



Space engineering

Mechanical — Part 5.1: Liquid and electric propulsion for spacecraft

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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.

The formulation of this Standard takes into account the existing ISO 9000 family of documents.

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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Scope

1.1 Object

This Part 5.1 of ECSS-E-30 belongs to the propulsion field of the mechanical discipline, as defined in ECSS-E-00, and defines the regulatory aspects applicable to elements and processes for liquid, including cold gas, and electrical propulsion for spacecraft. It specifies the activities to perform in the engineering of such propulsion systems, their applicability, and defines the requirements for the engineering aspects: functional, configurational, interfaces, physical, environmental, quality factors, operational and verification.

General requirements relating to Mechanical Engineering are defined in ECSS-E-30 Part 1.

1.2 Applicability

This Part 5.1 applies only to liquid, including cold gas, and electrical propulsion systems used in spacecraft and to related mechanical parts. Solid propulsion for spacecraft, and solid and liquid propulsion for launchers are not covered by this Part 5.1.

Other forms of propulsion currently under development (e.g. nuclear, nuclear-electric, solar-thermal and hybrid propulsion) are not presently covered by this Standard.

1.3 Tailoring

When viewed in 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.
[ECSS-M-00-02A, clause 3]

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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-E-00	Space engineering — Policy and principles
ECSS-E-10	Space engineering — Systems engineering
ECSS-E-10-02	Space engineering — Verification
ECSS-E-10-03	Space engineering — Testing
ECSS-E-20	Space engineering — Electrical and electronic
ECSS-E-30 Part 1	Space engineering — Mechanical — Part 1: Thermal control
ECSS-E-30 Part 2	Space engineering — Mechanical — Part 2: Structural
ECSS-E-30 Part 6	Space engineering — Mechanical — Part 6: Pyrotechnics
ECSS-E-30 Part 7	Space engineering — Mechanical — Part 7: Mechanical parts
ECSS-E-30 Part 8	Space engineering — Mechanical — Part 8: Materials
ECSS-E-50 ¹⁾	Space engineering — Communications
ECSS-E-70	Space engineering — Ground systems and operations
ECSS-Q-30	Space product assurance — Dependability
ECSS-Q-70-36	Space product assurance — Material selection for controlling stress-corrosion cracking
MIL-STD-461E	Requirements for the control of electromagnetic interference characteristics of subsystems and equipment
MIL-STD-1541A	Electromagnetic compatibility requirements for space systems

1) To be published.

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Terms, definitions, abbreviated terms and symbols

3.1 Terms and definitions

The following terms and definitions are specific to this Standard in the sense that they are complementary or additional to those contained in ECSS-P-001 and ECSS-E-30 Part 1.

3.1.1

beam divergence

semi-angle of a cone, passing through the thruster exit, containing a certain percentage of the current of an ion beam at a certain distance from that thruster exit

3.1.2

chill-down

process of cooling the engine system components before ignition to ensure that the cryogenic propellants enter the boost pumps in their proper state

NOTE On ground, chill-down may be done with dedicated cooling fluids, or with on-board propellants that are vented.

3.1.3

component

smallest individual functional unit considered in a subsystem

EXAMPLE Tanks, valves, regulators.

3.1.4

constraint

characteristic, result or design feature that is made compulsory or is prohibited for any reason

NOTE 1 Constraints are generally restrictions on the choice of solutions in a system

NOTE 2 Two kinds of constraints are considered, those that concern solutions, and those that concern the use of the system.

NOTE 3 For example, constraints can come from environmental and operational conditions, law, standards, market demand, investments and means availability, and organization policy.

3.1.5

contaminant

undesired material present in the propulsion system at any time of its life

3.1.6

de-orbiting

controlled return to Earth or burn-up in the atmosphere of a spacecraft or stage

3.1.7

electric thruster

propulsion device that uses electrical power to generate or increase thrust

3.1.8

external

entity or entities not related to “internal” or “interface”

NOTE See 3.1.14 for internal and 3.1.13 for interface.

3.1.9

graveyard orbit

orbit about 300 km or more above a GEO or GSO into which spent upper stages or satellites are being injected to minimize creation of debris in GEO or GSO

3.1.10

ground support equipment (GSE)

equipment adapted to support verification testing and launch preparation activities on the propulsion system

3.1.11

hypergolic propellants

propellants that spontaneously ignite upon contact with each other

3.1.12

impulse bit

time integral of the force delivered by a thruster during a defined time interval

NOTE It is expressed in Ns.

3.1.13

interface

direct interaction between two or more systems or subsystems

NOTE It is essential that there is a direct interaction.

3.1.14

internal

entity or entities of the system or subsystem itself only

3.1.15

launcher

vehicle intended to move a separate spacecraft from ground to orbit or between orbits

3.1.16

liquid rocket engine

chemical rocket motor using only liquid propellants

NOTE 1 It includes catalytic beds.

NOTE 2 The liquid rocket engine is the main part of a liquid propulsion system.

NOTE 3 A liquid rocket engine comprises

- combustion chamber or chambers;
- nozzle or nozzles;
- a propellant feed system (including injectors; pressure-fed or turbo-pump fed);
- an active or passive coolant system;
- an ignition system (in case of non-hypergolic propellants);
- valves;
- power systems (such as pre-combustion chamber and gas generator), if applicable.

3.1.17

maximum expected operating pressure (MEOP)

maximum expected pressure experienced by the system or components during their nominal life time

NOTE 1 It includes the effects of temperature, vehicle acceleration and relief valve tolerance.

NOTE 2 See 4.2.7 for requirements on MEOP.

3.1.18

minimum impulse bit

smallest impulse delivered by a thruster at a given level of reproducibility as a result of a given command

NOTE It is expressed in Ns.

3.1.19

mission life

life cycle from the delivery to the disposal

NOTE 1 For brevity, in this Standard it is referred to as the mission.

NOTE 2 The mission encompasses the complete life of the propulsion system: delivery, (incoming) inspection, tests, storage, transport, handling, integration, loading, pre-launch activities, launch, in-orbit life and disposal.

3.1.20

nozzle

device to accelerate fluids from a rocket motor to exhaust velocity

3.1.21

plasma

ionized gas

NOTE It contains neutral species, ions and electrons.

3.1.22

pressurant

fluid used to pressurize a system or subsystem

3.1.23

priming

ensuring that the system or subsystem conditions conform to operational conditions

3.1.24

propellant

material or materials that constitute a mass which, often modified from its original state, is ejected at high speed from a rocket engine to produce thrust

NOTE 1 In cold gas engines, the gas is accelerated due to the difference between storage and ambient pressure.

NOTE 2 In chemical rocket engines, either a combustion reaction between two kinds of propellants, fuel and oxidizer, or a decomposition reaction of a monopropellant provides the energy to accelerate the mass.

NOTE 3 In electric engines, either an electromagnetic or an electrostatic field accelerates the mass, which in some cases has been heated to high temperatures or electric heating provides additional energy to accelerate the mass (the latter in the case of power augmented thrusters and resistojets).

NOTE 4 Combinations of the above are possible.

3.1.25

propulsion system

system to provide thrust autonomously

NOTE 1 In this Standard it is also referred to as the system.

NOTE 2 It comprises every component necessary for the fulfilment of the mission, e.g. thrusters, propellants, valves, filters, pyrotechnic devices, pressurisation subsystem, tanks and electrical components such as power sources in case of electrical propulsion.

3.1.26

repeatability

ability to repeat an event with the same input commands

3.1.27

re-orbiting

injection of a spacecraft or stage into a graveyard orbit

3.1.28

simulant

fluid replacing an operational fluid for specific test purposes

NOTE 1 Normally the operational fluid is replaced because it is not or is less suitable for the specific test purposes.

NOTE 2 The simulant is chosen such that the characteristics of the operational fluid whose effects are evaluated in the system, subsystem or component test, are closely approximated by the characteristics of the simulant

3.1.29

sizing

process by which the overall dimensions of a system or subsystem are determined such that the system or subsystem meets the requirements

NOTE At the end of the sizing process, functional and material characteristics are determined as well. The sizing process responds to the functional requirements.

3.1.30

solid rocket motor

chemical rocket motor using only solid propellants

NOTE 1 The solid rocket motor is the main part of a solid propulsion system.

NOTE 2 A solid rocket motor comprises

- a motor case;
- the internal thermal protection system;
- the propellant grain;
- the nozzle or nozzles;
- the igniter.

3.1.31

spacecraft

vehicle purposely delivered by the upper stage of a launcher or transfer vehicle

EXAMPLE Satellite, ballistic probe, re-entry vehicle, space probes, space stations.

3.1.32

specific impulse (I_{sp})

<instantaneous specific impulse>

ratio of thrust to mass flow rate

<average specific impulse>

ratio of total impulse and total ejected mass during the same time interval used for the establishment of the total impulse

NOTE 1 It is expressed in Ns/kg or m/s.

NOTE 2 In engineering, often another definition is still used where the specific impulse is defined as the ratio of thrust to weight flow rate. This leads to an I_{sp} in seconds (s). The numerical value of I_{sp} expressed in seconds is obtained by dividing the I_{sp} expressed in m/s by the standard surface gravity, $g_0 = 9,80665 \text{ m/s}^2$.

3.1.33

subsystem

set of independent elements constituted to achieve a given objective by performing a specific function

NOTE See also ECSS-P-001A. For this Standard, the present definition is used.

3.1.34

thrust centroid time

time at which an impulse, of the same magnitude as the impulse bit, is applied to have the same effect as the original impulse bit

3.1.35

total impulse

time integral of the force delivered by a thruster or a propulsion system during a given time interval representative for the operation

NOTE It is expressed in Ns.

3.2 Definition of masses

3.2.1

mass

quantity of matter measured in terms of resistance to the acceleration by a force

NOTE Proper definition of masses is extremely important for a correct assessment of the propulsion system performance. This subclause states the terminology on propulsion related masses used in space systems. Such terminology is illustrated in figure 1.

In Tsjolkowski's equation,

$$\Delta V = I_{sp} \cdot \ln\left(\frac{M_0}{M_f}\right)$$

it is tacitly assumed that all masses leave the propulsion system with the same exhaust velocity.

In reality, launch systems eject masses at different velocities, and in some cases the ejected mass does not contribute at all to the velocity increment according to Tsjolkowski's equation. Examples are: lost oil from TVC systems and propellant used to achieve movements around the CoM (i.e. attitude control). Other mass is ejected at lower exhaust velocities, e.g. mass used for dump cooling, turbine exhaust gases.

