) shall be defined by TCS.

NOTE In case of an unacceptable or unbalanced concentration of power dissipation, the TCS may propose changes to the spacecraft configuration layout.

4.3.3 Electrical interface

a. The TCS design shall take into account the power dissipation profiles of all items on the spacecraft including energy dissipated in any cabling. Relevant harness (e.g. type, routing), grounding, electrical conductivity (e.g. to avoid ESD on external coatings) and EMC requirements shall be considered.

b. The TCS design shall define for all electrical TCS units the required power consumption (e.g. peak and average power, duty cycle) and shall specify the required voltage. If applicable for a TCS unit or item, grounding and EMC requirements shall be defined.

4.3.4 AOCS interface

a. Propulsion

1. The TCS design shall take into account any heat fluxes due to plume interaction, as well as the temperature profiles of the thruster components (e.g. nozzle, heat shield) during operation of a thruster.
2. The effects of heat soak after firing of (chemical propulsion) thrusters shall be taken into account.

NOTE In case of predicted unacceptable high temperatures on thruster components (e.g. valves, catalyst bed) the TCS may propose a modification of the thruster operation.

b. Attitude control

The TCS shall conform to the attitude control requirements, e.g. a mechanical pump of a fluid loop shall not cause or exceed any predefined momentum.

4.3.5 TM/TC interface

a. The TCS shall conform to the specified TM/TC channel features (e.g. accuracy, measurement frequency, down/up-link frequency, on-board or ground data handling, overridability).

b. The TCS shall specify the following:

1. the necessary telemetry channels to monitor spacecraft temperatures, TCS temperatures, pressures, flow rates, voltages (e.g. heaters), currents (e.g. Peltier), switch status;
2. all necessary telecommand channels (ground or onboard controlled) for the operation of the TCS.

4.3.6 OBDH and S/W interface

a. The TCS shall conform to the applicable OBDH and software specifications.

b. The TCS shall specify their requirements for implementation into the data handling subsystem, e.g. heater control laws, temperature sensor calibration data.

4.3.7 Launcher interface

a. The TCS shall conform to the specified launcher envelope both for static and dynamic conditions, and shall consider accessibility requirements, if specified.

b. The TCS shall be compatible with launch-pad air-conditioning requirements.

c. The TCS shall conform to the launcher depressurization profile and the heat fluxes from the fairing and the launcher interface.

4.3.8 GSE interface

a. The TCS shall conform to the specified GSE requirements.

b. The TCS shall specify all TCS relevant requirements for ground support equipment.

4.4 Design

4.4.1 General

a. Design requirements cover those requirements to be included on TCS hardware (and software if applicable) in order to ensure that the flight product fulfils the goal assigned to the TCS in terms of mission requirements (see subclause 4.1 and performance requirements see subclause 4.2).

b. The TCS is not a stand-alone subsystem, and therefore its design shall conform to interface requirements with other subsystems (see subclause 4.3) and shall aim for minimization of constraints on other subsystems or system.

c. The design shall conform to the environmental factors encountered during all mission phases and shall take due account of any possible effects/degradations caused by e.g. wear, non-condensable gas build-up, mechanical loads, test environment.

4.4.2 Budgets

a. A TCS design shall conform to the requirements for mass, size, power, energy, TM/TC channels and operational aspects throughout the TCS life cycle.

b. The priority list and weighting factors affecting requirements and constraints shall be agreed with the system authority.

c. The TCS shall establish a budget for each of above resources for agreement by the system authority.

4.4.3 Parts, materials and processes (PMP)

a. The TCS design shall make use, as much as possible, of space proven parts, materials and processes (e.g. preferred PMP list, ECSS-Q-70, ECSS-E-30 Part 8).

b. In cases where the TCS design intends to use parts, materials or processes which are new or have not yet reached a space-proven status, an acceptance or qualification programme (by similarity, analysis or test) shall be initiated in agreement with the system authority.

4.4.4 EEE components

a. The TCS design shall use space proven EEE components as much as possible.

b. In cases where the TCS design intends to use EEE components which are new or have not yet reached a space-proven status, an acceptance or qualification programme (by similarity, analysis or test) shall be initiated in agreement with the system authority.

4.4.5 Lifetime

The TCS design shall conform to the total lifetime, i.e. the relevant combination of all applicable mission phases.

4.4.6 Predictability and testability

The TCS shall be designed such that conformance to performance requirements (see subclause 4.2) can be demonstrated by thermal analyses or thermal tests.

NOTE Modularity of the TCS design is a possible solution to facilitate predictability and testability of the TCS design.

4.4.7 Flexibility

The TCS design shall be flexible so that it can:

- accommodate possible modifications in the requirements put on the TCS during the project development phases;
- offer a pertinent and easy trimming capability;
- offer a growth and in-orbit reconfiguration capability if so required.

4.4.8 Accessibility

a. The lay-out and design of the TCS hardware shall provide sufficient accessibility to allow for easy integration, removal, inspection and if required maintenance of TCS items, during the course of the on-ground project activities and if applicable, during in-orbit phases.

b. The TCS design shall not prevent access to other items.

4.4.9 Reliability

a. The TCS design shall take into account the system reliability requirements and shall demonstrate by analysis or test its conformance to the specified system reliability figures.

b. The TCS shall specify reliability requirements for the design of individual TCS items.

4.4.10 Redundancy

a. The TCS design shall take into account all applicable redundancy requirements defined by the system authority.

b. If necessary, the TCS shall propose additional or alternate redundancy measures to reduce subsystem risk, to remove single point failures and to meet the required reliability figures.

4.4.11 Interchangeability

TCS shall conform to all applicable interchangeability requirements.

4.4.12 Maintenance

a. The TCS shall be designed to require a minimum of preventive maintenance during the on-ground lifetime. If any maintenance is required, the TCS shall specify the necessary procedures.

b. Operational maintenance (i.e. maintenance during in-orbit phases) shall be avoided to the maximum extent possible.

4.4.13 Cleanliness

a. The TCS design shall fulfil all system specified cleanliness requirements (ECSS-Q-70).

b. TCS specific cleanliness requirements shall be specified and appropriate procedures shall be proposed to the system authority.

4.4.14 Safety

a. The TCS design shall not create any hazard to humans and other subsystems.

b. The TCS design shall conform to the safety requirements of ECSS-Q-40.

4.4.15 Availability

The TCS shall plan for an in-time availability of all necessary resources (e.g. long-lead items, items with limited lifetime).

4.5 Verification

4.5.1 General

a. Verification shall demonstrate that the thermal design of an item conforms to specified performance requirements.

b. Conformance of a thermal design to all of its requirements shall be demonstrated by satisfactory completion of a thermal verification programme.

c. In the verification programme conformance to each requirement shall be demonstrated by: similarity, inspection, analysis or testing.

d. Testing is the preferred method for verification of the performance requirements; any deviation from this approach shall be justified.

e. Verification activities shall be performed on each level i.e. component, sub-assembly and assembly.

f. Verification activities related to inspection and testing shall be performed under strict PA/QA control (ECSS-Q-20).

g. The TCS shall establish, at an early stage, a complete and coherent verification plan and matrix clearly indicating for each item and level the intended verification approach.

4.5.2 Review of design

Review of design shall be a verification method that all TCS drawings and TCS design description conform to the relevant TCS design definitions.

4.5.3 Verification by similarity

a. Verification by similarity shall be the demonstration of conformance to specified requirements by comparing the item with a similar item, whose conformance has already been verified.

b. Similarity between the two items shall exist with respect to

   1. thermal design and utilized hardware,
   2. mission requirements, and
   3. lifetime.

4.5.4 Verification by inspection

a. An inspection shall be a visual, non-obtrusive examination of spacecraft hardware.

b. No physical contact with the hardware shall take place during an inspection unless explicitly approved and planned.

4.5.5 Verification by analysis

a. Verification by analysis shall be the demonstration of conformance to relevant requirements through appropriate analytical modelling and corresponding performance predictions.

b. Verification by analysis shall be performed for all cases where fully representative testing is not possible such as, limitations of test facilities e.g. environmental, dimensional and behaviour of TCS items under reduced or increased gravity.

4.5.6 Verification by test

a. Verification by test shall be the demonstration of conformance to specified requirements through exposing the TCS item to test conditions as close as possible to the expected real conditions by performing thermal balance, thermal vacuum or climatic tests. Depending on the required level of verification, the test conditions shall be equal to the acceptance or qualification test levels.

   NOTE The thermal vacuum and climatic tests, including the change in temperature gradient induced by cycling between temperature extremes, can uncover latent defects in design, parts and workmanship.

b. The verification testing of the TCS shall include, if applicable, mechanical, electrical, hydraulic and thermal testing.

c. The testing programme shall be established as a function of the criticality of the design and the spacecraft model philosophy. In particular, development testing shall be performed, prior to the start of the formal qualification testing programme, in order to identify possible problems in the design and to modify the design, if necessary, prior to qualification.

d. The testing programme shall encompass the testing of progressively more complex assemblies. In addition, testing shall be based on

   1. test objectives and test success criteria well identified and defined in the test documentation, and
   2. a well defined environment.

4.5.7 Thermal Balance (TB) test

a. For TCS items controlled by radiative and conductive heat exchange, a thermal balance test shall be performed.

b. The objectives of the thermal balance test shall be to

   1. provide data for the verification of the thermal mathematical model as part of the TCS qualification,
   2. demonstrate the suitability of the TCS design,
   3. verify the performance of TCS hardware, and
   4. provide data about sensitivity of the TCS design with respect to parameter changes (e.g. heat dissipation).

c. In order to meet the thermal balance test objectives, adequate test instrumentation and test set-up (e.g. number and position of temperature sensors, heaters) shall be employed, to provide accurate data (e.g. temperatures, voltages, unit dissipation).

d. The thermal balance test conditions shall be defined and reproducible, so that accurate and reliable input for the thermal model correlation can be provided.

e. The thermal balance test conditions shall, as far as possible, encompass the worst thermal conditions expected throughout all mission phases.

f. A minimum of two steady-state test cases – a (worst) hot and a (worst) cold case – and, if appropriate, a transient case shall be performed.

g. For items having complex geometry, shape, apertures or utilizing specular reflective coatings a solar simulation shall be used.

NOTE The use of a solar simulator for representation of the solar incident flux is the preferred method in case of significant inaccuracies on absorbed fluxes.

h. The test item shall be in a fully thermally representative configuration. In particular, the TCS hardware shall be flight representative as well as any critical items or interface.

i. The design of the test adapter shall be such that the parasitic heat loads (radiative and conductive) on the test item are minimized and easily determined.

4.6 Production and manufacturing

4.6.1 General

The objective of production engineering shall be to ensure that the TCS and all its component parts, can be manufactured in the way intended and be of acceptable quality, reliability and reproducibility.

The production of thermal hardware includes:

- procurement;
- manufacturing;
- assembly;
- integration of thermal hardware.

4.6.2 Manufacturing process

a. In order to achieve high levels of safety and reliability, approved standard procedures shall be used where applicable.

b. Newly developed procedures require PA/QA approval(ECSS-Q-70).

c. Manufacturing activities shall include:

1. samples for evaluation and testing;
2. prototypes, components, representative sections or whole thermal hardware in order to
   - prove manufacturing processes and procedures,
   - test and evaluate, and
   - determine and prove new inspection procedures.
3. flight hardware.

4.6.3 Manufacturing drawings

a. Design and manufacturing drawings shall be produced in accordance with configuration management requirements of ECSS-M-40.

b. The drawings shall take into account the manufacturing process and the various manufacturing steps.

