ECSS-E-ST-35-01C
15 November 2008

EUROPEAN COOPERATION FOR SPACE STANDARDIZATION

Space engineering

Liquid and electric propulsion for spacecraft

ECSS Secretariat
ESA-ESTEC
Requirements & Standards Division
Noordwijk, The Netherlands

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-E-35-01 Working Group, reviewed by the ECSS Executive Secretariat and approved by the ECSS Technical Authority.

Disclaimer

Published by: ESA Requirements and Standards Division
ESTEC, P.O. Box 299,
2200 AG Noordwijk
The Netherlands

Change log

ECSS-E-ST-35-01A	Never issued
ECSS-E-ST-35-01B	Never issued
ECSS-E-ST-35-01C 15 November 2008	First issue

Table of contents

Tables

Introduction

The ECSS Propulsion standards structure is as follows.

ECSS-E-ST-35 Propulsion general requirements

- Standards, covering particular type of propulsion
  - ECSS-E-ST-35-01 Liquid and electric propulsion for spacecrafts
  - ECSS-E-ST-35-02 Solid propulsion for spacecrafts and launchers
  - ECSS-E-ST-35-03 Liquid propulsion for launchers
- Standard covering particular propulsion aspects
  - ECSS-E-ST-35-06 Cleanliness requirements for spacecraft propulsion hardware
  - ECSS-E-ST-35-10 Compatibility testing for liquid propulsion systems

1 Scope

This Standard defines the regulatory aspects applicable to elements and processes for liquid, including cold gas, and electrical propulsion for spacecraft. It specifies the activities to be performed in the engineering of such propulsion systems, their applicability, and defines the requirements for the engineering aspects: functional, interfaces, environmental, design, quality factors, operational and verification.

General requirements applying to all type of Propulsion Systems Engineering are defined in ECSS-E-ST-35.

This standard may be tailored for the specific characteristics and constraints of a space project in conformance with ECSS-S-ST-00.

2
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 revision 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 more recent editions of the normative documents indicated below. For undated references, the latest edition of the publication referred to applies.

ECSS-S-ST-00-01	ECSS system – Glossary of terms
ECSS-E-ST-10	Space engineering – System engineering general requirements
ECSS-E-ST-20	Space engineering – Electrical and electronic
ECSS-E-ST-20-06	Space engineering – Spacecraft changing
ECSS-E-ST-20-07	Space engineering – Electromagnetic compatibility
ECSS-E-ST-31	Space engineering – Thermal control general requirements
ECSS-E-ST-32	Space engineering – Structural general requirements
ECSS-E-ST-35	Space engineering – Propulsion general requirements
ECSS-Q-ST-30	Space product assurance – Dependability

3 Terms, definitions and abbreviated terms

3.1 Terms from other standards

For the purpose of this Standard, the terms and definitions from ECSS-S-ST-00-01 and ECSS-E-ST-35 apply.

3.2 Abbreviated terms

For the purpose of this Standard, the abbreviated terms from ECSS-ST-00-01 apply.

4 Liquid propulsion systems for spacecraft

4.1 Overview

Liquid propulsion systems for spacecraft provide the forces and torques for orbit transfer, orbit maintenance and attitude control. For manoeuvrable spacecraft, capsules and transport vehicles, they provide in addition the forces and torques for rendez-vous and docking.

Apart from what is specific for propellant combustion, liquid propulsion criteria are also applicable to cold gas propulsion systems.

The present clause 4 covers also the design and use of propulsion ground support equipment (GSE), defined in ECSS-E-ST-70.

4.2 Functional

4.2.1 Mission

a. The propulsion system shall conform to the spacecraft mission requirements including:

1. Ground operations

   NOTE For example: functional control, testing, propellant, simulant loading and spacecraft transportation.

2. Pre-launch and launch activities

   NOTE For example: integration, storage, ageing and transport.

3. In-orbit operations.

   NOTE For example: orbit transfer, orbit maintenance and attitude control) and the complete in-orbit life.

4.2.2 Functions

a. The propulsion system shall provide the total impulse, minimum impulse bit, thrust levels and torques required by the AOCS.

b. The following aspects shall be defined:

1. Thruster firing modes

   NOTE For example: steady state, off-modulation, pulse mode.

2. Thrust level and orientation
3. Thrust-vector control
4. Thrust centroid time
5. Minimum impulse bit
6. Impulse reproducibility
7. Total impulse
8. Cycle life
9. Mission life
10. Reliability level
11. Thrust noise
12. Propellant gauging.

c. The propulsion system shall fulfil its functions while subjected to the specified external loads during its mission, including:

1. mechanical loads;

   NOTE For example: quasi-static loads, vibrations, transportation.

2. thermal loads;
3. electrical loads.

4.3 Constraints

4.3.1 Accelerations

a. Limits on acceleration levels, induced or experienced by the propulsion system, shall be specified at spacecraft level.

NOTE This is in order to:

- avoid perturbations, e.g. during possible observations or experiments;
- protect sensitive equipments;
- design adequate tank PMD.

4.3.2 Pressure vessels and pressurized components

a. Support structures of pressure vessels and pressurized components shall allow deformations of the vessels due to pressure or temperature changes and cycles to occur without causing stresses that exceed acceptable limits.

4.3.3 Induced and environmental temperatures

a. The non-operating and operating temperature limitations of the propulsion system shall be specified.

4.3.4 Thermal fluxes

a. Thruster surroundings shall conform to the radiative and conductive heat fluxes rejected by the thrusters.

4.3.5 Thruster plume effects

a. Elements of the spacecraft sensitive to plume effects shall be identified.

b. The allowed plume effects on elements identified in clause 4.3.5a shall be specified at spacecraft level.

c. The generation of perturbing torques, forces, thermal gradients, contamination and erosion of surfaces, due to plume effects, shall be defined and documented accordingly.

d. The plume analysis specified in 4.3.5c shall be reported in conformance with the Plume analysis report DRD in ECSS-E-ST-35.

4.4 Interfaces

a. The liquid propulsion system shall conform to its specified spacecraft interfaces, including:

1. Structure

   NOTE For example: inserts, tank support structure and vibration levels.

2. Thermal

   NOTE For example: conduction, radiation levels, tank, thruster and line thermal control.

3. Power

   NOTE For example: valve drivers, pressure transducers, thermistors, heaters and thermocouples.

4. Electromagnetic compatibility

5. Pyrotechnics

   NOTE For example: pyrotechnic valves.

6. Mechanisms

   NOTE For example: valves, regulators, actuators and actuation system.

7. AOCS, OBDH and TM/TC.

   NOTE For example: commanding, handling of data for status and health monitoring and failure detection.

b. Interfaces shall be defined:

1. For ground tests and loading activities, with the propulsion GSE.

2. For safety and prelaunch operation with the launcher authorities.

4.5 Design

4.5.1 General

4.5.1.1 Architecture

a. The propulsion system architecture shall apply the requirements in ECSS-Q-ST-30.

b. The propulsion system architecture shall provide evidence that fail safe, redundancy, reliability and safety requirements are met.

4.5.1.2 Replacement of parts

a. For replacement of parts during development, testing and mission life pre-launch activities ECSS-E-ST-35, requirements 4.5.1c, d and e. shall be applied.

4.5.1.3 Water-hammer effect

a. A water-hammer effects analysis shall be performed to support the propulsion system design and ensure proper functioning.

b. The analysis specified in 4.5.1.3a shall be reported in conformance with the Propulsion transient analysis report DRD in ECSS-E-ST-35.

4.5.1.4 Piping

a. A pipework design analysis shall be performed including non-consumables, cross-coupling, leakage, pressure, eigenfrequencies, water-hammer.

b. The consequences in terms of operational restrictions shall be identified.

4.5.1.5 Closed volumes

a. The design of the propulsion system shall prevent hazardous pressure increase in closed volumes.

b. The need for any pressure relief capability shall be identified and analysed.

4.5.1.6 Pressure vessels and pressurized components

a. The design of pressure vessels and pressurized components shall:

1. Apply margins and factors of safety (FOS) for proof, burst and component life cycle.

   NOTE See ECSS-E-ST-32-02.

2. Conform to the environmental aspects, including but not limited to:

   (a) Temperature

   (b) Vibration

   (c) Humidity

   (d) Corrosive environment

   (e) Vacuum

   (f) Outgassing

   (g) Radiation.

4.5.1.7 Multi-tanks

a. If a multi-tank layout is used, inadvertent propellant transfer between tanks shall be prevented by design.

b. If PMD tanks are being used, the consequences of selecting parallel or series connections shall be analysed.

4.5.1.8 Cycles

a. The system and its components shall be designed for the expected number of cycles during the whole mission life, for both on-ground and in-service operation.

4.5.2 Selection

4.5.2.1 Reporting

a. The reporting shall be done in the DJF in conformance with ECSS-E-ST-10.