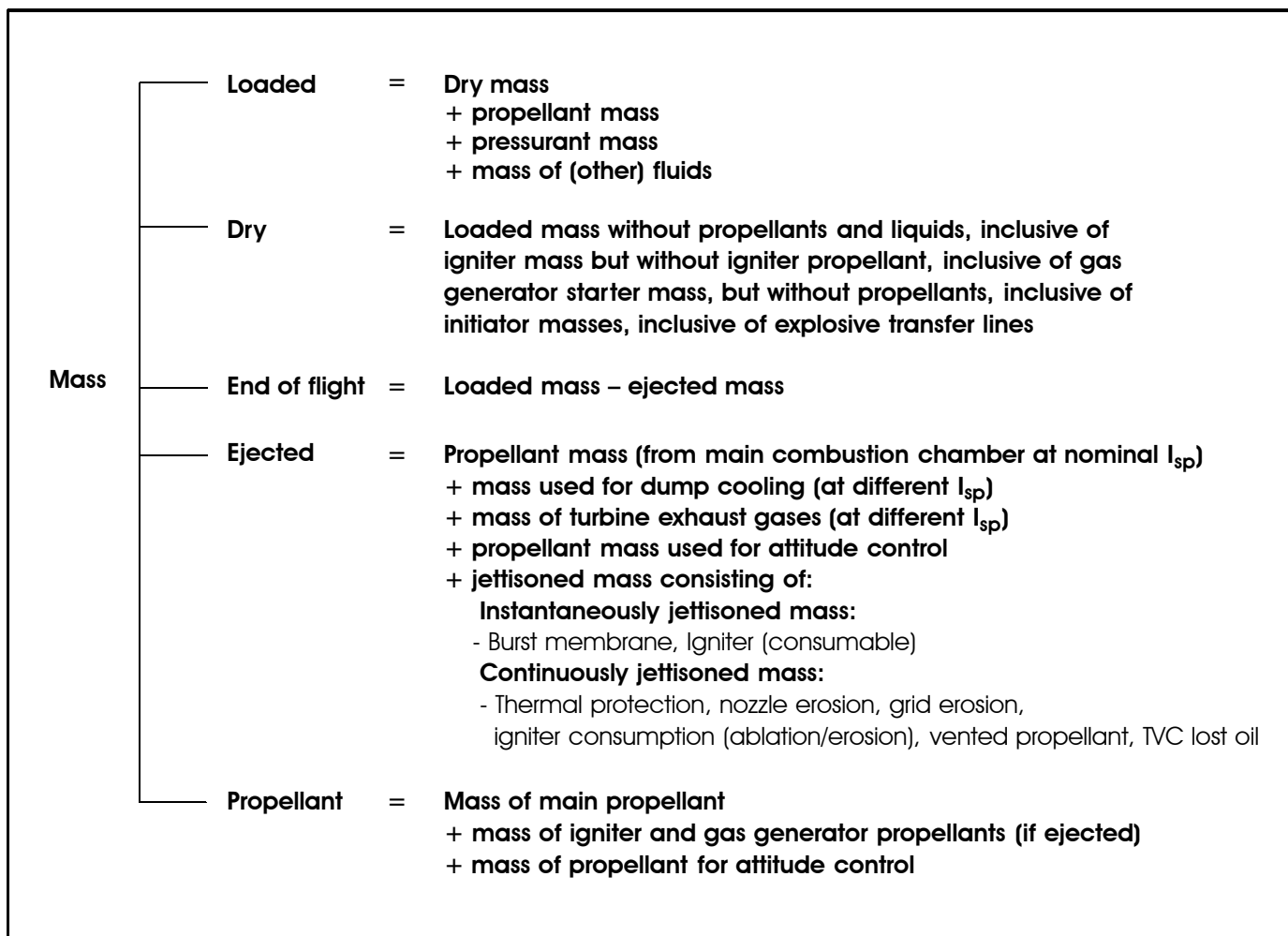


Figure 1: Definition of propulsion-related masses

3.2.2**loaded mass**

mass of a system just before the activation of the propulsion system

3.2.3**end of flight mass**

mass of a system directly after the end of the propulsion system operation

NOTE End of flight mass = loaded mass - ejected masses.

3.2.4**dry mass**

1. loaded mass without consumables, or

2. initial mass without propellants and fluids

NOTE 1 Dry mass can be weighed. Warning: explosive transfer lines and pyro valves usually are sealed, so that even when the explosive is consumed, they are not ejected from the system.

NOTE 2 Usually, initiators are considered part of the dry mass, as the mass of the explosive that leaves the propulsion system is negligible; initiators are mounted as conventional mechanical equipment.

NOTE 3 For solid propulsion systems, launchers and stages, it is defined as the initial mass without propellant mass (i.e. grains and igniter grains), which is equivalent to the one used in this standard.

3.2.5**ejected mass**

sum of the consumed propellant mass, the ejected pressurant gases, the instantaneously jettisoned masses and continuously jettisoned masses

NOTE 1 Not all propellants are ejected with the same velocity.

NOTE 2 Example of consumed pressurant gases is the pressurant gas sometimes ejected by spacecraft operating in blow-down mode.

NOTE 3 Examples of instantaneously jettisoned masses are burst membranes and consumable igniters.

NOTE 4 Examples of continuously jettisoned masses are erosion and ablation products, and lost oil from TVC systems.

3.2.6**propellant mass**

sum of the masses of the main propellant, the gas generator and starter propellants, the propellants for attitude control and the igniters propellants

NOTE Note that some of these propellants do not contribute to a velocity increment of the propulsion system.

3.3 Abbreviated terms

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

Abbreviation	Meaning
AIT	assembly, integration and test
AOCS	attitude and orbit control system
BOL	beginning-of-life
CoM	centre of mass
DCG	document content's guideline
DRD	document requirements definition
DRL	document requirements list
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EOL	end-of-life
FEEP	field emission electric propulsion
FOS	factor of safety
GEO	geostationary orbit
GSE	ground support equipment
GSO	geo-synchronous orbit
MDP	maximum design pressure
MEOP	maximum expected operating pressure
MMH	monomethyl hydrazine
MON	mixed oxides of nitrogen
MPD	magneto-plasma-dynamic thruster
NDI	non-destructive inspection
NTO	nitrogen tetroxide
OBDH	on-board data handling
PACT	power-augmented catalytic thruster
PCU	power conditioning unit
PED	positive expulsion device
PMD	propellant management device
PPT	pulsed plasma thruster
RAMS	reliability, availability, maintenance and safety
RCS	reaction control system
STD	surface-tension device
TBI	through-bulkhead initiator
TM/TC	telemetry and telecommand
TVC	thrust vector control
UDMH	unsymmetrical-dimethylhydrazine

3.4 Symbols

The following symbols are defined and used within this Standard:

Symbol	Meaning
g_0	standard surface gravity, 9,0665 m/s ²
I_{sp}	specific impulse
M_0	initial mass of a propulsion system
M_p	propellant mass
M_f	mass of the propulsion system at end of motor operation
Δp	difference of pressure
ΔV	ideal velocity increment of a rocket in a gravitation-free environment and without other disturbing forces (e.g. drag, solar wind or radiation pressure)

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Propulsion engineering activities

4.1 Overview

4.1.1 Characteristics of propulsion systems

The specification, design and development of a propulsion system always demands a strong interaction between those responsible for the system and those responsible for the propulsion engineering.

Propulsion systems have the following characteristics:

- They provide the thrust demanded.
- They use materials (e.g. propellants, simulants and cleaning agents) that can be toxic, corrosive, highly reactive, flammable, dangerous in direct contact (e.g. causing burns, poisoning, health hazards or explosions). The criteria for the choice and use of materials are covered by ECSS-E-30 Part 8.
- Handling, transportation and disposal of dangerous or toxic materials and fluids is subject to strictly applied local regulations (see 4.2.2 a.).
- Risks (e.g. contamination and leakages) are deeply analysed and covered, and RAMS studies are widely performed (see 4.2.2 b. and 4.2.2 c.).
- Rocket engines can be subject to instabilities, which can result in damage or loss of the motor of the vehicle. Adequate design and development involves the definition of solutions at system and vehicle level (see 4.2.2 d.).

4.1.2 Structure of requirements

The structure of the requirements used in this Standard is as follows:

- Common requirements to all types of propulsion systems are identified. They are covered in this clause 4.
- For each type of propulsion system, a common structure of requirements is adopted in accordance with the classification of engineering activities described in ECSS-E-00, as follows:
 - functional;
 - constraints;
 - interfaces;
 - configurational;
 - physical;
 - quality factors;

- operation and disposal;
- support;
- verification.

They are covered by the following clauses, one for each propulsion system covered by this Standard.

4.2 Generic

4.2.1 Introduction

The following requirements of this subclause 4.2 are applicable to any type of propulsion system.

4.2.2 General

- a. Local regulation for handling, transportation and disposal of dangerous or toxic material and fluids shall be strictly applied (see ECSS-Q-40).
- b. Risk (e.g. contamination and leakages) shall be analysed and covered.
- c. RAMS studies shall be performed.
- d. Acceptable levels for rocket engine instabilities shall be defined at system and vehicle level by the design and development effort.

4.2.3 Standards

Additional standards to those specified by the contract shall be specified or approved by the customer before use.

4.2.4 Quality system

The propulsion quality system shall conform to ECSS-Q-40.

4.2.5 Design

- a. Only mature, well tested, validated and well understood designs shall be used.
- b. The design shall be based on previously qualified designs, if these exist.
- c. Any modification shall be analysed and validated prior to implementation according to ECSS-E-10.

4.2.6 Materials

- a. Materials shall be selected according to ECSS-Q-70 and ECSS-E-30 Part 8.
- b. Propellant, pressurant, simulants or cleaning agents shall:
 1. be selected according to 4.2.3 if standards are available;
 2. be used in accordance with such standards.

NOTE Information on standards related to the use of conventional propellants, pressurants, simulants and cleaning agents is given in annex A.

4.2.7 Maximum expected operating pressure (MEOP)

The MEOP, multiplied by the factor of safety (FOS), shall not be higher than the maximum design pressure (MDP), i.e.

$$\text{FOS} \times \text{MEOP} \leq \text{MDP}$$

NOTE For definitions of FOS and MDP see ECSS-E-30 Part 2A.