4.6.4 Quality management

a. Quality management shall be based on an effective programme of quality control, inspection and surveillance, and shall form part of the overall product assurance requirements.

b. The following factors shall be included in the quality management:

1. procurement control;

2. manufacturer, supplier and subcontractor surveillance;
3. incoming inspection;
4. fabrication;
5. fit check;
6. integration and test;
7. cleanliness control;
8. traceability;
9. configuration control;
10. nonconformance control;
11. metrology and calibration;
12. handling, storage, prevention;
13. marking, labelling;
14. packing and shipping.

4.6.5 Cleanliness

The TCS shall define appropriate cleanliness levels and requirements for all stages of production and manufacturing of thermal hardware.

4.6.6 Procurement

a. The successful design and manufacture of space thermal hardware relies on the supply of qualified and approved materials, parts and processes in line with ECSS-Q-70.

b. Procurement shall conform to specifications derived by the user (often in conjunction with the supplier), in accordance with all applicable specifications and against a detailed purchase order.

4.6.7 Tooling

The TCS shall specify all necessary tooling, including jigs, fixtures and templates, considering

a. materials to be used in manufacture,
b. geometry of the parts,
c. number of parts required, and
d. production rate.

4.6.8 Integration

The TCS shall define appropriate procedures for all levels of integration, which shall include as a minimum the following:

a. specifications for parts and materials;
b. integration instructions;
c. preparation;
d. support equipment and tooling;
e. parts and materials;
f. method;
g. cleaning;
h. inspection;
i. testing.

4.6.9 Marking

The TCS shall establish a coherent thermal item identification plan which follows the project operation procedures. Marking of items shall be performed in accordance with quality assurance requirements.

4.6.10 Packaging, handling, transportation

a. The TCS shall establish requirements for packaging, handling and transportation to prevent any degradation of thermal hardware.

b. The TCS shall specify, if necessary, appropriate devices in order to monitor the quality of TCS hardware (e.g. contamination or witness samples, leakage detectors).

c. Items containing hazardous material or those requiring special packaging, handling and transportation shall be specifically identified.

4.6.11 Storage

a. The TCS shall ensure that storage conditions do not cause any degradation to the thermal hardware. If necessary, appropriate devices and procedures (e.g. periodical inspections or functional checks) shall be defined.

b. Items requiring special storage conditions or items containing hazardous material shall be specifically identified.

4.6.12 Repair

If necessary, the TCS shall establish adequate repair procedures and shall also define the required repair tools and thermal hardware.

4.6.13 In-service requirements

The TCS shall provide the means (e.g. appropriate TMMs) and the support to the system for in-service activities.

NOTE Support activities can occur during the commissioning phase and during spacecraft special events (e.g. in-orbit anomalies).

4.7 Product assurance

The TCS shall conform to ECSS-Q-20.

4.8 Deliverables

4.8.1 General

All products (e.g. hardware, software, models, documents.) required for delivery during the course of a project shall be clearly specified.

NOTE Figure 3 shows in a schematic way the product exchange between the different levels, i.e. system, TCS, supplier or thermal hardware manufacturer.

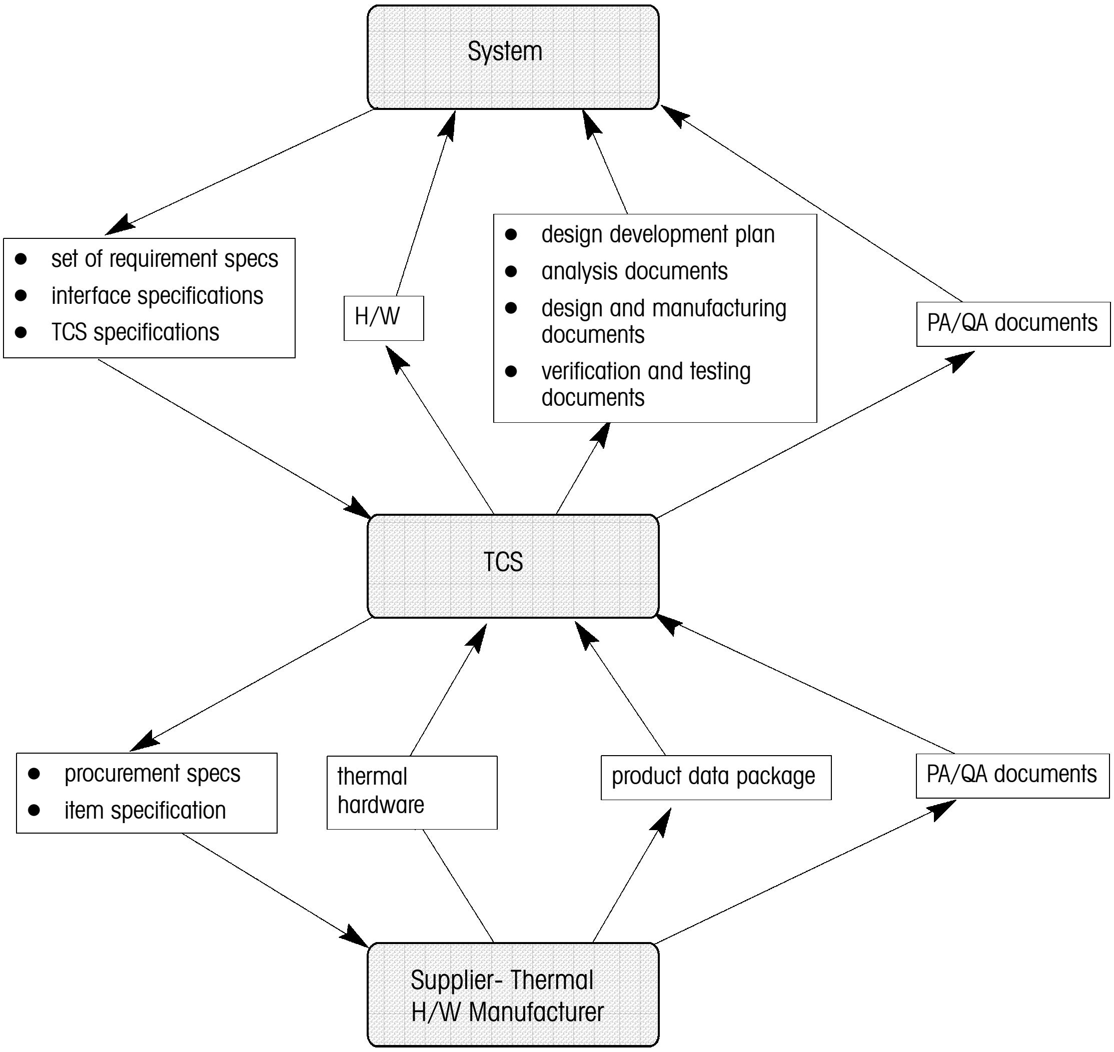

Figure 3: Product exchange between the system, TCS and the supplier or manufacturer

4.8.2 Hardware

The hardware to be delivered during the course of a project shall be clearly specified by the system authority at the beginning of the project.

Examples of the hardware to be delivered includes

- thermal hardware for different models (e.g. STM, EM, QM, FM),
- hardware for sample tests,
- spare and repair thermal hardware, and
- ground or integration support hardware (if required).

4.8.3 Documentation

a. The TCS shall be documented in accordance with all technical specifications, interface requirements documents and the agreed TCS specification provided by the system authority.

b. The organization responsible for the TCS shall issue all necessary specifications to lower-level supplier(s) or manufacturer(s) for the procurement of thermal hardware.

c. The documents required for the TCS shall include as a minimum the documents listed in Table 1. Where applicable reference is provided to the document requirements definition (DRD) title and the DRD controlling standard.

NOTE Table 2 provides a typical indication of the documentation delivery.

Table 1: Document requirements for TCS

Term used in this Standard	Document title	DRD controlling reference
AIV plan	AIV plan	ECSS-E-10
Declared materials list	Declared materials list	ECSS-Q-70
Declared processes list	Declared processes list	ECSS-Q-70
Design definition report	Design definition file	ECSS-E-10
Design and development plan	Design and development plan	ECSS-E-10
Drawing	Drawing	ISO 128
Geometric mathematical model	Mathematical models	ECSS-E-10
Interface control document	Interface control document	ECSS-E-10
Interface requirements document	Interface requirements document	ECSS-E-10
Specification	Technical specification	ECSS-E-10
Thermal mathematical model	Mathematical models	ECSS-E-10
Test procedure	Test procedure	ECSS-E-10-02
Test report	Test report	ECSS-E-10-02
Thermal analysis report	Analysis report	ECSS-E-10
Thermal budgets	Technical budget	ECSS-E-10
Test specification	Test specification	ECSS-E-10-02
Verification control document	Verification control document	ECSS-E-10-02

Table 2: Documentation schedule

	Phase A (Feasibility study)	Phase B (Definition phase)	Phase C/D (Implementation phase)
Analysis documentation			
Thermal analysis report	X	X	X
Design definition report		X	X
(plus other documents defined by the project)			
Design and manufacturing documentation			
Engineering drawings		X	X
Manufacturing drawings			X
(plus other documents defined by the project).			
Verification and testing documentation			
Test plan	(X)	X	X
Test procedure		(X)	X
Test report		X	X
(plus other documents defined by the project)			
D&D plan	(X)	X	X
PA/QA documentation			
PA plan	(X)	X	X
Declared material list		X	X
Declared process list		X	X
(plus other documents defined by the project)			
Note (X) indicates: Preliminary version			

4.9 Use standard to define project requirements

Provisions have been made in this Standard to cover all aspects and temperature levels of space products. Where necessary specific definitions and information is provided in normative annexes, i.e. to cover cryogenics (annex B) and high temperature application (annex C) where applicability matrices are defined for the tailoring of this Standard.

Annex A (normative)

Development approach

A.1 Uncertainties

A.1.1 Uncertainty philosophy

a. Temperature is usually the most important key thermal control in any TCS design. Therefore this annex addresses temperature uncertainties only. Uncertainties on other key thermal quantities shall be considered according to specific project requirements. In this case a similar approach to the one specified for temperature shall be applied.

b. 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 shall also to be considered.

c. All these different inaccuracies lead to temperature uncertainties which shall be considered on top of the calculated temperature range. Calculated temperatures increased or decreased by the appropriately assessed uncertainties shall be equal to or less than the TCS design temperatures.

d. 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 affecting the physical parameters.

e. The reduction of the uncertainty during the course of a project is the consequence of the use of more detailed models and improved knowledge of the properties (usually obtained by tests). In one particular phase the same item may be represented in different models with different temperature uncertainties.

f. Typical uncertainty values together with a short definition of the TCS activities and models relevant to the various phases are:

   1. Phase A:

   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.
   Typical uncertainty ± 15 K.

2. Phase B:

TCS coarse design, with overall spacecraft TMM where critical items are modelled explicitly.
Typical uncertainty ± 10 K.

3. Phase C/D:

TCS detailed design with detailed overall TMM, where all items are modelled explicitly.
Typical uncertainty ± 8 K before thermal balance tests.
Typical uncertainty, ± 5 K after thermal balance test and TMM correlation.

g. The above uncertainty values are recommended values for phases A and B. For phase C/D, a value of not more than ±8 K before TB-test shall be used. Any change of this value shall be specifically justified and agreed upon with the system authority.

h. In case of a feed-back controlled thermal design (e.g. VCHP, regulation heaters, fluid loops), the uncertainty values shall be adjusted and agreed upon.

A.1.2 Sources for temperature uncertainties

A.1.2.1 General

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

a. environmental parameters,

b. physical parameters,

c. modelling parameters, and

d. test facility parameters.