4.5.2.2 General

a. The selection shall be based on trade-off analyses of:

1. The propulsion system.

   NOTE For example: monopropellant, bipropellant, or cold gas.

2. The operating mode.

   NOTE For example: pressure regulated and blow-down.

b. Selected materials, propellants and test fluids shall be compatible for all components.

NOTE Compatibility includes:

- dissolution;
- chemical reaction;
- erosion;
- corrosion.

4.5.2.3 Propellant selection

4.5.2.3.1 General

a. The criteria to be used for propellant selection shall include:

1. Mission requirements
2. Resulting layout of the propulsion system
3. Availability of off-the-shelf components
4. Experience
5. Compatibility and contamination
6. Performance.

b. The propellant shall be defined and specified including:

1. Chemical composition
2. Purity
3. Cleanliness.

4.5.2.3.2 Propellant for Thruster qualification

a. Thruster qualification firing tests shall use the same propellant grade as the one selected for flight.

4.5.3 Sizing

a. The sizing process shall begin with a definition of the life phases of each subsystem or component, including at least:

1. Pressure cycles combined with temperature cycles
2. Propellant, pressurant and leakage budgets
3. Establishment of the operational envelope
4. Minimum and maximum electrical supply voltages
5. Interfaces with GSE functions
6. Evolution of the operational conditions.

b. The sizing process shall demonstrate margins based on:

1. Safety
2. Reliability requirements established by the customer

3. Industry and launch authorities, or agencies operational constraints
4. Thruster performance efficiency
5. Plume effects
6. Modelling errors and uncertainties.

c. Pressurant, propellant and contaminants budgets shall include:
1. Their impact on lifetime
2. Variation of performance during lifetime
3. Quantity for deorbiting
4. Residuals.

4.5.4 Design development

4.5.4.1 General

a. The development shall allow for an incremental verification at component or block level, if a fully representative functional test (i.e. hot firing and gravity-dependent functions) cannot be performed after the integration of the system components on the spacecraft.

b. If the flight version of the system is divided into independent blocks, they should be separated by safety barriers such as pyrovalves, latch valves or burst membranes.

4.5.4.2 Development tests

a. Development tests of each block should be defined to represent the conditions foreseen during the operation of the complete system.

b. At least the following characteristics of the propellant feed system shall be determined by hydraulic tests:
1. mass flow rate;
2. dynamic and static pressure;
3. temperature;
4. response time.

c. The testability at integrated spacecraft level and the ability to return after test to safe and clean conditions shall be demonstrated for each of the system blocks.

d. Design and procedures shall be defined according to 4.5.4.2c.

4.5.5 Contamination

4.5.5.1 External contamination

a. The thruster design, layout and orientation should prevent contaminant deposition on elements sensitive to contamination identified in clause 4.3.5a.

NOTE Contaminants deposition on sensitive elements, such as solar panels, star trackers, and optics, depends on the propellants used, the thruster characteristics, the layout of the propulsion system, the thruster orientation and the thruster duty cycle.

b. The potential hazard of contamination and the expected level of contamination due to thruster exhaust shall be included in the plume analysis.

NOTE See clause 4.3.5c.

4.5.5.2 Internal contamination

a. The propulsion system shall be designed to avoid the effects of internal contaminants, including propellant vapours, by:

1. Preventing intrusion, internal generation and circulation of contaminants.

2. Preventing or controlling accumulation of contaminants throughout the various parts of the system.

3. Preventing accumulation of contaminants during the various steps of production, verification and operation of the system.

NOTE 1 The presence of contaminants inside the propulsion system can lead to the loss of performance of some components or even to catastrophic failures.

NOTE 2 For example, propellant vapours can be considered as contaminants in a pressurisation system.

b. The expected maximum level of contaminants inside the propulsion system shall be specified.

c. The propulsion system design shall conform to the expected maximum level of contaminants.

4.5.6 Draining

a. The system design shall allow for on-ground draining.

b. The location of fill-and-drain valves and piping layout shall:

1. Prevent trapping of liquid in the system by on-ground draining.

2. Prevent contact between dissimilar fluids.

3. Allow purging of the system after draining.

4.5.7 Risk of explosion

a. For hydrazine and other monopropellants, adiabatic compression of vapours, hot spots or undesired contact with a catalyst material shall be avoided.

b. Propellant explosions, leakage of propellant and propellant vapours shall be prevented.

c. Item 4.5.7b shall be supported by analysis, simulation, or testing or all of them.

d. The propulsion system design shall ensure elimination of undesired mixtures, migration or leakage of propellant and propellant vapours, and condensation of fuel.

e. The propulsion system requirements shall specify operation under conditions different from operational conditions, such as ground tests.

4.5.8 Components guidelines

a. A design assessment for failure tolerance shall be performed for every component.

NOTE 1 See ECSS-Q-ST-30-02.

NOTE 2 Table 4-1 covers the component failure modes generally encountered in the use of standard components. Failure to operate are not mentioned while external leakage is only reported for tanks and tubing.

Table 4-1: Component failure modes

Component type	Failure mode	Failure detection	Failure prevention
Tanks, tubing	Crack growth	External leakage	Analysis
	Corrosion pitting	- Visual inspection - Contamination	- Surface treatment - Material selection
	Internal leakage (diaphragms)	- Decreased expulsion efficiency - gas bubble in propellant	- Design, manufacturing procedures, quality control - material selection
	Structural failure of PMD screens	- Visual inspection - X-ray, Ultrasound	Design, quality control manufacturing procedures
Pressure regulator	Internal leakage	Pressure test	Cleanliness

Component type	**Failure mode**	**Failure detection**	**Failure prevention**
Electrically actuated valves	- Undesired operation - Internal leakage	- Pressure test - Position indication - Internal leak test	- Electrical inhibits - Cleanliness
Pneumatically actuated valves	- Undesired operation - Internal leakage	- Pressure test - Position indication - Internal leak test	Cleanliness
Propellant fill-and-drain valves	Undesired operation	Leakage	Cleanliness
	Propellant mixing	Chemical reaction	Use of: - different colours for components - different connectors (size and thread)
Manually actuated valves	Internal leakage	- Pressure test - Internal leak test	- Cleanliness
Non-return valves	Internal leakage	- Pressure test - Internal leak test	- Cleanliness - Design assessment
Pyrovalves	Undesired operation	Pressure test	- Electrical inhibits - Cleanliness
	Particle generation	Pressure test & Ground test	Design assessment
Thrust chambers and nozzles	Structural failure	Firing test	Design assessment
	Overheating cooling circuit	Firing test	Design assessment
	Loss of catalyst integrity	Gas-flow test	- Shock absorber, orientation of thruster. - Preheating of catalyst bed
	Catalyst poisoning	Performance loss	- Use of purified anhydrous hydrazine; - Si-leaching minimization from bladder or diaphragm tanks.
Filters	Clogging	Pressure test	Cleanliness
Pressure transducer	Zero shift, measurement anomalies	Calibration	-
Orifices, cavitating venturis, flow restrictors	Clogging	Pressure test	Cleanliness

4.5.9 Filters

a. All filters used at system or component level shall be designed and positioned according to the results of contaminant control and reliability studies.

b. Filters shall be installed immediately downstream of potential particle generating components and, depending on the result of the failure risk analysis, directly upstream of components sensitive to pollution or contamination.

NOTE For example: actuation valves, pressure regulators, injectors and thrusters.

c. Design of filters shall cover at least:

1. Total throughput
2. Retention capacity
3. Pressure drop
4. Absolute and relative filtering rate
5. Particle size.

4.5.10 Pressure vessels

a. In order to eliminate explosion or leakage risks, requirements on design, development, production, verification and operation of pressure vessels for propulsion systems shall be addressed specifically.

NOTE For design and verification requirements of pressured vessels see ECSS-E-ST-32-02.

4.5.11 Propellant tanks

4.5.11.1 General

a. The tank design shall account for all forces acting on the propellant during ground handling and all mission phases.

b. To avoid propellant freezing and control propellant tank pressures, the tank and line temperatures shall be controlled during the whole mission.

c. The tank design shall comply with the propellant gauging requirements.

d. The reporting of the item identified in 4.5.11.1c shall be in conformance with the Gauging analysis report DRD in ECSS-E-ST-35.

e. Propellant tank design shall prevent ingestion of pressurant gas into the propellant supply lines during ground handling and all mission phases.

f. The tank design shall comply with sloshing requirements.

g. Propellant tanks shall provide the thrusters with propellants according to their specified conditions.

h. The tanks shall conform to the dynamic spacecraft specifications.

NOTE 1 Commonly used tanks on spacecraft are:

- Simple shell, (tank without internal devices).
- Positive Expulsion Device (PED) tanks (e.g. diaphragm, bladder and bellows).
- Surface Tension Device (STD) or Propellant Management Device (PMD) tanks.