4.2.8 Documentation

The establishment of specific documents and the level of detail presented therein shall conform to the system requirements from the document requirements list (DRL) and document contents guideline (DCG).

NOTE Table 1 provides a cross reference between the terms used in this Standard to identify project documents and the document requirements definition (DRD) specifying the contents of these documents.

Table 1: Terms used for project documents

Term used in text	DRD title	DRD reference
Detailed description	Design definition file	ECSS-E-10B ^a
Gauging analysis	Analysis report	ECSS-E-10-02A
Mechanical analysis	Analysis report	ECSS-E-10-02A
Performance analysis	Analysis report	ECSS-E-10-02A
Performance analysis	Mathematical models	ECSS-E-10B ^a
Plume analysis	Analysis report	ECSS-E-10-02A
Sloshing analysis	Analysis report	ECSS-E-10-02A
Thermal analysis	Analysis report	ECSS-E-10-02A
Thermal model	Mathematical models	ECSS-E-10B ^a
Transient analysis	Analysis report	ECSS-E-10-02A
Test documentation	Test plan Test procedure Test report Test specification Verification control document	ECSS-E-10-02A ECSS-E-10-02A ECSS-E-10-02A ECSS-E-10-02A ECSS-E-10-02A
User manual	User manual	ECSS-E-10B ^a
^a To be published.		

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Liquid propulsion systems for spacecraft

5.1 General

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 rendezvous and docking.

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

Propulsion systems for spacecraft often include: long-life operations, a large number of thrusters, many of which can be operated simultaneously, and multiple start-stop sequence constraints. The following is a non-exhaustive list of concerns related to liquid propulsion systems for spacecraft:

- long-term material compatibility;
- chemical and physical stability of the propellants;
- circulation and accumulation of contaminants;
- propellant or pressurant leakage;
- propellant or pressurant permeation in bladder and diaphragm tanks;
- evaluation and elimination of risks for the whole life cycle of the propulsion system, i.e. production, integration, operation, and disposal;
- system and components like thrusters, tanks and valves are cycle-limited;
- cross-coupling;
- failure management;
- start and stop sequences under vacuum conditions;
- protection against micrometeorites for pressure vessels.

These concerns also apply to the design and use of propulsion ground support equipment (GSE), defined in ECSS-E-70.

5.2 Functional

5.2.1 Mission

The propulsion system shall conform to the spacecraft mission requirements with respect to:

- a. pre-launch and launch activities (i.e. integration, storage, ageing and transport), in-orbit operation (i.e. orbit transfer, orbit maintenance and attitude control) and during the complete mission life;
- b. ground operation, i.e. functional control, testing, propellant, simulant loading and spacecraft transportation.

5.2.2 Functions

- a. The propulsion system shall provide the required total impulse, minimum impulse bit, thrust levels and torques defined by the AOCS.
- b. The following aspects shall be covered by design, analysis and validation:
 1. thruster firing modes (e.g. steady state, off-modulation and 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.
- c. The propulsion system shall be designed, analysed and validated for the specified external loads during its mission, including:
 1. quasi-static loads
 2. vibrations;
 3. transportation-induced loads;
 4. thermal loads;
 5. electrical loads.

5.3 Constraints

5.3.1 Accelerations

Acceleration levels shall be specified at spacecraft level.

NOTE That allows

- perturbations to be avoided, e.g. during possible observations or experiments;
- protection of sensitive equipment;
- adequate tank PMD design.

5.3.2 Pressure vessels and pressurized components

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.

5.3.3 Induced and environmental temperatures

The temperature limitations for the operation of the propulsion system shall be specified.

5.3.4 Thruster surroundings

- a. Thruster surroundings shall conform to the radiative and conductive thruster rejected heat fluxes.
- b. Sensitive elements shall be protected from thruster plume thermal flux and contamination.

NOTE This includes gas and particulates.

5.3.5 Thruster arrangement

Thruster arrangement on the spacecraft shall consider, and document accordingly, the generation of perturbing torques, forces and thermal gradients due to thruster plume effects.

5.4 Interfaces

- a. The liquid propulsion system shall conform to its spacecraft interfaces, including:
 1. Structure (e.g. inserts, tank support structure and vibration levels);
 2. Thermal control (e.g. conduction, radiation levels, tank, thruster and line thermal control);
 3. AOCS (e.g. definition of firing modes, thrust levels and impulse levels);
 4. Power supply (e.g. valve drivers, pressure transducers, thermistors, heaters and thermocouples);
 5. Electromagnetic compatibility;
 6. Pyrotechnics (e.g. pyrotechnic valves);
 7. Mechanisms (e.g. valves, regulators, actuators and actuation system);
 8. OBDH and TM/TC (e.g. handling of data for status and health monitoring and failure detection).
- b. Interfaces shall be defined:
 1. for loading activities, with the propulsion GSE;
 2. for safety, with the launcher authorities.

5.5 Configurational

5.5.1 General

5.5.1.1 Flow diagram

- a. The flow diagram shall take into account the requirements in ECSS-Q-30A, subclauses 3.3 and 4.4.

NOTE 1 The flow diagram of a liquid propulsion system is usually not subject to stringent requirements since it is highly dependent on customer specific requirements on redundancies (e.g. agreement on the number of single point failures), fail safe and reliability.

NOTE 2 In general, propulsion systems are designed with redundancy on thruster level in order to achieve AOCS functions. However, no redundancy is usually applied on tanks.

- b. The propulsion system flow diagram shall conform to fail safe, redundancy and reliability requirements.

5.5.1.2 Cycles

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

5.5.1.3 Replacement of parts

The layout and system design shall allow for easy replacement of parts, components and subsystems during development, testing and mission life.

5.5.1.4 Pressure and pressurized components

The design of pressure vessels and pressurized components shall:

- a. apply the factors of safety (FOS) and margins (on MEOP) for proof testing and subsequent component life cycle;

NOTE See also 4.2.7.

- b. take into account the environmental aspects, including
 1. Temperature;
 2. Vibration level;
 3. Humidity;
 4. Corrosive environment;
 5. Vacuum;
 6. Outgassing;
 7. Radiation.

5.5.1.5 Water hammer effect

The design of the propulsion system shall be performed taking the potential water hammer effect into account to avoid malfunctioning of the propulsion system.

5.5.1.6 Piping

- a. Piping shall be designed taking non-consumables, cross-coupling, leakage and overall layout into account;

NOTE See subclause 5.5.1.5 above for water hammer effect.

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

5.5.1.7 Closed volumes

- a. The design of the propulsion system shall analyse the risk of pressure increase in closed volumes and adjust the design accordingly.
- b. The need for a pressure relief capability shall be evaluated.

5.5.1.8 Multi-tanks

- a. If a multi-tank layout is used, inadvertent propellant transfer between tanks shall be minimized by design.
- b. If PMD tanks are being used, the consequences of selecting parallel or series connections shall be analysed.

5.5.2 Selection

5.5.2.1 General

- a. All components shall be compatible with the selected materials, propellants and test fluids.

NOTE Compatibility includes:

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

- b. The selection shall be based on trade-off analyses of:
1. the propulsion system;

EXAMPLE Monopropellant, bipropellant, or cold gas.

2. the operating mode.

EXAMPLE Pressure regulated and blow-down.

5.5.2.2 Propellant

5.5.2.2.1 General

- a. The selection of the propellant shall be based on:
1. mission duration;
 2. the resulting layout of the propulsion system;
 3. the availability of off-the-shelf thrusters;
 4. experience;
 5. compatibility and contamination;
 6. performance.
- b. The propellant shall be defined and specified.

5.5.2.2.2 Thruster qualification

- a. Thruster qualification firing tests shall use the same propellant grade as the one selected for flight.
- b. The qualification envelope, including margins, shall conform to the expected envelope of operating conditions, i.e. temperature, contamination, dissolved gas and pressure.

5.5.3 Sizing

5.5.3.1 General

The sizing process of components for a liquid propulsion system demands particular attention due to the evolution of the operational conditions.

5.5.3.2 Sizing process

- a. The sizing process shall begin with a thorough definition of the life phases of each element, including at least:
1. pressure cycles combined with temperature cycles;
 2. propellant, pressurant and leakage budgets;
 3. establishment of an envelope for the operating conditions;
 4. minimum and maximum electrical supply voltages;
 5. interfaces with GSE functions.

- b. The sizing process shall take into account the 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. The evaluation of total quantities of pressurant, propellant and contaminants shall be based on:
 - 1. their impact on lifetime;
 - 2. variation of performance during lifetime;
 - 3. quantity for disposal;
 - 4. unusable residuals.

5.5.4 Development

5.5.4.1 General

The development of liquid propulsion systems necessitates particular care due to the lack of opportunity to perform a fully representative functional test (i.e. hot firing and gravity-dependent functions) after the integration of the system components on the spacecraft. Therefore, the flight version of the system is usually divided into independent blocks separated by safety barriers such as pyrovalves, latch valves or burst membranes. System verification is performed by incremental verification at block level.

5.5.4.2 Verification tests

- a. Verification tests of each block should be defined to represent the conditions encountered 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 c. above.

5.5.5 External contaminants

- a. The thruster design, layout and orientation should prevent contaminant deposition on sensitive elements.

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, including water vapour,
 - 1. shall be analysed and

2. should be verified.
- c. The character and sensitivity of spacecraft sensitive elements shall be verified.

5.5.6 Internal contaminants

5.5.6.1 General

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

5.5.6.2 Internal contaminants effect prevention

- a. The propulsion system shall be designed to avoid the effects of internal contaminants, including propellant vapours, by minimising:
 1. intrusion, internal generation and circulation of contaminants;
 2. accumulation of contaminants throughout the various parts of the system;
 3. accumulation of contaminants throughout the various steps of production, verification and operation of the system.
- b. The expected maximum level of contaminants inside the propulsion system shall be identified.
- c. The propulsion system design shall conform to the expected maximum level of contaminants.

5.5.7 Explosion risk

- a. In the case of hydrazine and other monopropellants, rapid compression of vapours, hot spots or undesired contact with a catalyst material shall be avoided.
- b. propellant explosions and leakage of propellant and propellant vapours shall be prevented.