Typical inaccuracy values for above parameters are provided in annex D.1.5.

A.1.2.2 Environmental parameters

As far as applicable, the uncertainty shall account for inaccuracies in

a. solar and planetary radiation,

b. orbital and attitude parameters,

c. aerothermal fluxes, and

d. solar and planetary radiation.

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 shall be applied to these parameters. This is particularly relevant for items with low time constants.

A.1.2.3 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 shall be considered pertain to

a. bulk and surface material properties,

b. inter-material contact characteristics,

c. dimensions,

d. heat dissipations of units, and

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

A.1.2.4 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. Three different approximations are performed leading to discretisation errors:

a. two in space, with the physical reality discretised into finite isothermal elements with actual surfaces represented by idealised surfaces in order to get a set of ordinary differential equations;

b. another one in time with continuous time being represented by finite time steps.

Numerical algorithms with finite accuracy are used to solve the system of equations.

A.1.2.5 Test facility parameters

Inaccuracies for a special set of parameters shall be 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

a. the shroud and its thermo-optical properties,

b. solar simulation characteristics (spectrum, decollimation angle),

c. the temperature measurements, and

d. the thermal node or temperature sensor position error.

A.1.3 Sensitivity analysis and temperature uncertainty

a. The impact of all the applicable inaccuracies of annex B on the temperature predictions shall be assessed via adequate sensitivity analyses. Based on the TMM used for nominal temperature predictions, such sensitivity analyses shall be performed by replacing nominal 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.

b. The result of such an analysis run will provide a specific temperature uncertainty (i.e. difference between actual temperature and nominal temperature) either as function of one parameter or of a group of parameters. All these specific uncertainties shall be summed in the following way:

   1. specific temperature uncertainties due to inaccuracies in environmental, physical and test facility parameters (if applicable) are of statistical nature and shall be summed up as root sum squared. If any of these uncertainties can be clearly shown to be of systematic nature, it shall be added algebraically;

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

c. To summarize, the formula is:

$$\Delta T_i = \sqrt{\sum_{j=1}^{n_e} (\Delta T_{e,j})_i^2 + \sum_{k=1}^{n_p} (\Delta T_{p,k})_i^2 + \sum_{l=1}^{n_t} (\Delta T_{t,l})_i^2 + \sum_{r=1}^{n_m} (\Delta T_{m,r})_i^2} + (\Delta T_s)_i$$

where

ΔT_i overall uncertainty on thermal node i temperature r = 1;

$(\Delta T_{e,j})_i$ temperature uncertainty due to environmental parameters j on node i;

$(\Delta T_{p,k})_i$ temperature uncertainty due to physical parameters k on node i;

$(\Delta T_{t,l})_i$ temperature uncertainty due to test facility parameters l on node i;

$(\Delta T_{m,r})_i$ temperature uncertainty due to modelling method or parameters m on node i;

$(\Delta T_s)_i$ systematic temperature uncertainty on node i;

n_e number of environmental parameters;

n_p number of physical parameters;

n_t number of test facility parameters;

n_m number of modelling-related parameters.

d. The above formula shall be applicable to either flight prediction or test prediction. In the former case $(\Delta T_{t,l})_i = 0$; in the latter case $(\Delta T_{e,j})_i = 0$.

e. The above formula shall only be used if the parameters are independent of each other.

A.2 Margins

a. In line with the definitions of clause 3, the TCS margins shall normally be taken:

- Acceptance margin between 0 and 5 K
- Qualification margin between 0 and 5 K.

Any deviation shall be properly justified and agreed upon with the system authority.

b. For cryogenic and high temperature ranges see annex B and annex C.

A.3 Test approach and test success criteria

A.3.1 Test approach

A test programme shall be established for verification of thermal control requirements on different levels (system, subsystem, assemblies or units) considering also different test type levels (development, qualification, acceptance) as defined below.

a. Development tests

Development tests include all tests conducted to obtain information to aid in the design and manufacturing processes. Those tests are performed to generate design parameters, design margins, identify failure modes and to verify manufacturing processes.

Development tests may be informal in a controlled design and test documentation, formal certification and flight type hardware are usually not required.

b. Qualification tests

Qualification tests are formal contractual demonstrations that the design, manufacturing and assembly have resulted in hardware conforming to the specification requirements.

Qualification tests shall be performed on flight type hardware with a representative thermal control system.

c. Acceptance tests

Acceptance tests are the required formal tests carried out to demonstrate acceptability of an item for delivery. They are intended to demonstrate performance to specification requirements and to act as quality control screens to detect deficiencies of workmanship, material and quality.

A.3.2 Test success criteria

a. A test shall be considered successful if:

1. all test conditions defined prior to the test are met;
2. all parameters (e.g. temperatures, gradients) are within their applicable limits;
3. the predefined resources have not been exceeded (e.g. heater power, battery energy in an eclipse case).

b. In the specific case of a TB-test the following criteria for test completion shall be applied:

Steady-state conditions shall be considered achieved, if the temperature variation over a period of 5 hours is less than 0,1 K/h. In case the test object contains only items with low thermal inertia, the duration criteria can be relaxed.

c. Other methods to determine the steady-state temperature can be applied, if properly justified and agreed prior to performing the TB-test.

A.4 Correlation approach and correlation success criteria

A.4.1 General

a. Prior to the TB-test campaign, test temperature predictions with their respective uncertainties shall be provided using the thermal mathematical model together with the expected TB-test conditions. The test item including test adapter shall contain an adequate number of temperature measurement points and their location shall be compatible with the TMM nodes. For each measured temperature a corresponding calculated nodal temperature shall be provided.

b. Prior to the TB-testing and the correlation exercise, a coherent and complete list of temperature measurement points to be used for the derivation of test success criteria and for the correlation exercise shall be agreed between TCS and the system authority.

c. After successful TB-testing, an adequate correlation exercise between test measurement and analytical predictions shall be performed until the predefined correlation success criteria are fulfilled.

d. The correlation success criteria defined below shall be used (to be applicable on all temperature measurements and TMM-results previously agreed on). In order to achieve a successful correlation all three criteria have to be fulfilled simultaneously for all test phases.

A.4.2 Temperature level criteria

The sum of all temperature differences (measured value minus analytical value) divided by the number of analysed points shall be less than ±2K.

$$\Delta T = \frac{1}{N}\sum_{i=1}^{N}(T_{Mi} - T_{Pi}) \quad \leq \quad 2K$$

where

ΔT = global temperature deviation;

N = number of temperature points considered for correlation;

T_{Mi} = measured temperature;

T_{Pi} = calculated test temperature.

For external nodes (e.g. MLI, appendices) and selected structure nodes a higher value can be used after agreement with the system authority.

A.4.3 Standard deviation criteria

The standard deviation of all temperature differences (measured value minus analytical value) shall be less than 3 K.

For external nodes (e.g. MLI, appendices) and selected structure nodes a higher value can be used after agreement with the system authority.

$$\sigma = \frac{1}{N-1}\sqrt{\sum_{i=1}^{N}(\{T_{Mi} - T_{Pi}\} - \Delta T)^2} \leq 3K$$

where

σ = standard deviation (1σ).

A minimum of 25 temperature differences shall be considered for statistical reasons.

A.4.4 Individual unit success criteria

a. The differences (measured value minus analytical value) for individual units shall be less than the value of the pre-test uncertainty.

b. For temperatures concerning units, the temperature of the TRP (as defined in the ICD) shall be used as a minimum.

A.5 Analysis approach

A.5.1 Objectives of thermal analysis

a. Thermal analysis shall be used to support the thermal design activities and, in conjunction with tests and other means, is used to verify the TCS design.

b. Thermal analysis shall be used to demonstrate the TCS conformance to performance requirements through appropriate analytical modelling and corresponding performance predictions.

c. Thermal analysis shall also be used to provide interface temperatures or heat fluxes with other subsystems.

A.5.2 Thermal analysis methods

a. Lumped-parameter thermal analysis methods (LPM) should be used for the analysis of spacecraft TCS. If the nature of the physical problem being studied requires the availability of detailed temperature fields on the geometrical configuration, Finite Element Methods (FEM) or similar approaches should complement the LPM analysis.

b. The use of high-fidelity methods that model accurately the interaction between the incoming radiation and the spacecraft surfaces (e.g. Monte Carlo ray tracing) shall be mandatory for the thermal radiation analysis of systems, the thermal behaviour of which is substantially affected by the existence of diffuse or specular multi-reflections.

c. Prior to thermal analysis activities TCS shall define and agree with the system authority:

   1. the design cases to be analysed and their acceptance criteria,

2. the spacecraft models to be developed, detailing among other things:
   - the type of the models, i.e. GMMs used for the purpose of the calculation of radiative couplings and environmental heat loads and TMMs for temperature prediction
   - the resolution of the models. Detailed models shall be used to fully demonstrate that all TCS requirements are met and, if required, to provide temperature data for thermo-mechanical analysis. Reduced models shall be developed for integration at system level for interface requirement verification or test correlation purposes. Correlation criteria shall be specified, if models of different detail are to be created for the same physical item
   - the nature of the models (e.g. system versus instrument levels, external versus internal models, stowed versus deployed configurations).
3. the correlation criteria for the comparison between predicted and measured (test) results.

d. The analysis shall also include the determination of heat fluxes and of their sensitivity to the TCS design parameters.

A.5.3 Interfaces and deliverables

a. Thermal analysis requirements and methods shall be identified and recorded in the form of applicable documents.

b. Thermal analysis requirements shall be agreed upon by the organization responsible for drawing up the requirements and the supplier of the thermal analysis.

c. The technical specifications shall include the specification of the activities to be performed in the thermal analysis of spacecraft.

d. All models developed or used for the analysis are deliverables together with the following supporting documentation:
1. for the GMMs, reports and plots documenting reference frames, surface identifiers, areas, thermo-optical properties and radiative and thermal node numbering;
2. for the TMMs, reports and plots documenting thermal nodes, thermo-optical and bulk properties, internal heat dissipations, heater dissipations, heater control laws and set-point temperatures for heater switching, maximum and minimum temperatures (for operating and non-operating mode) and GMM or TMM look-up tables.

e. The thermal analysis requirements shall also define:
1. the thermal analysis methods and data exchange format;
2. the modelling and calculations requirements, including:
   - modelling assumptions, philosophies (e.g. prescribed MLI modelling approach) and analysis-specific calculation requirements (e.g. accuracy of the radiative calculations, specific algorithms to be used for transient runs).
   - integration requirements. Models shall be developed modularly to facilitate their integration in a hierarchical fashion. Furthermore, prescribed thermal node numbering shall be allocated for use in the different model components.
   - maintainability requirements. Comments shall be used with profusion in order to guarantee the high readability and maintainability of thermal analysis source data (e.g. models, analysis files). All natural language (comments, surface identifiers, labels) shall be in an agreed single language.
   - a set of analysis cases and relevant results for acceptance purposes.

f. The thermal analysis requirements shall specify the approach to be followed to guarantee the reliable communication of data among all parties involved in the analysis. This can be achieved either by

   1. the use of one single set of tools covering all stages of the thermal analysis, or

   2. allowing the use of several sets of tools but enforcing the use of a validated means of exchange (e.g. STEP-based protocols). In this case, the requirements document shall list the tool-specific features that guarantee the full exchangeability of models.

A.5.4 Quality

a. The supplier of thermal analysis deliverables shall establish and maintain procedures for the identification, documentation and appropriate review and approval of all changes and modifications.

b. Only validated tools shall be used for the thermal analysis.

c. Deliverable models shall be validated.