NOTE 2 Propellant tanks can contain the following additional devices:

- Anti-vortex, to ensure a proper propellant expulsion and to avoid gas ingestion.
- Sumps, to allow engine starts in a zero gravity environment; they can be combined with a gauging device and an anti-vortex device.
- Baffles or other anti-sloshing devices, selected and dimensioned according to spacecraft standards and mission requirements.
- Gauging devices, selected in conformance with the selected tank type and the spacecraft and mission requirements.

4.5.11.2 Positive expulsion device (PED) tanks

a. The materials used for PEDs shall be selected according to, at least:

1. Contamination into propellant

   NOTE For example: by silica-leaching.

2. Pressurant gas permeation through the PED
3. Propellant adsorption
4. Material compatibility.

   NOTE For example: very slow propellant decomposition and gas formation.

b. In case metallic diaphragms are used in a multiple tank configuration, the design shall prevent asymmetrical depletion.

c. The design of the PED tank shall comply with the launch configuration

NOTE For example: filling ratio.

4.5.11.3 Surface tension device (STD) tanks

a. Due to the difficulty of on-ground functional testing, the STD design shall be supported by:

1. A detailed analysis allocating margins for all mission phases.
2. A demonstration plan including tests.

   NOTE For example: neutral buoyancy, bubble point, expulsion against gravity.

4.5.12 Blow-down ratio

a. For propulsion systems working in blow-down mode, the ratio of pressurant volume between BOL and EOL shall be consistent with thruster specifications.

NOTE For example: I_{sp}, combustion stability and mixture ratio shift.

4.5.13 Flow calibration

a. The flow calibration of the propulsion system shall ensure the performance of thrusters for every phase of the mission and environmental conditions.

b. Flow calibration can be done at propulsion system or thruster level.

4.5.14 Thrusters

a. The thruster design shall comply with operating conditions including:

1. Inlet pressure range
2. Temperature range for both propellant and thruster
3. Voltage range.

4.5.14.2 Thruster alignment

a. The support structure shall allow the installation of a device to adjust thruster alignment.

4.5.14.3 Thrust mismatch

a. The difference in thrust between two thrusters operating in pair on the same branch shall meet the thrust mismatch requirements.

4.5.14.4 Flow calibration orifices

a. Flow calibration orifices, if necessary, shall be designed to adapt pressure and flow rates, based on the analysis of:

1. Pressure drop
2. Mixture ratio
3. Spacecraft CoM shift
4. Thruster cross-coupling
5. Temperature.

4.5.14.5 Heat soak-back

a. The thruster design shall allow nominal operation during possible heat soak-back conditions inherent to the specified thruster operation modes (i.e. duty cycles).

b. The thruster integrity shall not be impaired by heat soak-back.

4.5.14.6 Catalyst bed heating

a. Early thruster performance degradation of thrusters using catalysts shall be avoided by providing means to heat up the catalyst bed before firing.

4.5.14.7 Thermal environment

a. To avoid overheating of the thruster, its thermal behaviour, when integrated with the spacecraft, shall be analysed.

b. Reporting of the analysis specified in a. shall be in conformance with the Thermal analysis DRD in ECSS-E-ST-31 and the Addendum: Specific propulsion aspects for thermal analysis DRD in ECSS-E-ST-35.

4.5.14.8 Impulse bit repeatability

a. Impulse bit repeatability requirements shall comply with AOCS requirements.

b. The influence of impulse bit repeatability on the propellant budget at system level shall be defined.

NOTE Stringent requirements on impulse bit repeatability have an impact on propulsion system complexity due to the difficulties to identify and act upon the sources for deviations (e.g. dribble volume, valve function, soak-back conditions and previous thruster operation) and to verify conformity to the specification (e.g. test conditions and test evaluation).

4.5.15 Thrust-vector control (TVC)

a. Thrust-vector control shall allow adjustment of the thrust-vector direction on command.

b. At engine level, the following parameters shall be known:

1. Mass and CoM of the movable part of the engine
2. Inertia of the movable part of the engine
3. The needed torque

   NOTE The needed torque is calculated taking into account all contributions, joints, feed lines and other flexible lines or connections.

4. The engine structural dynamics in the operational configuration.

c. For the performance of the TVC system, the following parameters shall be used:

1. The maximum thrust deflection angle
2. The accuracy and repeatability
3. The response times for:
   (a) command to actuation;
   (b) actuation to full deflection and back.

d. The stiffness of the engine mounting, including feed lines and piping, and the actuator mounting on the engine shall meet the minimum values.

4.5.16 Pyrotechnic devices

a. Each pyrovalve should be designed to prohibit wrong connection.

NOTE For pyrotechnics devices, see ECSS-E-ST-33-11.

4.5.17 Mass imbalance

a. The maximum mass imbalance of the propulsion system shall be specified.

NOTE The spacecraft centre of mass changes through the mission due to tank depletion and thermal differentials.

4.5.18 Monitoring and failure detection

a. Health monitoring and failure detection shall be available through telemetry.

NOTE 1 Pressure and temperature of tanks, valve status and operating branch pressure measurements are recommended as a minimum.

NOTE 2 Thrusters operation and health can be monitored with thermocouples or thermistors, but also additional equipments (e.g. pressure transducers and accelerometers).

b. The minimum monitoring needs allowing a safe mode operation shall be identified.

c. The autonomous actions required to allow a safe operation shall be identified.

d. Monitoring shall ensure the propellant gauging function.

4.5.19 Ground support equipment (GSE)

4.5.19.1 General

a. The design of the propulsion GSE shall conform to the safety requirements of the facility where it is operated.

b. The design of the GSE and the procedures to operate it shall prevent the inadvertent activation of the systems and subsystems.

4.5.19.2 Fluid

a. The GSE design and the procedures to operate it shall prevent the spillage or venting of dangerous materials.

b. The design shall prevent overpressures exceeding the applicable MEOP with a safety factor.

c. The design shall provide evacuation lines to the facilities in case of operation of any relief valve.

NOTE See ECSS-E-ST-70 for general specification regarding ground support.

d. The design shall prevent contact between materials causing hazards, such as explosion, chemical reaction and poisoning.

e. The GSE design, functioning and procedures shall ensure that the fluids delivered to the spacecraft, including the effects of dissolved gas, are conforming to the required levels of:

1. Contamination
2. Pressure
3. Temperature
4. Cleanliness.

4.5.19.3 Electrical

a. The design of the GSE shall allow the safe check-out of all electrical components.

b. In case the GSE is used in the vicinity of inflammable or explosive materials, it shall be explosion proof.

4.6 Verification

4.6.1 General

a. A verification matrix shall be established indicating the type of verification method to apply for the individual requirements.

NOTE 1 For verification of liquid propulsion systems, see ECSS-E-ST-10-02.

NOTE 2 Verification is performed to demonstrate that the system or subsystem fully conforms to the requirements. This can be achieved by adequately documented analysis, tests, review of the design, inspection, or by a combination of them.

NOTE 3 In the following clauses of this clause 4.6, it is considered that:

- verification by review of the design is included in verification by analysis, and
- verification by inspection is included in verification by test.

4.6.2 Verification by analysis

4.6.2.1 Propellant and pressurant

a. Propellant and pressurant grade and the associated database on the physico-chemical characteristics, to be used for the analyses, shall be defined.

4.6.2.2 Steady state

4.6.2.2.1 General

a. Representative validated models shall be used.

4.6.2.2.2 Steady-state characteristics

a. The establishment of the steady-state characteristics for the complete set of operating conditions of the propulsion system shall be performed including:

1. The establishment of:

    (a) The pressure losses in lines and components.

    (b) The mixture ratio shifts and their effects on propellant residuals, propellant budgets and the thruster performance shifts.

    (c) The mass of unusable propellants due to tank expulsion efficiencies, line and component trapping, propellant vaporization, leakage and permeation, and thermal gradients between tanks.

    (d) In case of a blow-down analysis, the evaluation of the pressure through the mission life, using the temperature history during the mission.

2. The analysis of the aspects specified in 4.6.2.2.2a.1, reported in conformance with the Propulsion performance analysis report DRD in ECSS-E-ST-35.

3. The demonstration by the pressurant budget, that the amount of pressurant gas carried on-board, with the expected leakage, permeation, evaporation and pressurant dissolution, ensures a proper thruster inlet pressure throughout the mission.

4. The demonstration by the PMD analysis, of its proper functioning with a sufficient margin in all mission phases.

4.6.2.2.3 Thermal analysis

a. Thruster thermal analysis shall be:

1. performed to demonstrate its compatibility with the external environment and proper thruster operation.

    NOTE For example: limitation of flow control valve and surroundings temperature, and vapour lock.

2. reported in conformance with the Thermal analysis DRD in ECSS-E-ST-31 and the Addendum: Specific propulsion aspects for thermal analysis DRD in ECSS-E-ST-35.

4.6.2.2.4 Leakage budget

a. The maximum acceptable leakage rate of the system and its valves shall be analysed with regard to the total mission duration, on ground and in flight.