NOTE Hypergolic propellants like nitrogen oxides and hydrazine or hydrazine derivatives react violently when mixed together or, in some cases, when mixed in gaseous forms with air, pressurant or simulant. In particular in ambient conditions like operation in the atmosphere > 10 hPa, or due to backward acceleration, fuel can migrate and condense in oxidizer injection cavities during off time causing catastrophic failure.

- c. Item b. above shall be supported by simulation and testing.
- d. The propulsion system requirements shall emphasize the 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.

5.5.8 Components guidelines

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

NOTE Table 2 covers the component failure modes, apart from external leakage and failure to operate, generally encountered in the use of standard components.

Table 2: Component failure modes

Component type	Failure mode	Failure detection	Failure prevention	#
Tanks, tubing	Crack growth	External leakage	Analysis	(a)
Pressure regulator	Internal leakage	Pressure test	Cleanliness	(b)
Electrically actuated valves	- Undesired operation - Internal leakage	- Pressure test - Position indication - Internal leak test	- Electrical inhibits - Cleanliness	(c)
Pneumatically actuated valves	- Undesired operation - Internal leakage	- Pressure test - Position indication - Internal leak test	Cleanliness	(d)
Propellant fill-and-drain valves	Undesired operation	Leakage	Cleanliness	(e)
	Propellant mixing	Chemical reaction	Use of: - different colours for components - different connectors (size and thread)	(f)
Manually actuated valves	Internal leakage	- Pressure test - Internal leak test	- Cleanliness	(g)
Non-return valves	Internal leakage	- Pressure test - Internal leak test	- Cleanliness - Design assessment	(h)
Pyro-valves	Undesired operation	Pressure test	- Electrical inhibits - Cleanliness	(i)
	Particle generation	Pressure test & Ground test	Design assessment	(j)
Thrust chambers and nozzles	Structural failure	Firing test	Design assessment	(k)
	Overheating cooling circuit	Firing test	Design assessment	(l)
	Loss of catalyst integrity	Gas-flow test	- Shock absorber, orientation of thruster. - Preheating of catalyst bed	(m)
	Catalyst poisoning	Performance loss	- Use of purified anhydrous hydrazine; - Si-leaching minimization from bladder or diaphragm tanks.	(n)
Filters	Clogging	Pressure test	Cleanliness	(o)
Pressure transducer	Zero shift, measurement anomalies	Calibration	-	(p)
Orifices, cavitating venturis, flow restrictors	Clogging	Pressure test	Cleanliness	(q)

5.5.9 Mass imbalance

The maximum mass imbalance shall be specified.

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

5.5.10 Ground support equipment (GSE)

5.5.10.1 General

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

5.5.10.2 Fluid

- a. The equipment and the procedures to operate and design the equipment shall prevent the spillage or venting of dangerous materials.
- b. Relief valves shall be installed on all pressurized vessels and major portions of the lines.
- c. The GSE design shall provide evacuation lines to the facilities in case of operation of any relief valve (see ECSS-E-70).
- d. The design shall prevent contact between materials causing hazards, such as explosion, chemical reaction and poisoning, when coming into contact with each other.
- e. The GSE design, functioning and procedures shall ensure that fluids are delivered to the spacecraft conforming to their standards in respect of:
 1. contamination level;
 2. pressure;
 3. temperature;
 4. level of gas dissolved in the liquids.

5.5.10.3 Electrical

- a. The system shall allow access to verify electrical continuity of the propulsion system and functionality of valves and pressure transducers.
- b. The procedures to operate, and the design of the equipment shall prevent the inadvertent activation of the systems and subsystems.
- c. In case the GSE is used in the vicinity of inflammable or explosive materials, it shall be explosion proof.

5.5.11 Filters

5.5.11.1 Gas

- a. Gas filters shall be designed and positioned according to the results of contaminant control and reliability studies.

NOTE The design of filters for gas systems necessitates a particular attention due to the high impact of any resulting valve leakage on the system reliability.

- b. Design of gas filters shall cover at least:
 1. volume;
 2. pressure drop;
 3. absolute and relative filtering rate;
 4. particle size.

- c. Filters shall be installed immediately downstream of potential particle generating components and, depending on the result of the failure risk analysis, directly upstream of pollution sensitive components (e.g. actuation valves and pressure regulators)

5.5.11.2 Liquid

- a. Filters shall be installed immediately downstream of potential particle generating components and, depending on the result of the failure risk analysis, directly upstream of contamination sensitive components (e.g. actuation valves and injectors).
- b. Filters shall be installed upstream of AOCS thrusters (which have low thrust and long in-service operating time).

5.5.12 Draining

- a. The system design shall allow for on-ground draining.
- b. The location of fill-and-drain valves and piping layout shall prevent:
 1. trapping of liquid in the system by on-ground draining;
 2. contact between dissimilar fluids.

5.5.13 Blow-down ratio

For liquid propulsion systems working in blow-down mode, the ratio of pressurant volume between BOL and EOL shall be consistent with thruster specifications (e.g. I_{sp} , combustion stability and mixture ratio shift).

5.5.14 Pyrotechnic devices

For pyrotechnic devices, ECSS-E-30 Part 6 shall be applied.

5.5.15 Pressure vessels

- a. Design and verification requirements shall cover the effect of pressurization on vessels and lines as defined in ECSS-E-30 Part 2.
- b. 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.
- c. Leak before burst shall apply (according to MIL STD 1522A NOT 3).

5.5.16 Propellant tanks

5.5.16.1 Overview

Commonly used tanks on spacecraft are:

- Simple shell, normally used for spinning satellites;
- Positive Expulsion Device (PED) tanks (e.g. diaphragm, bladder and bellows);
- Surface Tension Device (STD) or Propellant Management Device (PMD) tanks.

5.5.16.2 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 difference between propellant tank pressure in multi-tank systems, the tank and line temperature shall be controlled during the whole mission.
- c. The propulsion system design shall take the propellant gauging requirements into account.

- d. Propellant tank design shall prevent ingestion of pressurant gas into the propellant supply lines.

NOTE 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 accordance with the selected tank type and the spacecraft and mission requirements.

5.5.16.3 Positive expulsion device (PED) tanks

- a. Due to the nature of filled elastomer diaphragms and bladders, the tank shall be designed paying specific attention to:
1. contamination by silica-leaching into hydrazine;
 2. pressurant gas permeation through the elastomer;
 3. propellant adsorption;
 4. lack of material compatibility (i.e. 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. Dimensioning of diaphragms, bladders and bellows shall be designed taking sloshing into account.

5.5.16.4 Surface tension device (STD) or propellant management device (PMD) tanks

- a. Bubble point tests should be performed on the STD and PMD.
- b. Propellant tanks shall provide the thrusters with propellants according to their specified conditions.
- c. The tanks shall conform to the dynamic spacecraft specifications.
- d. Functional tests should be performed on the PMD and STD during development.
- e. Due to the difficulty of on-ground functional testing, the STD or PMD design shall be supported by a detailed analyses allocating margins for all mission phases.

5.5.17 Thrusters

5.5.17.1 Impulse bit repeatability

Impulse bit repeatability requirements shall take the AOCS requirements and influence on propellant budget at system level into account.

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).

5.5.17.2 Thruster alignment

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

5.5.17.3 Thrust mismatch

The difference in thrust between two thrusters operating as a pair on the same branch shall be minimized.

5.5.17.4 Flow calibration orifices

Flow calibration orifices shall be designed to adapt pressure and flow rates to minimize thrust mismatches, based on the analysis of:

- a. pressure drop;
- b. mixture ratio
- c. spacecraft CoM shift
- d. thruster cross-coupling

5.5.17.5 Heat soak-back

- a. The thruster design shall demonstrate 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.

5.5.17.6 Catalyst bed heating

For monopropellant systems, to avoid early thruster performance degradation, means shall be provided to heat up the catalyst bed before firing.

5.5.17.7 Thermal environment

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

5.5.18 Thrust-vector control (TVC)

Thrust-vector control allows adjustment of the thrust-vector direction on command.

- a. 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.
- b. For the performance of the TVC system, the following parameters shall be taken into account:
 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.
- c. The stiffness of the engine mounting, including feed lines and piping, and the actuator mounting on the engine shall meet the minimum values.

5.5.19 Monitoring

- a. As a minimum, the pressure and the temperature of tanks, valve status and operating branch pressure shall be available through telemetry for health monitoring and failure detection.
- b. To monitor thruster operation and health,
 1. Small thrusters (e.g. attitude control thrusters) shall at least be equipped with thermocouples or thermistors and allow for the installation of special instrumentation for additional measurements;
 2. Larger thrusters
 - (a) shall be equipped with thermocouples or thermistors, and
 - (b) should be equipped with pressure transducers, accelerometers and allow for the installation of special instrumentation for additional measurements.

5.6 Verification

5.6.1 General

- a. For verification of liquid propulsion systems, ECSS-E-10-02 shall be applied.

NOTE 1 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 2 In the following subclauses of this subclause 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.
- b. For the liquid spacecraft propulsion system, a verification matrix shall be established indicating the type of verification method to apply for the individual requirements.

5.6.2 Verification by analysis

5.6.2.1 Propellant and pressurant

Before starting activities,

- a. agreement shall be reached on the use of a common propellant and pressurant grade, and the associated database on the physico-chemical characteristics;
- b. agreement shall be reached on the use of propellant and pressurant standards.

5.6.2.2 Steady state

By using a representative and validated propulsion subsystem model, including validated thruster models, at least the following major aspects shall be established:

- a. The steady-state characteristics for the complete set of operating conditions of the propulsion system, including:
 1. the establishment of:
 - (a) the pressure losses in lines and components;
 - (b) the mixture ratio shifts and their effects on propellant residuals, 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, taking the temperature history during the mission into account.
 - 2. the demonstration
 - (a) 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.
 - (b) by the PMD analysis, of its proper functioning with a sufficient margin in all mission phases.
- b. Thermal analysis

Thruster thermal analysis shall be performed to demonstrate its compatibility with the external environment and proper thruster operation (e.g. limitation of flow control valve and surroundings temperature, and vapour lock.)
- c. Leakage budget

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.
- d. Contamination control

Analysis of the total contamination throughout the mission shall show that a sufficient margin exists before blocking of flow passages (e.g. in filters, valves and orifices), and a subsequent reduction in system performances occurs.
- e. Thruster plumes
 1. The impact of the thruster plumes on the structure, experiments, spacecraft motion and thruster performances shall be analysed and established to properly position thrusters.
 2. It shall be established whether protection devices are required.
 3. The effects on thruster performances shall be evaluated.