Annex B (normative)

Cryogenic temperature range

B.1 Applicability

B.1.1 General

This normative annex B shall be applied for TCS which include cryogenic cooling.

NOTE 1 Subclause B.2 provides additional definitions for the temperature range T < 120 K.

NOTE 2 Subclause B.3 presents an applicability matrix providing additional comments, descriptions or requirements necessary to cover the cryogenic temperature range within TCS activities.

B.1.2 Cryogenic definitions (exceptions)

All definitions for CCSs that operate in a regime where quantum mechanical effects play a major role e.g. sub-kelvin cooling and superconductors, shall be assessed by the CCS responsible and system authority for their suitability.

B.2 Complementary definitions for the cryogenic temperature range

B.2.1
cryogenic cooling system (CCS)

system whose role is to provide cryogenic cooling (T < 120 K) to a defined item, instrument or spacecraft subsystem

NOTE The CCS provides either bulk or point cooling with well-defined interfaces for assessing the cryogenic heat leak on the CCS.

B.2.2
cryogenic downtime

percentage of the total time that the CCS is unable to conform to the nominal operating requirements

B.2.3
cryogenic deadtime
percentage of the total time that the instrument is capable of fulfilling its primary mission objective, but is unable to do so because the CCS is out of nominal operating specification

B.2.4
maximum cryogenic heat leak
sum of all heat flowing into the cold side of the CCS for the simultaneous combination of the most unfavourable conditions e.g. all heaters and sensors energized, mechanisms moving

B.2.5
maximum cryogenic temperature
temperature of a defined item when the total heat leak flowing into the CCS is the maximum cryogenic heat leak

B.2.6
nominal cryogenic heat leak
sum of all heat flowing into the cold side of the CCS in a nominal steady state operation

B.2.7
nominal cryogenic temperature
temperature of a defined item when the total heat leak flowing into the CCS in nominal steady state conditions is the nominal cryogenic heat leak

B.2.8
total cryogenic heat leak
sum of all heat flowing into the cold side of the CCS in steady state operation

B.2.9
transient cryogenic heat leak
sum of all heat flowing into the cold side of the CCS at a defined temperature during a reproducible transient cool down procedure

B.2.10
ultimate cryogenic heat leak
maximum cryogenic heat leak multiplied by a safety coefficient defined by the system authority

B.2.11
ultimate cryogenic temperature
temperature of a defined item when the total heat leak flowing into the CCS is the ultimate cryogenic heat leak

B.3 Applicability matrix

Subclause	Applicable: Y Applicable with additions: Y* New, additional requirement: New	
3.1	Y*	Thermodynamic Temperature Two Kelvin temperatures are to each other as the heat transferred during isothermal processes at these temperatures, provided that these isothermal processes terminate on the same adiabatic surfaces. If Q and Q_s are the absolute values of the heats transferred at temperatures T and T_s, respectively, the original Kelvin definition provides the relation: $$T = T_s \frac{Q}{Q_s}$$ Although the choice of the sign for T_s is arbitrary, normal thermodynamic systems with an infinite number of energy levels are defined with T_s positive. All definitions related to temperatures (e.g. temperature difference, gradient) shall be tailored to the relevant cryogenic temperature range.
3.2	Y*	The unit acceptance and design margins shall be tailored to the relevant cryogenic range.
3.3	Y	
4.1	Y	
4.2	Y	
4.2.2	Y	
4.2.2.a	New	Temperatures as measured at an agreed sensor shall not exceed a maximum value under all nominal operating conditions, with the allowable temperatures and heat fluxes defined by the system authority.
4.2.4	Y*	Temperature-related requirements (e.g. temperature gradient, stability) shall be tailored to the relevant cryogenic temperature range. Furthermore any requirement on parasitic heat leaks shall be considered.
4.3	Y	
4.4	Y	
4.5	Y	
4.5.5.c	New	The CCS shall, whenever possible, be verified by testing at instrument or subsystem level. The test objectives and set-up shall be agreed with the system authority on a case by case basis taking into account all relevant interfaces. In general testing at very low cryogenic temperatures shall be first performed in a specialized laboratory.
4.6	Y	
4.6.13.a	New	The CCS shall be capable of performing all in-orbit activities defined by the system authority. Such activities shall include: • determination of the amount of cryogen remaining in a reservoir; • adjustments of cryocooler stroke and phase; • de-contamination of cryogenic radiators.
4.7	Y	
4.8	Y	
A.1.1	Y*	The TCS requirements outlined in A.1.1 shall be tailored to suit the CCS temperature ranges. In particular, attention shall be paid to the importance of not rising above a maximum temperature.

Subclause	Applicable: Y Applicable with additions: Y* New, additional requirement: New	
A.1.2	Y*	The sources of temperature uncertainties for CCS temperature predictions shall be tailored for the CCS temperature range and shall include the following: a. Environmental parameters only directly applicable for cryogenic radiators. b. Physical parameters as A.1.2.3. c. Modelling parameters as A.1.2.4. d. Test facility parameters as A.1.2.5.
A.1.3	Y*	A sensitivity analysis on the CCS temperature predictions shall be performed in a manner that is tailored to the particular temperature range concerned.
A.2	Y*	Margins shall be defined according to the selected CCS.
A.3	Y	
A.4	Y*	The applicability of TCS correlation approach shall be tailored to the CCS temperature range. For the external shell of a cryocooler A.4 is likely to be applicable, while for the use of a dilution refrigerator at 50 millikelvin A.4 is unlikely to be applicable.
A.5.1	Y*	For certain CCSs such as cooling via adiabatic demagnetization the requirement to model the cooling mechanism itself shall be waived. In this case detailed thermal calculations shall be required.
A.5.2	Y*	CCS thermal analysis methods shall be tailored to suit the particular temperature range in question.
A.5.3	Y	
A.5.4	Y	

Annex C (normative)

High temperature range

C.1 Applicability

This normative annex C shall be applied for TCS which include high temperature items, e.g. thermal protection systems (TPS).

NOTE 1 Subclause C.2 provides additional definitions for the temperature range T > 420 K.

NOTE 2 Subclause C.3 presents an applicability matrix providing additional comments, descriptions or requirements necessary to cover the high temperature range within TCS activities.

C.2 Complementary definitions for the high temperature range

C.2.1
ablation

chemical change and removal of surface material due to the action of aerodynamic heating

NOTE This process consumes energy and thus provides a cooling effect in the underlying material level.

C.2.2
aerodynamic heating

increase in the temperature of a fluid, and the solid surface over which it flows, caused by viscous stresses in the fluid boundary layer doing shearing work in the fluid at high velocity and caused by fluid compression

C.2.3
allowable temperatures

maximum temperatures specified for thermally protected items like primary and secondary structures, to ensure the structure integrity

C.2.4
arc-jet test

testing method or condition which most closely represents the actual entry flight environment

C.2.5
combined loads

combination of thermal and mechanical loads acting simultaneously on the TPS

C.2.6
hot structure

primary mechanical load carrying structure which is directly exposed to the high temperatures caused by aerodynamic flow

C.2.7
induced environment

set of environmental conditions for a given item created by the operation or movement of the item itself (e.g. the set of loading conditions due to atmospheric flight)

C.2.8
limit aero-thermal heat fluxes

maximum (respectively minimum) local heat flux values, or the most unfavourable simultaneous combination of the constituting terms (in the sense of maximizing-resp. minimizing these heat fluxes) liable to be attained in the different areas of the vehicle during the normal service life for the corresponding mission instant

NOTE Limit aero-thermal heat flux applies to TPS and hot structures only.

C.2.9
limit temperatures (during atmospheric flight)

maximum (respectively minimum) local temperatures resulting from the application of the least favourable heat fluxes histories expected on normal missions inside the bounds of the limit fluxes

C.2.10
nominal aero-thermal heat fluxes

nominal local heat flux values expected for nominal mission and nominal atmospheric conditions

NOTE Nominal aero-thermal heat flux applies to TPS and hot structures only.

C.2.11
nominal temperatures (during atmospheric flight)

local temperatures resulting from the application of the nominal heat fluxes histories

C.2.12
protected structure

primary mechanical load carrying structure which is covered by a thermal protection layer, the latter exposed to the aerodynamic flow

C.2.13
thermal protection subsystem (TPS)

thermal control hardware suited to protect the spacecraft against the aerodynamic heating

EXAMPLE ceramic tiles, ablative materials

C.2.14
ultimate aero-thermal heat fluxes

heat fluxes deduced from the limit heat fluxes upper bound values through aero-convective upper bound limit heat fluxes (launch and re-entry) multiplied by a safety coefficient J_ϕ; i.e.:

$$\phi_{ultimate(Twall)} = J_\phi \times \phi_{limit(Twall)}$$

or

$$\phi_{ultimate(Twall)} = J_\phi \times h_{Ta-(Twall)}$$

where:

h is a convective coefficient (W/m^{2}K);

T_a the temperature relative to the fluid;

T_{wall} the local wall temperature.

For normal missions, J_ϕ is set to 1,5 (TBC)

NOTE Ultimate aero-thermal heat flux applies to TPS and hot structures only.

C.2.15
ultimate temperatures (during atmospheric flight)

local instantaneous temperatures resulting from the application of ultimate fluxes histories

C.3 Applicability matrix

Subclause	Applicable: Y Applicable with additions: Y* New, additional requirement: New	
3	Y	
4.1	Y	
4.2	Y	
4.2.2.a	New	Temperatures of all protected items shall not exceed the allowable temperatures under all heating cases, both allowable temperatures as well as heat fluxes to be provided by the system authority.
4.2.4.g	New	In addition the TPS shall • limit temperature gradients on the protected element, • respect both, aerodynamic shape tolerances and roughness constraints, and • withstand fast pressure decreases and increases encountered during launch and re-entry.
4.3	Y	
4.3.3	Y*	Note: For a TPS only, this subclause is not applicable.
4.3.4 b.	Y*	Note: For a TPS only, this subclause is not applicable.
4.3.6	Y*	Note: For a TPS only, this subclause is not applicable.
4.4	Y	
4.5	Y	
4.5.6 f.	New	Thermal tests on thermal protections shall be coupled with simultaneous or sequential mechanical tests (as pressure loading, structure deflections, vibrations). Apart from elementary characterization tests, thermal protections should not be tested alone, but in association with the supporting structure or equipment, or an equivalent mock-up, in order to provide representative thermal interface conditions. As the flight environment conditions are unknown in detail and very difficult to simulate on large test articles with ground test facilities, the demonstration of external thermal protection flight ability may be brought through simplified, or separated test conditions but with the justification (by analyses) that the set of performed tests are conservative with respect to the requirements and the load envelope one has to comply with. In addition to classical means, as far as applicable, thermal protection verification by test relies on arc-jet facilities and high temperature radiation facilities.
4.6	Y	
4.6.13	Y*	Note: For a TPS only, this subclause is not applicable.
4.7	Y	
4.8	Y	
A.1.1	Y*	The thermal function of the TPS shall reduce the incoming (or outgoing) heat flux or the accumulated heat quantity on an equipment, structure or other item specified by the system authority. Margins are already integrated by the system authority in the prescribed aero-thermal fluxes and the allowable temperatures of the items which shall be protected. No additional margins shall be taken by the TPS.