4.6.2.2.5 Contamination

a. Analysis of the total contamination throughout the mission shall show that a sufficient margin exists before blocking of flow passages, and a subsequent reduction in system performances occurs.

NOTE Blocking of flow passages can occur in, e.g. filters, vales and orifices.

4.6.2.2.6 Plume analysis

a. The impact of the thruster plumes on the structure, experiments and spacecraft motion shall be analysed at spacecraft level.

b. It shall be established whether protection devices are required at spacecraft level.

c. The plume effects on the propulsion system performance shall be evaluated.

d. The plume analysis shall be reported in conformance with the Plume analysis report DRD in ECSS-E-ST-35.

4.6.2.2.7 Gauging analysis

a. The gauging analysis shall demonstrate that the required accuracy is obtained with the on-board measurement equipment and its related data handling.

b. The gauging analysis shall be reported in conformance with the Gauging analysis report DRD in ECSS-E-ST-35.

4.6.2.2.8 CoM shift

a. Analyses shall show that the spacecraft CoM remains within the specified CoM shift.

4.6.2.2.9 Tank pressurization

a. The effects of temperature and pressure on the pressurant, propellant and tank shell, pressurant dissolution and tank shell deformation shall be used for an accurate tank pressurization analysis.

4.6.2.3 Transients

4.6.2.3.1 Reporting

a. The transient analyses of clause 4.6.2.3 shall be reported in conformance with the Propulsion transient analysis report DRD in ECSS-E-ST-35.

b. The mathematical modelling specified in 4.6.2.3 shall be reported in conformance with the Mathematical modelling for propulsion analysis DRD in ECSS-E-ST-35.

4.6.2.3.2 Pressure transients

a. The effects of rapid pressurization due to line priming shall be assessed by analysis.

b. The risk of propellant adiabatic decomposition shall be analysed.

4.6.2.3.3 Thruster cross-coupling

a. If several thrusters are operated simultaneously, the cross-coupling effect of pressure fluctuations created by the actuation of flow control valves (i.e. thruster performance and valve operation) shall be analysed.

4.6.2.3.4 Water-hammer effects.

a. Water-hammer effects shall be analysed including:

1. Failure of lines (tubes) or components
2. Adiabatic decomposition of propellants
3. Cross-coupling between valves or thrusters.

4.6.2.3.5 Sloshing

a. Oscillations induced by the motion of the propellant in the tanks on the spacecraft structure and stability shall be analysed.

b. A representative model of the tank and fluid behaviour shall be used for the sloshing analysis.

c. Sloshing analysis shall be reported in conformance with the Sloshing analysis report DRD in ECSS-E-ST-35.

4.6.2.3.6 Spin load

a. The effect of spacecraft rotation on propellant motion during the mission shall be assessed by analysis.

4.6.3 Verification by test

4.6.3.1 Thruster firing test

a. The conformity of the thrusters to their requirements shall be verified by test.

b. Thruster firing tests shall be performed to verify the performance of the thrusters with the following parameters:

1. Range of inlet pressures
2. Ambient pressure
3. Propellant temperatures
4. Dissolved gas in propellant

5. Thermal environment
6. Specified duty cycles
7. Lifetime
8. Initial chamber temperature
9. Contaminants throughput
10. Valve voltage.

c. Thruster firing tests shall verify:

1. Combustion stability
2. Start and stop transient
3. Thermal design
4. performance over life, including at least:
   (a) I_{sp}
   (b) Thrust level
   (c) Impulse bit
   (d) Response delays
   (e) Thruster temperature.

d. Thruster firing tests shall be used to establish the performance model.

4.6.3.2 Proof pressure test

a. Proof pressure tests shall be performed on all pressure vessels and pressurized components.

NOTE For minimum factors of safety, see ECSS-E-ST-32-02.

b. As proof pressure tests are major contributors to crack growth, the number of proof pressure tests shall conform to the fracture control plan.

c. Stress corrosion cracking effects resulting from proof pressure tests may be neglected if the total duration of these tests is limited, this limit being defined on a case by case basis.

NOTE 1 This limit depends on the characteristics of materials in contact and mission requirements.

NOTE 2 See ECSS-Q-ST-70-36 and NASA-MSFC-SPEC-522B.

d. A system proof test shall be conducted at a pressure higher than the system MEOP.

NOTE For details on 'proof pressure test' see ECSS-E-ST-10-03.

e. Component proof pressure tests shall conducted at a pressure higher than the particular MEOP of this component.

NOTE For details on 'proof pressure test' see ECSS-E-ST-10-03.

f. All welds in lines and fittings shall either be proof tested to at least 1,5 MEOP or subject to full NDI.

NOTE The proof testing can be restricted to component-level verification.

4.6.3.3 Burst pressure test

a. Only the qualification test programmes for pressure vessels and other pressurized components, except lines and fittings, shall include a burst test.

b. The test shall be performed either

— up to rupture; or

— up to the design burst pressure as defined in ECSS-E-ST-32 maintained for a minimum 30 seconds.

c. Fluids used for burst pressure should be liquids;

d. Fluids used for burst pressure shall:

1. Not pose a hazard to test personnel.

2. Be compatible with the structural material in the pressurized hardware.

NOTE See also ISO/CD 14623-1, ISO/AWI 14623-2, AIAA S-080-1998, AIAA S-081-1999.

4.6.3.4 Cleanliness control

4.6.3.4.1 Particulate

a. A control of the maximum allowable number of particles shall be performed adequately, using the system, subsystem, and component level requirements and the particle size, particle type and the minimum clearances.

4.6.3.4.2 Non-volatile residue

a. The non-volatile residue content of liquid to enter the propulsion system shall be specified in the standards for these liquids.

b. A control of the non-volatile residue content in the liquid introduced into the system and of the wetted surfaces shall be performed.

4.6.3.5 Contamination control

a. In case the parameters for total contamination defined 4.5.5 cannot be verified by analysis, specific tests shall be conducted to establish the evolution of the level of contamination over time.

NOTE Accelerated tests can be used.

b. The total contamination verification shall include at least the following aspects when applicable:

1. Dissolution of silica into hydrazine and hydrazine compounds.

2. The chemical reaction between propellants and metals.

3. The dissolution of chemicals from seals, diaphragms, and other elements into propellants or gases.

4.6.3.6 Compatibility

a. In case the compatibility between propellants and materials in possible contact with each other, and between dissimilar materials in contact with each other, is not known, the conformance to the compatibility requirements shall be established over time.

NOTE Accelerated tests can be used.

4.6.3.7 Pressure transients test

a. In those cases where verification by analysis is considered inadequate, tests shall be performed to verify the adequacy of the design of the propulsion system with respect to pressure and flow transients.

b. Cases addressed in 4.6.3.7a shall include at least:

1. Water-hammer effects

2. Transients during system pressurisation

3. Design of flow orifices

4. Thruster cross-coupling effects

5. Hydrazine detonation due to adiabatic compression when applicable.

c. Due to the very quick response of the phenomena, high-frequency measurement devices and data acquisition shall be used for pressure transients test.

d. The system or subsystem to be tested shall be representative of the flight one.

e. For the tests, real propellants and pressurant gases should be used.

f. For liquid propellants, gas saturation shall be representative.

4.6.3.8 Tank expulsion efficiency

a. A verification of the tank expulsion efficiency shall be performed.

b. The test results, in combination with analysis, shall demonstrate the adequacy of the design with the specified margin under all mission conditions.

4.6.3.9 Flow test

a. During propulsion system development flow tests shall be performed to measure the performance of the feed system.

NOTE For example: pressure losses.

b. During system AIT a flow test shall be performed to verify the proper functioning of the system.

NOTE For example: gas flow test, proper connection of valves.

c. In case the pressure loss models or the models for the dynamic behaviour of the system are insufficiently known, this flow test should be extended to provide the required data.

4.6.3.10 Leak test

a. The system and the system components shall be tested for internal and external leakage.

b. A thruster gas flow test shall be performed at system level.

NOTE By performing a flow test on a thruster, the confidence in the functioning of the thruster without a hot firing test is increased. The verification of the pressure through the thruster injector head gives an indication of possible blockage by particles.

4.6.3.11 Dryness

a. The level of residual humidity shall be specified.

b. The dryness control shall be performed before loading and after unloading.

NOTE Humidity in the system can affect the material (e.g. stress corrosion) and the propellant quality.

4.6.3.12 Electrical test

a. All electrical components shall be tested for their functionality.

b. In case a functional test is not possible electrical continuity shall be tested.

NOTE For example: a functional test is not possible in the case of initiators and pyrotechnic devices,

4.6.3.13 Thruster alignment

a. Thruster alignment shall be tested for conformity to the requirements.

4.6.3.14 Calibration

a. All components or subsystems that provide data shall be calibrated.

4.6.3.15 Ageing

a. For propulsion systems which are designed to be activated after extremely long periods, or which are designed to operate for long time, it shall be verified that the propulsion system still conforms to all requirements after representative ageing tests.