NOTE When the thrusters are firing, hot gases and particles are being expelled. Combustion gases interference with the spacecraft surfaces can reduce the propulsion performances and expelled contaminants can affect, for example, solar panels, sensors, and optical instruments.
- f. Gauging analysis

Analysis shall demonstrate that the required accuracy is obtained with the on-board measurement equipment and its related data handling.
- g. CoM shift

Analyses shall show that the spacecraft CoM remains within the specifications.

NOTE Throughout the mission, propellant is consumed from the tanks and the spacecraft CoM moves.
- h. Loading analysis

For accurate tank pressurization, the effects of temperature on the pressurant, propellant and tank shell, the pressurant dissolution and tank shell deformation due to pressure shall be analysed and established, and accounted for.
- i. Leak before burst analysis

Leak before burst characteristics of gas tanks shall be obtained by analysis.

5.6.2.3 Transients

5.6.2.3.1 Pressure transients

- a. The effect on sensitive elements of rapid pressurization due to line priming shall be analysed.
- b. The risk of propellant adiabatic decomposition shall be taken into account.

5.6.2.3.2 Sloshing

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

NOTE Sloshing of propellant in tanks can have an impact on spacecraft stability.

- b. If diaphragm, bladder tanks or anti-sloshing devices (i.e. baffles) are used, the effect of the diaphragm, bladder or anti-sloshing device on the liquid surface shall be taken into account.

5.6.2.3.3 Spin load

The effect of spacecraft rotation on propellant motion during the mission shall be analysed.

5.6.2.3.4 Thruster cross-coupling

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 and established.

5.6.2.3.5 Water-hammer effects.

The following water hammer effects shall be analysed:

- a. failure of lines (tubes) or components;
- b. adiabatic decomposition of propellants;
- c. cross-coupling between valves or thrusters.

NOTE The rapid opening and closing of valves can cause severe pressure perturbations in a propulsion system, known as water-hammer effects.

5.6.3 Verification by test

5.6.3.1 Thruster firing test

- a. The conformity of the thruster behaviour to the thruster requirements shall be verified by test.
- b. Thruster firing tests shall be performed to define the thruster performance. The following parameters are of particular importance:
 1. range of inlet pressures;
 2. ambient pressure;
 3. feed-line pressure loss;
 4. propellant temperatures;
 5. dissolved gas in propellant;
 6. thermal environment;
 7. specified duty cycles;
 8. lifetime;
 9. initial chamber temperature;

10. contaminants throughput;
11. valve voltage.
- c. Thruster firing tests shall verify:
 1. good 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) mixture ratio.

5.6.3.2 Proof pressure test

- a. Proof pressure tests shall be performed depending on the performed NDI, load assumptions used for design and safety rules to apply on all pressure vessels and pressurized components.
- b. The minimum factors of safety shall be applied (see ECSS-E-30 Part 2).

NOTE The proof pressure test is used to give evidence of satisfactory workmanship and material quality.

- c. As proof pressure tests are major contributors to crack growth, the number of proof pressure tests shall be reduced to a minimum taking into account the following rules:

1. stress corrosion cracking effects (see ECSS-Q-70-36 and NASA-MSFC-SPEC-522B) 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 This limit depends on the characteristics of materials in contact and mission requirements.

2. a system proof test shall be conducted at a pressure higher than the system MEOP (see MIL STD 1522A NOT 3).
3. component proof pressure tests shall take into account the particular MEOP of this component including transient pressure peaks.
4. All welds in lines and fittings shall either be proof tested to at least 1,5 MEOP or subject to full X-ray NDI.

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

5.6.3.3 Burst pressure test

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

NOTE The burst pressure is the MEOP multiplied by the ultimate factor of safety as defined in ECSS-E-30A Part 2 subclause 4.2.5.15.

- b. The test shall go either
 - up to burst; or
 - up to the design burst pressure, which shall be maintained for a short time (i.e. a few minutes).
- c. For safety reasons, fluids used for burst pressure
 - 1. should be liquids;
 - 2. shall not pose a hazard to test personnel; and
 - 3. shall be compatible with the structural material in the pressurized hardware (see also ISO/CD 14623-1, ISO/AWI 14623-2, AIAA S-080-1998, AIAA S-081-1999).

5.6.3.4 Cleanliness

5.6.3.4.1 Particulate

A control of the maximum allowable number of particles shall be performed adequately, taking into account the system, subsystem, and component level requirements and the particle size, particle type and the minimum clearances (see MIL-STD-1774 NOT 2 and ISO/CD 14952-1 to -6).

5.6.3.4.2 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.

5.6.3.5 Ageing

For propulsion systems which are designed to be activated after extremely long periods (e.g. for deep space or interplanetary missions), or which are designed to operate for an extremely long time, it shall be verified that the propulsion system still conforms to all requirements after representative ageing tests.

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

5.6.3.6 Contamination control

- a. In case the parameters for total contamination defined 5.6.2.2 a.2.(b) cannot be verified by analysis, specific tests shall be conducted to establish the evolution of the level of contamination over time.

NOTE Accelerated tests may be used.

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

5.6.3.7 Compatibility

To ensure that the system or subsystem conforms to the compatibility requirements, 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 compatibility shall be established over time.

NOTE Accelerated tests may be used.

5.6.3.8 Flow test

- a. A flow test shall be performed to verify the proper functioning of the system.
- b. 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.

5.6.3.9 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.

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.

5.6.3.10 Dryness

- a. An acceptable level of residual humidity shall be defined.
- 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.

5.6.3.11 Electrical test

- a. All electrical components shall be tested for their functionality.
- b. Where that is not possible (e.g. in the case of initiators and pyrotechnic devices) they shall be tested for their electrical continuity.

5.6.3.12 Thruster alignment

Thruster alignment shall be tested for conformity to the requirements.

5.6.3.13 Tank expulsion efficiency

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

NOTE For PMD tanks, only partial testing is feasible under gravity.

- b. Combination of test results and analyses shall demonstrate the adequacy of the design for tank expulsion with a sufficient margin under all mission conditions.

5.6.3.14 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 a. above shall include at least:
 - 1. water-hammer effects;
 - 2. design of flow orifices;
 - 3. thruster cross-coupling effects;
 - 4. hydrazine detonation due to adiabatic compression.
- 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 identical to the flight one.
- e. For tests on adiabatic detonation, only flight-grade hydrazines shall be used.

NOTE In other cases, simulants may be used to obtain data on pressure transients and flow levels.

5.6.3.15 Calibration

- a. All components or subsystems that provide data outputs shall be calibrated.
- b. Conformity to the requirements of these components or subsystems shall be demonstrated.

5.6.4 Data exchange for models

Test results, thermal and mechanical models and performance models shall be established and structured with a commonly agreed structure and format.

5.7 Quality factors

5.7.1 Reliability

The design shall take into account requirements on reliability with respect to:

- a. the probability of success of the mission;
- b. design life.

5.7.2 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.

5.8 Operation and disposal

5.8.1 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 observe the operational limits of the components, subsystems and systems, and shall take into account 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 (e.g. explosion, toxicity and corrosion).

5.8.2 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 (e.g. cap removal, latch valve actuation and pipe disconnection).
- d. During AIT operations
 1. tests at component and system level shall be performed.
 2. all the resulting requirements shall be included in the component and system mission profiles.
- e. The operational procedures shall account for all specific requirements from the planned launch agencies (launcher and launch site).

5.8.3 Tank operation

- a. To avoid thermal loads and condensation effects on tank shells, pressurization and depressurization operations shall limit the pressure gradients.
- b. During tank operation the limiting Δp for diaphragm tanks shall not be exceeded.

5.8.4 Disposal

5.8.4.1 Disposal of contaminated, toxic and dangerous products

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

5.8.4.2 Disposal before operation

Local safety standards shall be applied for dangerous materials that can be contained in the propulsion system and the GSE after draining and drying, such as mixtures of propellants and simulants in the ends of pipes or pyrotechnic devices.

5.8.4.3 Disposal after operation

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.

5.9 Support

The following analyses, specific for a propulsion system, shall be delivered as a minimum:

- a. Performance analysis;
- b. Transient analysis;
- c. Sloshing analysis;
- d. Thermal analysis;
- e. Plume analysis;
- f. Gauging analysis;
- g. Mechanical analysis.

NOTE 1 These documents also include the available test results.

NOTE 2 Documents related to Management, Quality and Product Assurance and System engineering are covered by specific standards in ECSS-M, ECSS-Q and ECSS-E-10.

NOTE 3 Table 1 (see clause 4) provides a cross-reference between terms used in this volume to identify project documents and the Document Requirements Definition, which specifies the contents of these documents.

Electric propulsion systems for spacecraft

6.1 General

Electric propulsion is based on the acceleration of a propellant (or propellant combustion products) 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 (i.e. resistojets, arcjets and PACTs);
- electrostatic thrusters (i.e. ion thrusters with a grid, Hall-effect thrusters and FEEP thrusters);
- electromagnetic thrusters (i.e. MPD and PPT).

Electric propulsion uses electrical power either to:

- increase the performance of the chemical thrusters, as in power-augmented thrusters or in arcjets;
- produce high-velocity particles directly through ionisation and acceleration in an electromagnetic field, as in electrostatic and electromagnetic thrusters.

Electric propulsion is characterized by a high flexibility allowing its use for station keeping, attitude control, orbit transfer and manoeuvres, interplanetary flight, and de-orbiting. Electric propulsion thrusters are characterized by very high specific impulses, very low thrusts and very long operation times.

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

Three operational subsystems can be distinguished:

- a propellant storage and supply subsystem, where spacecraft liquid propulsion rules are applicable (see clause 5 of this Standard), unless otherwise stated;
- a power supply and control and processing subsystem, not under the scope of this ECSS Standard, and where ECSS-E-20 is applicable;
- a thruster subsystem, subject of the present clause 6.

Depending on the type of electric propulsion 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.

6.2 Functional

6.2.1 Mission

The propulsion system shall conform to the spacecraft mission requirements with respect to:

- a. pre-launch and launch activities (i.e. integration, storage, ageing and transport), in-orbit operation (i.e. orbit transfer, orbit maintenance and attitude control) and during the complete mission life;
- b. ground operation, i.e. functional control, testing, propellant, simulant loading and spacecraft transportation.