Subclause	Applicable: Y Applicable with additions: Y* New, additional requirement: New	
A.1.2	Y*	During the design process worst case characteristics of the chosen materials shall be used. Depending on the design case these might be minimum or maximum values (e.g. minimum thermal conductivity, maximum mechanical strength).
A.1.3	Y*	Note: For a TPS only, this subclause is not applicable.
A.2	Y*	Note: For a TPS only, this subclause is not applicable.
A.3	Y*	Acceptance tests can only be performed on reusable TPS. However, the correct assembly of the TPS with the supporting structure shall be verified by appropriate methods.
A.4	Y*	Note: For a TPS only, this subclause is not applicable.
A.5.1	Y	
A.5.2	Y*	The use of lumped-parameter thermal analysis methods (LPM) is not mandatory for the analysis of spacecraft TPS. If the nature of the physical problem being studied requires the availability of detailed temperature fields on the geometrical configuration, Finite Element Methods (FEM) or similar approaches could substitute or complement the LPM analysis. Prior to thermal analysis activities TPS shall define and agree with the system authority a. the design cases to be analysed and their acceptance criteria, and b. the models to be developed
A.5.3	Y	
A.5.4	Y	

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Annex D (informative)

TCS development methodology

D.1 Conventional temperature range

D.1.1 General

To reach an acceptable thermal design, a two-step approach should be followed (see flowcharts in Figure D‐1 and D‐2).

a. First stage (preliminary) configuration.

b. Final thermal design.

Based on the overall system definition, a thermal control subsystem (TCS) definition is issued. This definition contains all the information concerning the thermal subsystem.

D.1.2 First stage (preliminary) configuration

Based on these requirements, a preliminary configuration of the spacecraft is established and a preliminary analysis performed. After the necessary iterations to reach a consistent thermal design, at least one more loop is required to check, if the proposed TCS is still consistent with the overall system definition. In case there are any impacts on system level (or if the system level specifications have been changed in the meantime) a further re-iteration is necessary. At the end of this step a first stage thermal control configuration is available.

D.1.3 Final thermal design

The second step, the detailed final thermal design, typically starts with the first stage (preliminary) thermal control configuration and the updated or reviewed TCS specification coming from the system. Based on a more detailed configuration, a detailed global thermal analysis is performed, supported, where necessary, by local analyses. Once an acceptable thermal design has been reached, a further iteration is recommended to check compatibility with system definition (and hence the other subsystem definitions). The next activities are the test predictions to correlated after thermal verification tests with the test results. If this correlation is acceptable, the thermal model is used to perform flight predictions. If, however, the correlation shows problems, the TMM and the hardware configuration have to be carefully checked to see whether the actual configuration (hardware) requires modification or update of the TMM. Following a configuration update, the system authority decides, based on the TCS recommendations whether a re-test is to be performed.

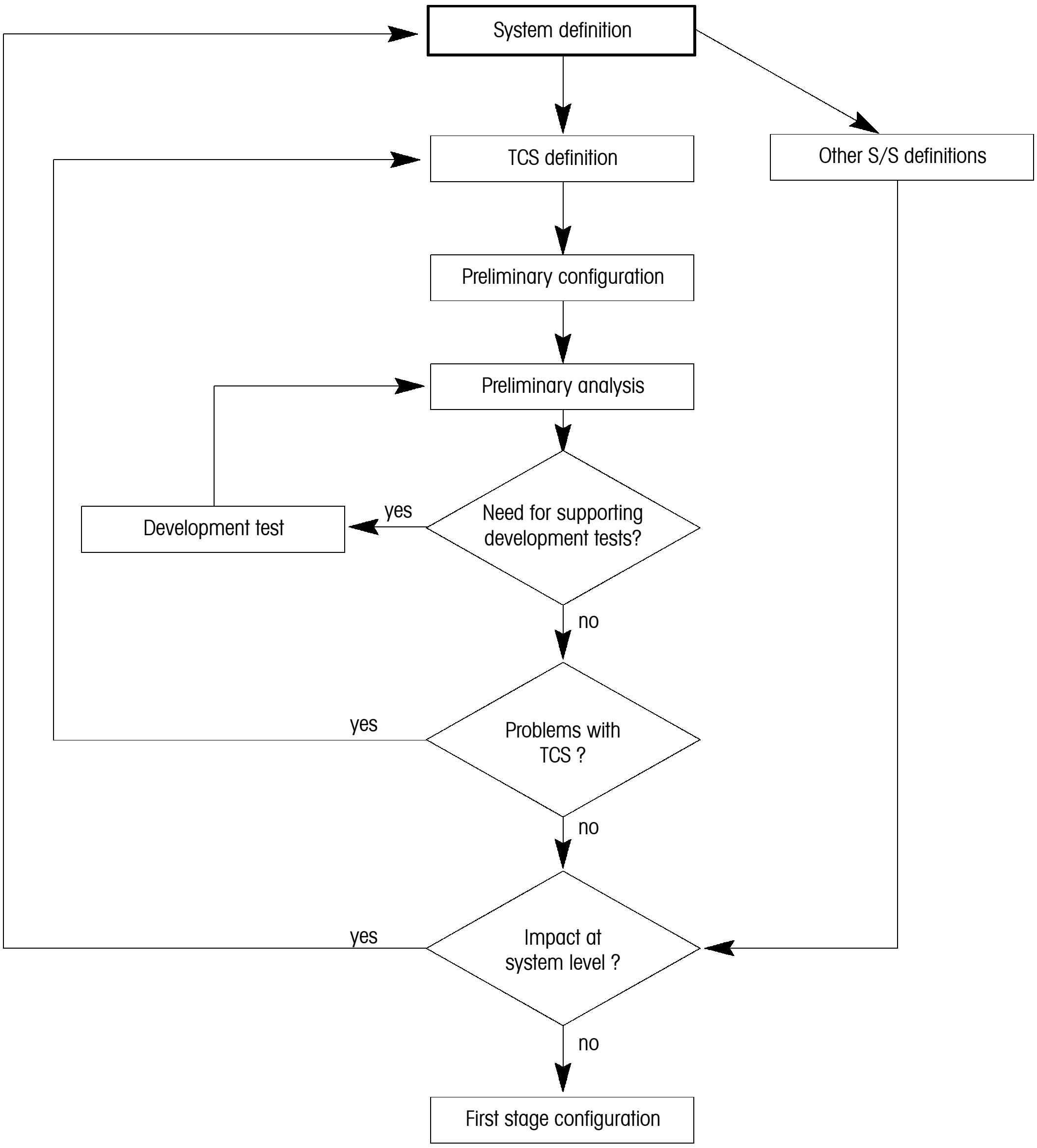

Figure D-1: TCS development approach (first stage)

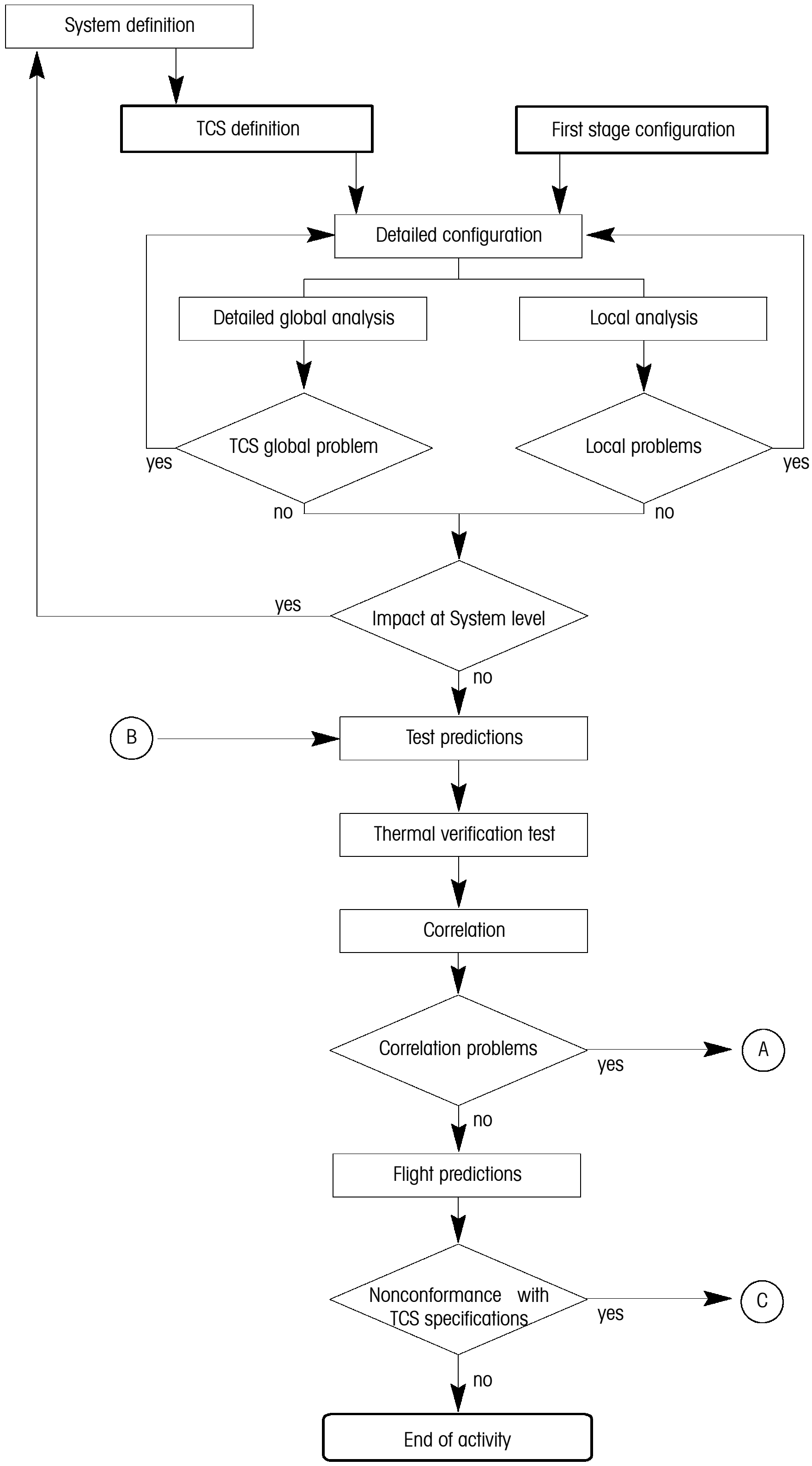

Figure D-2: TCS development approach (final design)

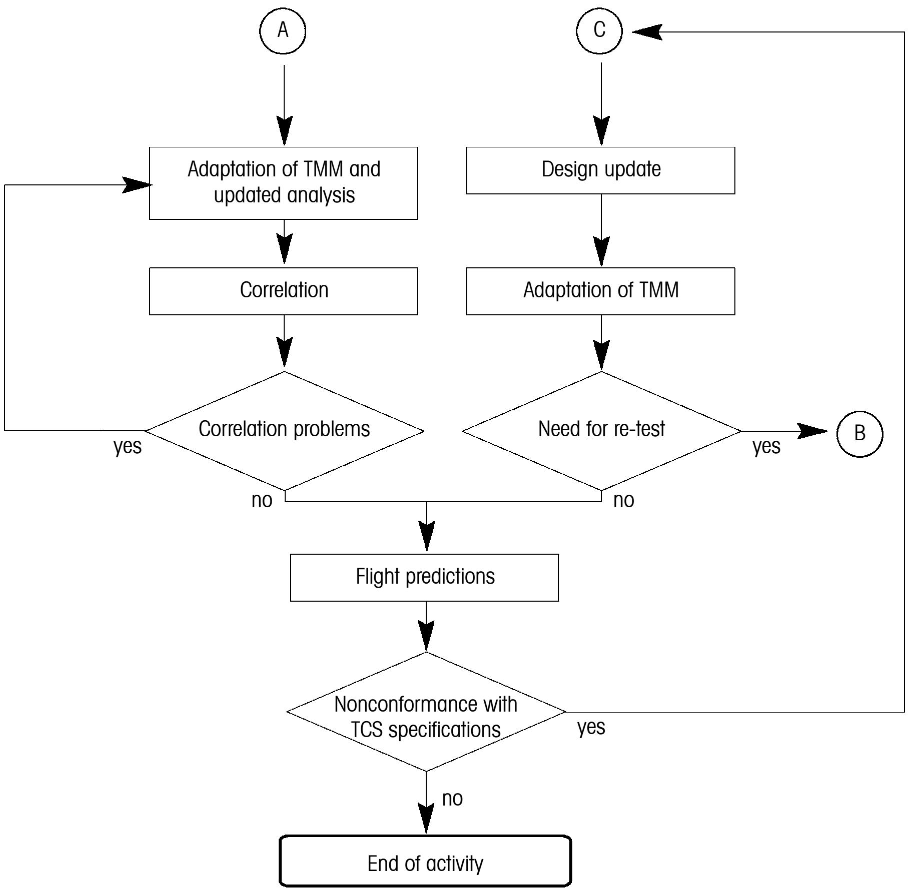

Figure D-2 continued: TCS development approach (final design)