NOTE 1 Tests can be performed at sample or component level, subsystem level or system level.

NOTE 2 Example for extremely long periods: deep space or interplanetary missions.

4.6.4 Data exchange for models

a. Test results, as well as all models shall be established and structured with a commonly agreed structure and format.

NOTE Examples of such models are: thermal, mechanical, performance models.

4.7 Quality factors

4.7.1 Reliability

a. The design shall comply with the reliability requirements with respect to:

1. The probability of success of the mission
2. The design life.

4.7.2 Production and manufacturing process

a. Procedures shall be established and maintained to ensure that the production of components, subsystems and systems conforms to all the requirements.

b. Procedures to avoid contamination, to achieve and maintain cleanliness and to guarantee reproducibility shall be established and maintained.

c. All fluids entering the propulsion system or the propulsion GSE shall be verified for purity, particulate content and non-volatile residues.

4.8 Operation and disposal

4.8.1 General

a. Any operation of the system or part of it shall be described in a procedure.

b. Before operation, the contents of the procedure shall be verified and approved by the facility operator.

c. The operation procedures shall:

   1. Observe the operational limits of the components, subsystems and systems.

   2. Conform to the limited life cycle of the system and its components.

d. The number of cycles a system has undergone and the number of cycles, that cycle limited components have undergone during ground operations shall be recorded in the system and component documentation.

e. At the end of any operation, the propulsion system shall be configured by isolating, draining or venting the system, to minimize risks.

   NOTE Minimize the risks of, e.g. explosion, toxicity and corrosion.

4.8.2 Operations on ground

a. The operation procedures shall identify any risk for personnel, installations and system.

b. The transportation and handling procedures for the system or subsystem shall conform to the system, subsystem and component requirements.

c. Special attention shall be given to safety and contamination issues for every operation where:

   1. Fluids are put in motion, either via their introduction into the propulsion system, or via expulsion from the propulsion system.

   2. Barriers are removed.

   NOTE For example: cap removal, latch valve actuation and pipe disconnection.

d. Tests at component and system level to be performed during AIT operations shall be included in the component and system requirements.

e. The operational procedures shall comply with all specific requirements of the sites where the operations are performed.

4.8.3 Tank operation

a. Pressure gradients during pressurization and depressurization operations shall be limited not to exceed the allowed temperatures.

b. During tank operation the limiting Δp for diaphragm tanks shall not be exceeded.

4.8.4 Disposal

a. Disposal of contaminated, toxic and dangerous materials or fluids or equipment shall be performed according to the applicable local regulations and facility rules.

b. After operation of a propulsion system, special procedures shall be established in case manned interventions are planned.

NOTE After the operation of a propulsion system, a number of safety barriers no longer exist.

4.9 Supporting documents

a. For supporting documents, ECSS-E-ST-35 clause 4.11 shall be applied.

b. The following specific analyses and documents, shall be delivered as a minimum:

1. Performance analysis (in conformance with ECSS-E-ST-35)
2. Transient analysis (in conformance with ECSS-E-ST-35)
3. Sloshing analysis (in conformance with ECSS-E-ST-35)
4. Thermal analysis (in conformance with ECSS-E-ST-31 and ECSS-E-ST-35)
5. Plume analysis (in conformance with ECSS-E-ST-35)
6. Gauging analysis (in conformance with ECSS-E-ST-35)
7. Mathematical modelling (in conformance with ECSS-E-ST-35)

NOTE 1 These documents also include the available test results.

NOTE 2 ECSS-E-ST-35 clause 4.11 provides a table with cross-reference between terms used in this volume to identify project documents and the Document Requirements Definition, which specifies the contents of these documents.

5
Electric propulsion systems for spacecraft

5.1 Overview

Electric propulsion is based on the acceleration of a propellant by electric heating or electric and magnetic body forces.

Depending on the working principle of the thruster, electric propulsion is subdivided in the following three main categories:

- Electro-thermal thrusters (e.g. resistojets, arcjets, PACTs).
- Electrostatic thrusters (e.g. ion thrusters with a grid, Hall-effect thrusters, FEEP thrusters).
- Electromagnetic thrusters (e.g. MPD and PPT).

Electric propulsion thrusters are characterized by high specific impulses, low thrusts and long operation times.

Electric propulsion is also characterized by strong interactions with other spacecraft subsystems, such as power-supply subsystems and thermal control subsystems.

The EP system can be separated into three subsystems;

- A propellant storage and supply subsystem, where spacecraft liquid propulsion rules are applicable (see clause 4 of this Standard), unless otherwise stated,
- A power supply control and processing subsystem, not under the scope of this ECSS Standard, and where ECSS-E-ST-20 is applicable, unless otherwise stated,
- A thruster subsystem.

Depending on the type of EP system and the hosting spacecraft, a specific component can belong to one or another of the previously defined subsystems, according to the design, procurement or for contractual reasons.

5.2 Functional

5.2.1 Mission

a. The propulsion system shall conform to the spacecraft mission requirements including:

1. Ground operation (including functional control, testing, propellant, simulant loading and spacecraft transportation).
2. Pre-launch and launch activities (including integration, storage, ageing and transport).
3. In-orbit operation (including orbit transfer, orbit maintenance and attitude control) and the complete in-orbit life.

5.2.2 Function

a. The propulsion system shall provide the total impulse required to fulfil the mission objectives.

b. The propulsion system shall provide the thrust and torques defined by the AOCS.

c. The propulsion system shall be able to operate in a number of modes defined by the AOCS.

NOTE Example the modes: off, standby, steady state thrust, pulsed thrust.

d. The specific propulsion system operational modes shall also be defined.

e. The propulsion system shall provide the means to align, adjust or both the thrust vector, as defined by the AOCS.

f. The propulsion system shall provide the means for propellant gauging during the mission.

5.2.3 Performance

a. The following general performance requirements shall be defined:

1. Specific impulse
2. Propellant mass flow rate
3. Electrical power consumption
4. Thrust vector alignment and control
5. Beam divergence.

b. The following thrust performance requirements shall be defined:

1. Thrust level and range
2. Thrust modulation
3. Thrust resolution and accuracy
4. Thrust noise.

c. Thruster response times shall be defined with respect to:

1. Start-up (time to achieve nominal thrust)
2. Changes in thrust level during normal operation
3. Shut-down (time to transit from nominal to zero thrust).

d. Repeatability of performance (between different flight units and between consecutive firings of a single unit) shall be determined in terms of:

1. Bias
2. Linearity
3. Hysteresis
4. Scale factor.

e. The following lifetime and reliability requirements shall be defined:

1. Total impulse
2. Cycle life
3. Mission life
4. Reliability level.

f. All external loads applicable to the propulsion system shall be specified, including:

1. Mechanical loads

   NOTE For example: quasi-static loads; vibrations, transportation.

2. Thermal loads
3. Electrical loads.

5.3 Constraints

5.3.1 General

a. The constraints induced by thruster initialisation, start up and restart sequences shall be identified and reported in the DJF.

5.3.2 Thermal fluxes

a. Maximum values of thermal fluxes of the thruster subsystem shall be defined.

b. Since the heat dissipated by the power supply subsystem can be significant even with a good efficiency, if overheating of the system is shown by the thermal analysis, a specific layout of the spacecraft or specific devices for the cooling of the subsystem shall be provided.

c. Thruster surroundings shall conform to the radiative and conductive heat fluxes rejected by the thrusters.

d. Reporting shall be in conformance the Thermal analysis DRD in ECSS-E-ST-31 and the Addendum: Specific propulsion aspects for thermal analysis DRD in with ECSS-E-ST-35.

5.3.3 Thruster plume effects

a. The plume effects analysis on the spacecraft shall be performed and reported in conformance with clause 4.3.5 and 4.6.2.2.6.

b. The plume analysis shall include the effects of primary ions and charge exchange ions around the thrusters.

5.3.4 High frequency current loops

a. The spacecraft electrical architecture shall be compliant to induced high frequency current loops.

NOTE Due to the plasma nature of some plumes, a high frequency current loop can be induced during thruster firing including the thruster, plasma, the solar array (e.g. the spacecraft mechanical structure and the thruster power supply subsystem).

5.3.5 Electromagnetic compatibility

a. The electromagnetic compatibility of the EP system with the spacecraft shall be ensured.

NOTE For example: payload, telemetry, TM and TC and pyrotechnic devices.

5.3.6 Spacecraft charging

a. In case of thrusters generating an electrically charged beam (i.e. electrostatic thrusters), the thruster shall have a device, the neutralizer, which prevent inducing a charge on the subsystem and therefore the spacecraft.

b. For spacecraft charging and beam neutralisation related effects, ECSS-E-ST-20-06 shall be applied.

5.4 Interfaces

5.4.1 Interface with the spacecraft

a. The EP system shall conform to its specified spacecraft interfaces, including:

1. Structure

    NOTE For example: inserts, tank support structure and vibration levels.