6.2.2 Functions

- a. The propulsion system shall provide the required total impulse, minimum impulse bit, thrust levels and torques defined by the AOCS.
- b. The following aspects shall be covered:
 1. thruster firing modes (e.g. steady state and pulse modes);
 2. thrust level and orientation;
 3. thrust-vector control;
 4. thrust modulation;
 5. minimum impulse bit;
 6. impulse reproducibility;
 7. total impulse;
 8. cycle life;
 9. mission life;
 10. reliability level;
 11. thrust noise.
- c. All external loads shall be specified and taken into account:
 1. quasi-static loads
 2. vibrations;
 3. transportation induced loads;
 4. thermal loads;
 5. electrical loads.

6.2.3 Performances

- a. Performances shall be specified with reference to the following operating variables or to a range of them:
 1. lifetime;
 2. thrust and throttling range and accuracy;
 3. propellant mass flow rate;
 4. electrical power consumption;
 5. specific impulse and range;
 6. total impulse and operating cycles;
 7. beam divergence.
- b. In addition, repeatability of performances between flight units and predictability of performances between consecutive firings of a single unit shall be addressed:
 1. Bias;

2. Scale factor (i.e. the ratio between commanded and required force, for a given engine);
3. Disturbance.
- c. Thrust-vector alignment requirements shall be defined in function of:
 1. the geometric thruster alignment;
 2. the thrust-vector alignment evolution between successive firings or during a single firing;
 3. the thrust-vector alignment dispersion between flight units.
- d. Response time shall be defined with respect to:
 1. on-off operations;
 2. change in thrust level.

6.3 Constraints

6.3.1 General

For use of electric propulsion on a spacecraft, special care shall be paid with regard to:

- a. Thruster priming, start up and restart sequences of:
 1. thrust level;
 2. I_{sp} ;
 3. power consumption;
 4. throttleability.
- b. The interaction between the ion beam and parts of the spacecraft (e.g. solar panel and antennas) that can perturb the torque and force system of the whole spacecraft during thruster operations;
- c. plume effect on the spacecraft;
- d. maximum values of thermal fluxes for the power supply and thruster subsystems;
- e. electromagnetic compatibility with the spacecraft electrical subsystem and the payload.

6.3.2 High frequency current loops

6.3.2.1 General

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). These currents can have an impact on sensitive electronics.

6.3.2.2 Impact on sensitive electronics

The spacecraft electrical architecture shall consider the high frequency current loops referred in 6.3.2.1 to minimize their impact on sensitive electronics.

6.3.3 Plume effects

- a. If thruster plumes contain erosion products, the following effects on spacecraft surfaces (e.g. solar arrays, antennas and radiators) of plumes shall be analysed and accounted for in the system design:
 1. erosion of surfaces;
 2. change of surface properties (e.g. optical, thermal and electrical);
 3. heating;

4. electric charging;
 5. adverse effects on radio communication due to plasma;
- b. The design of the system shall conform to the results of these analyses.

6.3.4 Thermal fluxes

Even with a good efficiency, the heat dissipated by the power supply subsystem can be significant. 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.

NOTE Another heat source is the thruster.

6.3.5 Electromagnetic compatibility

Compatibility of electric thrusters with all the electromagnetic transmissions (e.g. payload, telemetry, TM/TC and pyrotechnic devices) shall be ensured.

NOTE When operating, electric thrusters create electromagnetic fields.

6.3.6 Electric charging

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

6.4 Interfaces

6.4.1 Interface with the spacecraft

- a. The electric propulsion system shall conform to its spacecraft interfaces, including:
1. Structure (e.g. inserts, tank support structure and vibration levels);
 2. Thermal Control (e.g. conduction, radiation levels, tank, thruster and line thermal control);
 3. AOCS (e.g. definition of operating modes, thrust levels and impulse levels);
 4. Power supply (e.g. valve drivers, pressure transducers, thermistors, heaters and thermocouples);
 5. Electromagnetic compatibility;
 6. Pyrotechnics (e.g. pyrotechnic valves);
 7. Mechanisms (e.g. valves, regulators, actuators and actuation system);
 8. OBDH and TM/TC (e.g. handling of data for status and health monitoring and failure detection).
- b. Interfaces shall be defined with:
1. the propulsion GSE, for loading activities;
 2. the launcher authorities, for safety.

6.4.2 Interface with the power bus

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

- a. the bus tension and its accuracy;
- b. the maximum available power;

- c. the bus impedance in relation to the frequency to access the capacity of the bus to sustain surge currents;
- d. the EMI level from the bus to assess the susceptibility of the PCU.

6.5 Configurational

6.5.1 General

6.5.1.1 Flow diagram

- a. The flow diagram shall take into account the requirements in ECSS-Q-30A subclauses 3.3 and 4.4.

NOTE 1 In general, electric propulsion systems are designed with redundancy on thruster level and power subsystem level in order to meet their requirements. However, usually no redundancy is applied on tanks.

NOTE 2 The flow diagram of an electric propulsion system is not usually subject to stringent redundancy requirements, since it is highly dependent on customer specific requirements on redundancies (e.g. agreement on the number of single-point failures), fail safe and reliability.

- b. The propulsion system flow diagram shall take into account specific fail-safe, redundancy and reliability requirements.

6.5.1.2 Cycles

The system design shall take into account the cycles that are expected to be experienced during the whole mission life (at component, propulsion and spacecraft system level, and for both on-ground and in-service operation).

6.5.1.3 Replacement of parts

The layout and system design shall allow for easy replacement of parts, components and subsystems during development, testing and mission life.

6.5.1.4 Pressure and pressurized components

The design of pressure vessels and pressurized components shall:

- a. be done applying the factors of safety (FOS) and margins (on MEOP) for proof testing and subsequent component life cycle;
- b. take the environmental aspects into account.

6.5.1.5 Water-hammer effect

The design of the propulsion system shall be performed taking potential water-hammer effects into account.

6.5.1.6 Closed volumes

- a. The design of the electric propulsion system shall take the risk of pressure increase in closed volumes into account.
- b. The need for a pressure-relief capability shall be evaluated.

6.5.1.7 Multi-tanks

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

6.5.1.8 Electromagnetic compatibility

Electric propulsion systems shall be designed in order to be electromagnetically compatible with the other parts of the spacecraft.

6.5.1.9 Electric discharges

Where high-voltage components, harnesses and connectors are involved, the electric propulsion system shall be designed to avoid risks of discharge on other spacecraft parts.

6.5.2 Selection

6.5.2.1 Propulsion system

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

EXAMPLE 1 Examples of electric propulsion systems are arcjets, ion engines with grids, Hall-effect thrusters, and field-emission thrusters.

EXAMPLE 2 Examples of operating mode are pressure-regulated, blow-down, continuous operation and pulsed operation.

NOTE The use of electric propulsion usually implies long periods of thruster operation. The selection of the most suitable electric propulsion system is strongly mission-dependent. The selected thruster firing strategy during the mission has a severe impact on the mission performance (i.e. duration, payload capability, electrical power usage, design and sizing of other subsystems).

- b. In order to achieve a good integration of the electric propulsion system in the global spacecraft architecture and planned mission, the designer of such system shall coordinate and interact with the designer of the complete spacecraft.

NOTE This is particularly important for one-of-a-kind missions.

- c. All components shall demonstrate compatibility with the selected materials, propellants and test fluids.
- d. The choice of the electric propulsion system shall take into account the available electrical power for the electric propulsion system during the whole duration of the mission.

NOTE In view of the significant power consumption, the use of an electric propulsion system can affect the availability of power for other spacecraft subsystems and payloads, in particular during transient operations (e.g. start-up and throttling).

- e. The impact of the use of electric propulsion on the spacecraft power system shall be analysed and taken into account in the selection of the electric propulsion system.

6.5.2.2 Propellant

6.5.2.2.1 General

- a. The selection of the propellant shall be based on:
1. mission duration;
 2. compatibility, contamination, and performances.
- b. The propellant shall be defined and specified.

6.5.2.2.2 Thruster qualification

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

- b. It shall be verified that the qualification envelope meets, including margins, the expected envelope of operating conditions, i.e. temperature, contamination, and pressure.

6.5.3 Sizing

6.5.3.1 General

The sizing process of components for an electric propulsion system requires particular precautions due to the evolution of the operational conditions.

The evaluation of the required total amount of propellant, pressurant and any contaminants is a major input for the sizing process (e.g. impact on lifetime, variation of performance during lifetime, quantities for disposal and unusable residuals). The available electrical power to the propulsion system throughout the mission is the other major input for the sizing process.

6.5.3.2 Sizing process

- a. The sizing process shall begin with a thorough definition of the life phases of each element, including at least:
 - 1. pressure cycles combined with temperature cycles (e.g. arcjets and resistojets);
 - 2. propellant, pressurant and leakage budgets;
 - 3. establishment of a box for the operating conditions;
 - 4. minimum and maximum electrical supply voltages;
 - 5. interaction with GSE functions.
- b. The sizing process shall account for the margins based on:
 - 1. safety;
 - 2. reliability requirements established by the customer, industry and launch authorities or agencies
 - 3. operational constraints;
 - 4. thruster performance efficiencies;
 - 5. plume effects;
 - 6. modelling errors and uncertainties.

6.5.4 Design development

6.5.4.1 Safety barriers

The flight version of the system should be divided into independent subsystems separated by safety barriers such as pyrovalves, latch valves, burst membranes and electrical switches and connectors.

NOTE The development of electric propulsion systems deserves particular care due to the impossibility to perform a fully representative functional test (i.e. hot firing in vacuum and long duration of operations) after the integration of the system components on the spacecraft

6.5.4.2 Verification

- a. System verification shall be performed by incremental verification at subsystem level.
- b. System verification should use electrical simulators for thrusters at spacecraft level.

- c. The verification tests of each block shall be defined to represent as closely as possible the conditions that are expected to be encountered during the operation of the complete system;
- d. The testability at integrated spacecraft level and the capability to return after test to safe and clean conditions shall be demonstrated for each system and subsystem. The design and procedures shall be defined accordingly.

6.5.5 Components guidelines

For standard electric propulsion components, subclause 5.5.8 is applicable.

Specific components for electric propulsion are dealt with in the following subclauses of this subclause 6.5.

6.5.6 Thrusters

6.5.6.1 General

The design requirements in this subclause are applicable to all the thruster types of electric propulsion systems.