D.1.4 Reason for thermal analyses

a. Thermal analyses are carried out to:

1. verify the item thermal design, showing the fulfilment of all the relevant specification requirements through the specified mission phase. This includes the prediction of temperatures, heat fluxes, pressure distributions (if applicable) as well as the prediction of the control system (heaters, valves) performance;
2. predict the item temperature, heat fluxes, pressures (if applicable) distribution during the thermal testing (TB, TV, functional) as well as the performance of the control system;
3. predict the item flight temperature distribution and its control system performance (after the correlation between analyses and test results has been performed). This is particularly important when unforeseen events change either the operational modes or the mission parameters;
4. provide input to TV-test procedures and TV-test performance;

b. A thermal analysis is generally performed through the steps shown in Figure D-3, i.e.:

1. definition of a GMM of the item. The item is represented by a series of surfaces, each having definite geometry and thermo-optical properties, to determine the mutual interrelationship (radiative interchange factors) and the relationship with the environment. In case the item is exposed to any heat source (sun, planetary albedo and infrared emission), the GMM allows the calculation of the relevant fluxes;

2. definition of a TMM of the item. The item is represented by a thermal network of physical volumes ("nodes") interconnected by a series of conductors (radiative, solid or fluidic) and subject to the specified boundary conditions, environment fluxes and internal heat dissipation;
3. solution of the TMM, i.e. of the systems of equations associated with the physical model of heat exchange.

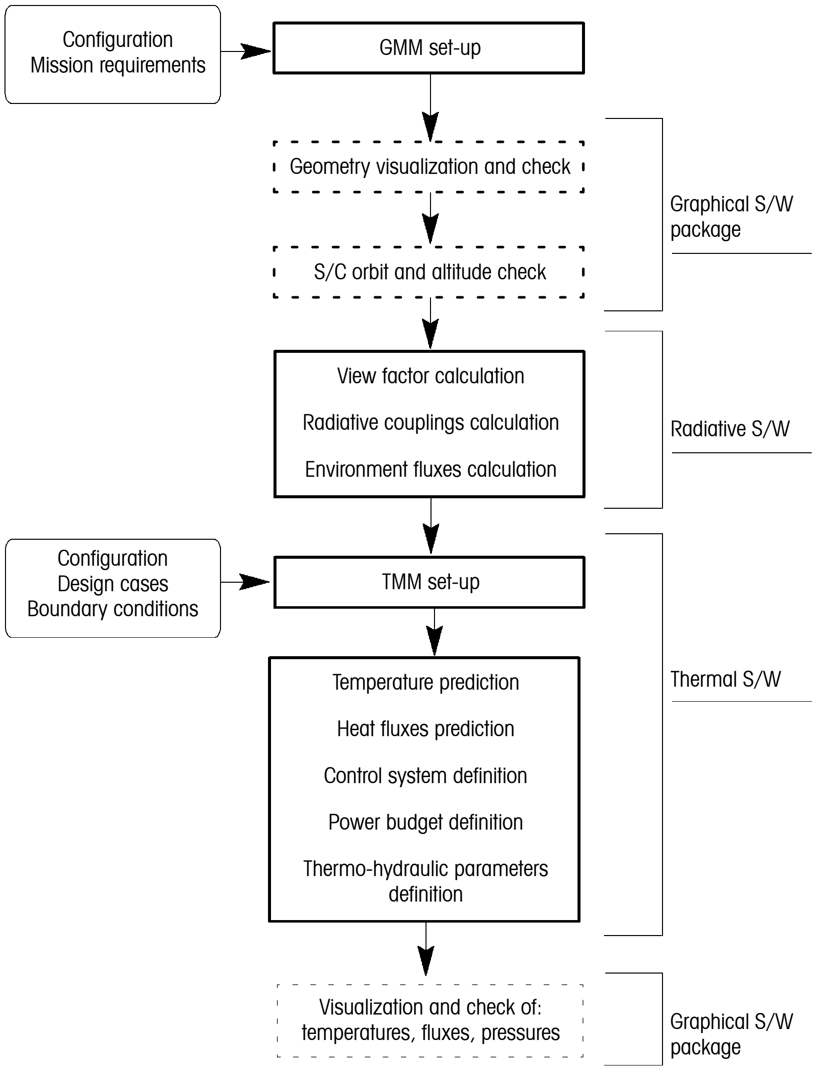

Figure D-3: Modelling philosophy

D.1.5 Typical parameter inaccuracies

a. 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 following values, shown in Table D-1, are typically considered.

Table D-1: Parameter inaccuracies (pre-phase A and phase B)

Parameter	Inaccuracy
MLI conductance	± 50 %
External radiative connections	± 20 %
Internal radiative connections	± 10 %
Linear connections	± 50 %
External heat loads	± 20 %
Internal heat loads	
- large values	± 20 %
- small values	± 40 %

b. For later, more advanced project stages (typically phase B and phase C/D), the following inaccuracies, shown in Table D-2, are typical.

Table D-2: Parameter inaccuracies (phase B and phase C/D)

a) Environmental parameters	
Solar intensity	± 21 W/m2
Earth radiation	± 65 W/m2 [a]
Albedo factor	± 0,1 [a]
b) Physical parameters	
Absorptivity	± 0,03
Emissivity	± 0,03
Emissivity (< 0,2)	± 0,02
Radiating area (effective)	± 5 %
Effective MLI conductance	± 50 %
Thermal conductivity	
• homogenous materials	± 10 %
• 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 of	
• equipment	± 25 %
• structures	± 15 %

Table D-2: Parameter inaccuracies (phase B and phase C/D) ***(continued)***

c) Modelling parameters	
Shape (view) factors (simple geometry)	± 10 %
Shape (view) factors (complex geometry)	± 50 %
d) Test facility parameters [b]	
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 (e.g. leaks, blockage)	± 10 %
Temperature sensor measurement accuracy	± 1,5 °C
Nodal or sensor position error	± 3 °C

[a] for low Earth orbit (LEO)

[b] Facility parameters are typical values for reference. Actual values are facility dependent.

D.2 Cryogenic temperature range

D.2.1 General

The TCS development philosophy outlined in D.1 should be followed for CCS developments with the following comments:

An important part for the definition of any mission is the recognition of the options available. With the CCS often being at the centre of the feasibility of missions, Figure D-1 should be amended as shown in Figure D-4.

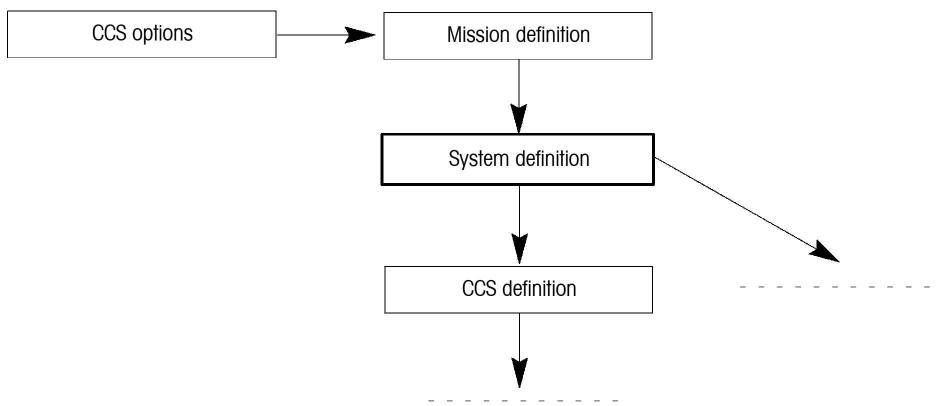

Figure D-4: CCS development approach

D.2.2 Reason for thermal analyses

Except for cryogenic regimes where quantum mechanical effects play a major role the reasons for implementing cryogenic thermal analyses are similar to those outlined in D.1.4.

D.2.3 Typical parameter inaccuracies

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 should be defined based on the actual project requirements.

Annex E (informative)

Physical quantities, constants and dimensionless numbers

E.1 General

The information provided in this informative annex has been compiled from various reference sources and has been reproduced here as a convenient method of grouping formulae, standard values and common terms connected with thermal engineering in a single annex. Although the annex has been prepared carefully, no responsibility shall be implied for its correctness. Use of the information is done, on the understanding that the original source information takes precedence over the information provided in cases of dispute.

The coherent system of units to be used shall be the International System of Units (SI) described in the International Standard for Quantities and Units (ISO 31).

E.2 SI base units

Table E-1 gives the seven base quantities, assumed to be mutually independent, on which the SI is founded; and the definition, names and symbols of their respective units, called "SI base units". The kelvin and its symbol K are also used to express the value of a temperature interval or a temperature difference.

Table E-1: SI base units

Base quantity		SI base unit	
Name	**Symbol**	**Name**	**Symbol**
length	l	metre	m
mass	m	kilogram	kg
time	t	second	s
electric current	I	ampere	A
thermodynamic temperature	T	kelvin	K
amount of substance	n	mole	mol
luminous intensity	I_v	candela	cd

Definitions of the SI base units and the radian and steradian

Metre (17th CGPM, 1983)

The metre is the length of the path travelled by light in vacuum during a time interval of 1/299792458 of a second.

Kilogram (3d CGPM, 1901)

The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.

Second (13th CGPM, 1967)

The second is the duration of 9192631770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium-133 atom.

Ampere (9th CGPM, 1948)

The ampere is that constant electric current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.

Kelvin (13th CGPM, 1967)

The kelvin, unit of thermodynamic temperature, is the fraction 1/273,16 of the thermodynamic temperature of the triple point of water.

Mole (14th CGPM, 1971)

The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0,012 kilogram of carbon 12.

When the mole is used, the elementary entities are specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

Candela (16th CGPM, 1979)

The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 × 1012 hertz and that has a radiant intensity in that direction of (1/683) watt per steradian.

Radian

The radian is the plane angle between two radii of a circle that cut off on the circumference an arc equal in length to the radius.

Steradian

The steradian is the solid angle that, having its vertex in the centre of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere.