2. Thermal

    NOTE For example: conduction, radiation levels, tank, thruster and line thermal control.

3. Power

    NOTE For example: valve drivers, pressure transducers, thermistors, heaters and thermocouples.

4. Grounding

5. Electromagnetic compatibility

6. Pyrotechnics

    NOTE For example: pyrotechnic valves.

7. Mechanisms

    NOTE For example: valves, regulators, actuators and actuation system.

8. AOCS, OBDH and TM/TC.

    NOTE For example: commanding, handling of data for status and health monitoring and failure detection.

b. Interfaces shall be defined:

1. For ground tests and loading activities with the GSE.

2. For safety and prelaunch operation with the launcher authorities.

5.4.2 Interface with the power bus

a. The following parameters shall be available to the propulsion subsystem designer:

1. Bus voltage and its accuracy.

2. Maximum available power.

3. Bus impedance in relation to the frequency to access the capacity of the bus to sustain surge currents.

4. EMI level from the bus to assess the susceptibility of the power supply and control unit.

5.5 Design

5.5.1 General

5.5.1.1 Architecture

a. The EP system architecture shall apply the requirements of ECSS-ST-Q-30.

b. The propulsion system architecture shall conform to fail safe, redundancy, reliability and safety requirements.

5.5.1.2 Replacement of parts

a. For replacement of parts during development, testing and mission life pre-launch activities ECSS-E-ST-35 clauses 4.5.1c, d and e. shall be applied.

5.5.1.3 Water-hammer effect

a. A water-hammer effects analysis shall be performed to support the propulsion system design and ensure proper functioning.

b. The analysis specified in 5.5.1.3a shall be reported in conformance with the Propulsion transients analysis report DRD inECSS-E-ST-35.

5.5.1.4 Piping

a. A pipework design analysis shall be performed including non-consumables, leakage, pressure, eigenfrequencies and potential cross-coupling, water-hammer, bending by mechanisms effects.

b. The consequences in terms of operational restrictions shall be identified.

5.5.1.5 Closed volumes

a. For closed volumes the requirements of clause 4.5.1.5 shall be applied.

5.5.1.6 Pressure vessels and pressurized components

a. For the design of pressure vessels and pressurized components, the requirements of clause 4.5.1.6 shall be applied.

5.5.1.7 Multi-tanks

a. If a multi-tank layout is used, the requirements of clause 4.5.1.7 shall be applied.

5.5.1.8 Mass imbalance

a. For mass imbalance the requirements of clause 4.5.17 shall be applied.

5.5.1.9 Cycles

a. The system shall meet the requirements on the number of cycles and cycle life for the whole mission at component, propulsion and spacecraft system level, for both on ground and in-service operation.

5.5.1.10 Electromagnetic compatibility

a. Electric propulsion systems shall be electromagnetically compatible with the other parts of the spacecraft.

5.5.1.11 High voltages

a. Where high-voltages are involved, the EP system shall be designed to avoid risks of electrical shorts and breakdowns.

b. The HV power outputs to the thruster shall be defined in terms of voltage and power needs.

c. The grounding concept for the HV elements shall be defined including the paths for routing this HV power.

NOTE The safety requirements (i.e. ECSS-Q-ST-40) apply when designing the HV elements.

5.5.2 Selection

5.5.2.1 Reporting

a. The reporting shall be done in the DJF in conformance with ECSS-E-ST-10.

5.5.2.2 Propulsion system selection

a. The propulsion system and operating modes selection shall be supported by detailed mission and trade-off analyses.

b. The choice of the EP system shall be made using the available electrical power for the EP system during the whole duration of the mission.

c. Compatibility of the selected materials, propellants and test fluids shall be demonstrated for all components.

5.5.2.3 Propellant selection

5.5.2.3.1 General

a. The criteria to be used for propellant selection shall include:

1. Mission requirements
2. Compatibility and contamination
3. Performance.

b. The propellant shall be defined and specified including;

1. Chemical composition
2. Purity
3. Cleanliness.

5.5.2.3.2 Propellant for thruster qualification

a. Thruster qualification firing tests shall use the same propellant grade as the one selected for flight.

5.5.3 Sizing

5.5.3.1 General

a. The sizing of components for an EP system shall include the evolution of the operational conditions.

b. Propellant, pressurant and contaminants budgets are major inputs for the sizing process and shall be available.

NOTE For example: impact on lifetime, variation of performance during lifetime, quantities for disposal and unusable residuals.

c. The electrical power available to the propulsion system throughout the mission is also a major input for the sizing and shall be determined.

5.5.3.2 Sizing process

a. The sizing process shall begin with a definition of the life phases of each element, including at least:

1. Thrust level and range
2. Total impulse
3. Available power
4. Mass budget
5. Operating cycles
6. Propellant, pressurant and leakage budgets
7. Capacity of protections for sensitive components

   NOTE For example: oxygen absorbers for hollow cathodes.

8. Accommodation envelop.

b. The sizing process shall account for margins based on:

1. Safety
2. Reliability requirements established by the customer
3. Industry and launch authorities or agencies operational constraints
4. Thruster performance efficiency
5. Plume effects
6. Modelling errors and uncertainties.

c. Pressurant, propellant and contaminants budgets shall include:

1. Their impact on lifetime
2. Variation of performance during lifetime
3. Quantity for deorbiting
4. Residuals.

5.5.4 Design development

5.5.4.1 General

a. The development shall allow for an incremental verification at component, subsystem and propulsion system level, if a fully representative functional test cannot be performed after the integration of the system on the spacecraft.

b. If the flight version of the system is divided into independent blocks, they should be separated by safety barriers.

5.5.4.2 Development tests

a. Development tests shall be performed by incremental test at component, subsystem and system level.

NOTE Development tests at spacecraft level can be performed with electrical simulators for thrusters.

b. The design and procedures shall be defined such that the testability at integrated spacecraft level and the capability to return after test to safe and clean conditions is guaranteed for each system and subsystem.

5.5.5 Contamination

5.5.5.1 External contamination

a. The thruster design, layout and orientation should prevent contaminant deposition on elements sensitive to contamination identified in clause 4.3.5a.

NOTE Contaminants deposition on sensitive elements, such as solar panels, star trackers, and optics, depends on the propellants used, the thruster characteristics, the layout of the propulsion system, the thruster orientation and the thruster duty cycle.

b. The potential hazard of contamination and the expected level of contamination due to thruster exhaust, shall be included in the plume analysis.

c. The potential hazard due to external contamination to the thruster shall be analysed.

NOTE Example of contamination to the thruster: by chemical propulsion or debris.

5.5.5.2 Internal contamination

a. The propulsion system shall be designed to avoid the effects of internal contaminants by:

1. Preventing intrusion, internal generation and circulation of contaminants.

2. Preventing or controlling accumulation of contaminants throughout the various parts of the system.

3. Preventing accumulation of contaminants during the various steps of production, verification and operation of the system.

NOTE Electric thrusters or some of their components (e.g. neutralizers and ionization chambers) are sensitive to chemical contamination that, causing a change of the surface properties, can poison temporarily or indefinitely the components and affect their performance and operating life.

b. The propulsion system shall conform to the specified maximum level of contaminants.

NOTE For engineering requirements on materials, see ECSS-E-ST-32-08.

5.5.6 Propellant protection

a. Unwanted oxidation of propellants shall be prevented.

b. For propellants subject to oxidation under ambient conditions, exposure to air shall be prevented.

NOTE Example of such propellant is Caesium.

5.5.7 Components guidelines

a. A design assessment for failure tolerance shall be performed for every component.

NOTE See ECSS-ST-Q-30-02.

5.5.8 Propellant management assembly

5.5.8.1 General

a. The propellant management assembly design shall allow for on-ground draining.

NOTE Clause 5.5.8 addresses specific requirements on the propellant management assembly and components used in EP systems.

b. The location of fill-and-drain valves and piping layout shall prevent:

1. Trapping of propellants or simulants fluids in the system by on-ground draining.
2. Contact between dissimilar fluids.

c. For fluids with a high triple-point, it shall be ensured, either

— that the fluid is maintained in a gaseous state, or

— active thermal control of the propellant management assembly is implemented.

5.5.8.2 Flow control unit

a. In case the mass flow rate is not-self-adjusted, the design shall address the specific issues related to the very small, well regulated mass flow rates used in electric propulsion.

NOTE Example of self-adjusted mass flow rate is by capillary-fed thrusters.

5.5.8.3 Pressure regulators

a. The design of a pressure regulator shall be compatible with the propellant throughput and cycle life as required for the mission.

NOTE Pressure regulators for electric propulsion, have to deliver very small flow rates for extended period of time compared to liquid propulsion.

5.5.8.4 Oxygen absorbers

a. The use of oxygen absorbers shall be assessed.

b. Oxygen absorbers shall be located as close as possible to components that can be contaminated.