NOTE 1 There is a wide range of electric propulsion thrusters belonging to the general classification given in subclause 6.1.

NOTE 2 The thruster design requirements are also strongly mission-dependent.

6.5.6.2 Mean thrust level

- a. The thruster shall be designed in order to provide a mean thrust level and a maximum thrust range corresponding to the given electrical and mass-flow input parameters throughout the mission.

NOTE This is because of the low thrust levels of electric propulsion thrusters, in most cases well below 1 N, and their long operational life.

- b. The thruster shall be designed in order to provide the requested thrust stability (i.e. drift and fluctuations) and repeatability.
- c. Requirements covered by a. and b. above shall follow from the AOCS analysis.

6.5.6.3 Thrust modulation

The thruster shall provide the capability of being modulated in high- and low-frequency modes if required by AOCS.

6.5.6.4 Thrust mismatch

The difference in thrust between two thrusters operating as a pair on the same branch shall be minimized.

6.5.6.5 Thrust noise

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

NOTE 1 Be aware that some applications of electric propulsion thrusters demand very accurate control of the generated thrust.

NOTE 2 Thrust noise is usually composed of a contribution from the thruster and one from the power electronics.

6.5.6.6 Thrust-vector alignment

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

- a. 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 thrust-vector-sensitive components inside the thruster;
 3. a combination of 1. and 2. above.

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. The second solution is anyhow introduced in the design because it allows the alignment of the thruster with the spacecraft reference frame.

- b. 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 the erosion of thrust-vector-sensitive components during operations.

6.5.6.7 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. scale factor;
 3. hysteresis;
 4. response time of the system.

NOTE Thrust can change due to these parameters.

6.5.6.8 Electrical parameters

- a. The thruster design shall be optimized in order to minimize the impact on the spacecraft electrical system and to maximize the thruster performance in every mission phase.

NOTE The thrust generated is directly affected by the electrical input parameters.

- b. This optimization process shall always be performed in the framework of a design optimization process at electric propulsion subsystem level.

6.5.6.9 Thermal environment

- a. The heat fluxes at the interface between the thruster and supporting structure should be minimized.
- b. To avoid overheating of the thruster, its thermal behaviour, when integrated with the spacecraft, shall be analysed.

6.5.6.10 Operational lifetime

The design of the erosion sensitive components of the thruster shall be compatible with the operational life of the thruster.

NOTE Electric propulsion thrusters operate for long periods during the mission (in some cases for several thousands of hours) in continuous or cyclic mode.

6.5.7 Thrust-vector control

6.5.7.1 Devices for thrust-vector control

Devices used for thrust-vector control shall be

- a. actively controlled pointing mechanisms supporting the thruster, as explained in 6.5.7.2 below; or
- b. thrust-vector steering solutions within the thruster itself, as explained in 6.5.7.3 below.

NOTE Be aware that 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.

6.5.7.2 Thruster orientation mechanism

For the design of thruster orientation mechanisms for electric propulsion, subclause 5.5.18 of this Standard shall be applied.

6.5.7.3 Internal thrust-vector steering devices

- a. If internal thrust-vector steering solutions are being introduced into the design of electric thrusters, this should be done on the thrust-vector-sensitive components.
- b. Such solutions shall be based on magnetic or mechanical steering solutions.

6.5.8 Propellant management assembly

6.5.8.1 General

In this subclause 6.5.8 the components of the propellant management assembly are listed and particular design drivers are addressed for components particular to electric propulsion systems.

6.5.8.2 Standard components and fluids

- a. For standard components of the propellant management assembly, subclause 5.5.8 of this Standard shall be applied.
- b. For fluids with a high triple-point, it shall be assured that the fluid is maintained in a gaseous state. Otherwise, active thermal control of the propellant management assembly shall be implemented.

NOTE Electric propulsion systems have specific components in their propellant management assembly.

6.5.8.3 Flow control unit

6.5.8.3.1 General

Electric propulsion systems demand very small, well-regulated, propellant mass flow rates as compared to liquid propellant systems.

6.5.8.3.2 Not-self-adjusted mass flow rate

In case the mass flow rate is not-self-adjusted (e.g. by capillary-fed thrusters), the specific design requirements shall take the aspects addressed in 6.5.8.3.1 into account.

6.5.8.4 Pressure regulators

- a. Pressure regulators shall be able to control the pressure of the propellant within levels compatible with the thruster operational parameters.

NOTE 1 In an electric propulsion system, the pressure regulator represents a critical component.

NOTE 2 Pressure regulators for electric propulsion systems fall in several categories such as mechanical, electronic, or thermal regulators.

NOTE 3 Pressure regulators can be inserted into parts of the propellant feed system common to all the branches, locally into lines feeding different thrusters or other propellant-fed devices, or both.

- b. The specifications for the pressure regulator shall be in full agreement with:
1. the requirements stemming from the topology of the propellant feed system;
 2. the location of the pressure regulator in the propellant feed system.

6.5.8.5 Valves

The strict requirements in terms of leakage resulting from the size and the mass flow rates of electric propulsion systems shall be taken into account.

NOTE 1 Electric propulsion systems are usually small and operate with very small mass flow rates compared to similar devices for liquid propulsion systems. This results in very strict requirements in terms of leakage rates.

NOTE 2 This subclause is also applicable to the valves for gaseous propellants which are often used for electric thrusters.

6.5.8.6 Oxygen absorbers

- a. The use of oxygen absorbers shall be considered.
- b. They should be located as closely as possible to the sensitive component.

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 electric propulsion systems such as cathodes and neutralizers can be oxygen contamination sensitive.

6.5.8.7 Propellant filters

For gas and liquid filters design, subclause 5.5.11 of this Standard shall be applied.

6.5.8.8 System draining

- a. The system design shall allow for on-ground draining.
- b. The location of fill-and-drain valves and piping layout shall prevent:
1. trapping of propellants in the system by on-ground draining;
 2. contact between dissimilar fluids.

6.5.9 Propellant tanks

6.5.9.1 General

- a. Propellant tanks shall provide the thrusters with propellants according to their specified conditions.
- b. The tanks shall conform to the dynamic spacecraft specifications.

NOTE Due to the large variety of propellants used for electric propulsion thrusters (i.e. gaseous, liquid and solid), different tank design rules are applicable, depending on the propellant, as specified in the following subclauses.

- c. In the case of liquid metal propellants, capillary feeding devices shall be used.
- d. In the case addressed in c. above, if applicable to the tank design, a mechanism shall be introduced to prevent the unwanted leakage of propellant.

6.5.9.2 Liquid propellant tanks for electric propulsion systems

For tanks for electric propulsion systems using liquid propellants, subclause 5.5.16 of this Standard shall be applied.

6.5.9.3 Gaseous propellant tanks for electric propulsion systems

For tanks for electric propulsion systems using gaseous propellants (e.g. xenon), subclause 5.5.15 of this Standard shall be applied.

NOTE 1 Some gaseous propellants, such as xenon, are usually stored in supercritical condition.

NOTE 2 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 accordance to the spacecraft Eigen-frequencies.

6.5.10 Blow-down ratio

For electric propulsion systems working in blow-down mode (i.e. arcjets and resis-tojets), the ratio of pressurant volume between BOL and EOL shall be consistent with thruster specifications (e.g. I_{sp} , combustion stability and mixture ratio shift).

6.5.11 Pressure vessels

- a. Design and verification requirement shall cover the effect of pressurization on vessels and lines as defined in ECSS-E-30 Part 2.
- b. In order to eliminate explosion or leakage risks, requirement on the design, development, production, verification and operation of pressure vessels for propulsion systems shall be addressed specifically.
- c. Leak before burst shall apply (see MIL STD 1522A NOT 3).

6.5.12 Power supply, control and processing subsystem

6.5.12.1 Power supply, control and processing equipment

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

NOTE 1 The purpose of the power supply, control and processing devices in an electric propulsion 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 electric propulsion 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 electric propulsion 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 electric propulsion system to provide cross-strapping of electrical power between the power supplies and several thrusters.

6.5.12.2 Electrical filters

To optimize the thruster operation, the use of standard power control units for different propulsion system configurations on different spacecraft, electrical filters shall be implemented in some cases.

NOTE This applies in particular to Hall-effect thrusters, that are subject to plasma oscillations. Plasma oscillation phenomena can have an effect on spacecraft EMC.

6.5.13 Monitoring

Monitoring devices for physical parameters (e.g. pressure and temperature), and Langmuir probes and retarding potential analysers, should be used.

NOTE 1 Monitoring device principles for pressure and temperature in electric propulsion systems do not differ from those for liquid propulsion. However, other types of monitoring devices, such as Langmuir probes and retarding potential analysers, are more compatible with the long operational time of an electric propulsion system.

NOTE 2 Monitoring of physical parameters has two purposes:

- the health status of the system;
- adjust the actual to the expected performance.

6.5.14 Pyrotechnic devices

For pyrotechnic devices, ECSS-E-30 Part 6 shall be applied.

6.5.15 Ground support equipment (GSE)

6.5.15.1 General

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

6.5.15.2 Fluid

- a. The equipment and the procedures to operate and design the equipment shall prevent the spillage or venting of dangerous materials.
- b. Relief valves shall be installed on all pressurized vessels and major portion of the lines.
- c. The GSE design shall provide evacuation lines to the facility in case of operation of any relief valve (see ECSS-E-70).

- d. The design shall prevent contact between materials causing a hazard when coming into contact with each other.
- e. The GSE design, functioning and procedures shall ensure that fluids are delivered to the spacecraft conforming to their specifications with respect to:
 - 1. contamination level;
 - 2. pressure;
 - 3. temperature;
 - 4. level of gas dissolved in the liquids.
- f. The loading of propellant in supercritical condition (e.g. xenon) 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.

6.5.15.3 Electrical

- a. The system shall allow access to verify electrical performance and functionality of all electrical components of the electric propulsion system.
- b. The procedures to operate and the design of the equipment shall prevent the inadvertent activation of the spacecraft components.
- c. In case the GSE is built to operate in the vicinity of inflammable or explosive materials, it shall be explosion-proof.

6.5.16 Contaminants

6.5.16.1 External contaminants

The thruster design, layout and orientation shall minimize the risks of contaminant deposition on sensitive elements (e.g. solar panels, star trackers and optics.)

6.5.16.2 Internal contaminants

- a. Chemical cleanliness of fluids and walls of the propellant storage and distribution subsystem shall be defined in terms of the maximum contaminant concentration.