E.3 SI derived units with special names and symbols, including the radian and steradian

Table E-2: SI derived units with special names and symbols, including the radian and steradian

Derived quantity		SI derived unit			
Name	**Symbol**	**Special name**	**Special symbol**	**Expression in terms of other SI units**	**Expression in terms of SI base units**
plane angle	α, β, γ, θ, ϕ	radian	rad		$m \times m^{-1} = 1$
solid angle	Ω	steradian	sr		$m^{2} \times m^{-2} = 1$
frequency	f, υ	hertz	Hz		s^{-1}
force	F	newton	N		$m \times kg \times s^{-2}$
pressure, stress	p, σ, τ	pascal	Pa	N/m^{2}	$m^{-1} \times kg \times s^{-2}$
energy, work, quantity of heat	E, W, Q	joule	J	$N \times m$	$m^{2} \times kg \times s^{-2}$
power, radiant flux	P, Φ	watt	W	J/s	$m^{2} \times kg \times s^{-3}$
electric charge, quantity of electricity	Q	coulomb	C		$s \times A$
electric potential, potential difference, electromotive force	V, U, E	volt	V	W/A	$m^{2} \times kg \times s^{-3} \times A^{-1}$
capacitance	C	farad	F	C/V	$m^{-2} \times kg^{-1} \times s^{4} \times A^{2}$
electric resistance	R	ohm	W	V/A	$m^{2} \times kg \times s^{-3} \times A^{-2}$
electric conductance	G	siemens	S	A/V	$m^{-2} \times kg^{-1} \times s^{3} \times A^{2}$
magnetic flux	Φ	weber	Wb	$V \times s$	$m^{2} \times kg \times s^{-2} \times A^{-1}$
magnetic flux density	B	tesla	T	Wb/m^{2}	$kg \times s^{-2} \times A^{-1}$
inductance	L	henry	H	Wb/A	$m^{2} \times kg \times s^{-2} \times A^{-2}$
Celsius temperature [a]	t, θ	degree Celsius	°C		K
luminous flux	Φ	lumen	lm	$cd \times sr$	$cd \times sr$
illuminance	E	lux	lx	lm/m^{2}	$m^{-2} \times cd \times sr$

[a] Degree Celsius: In addition to the quantity thermodynamic temperature (symbol T), expressed in the unit Kelvin, use is also made of the quantity Celsius temperature (symbol q) defined by the equation

$$\theta = T - T_0$$

where T_0 = 273,15 K by definition. To express Celsius temperature, the unit degree Celsius, symbol ºC, which is equal in magnitude to the unit Kelvin, is used; in this case, "degree Celsius" is a special name used in place of "Kelvin". An interval or difference of Celsius temperature can, however, be expressed in the unit Kelvin as well as in the unit degree Celsius. (Note that the thermodynamic temperature T_0 is exactly 0,01 K below the thermodynamic temperature of the triple point of water.)

E.4 Other SI units

Table E-3: Other SI units

Quantity	Symbol	Definition	SI derived unit	
			Name	Symbol
Area	A, S	$A = \iint dx\, dy$	square metre	m^2
Volume	V	$A = \iiint dx\, dy\, dz$	cubic metre	m^3
Speed, velocity	v, c	$V = \frac{dl}{dt}$	metre per second	m/s
Acceleration	a, g	$a = \frac{dv}{dt}$	metre per second squared	m/s^2
Angular velocity	ω	$\omega = \frac{d\phi}{dt}$	radian per second	rad/s
Angular acceleration	α	$\alpha = \frac{d\omega}{dt}$	radian per second squared	rad/s^2
Time constant	τ	Time after which the quantity would reach its limit if it maintained its initial rate of variation	second	s
Rotational frequency	n	Number of revolutions divided by time	reciprocal second	s^{-1}
Wavelength	λ	Distance in the direction of propagation of a periodic wave between two successive points where at a given time the phase is the same	metre	m
Wavenumber	σ	$\sigma = \frac{1}{\lambda}$	reciprocal metre	m^{-1}
Volumic mass, density	ρ	Mass divided by volume $\rho = \frac{m}{V}$	kilogram per cubic metre	kg/m^3
Moment of force	M		Newton metre	Nm
(dynamic) Viscosity	μ	Shear stress divided by the velocity gradient perpendicular to the shear stress plane	Pascal second	Pa s
Kinematic viscosity	ν	Dynamic viscosity divided by density $\nu = \frac{\mu}{\rho}$	metre squared per second	m^2/s
Surface tension	σ	Force perpendicular to a line element in a surface divided by the length of the line element	Newton per metre	N/m
Mass flow rate	q_m	Mass of matter which crosses a given surface divided by time	kilogram per second	kg/s
Cubic expansion coefficient	αv, α	$\alpha = \frac{1}{V}\left(\frac{dV}{dT}\right)$	reciprocal Kelvin	K^{-1}
(quantity of) Heat	Q		Joule	J

Table E-3: Other SI units *(continued)*

Quantity	Symbol	Definition	SI derived unit	
			Name	Symbol
Heat flow rate	Φ	Rate at which heat crosses a given surface	Watt	W
Density of heat flow rate	q	Heat flow rate divided by area $q = \frac{\Phi}{A}$	Watt per square metre	W/m^2
Thermal conductivity	λ	Density of heat flow rate divided by temperature gradient	Watt per metre Kelvin	W/(m K)
(surface) Coefficient of heat transfer	K, h	Density of heat flow rate divided by temperature difference	Watt per square metre Kelvin	$W/(m^2 K)$
Coefficient of thermal insulation	M	Temperature difference divided by density of heat flow rate $M = \frac{1}{K} = \frac{1}{h}$	square metre Kelvin per Watt	m^2 K/W
Thermal resistance	R	Temperature difference divided by heat flow rate	Kelvin per Watt	K/W
Thermal conductance	G	$G = \frac{1}{R}$	Watt per Kelvin	W/K
Heat capacity	C	$C = \frac{dQ}{dT}$	Joule per Kelvin	J/K
Specific heat capacity	c, c_p, c_v, c_{sat}	Heat capacity per unit mass Subscripts refer to physical conditions as: constant pressure, constant volume, saturation etc.	Joule per kilogram Kelvin	J/(kg K)
Thermal diffusivity	a	$a = \frac{\lambda}{(\rho \times cp)}$	square metre per second	m^2/s
Ratio of specific heat capacities	γ	$\gamma = \frac{c_p}{c_v}$	one	1
Entropy	S	When a small quantity of heat dQ is received by a system the thermodynamic temperature of which is T, the entropy of the system is increased by dQ/T, provided that no irreversible change takes place in the system	Joule per Kelvin	J/K
Specific entropy	s	Entropy divided by mass	Joule per kilogram Kelvin	J/(kg K)
Thermodynamic energy	U	For a closed thermodynamic system $\Delta U = Q + W$ where Q is heat transferred to the system and W is work done on the system	Joule	J
Enthalpy	H	$H = U + pV$	Joule	J
Helmholtz free energy	F	$F = U - TS$	Joule	J
Gibbs free energy	G	$G = U + pV - TS = H - TS$	Joule	J

Table E-3: Other SI units *(continued)*

Quantity	Symbol	Definition	SI derived unit Name	SI derived unit Symbol
Specific thermodynamic energy	u	Thermodynamic energy divided by mass	Joule per kilogram	J/kg
Specific enthalpy	h	Enthalpy divided by mass	Joule per kilogram	J/kg
Specific Helmholtz free energy	f	Helmholtz free energy divided by mass	Joule per kilogram	J/kg
Specific Gibbs free energy	g	Gibbs free energy divided by mass	Joule per kilogram	J/kg
Radiant energy	Q, W	Energy emitted, transferred or received as radiation	Joule	J
Radiant energy density	w	Radiant energy in an element of volume, divided by that element	Joule per cubic metre	J/m^3
Spectral concentration of radiant energy density (in terms of wavelength)	w_λ	Radiant energy density in an infinitesimal wavelength interval, divided by the range of that interval	Joule per metre to the fourth power	J/m^4
Radiant energy flux or radiant power	Φ, P	Power emitted, transferred or received as radiation	Watt	W
Radiant intensity	I	In a given direction from a source, the radiant energy flux leaving the source, or an element of the source, in an element of solid angle containing the given direction, divided by that element of solid angle	Watt per steradian	W/sr
Radiance	L	At a point on a surface and in a given direction, the radiant intensity of an element of the surface, divided by the area of the orthogonal projection of this element on a plane perpendicular to the given direction	Watt per steradian square metre	$W/(sr\ m^2)$
Radiant exitance	M	At a point on a surface, the radiant energy flux leaving the element of the surface, divided by the area of that element	Watt per square metre	W/m^2
Stefan-Boltzmann constant	σ	The constant σ in the expression for the radiant exitance of a full radiator (back body) at the thermodynamic temperature T. $M = \sigma T^4$	Watt per square metre Kelvin to the fourth power	$W/(m^2K^4)$
Emissivity	ϵ	Ratio of radiant exitance of a thermal radiator to that of a full radiator (black body) at the same temperature	one	1

Table E-3: Other SI units *(continued)*

Quantity	Symbol	Definition	SI derived unit	
			Name	Symbol
Spectral emissivity	$\epsilon(\lambda)$	Ratio of spectral concentration of radiant exitance of a thermal radiator to that of a full radiator (black body) at the same temperature	one	1
Directional spectral emissivity	$\epsilon(\lambda, \theta, \phi)$	Ratio of spectral concentration of radiance in a given direction θ, ϕ, of a thermal radiator to that of a full radiator (black body) at the same temperature	one	1
Luminous flux	Φ	The luminous flux $d\Phi$ of a source of luminous intensity I in an element of solid angle $d\Omega$ is given by $d\Phi = Id\Omega$	lumen	lm
Spectral absorptance	$\alpha(\lambda)$	Ratio of the spectral concentration of radiant or luminous flux absorbed to that of the incident radiation	one	1
Spectral reflectance	$\rho(\lambda)$	Ratio of the spectral concentration of radiant or luminous flux reflected to that of the incident radiation	one	1
Spectral transmittance	$\tau(\lambda)$	Ratio of the spectral concentration of radiant or luminous flux transmitted to that of the incident radiation	one	1
Absorptance	α	Weighted average of $\alpha(\lambda)$ over a wavelength band	one	1
Reflectance	ρ	Weighted average of $\rho(\lambda)$ over a wavelength band	one	1
Transmittance	τ	Weighted average of $\tau(\lambda)$ over a wavelength band	one	1

E.5 Units accepted for use with the SI

Table E-4: Units accepted for use with the SI

Quantity	Name	Symbol	Value in SI units
time	minute	min	1 min = 60 s
	hour	h	1 h = 60 min = 3600 s
	day	d	1 d = 24 h = 86400 s
plane angle	degree	°	1° = (π/180) rad
	minute	’	1’ = $(1/60)^{\circ}$ = (π/10800) rad
	second	”	1” = (1/60)’ = (π/648000) rad
volume	litre	L	1 L = 1 dm^3 = 10^{-3} m^3
mass	tonne or metric ton	t	1 t = 10^3 kg
pressure	bar [a]	bar	1 bar = 0,1 MPa = 100 kPa = 10^5 Pa

[a] Units temporarily accepted. Its use should be restricted to the existing uses in the field of fluid pressure.

E.6 Units accepted for use with the SI whose values in SI units are obtained experimentally

Table E-5: Units accepted for use with the SI whose values in SI units are obtained experimentally

Name	Symbol	Definition
electronvolt	eV	kinetic energy acquired by an electron in passing through a potential difference of 1 × V in vacuum; 1 eV = 1,602176462(63) × 10^{-19} J with a relative standard uncertainty of 3,9 × 10^{-8}
unified atomic mass unit	u	equal to 1/12 of the mass of an atom of the nuclide ^{12}C; 1 u = 1,66053873(13) × 10^{-27} kg with a relative standard uncertainty of 7,9 × 10^{-8}

E.7 1998 CODATA recommended values of the fundamental physical constants

This list of the fundamental constants of physics and chemistry is based on a least-squares adjustment with 17 degrees of freedom. The digits in parentheses are the one-standard deviation uncertainty in the last digits of the given value. Since the uncertainties of many of these entries are correlated, the full covariance matrix must be used in evaluating the uncertainties of quantities computed from them.