NOTE Residual oxygen can be present in the propellant, due to its adherence to the propellant management assembly pipelines or because of the impurity of the propellant itself. Components of EP systems such as cathodes and neutralizers can be oxygen contamination sensitive.

5.5.8.5 Propellant filters

a. For gas and liquid filters design, clause 4.5.9 shall be applied.

5.5.9 Pressure vessels

a. For pressure vessels design, clause 4.5.10 shall be applied.

5.5.10 Propellant tanks

a. Propellant tanks shall provide the thrusters with propellants according to their specified conditions.

b. For propellant tanks design of EP systems using gaseous propellants, clause 4.5.10 shall be applied.

NOTE Example of gaseous propellant: xenon.

c. For propellant tanks design of EP systems using liquid propellants, clause 4.5.11 shall be applied.

NOTE 1 A large variety of propellants are used for electric propulsion thrusters (i.e. gaseous, liquid and solid); therefore different tank design rules are applicable.

NOTE 2 Some gaseous propellants, such as xenon, are usually stored in supercritical condition.

NOTE 3 The fluid characteristics of supercritical Xenon (e.g. density) can be substantially different from those of a simulant pressurant gas during environmental testing (e.g. vibration testing). Thus, analysing this point during system design can prevent coupling modes between the spacecraft structure, xenon tank and the xenon itself as a free-moving high density fluid. With this objective, selection of the xenon tank and tank shape is done in conformance to the spacecraft eigenfrequencies.

5.5.11 Blow-down ratio

a. For EP systems working in blow-down mode clause 4.5.12 shall be applied.

5.5.12 Thrusters

5.5.12.1 Thrust level

a. The thruster shall provide the required performance over the full thrust range.

b. The thruster shall provide the requested thrust stability (i.e. drift and fluctuations) and repeatability.

5.5.12.2 Thrust noise

a. The thrust random variation around its mean value, or thrust noise, shall be maintained within the specified range.

NOTE Thrust noise is usually composed of contributions from the thruster, the propellant feed system and the power electronics.

5.5.12.3 Thrust accuracy

a. Thrust shall remain within the ranges derived from the AOCS analysis.

b. Transfer functions, when needed, shall account for the following parameters:

1. Bias
2. Dcale factor
3. Hysteresis
4. Response time of the system.

5.5.12.4 Thrust modulation

a. The thruster shall be capable of high- and low- frequency modes modulation if required by AOCS.

5.5.12.5 Thrust mismatch

a. The difference in thrust between two thrusters operating in pair on the same branch shall not exceed the specified value.

5.5.12.6 Thrust-vector alignment

a. Thrust-vector alignment shall be obtained by correction methods over geometrical and operational factors as specified in 5.5.12.6b and 5.5.12.6c.

b. The thrust misalignment due to geometrical factors shall be corrected by

1. Introducing structural devices into the thruster support to adjust the thrust alignment.
2. Fine adjustment of the components inside the thruster with influence on the thrust-vector.
3. A combination of 5.5.12.6b.1 and 5.5.12.6b.2.

NOTE Geometrical factors are the mounting of the thrust-vector-sensitive components (i.e. grids) and the mechanical interface between the thruster and the spacecraft. This type of misalignment can be corrected either by fine adjustment of the thrust-vector-sensitive components inside the thruster, or by introducing structural devices into the thruster support to adjust the thrust alignment.

c. The effect of operational factors shall be compensated by the introduction at system level of thrust-vector control systems.

NOTE Operational factors are mainly due to electro-thermal distortions or the erosion of thrust-vector-sensitive components during operations.

5.5.12.7 Electrical parameters

a. The thruster design shall be derived from a trade-off considering the impact on the spacecraft electrical system and the thruster performance in every mission phase.

NOTE The impact on the spacecraft electrical systems is minimized while maximizing the thruster performance.

b. Requirement 5.5.12.7a shall be performed in the framework of a design optimization process at EP subsystem level.

5.5.12.8 Thermal environment

a. The heat fluxes at the interface between the thruster and supporting structure shall be specified.

b. To avoid overheating of the thruster, its thermal behaviour, when integrated on the spacecraft, shall be analysed.

c. Reporting shall be in conformance with the Thermal analysis DRD in ECSS-E-ST-31 and the Addendum: Specific propulsion aspects for thermal analysis DRD in ECSS-E-ST-35.

5.5.12.9 Operational lifetime

a. The design of life limited components of the thruster shall be compatible with the operational life of the thruster.

5.5.12.10 Operational cycles

a. The EP system design shall be compliant to the mission cycle requirements.

5.5.12.11 Thrust interruption

a. The thruster shall be designed to avoid such thrust interruptions.

b. The thruster shall be designed such that if interruptions are experienced they do not degrade life or performance.

NOTE 1 Depending on the technology, thrust interruptions are also called sparcs (FEEP), arcs, beam out or flameout.

NOTE 2 Many electric propulsion thrusters experience thrust interruption during operation.

5.5.12.12 Neutraliser

a. The neutraliser, if needed, shall be designed to deliver the required neutralisation current over the mission lifetime

NOTE The neutraliser is generally considered a thruster component.

5.5.13 Thrust-vector control

5.5.13.1 Devices for thrust-vector control

a. Devices used for thrust-vector control shall be either

1. actively controlled pointing mechanisms supporting the thruster, subject of clause 5.5.13.2 ; or
2. thrust-vector steering solutions within the thruster itself, subject of clause 5.5.13.3.

NOTE Thrust-vector control of electric thrusters is often used

- for propellant consumption minimization by maintaining the thrust-vector through the CoM of the satellite, which normally changes during the mission; or
- to change the general orientation of the thruster between different operational configurations.

5.5.13.2 Thruster orientation mechanism

a. For the design of thruster orientation mechanisms for electric propulsion, clause 4.5.15 shall be applied.

5.5.13.3 Internal thrust-vector steering devices

a. If internal thrust-vector steering solutions are being introduced into the design, the impact on life time and performance shall be assessed.

5.5.14 Power supply, control and processing subsystem

5.5.14.1 General

a. For power supply, control and processing equipment, ECSS-E-ST-20 shall be applied.

NOTE 1 The purpose of the power supply, control and processing devices in an EP system is to provide the thruster and other electrically-powered components with the adequate electrical input parameters during transient and at steady-state operations.

NOTE 2 Depending on the type of EP system, the power supply, control and processing functions can be performed by dedicated equipment or carried out as part of the tasks of the spacecraft power system.

NOTE 3 Most commonly, the power conditioning devices of an EP system include also functions to control and process incoming and outgoing data and commands.

NOTE 4 For redundancy, operational purposes and mass optimization, thruster switching devices can be introduced in the EP system to provide cross-strapping of electrical power between the power supplies and several thrusters.

5.5.14.2 Compatibility with thruster

a. The compatibility assessment between the power supply outputs and the thruster shall be performed.

b. A design analysis shall be performed to identify if a filter unit is required to meet the EMC requirements.

c. If a filter unit is required, its design and location shall be defined.

5.5.15 Electrical design

5.5.15.1 General

a. The electrical design shall conform to ECSS-E-ST-20.

5.5.15.2 Electromagnetic compatibility (EMC)

a. For electromagnetic compatibility, design of the thruster, harnesses and power unit should conform to ECSS-E-ST-20 and ECSS-E-ST-20-07.

b. The design of the following shall conform to ECSS-E-ST-20 and ECSS-E-ST-20-07.

1. Interference
2. susceptibility
3. grounding
4. Shielding
5. Isolation.

5.5.15.3 Electric reference potential, grounding, insulation

a. The grounding scheme and insulation shall limit interferences with other spacecraft systems to within the specified levels.

NOTE For an operating thruster, the electrical reference potential strongly depends on the interactions between the thruster generated plasma and the satellite mechanical structure through the external environment. As a consequence, the reference potential can differ from the potential of the common structure (i.e. ground).

b. Reporting shall be available in DJF and DJD.

NOTE For DJF and DJD see ECSS-E-ST-10.

5.5.15.4 Electrostatic discharge protection

a. The EP system shall be protected from electrostatic discharges caused by:

1. Charge accumulation on inactive thruster electrodes exposed to space or plasma from another operating engine.

2. Transients spikes.

NOTE For example: during thruster start-up, and shut-down.

5.5.15.5 Parasitic discharge prevention

a. The design of the EP system should prevent parasitic discharges between parts of the thruster at different potentials.

NOTE 1 Parasitic discharges in electrostatic engines can possibly not be avoided completely.

NOTE 2 During operation, the thruster is partially immersed in ambient plasma and its own generated plasma.

b. The design of the EP system shall prevent the presence of gases during the operation of the thruster.

NOTE Parasitic discharge can be enhanced by the presence of gas. Gas can appear due to venting, trapped gas or outgassing.

5.5.16 Pyrotechnic devices

For pyrotechnic devices ECSS-E-ST-33-11 applies.