Table E-6: 1998 CODATA recommended values of the fundamental physical constants (atomic constants not included)

Quantity	Symbol	Value	Units	Relative standard uncertainty
Universal constants				
Speed of light in vacuum	c	299792458	ms^{-1}	(exact)
Magnetic constant	μ_0	$4\pi \times 10^{-7}$ = $12{,}566370614 \times 10^{-7}$	NA^{-2}	(exact)
Electric constant	ϵ_0	$1/\mu_0 c^2$ = $8{,}854187817 \times 10^{-12}$	$F\ m^{-1}$	(exact)
Newtonian constant of gravitation	G	$6{,}673(10) \times 10^{-11}$	$m^3\ kg^{-1}\ s^{-2}$	$1{,}5 \times 10^{-3}$
Planck constant	h	$6{,}62606876(52) \times 10^{-34}$	J s	$7{,}8 \times 10^{-8}$
in electron volts, h/{e}		$4{,}13566727(16) \times 10^{-15}$	eV s	$3{,}9 \times 10^{-8}$
$h/2\pi$		$1{,}054571596(82) \times 10^{-34}$	J s	$7{,}8 \times 10^{-8}$
in electron volts, $\hbar$/{e}	$\hbar$	$6{,}58211889(26) \times 10^{-16}$	eVs	$3{,}9 \times 10^{-8}$
Planck mass, $(\hbar c/G)^{\frac{1}{2}}$	m_P	$2{,}1767(16) \times 10^{-8}$	kg	$7{,}5 \times 10^{-4}$
Planck length, $\hbar/m_P c = (\hbar G/c^3)^{\frac{1}{2}}$	l_P	$1{,}6160(12) \times 10^{-35}$	m	$7{,}5 \times 10^{-4}$
Planck time, $l_P/c = (\hbar G/c^5)^{\frac{1}{2}}$	t_P	$5{,}3906(40) \times 10^{-44}$	s	$7{,}5 \times 10^{-4}$

Table E-6: 1998 CODATA recommended values of the fundamental physical constants (atomic constants not included) *(continued)*

Quantity	Symbol	Value	Units	Relative standard uncertainty
Physico-chemical constants				
Avogadro constant	N_A, L	$6,02214199(47) \times 10^{23}$	mol^{-1}	$7,9 \times 10^{-8}$
Atomic mass constant				
$m_u = \frac{1}{12}m(^{12}C) = 1$ u	m_u	$1,66053873(13) \times 10^{-27}$	kg	$7,9 \times 10^{-8}$
$= 10^{-3}\,kg\,mol^{-1}/N_A$				
energy equivalent	m_uc^2	$1,49241778(12) \times 10^{-10}$	J	$7,9 \times 10^{-8}$
in MeV		931,494013(37)	MeV	$4,0 \times 10^{-8}$
Faraday constant, N_Ae	F	96485,3415(39)	C mol^{-1}	$4,0 \times 10^{-8}$
Molar Planck constant	N_Ah	$3,990312689(30) \times 10^{-10}$	J s mol^{-1}	$7,6 \times 10^{-9}$
	N_Ahc	0,11962656492(91)	J m mol^{-1}	$7,6 \times 10^{-9}$
Molar gas constant	R	8,314472(15)	J mol^{-1} K^{-1}	$1,7 \times 10^{-6}$
Boltzmann constant, R/N_A	k	$1,3806503(24) \times 10^{-23}$	J K^{-1}	$1,7 \times 10^{-6}$
in electron volts k^{-1}	k/{e}	$8,617342(15) \times 10^{-5}$	eV K^{-1}	$1,7 \times 10^{-6}$
in hertz K^{-1}	k/h	$2,0836644(36) \times 10^{10}$	Hz K^{-1}	$1,7 \times 10^{-6}$
in wavenumbers K^{-1}	k/hc	69,50356(12)	m^{-1} K^{-1}	$1,7 \times 10^{-6}$
Molar volume (ideal gas), RT/p T = 273,15 K, p = 101,325 kPa	V_m	$22,413996(39) \times 10^{-3}$	m^3 mol^{-1}	$1,7 \times 10^{-6}$
Loschmidt constant, N_A/V_m	n_o	$2,6867775(47) \times 10^{25}$	m^{-3}	$1,7 \times 10^{-6}$
T = 273,15 K, p = 100 kPa	V_m	$22,710981(40) \times 10^{-3}$	m^3 mol^{-1}	$1,7 \times 10^{-6}$
Sackur-Tetrode constant (absolute entropy constant) [a] $5/2 + \ln\{(2\pi m_u kT1/h^2)^{3/2} kT_1/p_o\}$				
T_1 = 1 K, p_o = 100 kPa	So/R	-1,1517048(44)		$3,8 \times 10^{-6}$
T_1 = 1 K, p_o = 101,325 kPa		-1,1648678(44)		$3,7 \times 10^{-6}$
Stefan-Boltzmann constant,				
$(\pi^2/60)k^4/\hbar^3c^2$	σ	$5,670400(40) \times 10^{-8}$	W m^{-2} K^{-4}	$7,0 \times 10^{-6}$
First radiation constant, $2\pi hc^2$	c_1	$3,74177107(29) \times 10^{-16}$	W m^2	$7,8 \times 10^{-8}$
Second radiation constant, hc/k	c_2	$1,4387752(25) \times 10^{-2}$	m K	$1,7 \times 10^{-6}$
Wien displacement law constant, $b = \lambda_{max}T = c_2/4,965114231...$	b	$2,8977686(51) \times 10^{-3}$	m K	$1,7 \times 10^{-6}$

[a] The entropy of an ideal monatomic gas of relative atomic weight A_r is given by:

$$S = S_o + \frac{3}{2}R\ln A_r - R\ln\left(\frac{p}{p_o}\right) + \frac{5}{2}R\ln\left(\frac{T}{K}\right)$$

E.8 Standard values and their relationship to SI units

Table E-7: Standard values and their relationship to SI units

Quantity	Symbol	Value	Units	Relative standard uncertainty
Standard atmosphere	atm	101325	Pa	(exact)
Standard acceleration of gravity	gn	9,80665	m s^{-2}	(exact)

E.9 Sun-earth physical constants

Table E-8: Sun-Earth physical constants

Distance to the Sun	1,4959787 × 10^8 km (equals 1 AU by definition)
Solar Constant [a]	(1371 ± 10) W/m^2 at 1 AU
Eccentricity of Orbit [b]	0,0167295
Orbital Period (Sidereal) [c]	365,25636 days
Radius of the Earth (equatorial)	6378140 m
Earth Rotation Rate	7,2921 × 10^{-5} rad/s
Gravitational Constant for the Earth (μE)	3,986012 × 10^{14} N m^2/kg
Inclination of the Equator [d]	23,45°
Period of Rotation (Sidereal)	23,934 h (86162,4 s)
Space Sink Temperature	3 K (absolute)
Solar Radiation Pressure at 1 AU	9,02 × 10^{-6} N/m^{-2} (100-percent reflecting)

[a] The spectrum of the Sun is a black body spectrum with a characteristic temperature of 5762 K. The +10 and -10 W/m^2 are due to the natural variability of the solar output and measurement uncertainty.

[b] The eccentricity gives the non-circular nature of an orbit. The maximum distance from the Sun is (1+ecc) times the average radius; the minimum distance is (1-ecc) times the average radius.

[c] The sidereal period is measured with respect to the “fixed” stars rather than with respect to the Sun.

[d] The inclination of the Equator is with respect to the Earth’s orbital plane.

E.10 Characteristic (dimensionless) numbers

Table E-9: Characteristic (dimensionless) numbers

Name	Symbol and definition	Application and remarks
Euler	$Eu = \frac{\Delta p}{\rho v_2}$	Fluid friction in conduits
Fourier	$Fo = \frac{\lambda t}{c_p \rho l^2} = \frac{at}{l^2}$	Unsteady state heat conduction
Froude	$Fr = \frac{v}{\sqrt{lg}}$	Wave and surface behaviour. Sometimes called Reech number.

Table E-9: Characteristic (dimensionless) numbers *(continued)*

Name	Symbol and definition	Application and remarks
Grashof	$Gr = \frac{l^3 g \alpha \Delta T}{v^2}$	Heat transfer by free convection $-\frac{\Delta\rho}{\rho} = \alpha\Delta T$
Knudsen	$Kn = \frac{Kl}{\lambda}$	Flow of low-density gases
Lewis	$Le = \frac{\lambda}{pc_p D} = \frac{a}{D}$	Heat and mass transfer Le = Sc/Pr
Mach	$Ma = \frac{v}{c}$	Compressible flow
Nusselt	$Nu = \frac{Kl}{\lambda}$	Heat transfer by forced convection The name Biot number, *Bi*, is used when the Nusselt number is reserved for convective transport of heat.
Péclet	$Pe = \frac{pc_p vl}{\lambda} = \frac{vl}{a}$	Diffusion in packed beds Pe = Re × Pr
Prandtl	$Pr = \frac{\mu c_p}{\lambda} = \frac{v}{a}$	Heat conduction in streamline flow
Rayleigh	$Ra = \frac{l^3 \rho^2 c_p g \alpha \Delta T}{\mu\lambda} = \frac{l^3 g \alpha \Delta T}{va}$	Heat transfer by free convection Ra = Gr × Pr
Reynolds	$Re = \frac{\rho vl}{\mu} = \frac{vl}{\nu}$	Dynamic similarity. The following relations are valid: Re = Pe/Pr, Re^2 = Gr × Ga × Fr
Schmidt	$Sc = \frac{\mu}{\rho D} = \frac{\nu}{D}$	Mass transfer
Stanton	$St = \frac{K}{\rho v c_p}$	Forced convection. The relation St = Nu/(Re × Pr) = Nu/Pe is valid. Sometimes called the Margoulis number, Ms. j = St × $Pr^{2/3}$ is called the heat transfer factor.
Strouhal	$Sr = \frac{lf}{v}$	Vortex streets (f = frequency of vortex)
Weber	$We = \frac{\rho v_2 l}{\sigma}$	Bubble formation, breaking of liquid jets

Symbols used in the definitions:

l	a characteristic length	c_p	massic heat capacity at constant pressure
v	a characteristic speed	α	cubic expansion coefficient: (1/V) dV/dT
t	a characteristic time interval	l_o	mean free path
ΔT	a characteristic temperature difference	λ	thermal conductivity
Δp	pressure difference	a	thermal diffusivity: $\lambda/\rho c_p$
g	acceleration of free fall	K	coefficient of heat transfer: heat/(time x cross-sectional area x temperature difference)
ρ	volumic mass (density)	D	diffusion coefficient
μ	dynamic viscosity	f	a characteristic frequency
ν	kinematic viscosity: μ/ρ	c	speed of sound
σ	surface tension		

Bibliography

The publications listed below were used in the preparation of this Standard, and contain background information relating to the subject addressed.

	VDI Wärmeatlas
NASA-SP-30425	Space station program natural environment definition for design
NASA-TM-82478	Space and planetary environment criteria guidelines for use in space vehicle development
NASA-TM-86498	Natural environment design criteria
NASA-TM-86522	Orbital atmospheric model

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