5.5.17 Monitoring and failure detection

a. The requirements of clause 4.5.18 shall be applied.

b. EP systems shall include the monitoring of the electrical parameters.

c. Monitoring of the plasma parameters should be done by plasma diagnostics packages.

NOTE Langmuir probes and retarding potential analysers are typical devices that can be used to monitor plasma parameters.

5.5.18 Ground support equipment (GSE)

5.5.18.1 General

a. The design of the propulsion GSE shall respect the safety requirements of the facility where it is operated.

5.5.18.2 Fluid

a. For the design of GSE handling fluids, the requirements of clause 4.5.19.2 shall be applied.

b. The loading of propellant in supercritical condition shall be performed by means of dedicated equipment and following procedures preventing the presence of liquid propellant in any part of the propellant feed subsystem.

NOTE Example of this kind of propellant: xenon.

5.5.18.3 Electrical

a. The design of the GSE shall allow the safe check-out of all electrical components of the EP system.

b. The procedures to operate and the design of the equipment shall prevent the inadvertent activation of the spacecraft components.

c. As thrusters cannot normally be operated under atmospheric conditions, an electrical thruster simulator shall be available in order to allow tests to be performed on the EP system.

d. The GSE shall be designed to prevent inadvertent electrical discharge.

e. In case the GSE is used in the vicinity of inflammable or explosive materials, it shall be explosion proof.

5.6 Verification

5.6.1 General

a. A verification matrix shall be established indicating the type of verification method to be applied for the individual requirements.

NOTE 1 For verification of electric propulsion systems, see ECSS-E-ST-10-02.

NOTE 2 Verification is performed to demonstrate that the system or subsystem fully conforms to the requirements. This can be achieved by adequately documented analysis, tests, review of the design, inspection, or by a combination of them.

NOTE 3 In the following clauses of this clause 5.6 it is considered that:

- verification by review of the design is included in verification by analysis, and
- verification by inspection is included in verification by test.

5.6.2 Verification by analysis

5.6.2.1 General

a. For EP system, the following shall be applied:

1. Clause 4.6.2.

2. The additional clauses of this clause 5.6.2.

NOTE Methodology principles for the verification by analysis of an EP system are similar to the ones for liquid propulsion systems presented in the clause 4.6.2. However, new elements are being introduced by additional physical phenomena and the modelling of additional components, such as:

- electric thrusters often generate electrically charged particles;
- the generated plume is quite rarefied, but with high kinetic energy;
- the thrusters use electrostatic, magnetic and electromagnetic fields or utilize electric arcs or heaters for their operations;
- In addition, electric thruster operations are normally of much longer;
- duration than liquid thruster operations and this can also have an impact on the analysis to perform.

5.6.2.2 System analyses

a. The following analyses shall be made:

1. Power, propellant, mass and TM/TC budgets.

2. Mechanical and thermal.

3. Performance.

4. EMC.

5. Spacecraft interactions.

NOTE For example: plume effects, potential control, communication interferences.

6. EP system venting.

7. Life time.

5.6.2.3 Mutual effects of electrostatic and magnetic fields

a. In case multiple electric thrusters are used simultaneously, the mutual effects of the electrostatic and magnetic fields on thrusters and EP system performance shall be assessed.

5.6.2.4 Lifetime

a. Analytical tools capable of predicting the evolution in time of the operational parameters of the system and the degradation of life-critical components shall be developed to support the qualification processes of EP systems.

b. These tools shall be verified by means of a thruster life test.

5.6.2.5 Time-related phenomena

a. At least the following specific phenomena during transient phases shall be evaluated when analysing the EP system:

1. Gas pressure oscillations
2. Inrush power consumption
3. Electrostatic and electromagnetic perturbations.

NOTE Transient phases are for example: start-up and shut-down.

b. The time response of an EP system shall be analysed.

NOTE This is of particular interest in some cases, such as applications where the thrusters are operated as actuators in closed-loop systems for fine pointing and control requirements or for autonomous operations.

c. The analyses specified in 5.6.2.5a and 5.6.2.5b shall be reported in conformance with the Propulsion transients analysis report DRD in ECSS-E-ST-35.

5.6.3 Verification by test

5.6.3.1 General

a. In case the implications of the functioning of an electrical propulsion system on the spacecraft system level cannot be fully verified by analysis, specific tests shall be performed.

NOTE These tests can be performed:

- at component level where sufficient information can be obtained to assess the effects on system or subsystem level; or
- at system or subsystem level; or
- at spacecraft level.

b. The verification tests of each block shall be defined to represent the conditions that are expected to be encountered during the operation of the complete system.

c. Test methods related to acceptance, environmental tests, EMC tests, plume tests, and life tests shall be defined.

NOTE Particularly those described in the following clauses.

5.6.3.2 Operating test

a. The following aspects shall be defined with reference to their impact on performance:

1. Vacuum pressure level
2. Type and capacity of pumping
3. Minimum distance of the thruster to the vacuum chamber walls
4. Measurement and calibration of diagnostics
5. Effect of backsputter products.

NOTE This is because most of the electric thrusters can only be operated in vacuum.

5.6.3.3 Electromagnetic compatibility (EMC) test

a. EMC tests shall be performed at propulsion system level using flight representative power supplies and conditioning systems, harnesses and thruster.

b. Bias from ground-type interference shall be assessed for a precise analysis of the results of such tests.

NOTE For these tests ECSS-E-ST-20-07 applies.

5.6.3.4 Plume characterization tests

a. Plume characterization tests shall cover at least the following aspects;

1. Main beam characterisation

   NOTE For example: divergence, energy distribution, plasma density.

2. Thrust vector alignment
3. Erosion products characterisation
4. Back flow CEX characterisation.

   NOTE For example: density, energy distribution.

b. The tests shall be defined in terms of:

1. Vacuum pressure level
2. The distance from the thruster exit to the probes
3. The distance from the thruster exit to the vacuum chamber walls.

5.6.3.5 Life tests

a. A life test shall be performed on one complete functional chain at least (i.e. thruster, flow control system and the power supply system, filters).

b. Life tests shall be conducted according to the mission duty cycles, with a reduction of the off-cycle duration in agreement with a good representation of the thermal transients.

c. For facility back-sputtering, it shall be demonstrated that the design of the test facility limits the quantity of sputtered material, and that back-sputtering is measured.

d. Life tests shall use flight-grade propellant.

e. The purity of the propellant shall be monitored.

f. The health status of the propulsion system shall be monitored during the life test, on a regular basis, by performance tests in conformance with 5.6.3.6.

5.6.3.6 Performance tests

a. Performance tests, including direct thrust measurement, shall verify that the performances of the system, including the thruster, flow control unit and the power supply and conditioning, conform to the requirements.

NOTE Performance tests can be included in the life tests.

5.6.3.7 Calibration

a. All components or subsystems which provide data shall be calibrated.

b. Conformity to the requirements of the components or subsystems, specified in 5.6.3.7a, shall be demonstrated.

5.6.4 Data exchange for models

a. Tests results, as well as all models, shall be established and structured with a commonly agreed structure and format.

NOTE Example of these models are: thermal, mechanical, electric, magnetic, performance models.

5.7 Quality factors

5.7.1 Reliability

a. For reliability, clause 4.7.1 shall be applied.

5.7.2 Production and manufacturing

a. For production and manufacturing, clause 4.7.2 shall be applied.

5.8 Operation and disposal

a. For operation and disposal, clause 4.8 shall be applied.

5.9 Supporting documents

a. For deliverables, clause 4.9 shall be applied.

b. Additionally, an EMC analysis shall be delivered.

Bibliography

ECSS-S-ST-00	ECSS system – Description, implementation and general requirements
ECSS-E-ST-10-02	Space engineering – Verification
ECSS-E-ST-10-03	Space engineering – Testing
ECSS-E-ST-32-02	Space engineering – Structural design and verification of pressurized hardware
ECSS-E-ST-32-08	Space engineering – Materials
ECSS-E-ST-33-11	Space engineering – Explosive systems and devices
ECSS-E-ST-70	Space engineering – Ground systems and operations
ECSS-Q-ST-30-02	Space product assurance – Failure modes, effect (and criticality) analysis (FMEA/FMECA)
ECSS-Q-ST-40	Space product assurance – Safety
ECSS-Q-ST-70-36	Space product assurance – Material selection for controlling stress-corrosion cracking
NASA-MSFC-SPEC-522B	Design criteria for controlling stress corrosion cracking
ISO/CD 14623-1	Space systems - Pressure vessel structural design - Part 1: Metallic pressure vessels
ISO/AWI 14623-2	Space systems - Pressure vessel structural design - Part 2: Composite pressure vessels
ANSI/AIAA S-080-1998	Metallic Pressure Vessels, Pressurized Structures, and Pressure Components
ANSI/AIAA S-081-1999	Composite Overwrapped Pressure Vessels (COPVs)