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 propellant, gases and fluids shall conform to their respective applicable specifications.
- c. The materials shall conform to ECSS-E-30 Part 8.

6.5.17 Electrical design

6.5.17.1 General

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

6.5.17.2 Electromagnetic compatibility (EMC)

- a. For electromagnetic compatibility, design of the thruster and power unit should conform to MIL-STD-1541A and MIL-STD-461E.
- b. The design of the following shall conform to MIL-STD-1541A and MIL-STD-461E:
 - 1. interference;
 - 2. susceptibility;

3. grounding;
4. shielding;
5. isolation.

6.5.17.3 Electric reference potential, grounding, insulation

- a. The grounding scheme and insulation shall be optimized to limit interference.

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. An electrical filtering device shall be designed to control the propagation of these oscillations through common mode currents.

NOTE The electrical reference potential suffers natural oscillations and random transients which are part of the thruster nominal operation.

6.5.17.4 Electrostatic discharge protection

The electric propulsion system shall be protected from over-voltages caused by:

- a. electrostatic charge accumulation on inactive thruster electrodes which are exposed to space;
- b. electrostatic discharge surging onto or close to these inactive electrodes;
- c. thruster start-up, and shut-down or excessive transient spikes.

6.5.17.5 Parasitic discharge prevention

The design of the electric propulsion system:

- a. should prevent discharges between parts of the thruster at different potentials, by specific design features;

NOTE 1 Parasitic discharge in electrostatic engines cannot be avoided completely.

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

- b. 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.

6.6 Physical

6.6.1 Materials

- a. The materials exposed to the propellant shall be selected to be compatible with it.
- b. The specifications for operating fluids shall include:
 1. chemical nature;
 2. purity;
 3. feed pressure;
 4. temperature.
 5. cleanliness

- c. The materials used for the magnetic circuits of thrusters shall be selected according to their magnetic properties (e.g. saturation and Curie point) at the worst case temperature.

6.6.2 Mass imbalance

The maximum mass imbalance shall be specified.

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

6.7 Verification

6.7.1 General

- a. For verification of electrical propulsion systems, ECSS-E-10-02 shall be applied.

NOTE 1 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 2 In the following subclauses of this subclause 6.7, 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.

- b. For the electrical propulsion system, a verification matrix shall be established indicating the type of verification method to be applied for the individual requirements.

6.7.2 Verification by analysis

6.7.2.1 General

For electric propulsion system, the following shall be applied:

- a. subclause 5.6.2;
- b. the additional subclauses of this subclause 6.7.2.

NOTE Methodology principles for the verification by analysis of an electric propulsion system are similar to the ones for liquid propulsion system presented in the subclause 5.6.2. 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.

6.7.2.2 Mutual effects of electrostatic and magnetic fields

The mutual effects of the electrostatic and magnetic fields on simultaneously operating electric thrusters shall be assessed.

6.7.2.3 Power, propellant and thruster

- a. The following power and propellant analyses shall be made:
 1. budget;
 2. mechanical and thermal;
 3. performance.
- b. specific analysis of the possible interference between the electric thruster and the spacecraft shall be performed, including:
 1. electrostatic (i.e. surface and bulk charging);
 2. mechanical and thermal;
 3. contamination and erosion;
 4. communication;
 5. electromagnetic.

6.7.2.4 Lifetime

The verification of the actual lifetime of electric propulsion systems is usually performed by means of long-duration tests (even of thousands of hours). The use of simulation tools capable of predicting the evolution in time of the operational parameters of the system and the degradation of life-critical components can introduce significant benefits for the verification and qualification processes of electric propulsion systems.

6.7.2.5 Time-related phenomena

- a. At least the following specific phenomena during transient phases (e.g. start-up and shut-down) shall be evaluated when analysing the electric propulsion system:
 1. gas pressure oscillations;
 2. inrush power consumption;
 3. electrostatic and electromagnetic perturbations.
- b. The time response of an electric propulsion system should 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.

6.7.3 Verification by test

6.7.3.1 General

- a. In case the implications of the functioning of an electrical propulsion system on the spacecraft system level cannot be fully perceived or anticipated, specific tests shall be performed.

NOTE These tests may 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. Test methods related to acceptance, environmental tests, EMI and EMC tests, plume tests, and life tests shall be defined, particularly those described in the following subclauses.

6.7.3.2 Operating test

Because most of the electric thrusters can only be operated in deep vacuum, the following shall be defined with reference to their impact on performance:

- a. vacuum pressure level;
- b. measurement and calibration of the thruster;
- c. the type of pumping;
- d. the minimum distance of the thruster to the walls of the vacuum chamber.

6.7.3.3 Electromagnetic compatibility (EMC) test

- a. EMC tests shall be performed on the thruster or thruster simulator and on the power supply and conditioning system with a harness configuration as close as possible to the flight standard.
- b. Bias from ground-type interference shall be assessed for a precise analysis of the results of such tests.

6.7.3.4 Plume characterization tests

Plume characterization tests shall be defined in terms of:

- a. vacuum pressure level;
- b. the distance from the thruster exit to the probe rack;
- c. the distance from the thruster exit to the vacuum chamber walls.

NOTE 1 Plume characterization tests aim to measure ion current and ion energy distribution and beam divergence.

NOTE 2 These plume characterization tests can also help the identification of possible thrust-vector misalignments.

6.7.3.5 Life tests

- a. Life tests shall be performed on the thruster and the power supply system.
- 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. Facility back-spattering shall be minimized and precisely measured.
- d. Life tests shall use flight-grade propellant.
- e. The purity of the propellant shall be monitored.

6.7.3.6 Performance tests

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

NOTE Performance tests can be included in the life tests.

6.7.3.7 Calibration

- a. All components or subsystems which provide data output shall be calibrated.
- b. Conformity to the requirements of these components or subsystems shall be demonstrated.

6.7.4 Data exchange for models

Test results, thermal, mechanical, electric and magnetic models and performance models shall be established and structured with a commonly agreed structure and format.

6.8 Quality factors

6.8.1 Reliability

The design shall take into account reliability requirements with respect to:

- a. the probability of the success of the mission;
- b. the design life.

6.8.2 Production and manufacturing

Production and manufacturing shall conform to ECSS-E-00A subclause 7.1, and ECSS-E-10A subclause 4.7.3.

6.9 Operation and disposal

- a. For operation and disposal, subclause 5.8 of this Standard shall be applied.
- b. Additionally, special attention shall be paid to safety and contamination issues for every operation where connections or disconnections of electrical or electromagnetic components are being made.

6.10 Support

- a. For deliverables, subclause 5.9 of this Standard shall be applied.
- b. Additionally, an EMC analysis shall be delivered.

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Annex A (informative)

Standards for propellants, pressurants, simulants and cleaning agents

A.1 Rational

Testing, cleaning, drying and disposal of propulsion systems use specific non-structural materials such as propellants, pressurants, simulants and cleaning agents. A list of supporting documents for the use, handling, storage and disposal of these materials is given in the following subclauses.

A.2 Propellants

A.2.1 Storable propellants

CPIA³⁾ Publication 194 Change 1

Chemical Rockets/Propellant Hazards, Vol. 3: Liquid Propellant Handling, Storage and Transportation.

IATA⁴⁾ 32EME ED

Reglementation pour le Transport de Marchandises Dangereuses

ST/SG/AC.10/1/Rev. 11 United Nations Recommendations on the Transport of Dangerous Goods

ST/SG/AC.10/1/Rev.11/Corr.1

ST/SG/AC.10/1/Rev.11/Corr.2

ST/SG/AC.10/11/Rev.3 United Nations Recommendations on the Transport of Dangerous Goods: Tests and Criteria

A.2.2 Solid propellants

MIL-STD-2100

Propellant, Solid, Characterisation of (except gun propellant)

3) Chemical Propulsion Information Agency

4) International Air Transport Association

A.2.3 Liquid

A.2.3.1 Hydrazine (N₂H₄)

MIL-PRF-26536E(1) Propellant, hydrazine

ISO 14951-7 :1999 Space systems — Fluid characteristics — Part 7: Hydrazine propellant

A.2.3.2 Monomethylhydrazine (MMH)

MIL-PRF-27404C Propellant, Monomethylhydrazine

ISO 14951-6:1999 Space systems — Fluid characteristics — Part 6: Monomethylhydrazine propellant

A.2.3.3 Nitrogen tetroxide (NTO) and mixed oxides of nitrogen (MON)

MIL-PRF-26539E Propellants, dinitrogen tetroxide

A.2.3.4 MON-1 and Type MON-3

ISO 14951-5:1999 Space systems — Fluid characteristics — Part 5: Nitrogen tetroxide propellant

A.2.3.5 Unsymmetrical-dimethylhydrazine (UDMH)

MIL-PRF-25604E Propellant, Uns-dimethylhydrazine

A.2.3.6 Mixed amine fuel (MAF)

MIL-P-23741A(1) Propellant, mixed amine fuel, MAF-1

MIL-P-23686A(1) Propellant, mixed amine fuel, MAF-3

A.2.3.7 Kerosene (RP-1)

MIL-P-25576C(2) Propellant, kerosene

ISO 14951-8:1999 Space systems — Fluid characteristics — Part 8: Kerosene propellant

A.2.4 Gas

A.2.4.1 Gaseous propellants

ISO 14951-11:1999 Space systems — Fluid characteristics — Part 11: Ammonia

ISO 14951-12:1999 Space systems — Fluid characteristics — Part 12: Carbon dioxide

A.2.4.2 Cryogenic propellants

MIL-PRF-25508F Propellant, Oxygen

ISO 14951-1:1999 Space systems — Fluid characteristics — Part 1: Oxygen

MIL-PRF-27201C Propellant, Hydrogen

ISO 14951-2:1999 Space systems — Fluid characteristics — Part 2: Hydrogen propellant

A.3 Pressurants

MIL-A-18455C Not 1 Argon, Technical

ISO 14951-9:1999 Space systems — Fluid characteristics — Part 9: Argon

MIL-PRF-27415A(1) Propellant pressuring agent, argon

MIL-PRF-27401D Propellant pressuring agent, nitrogen

ISO 14951-3:1999	Space systems — Fluid characteristics — Part 3: Nitrogen
MIL-PRF-27407B	Propellant pressuring agent, helium
ISO 14951-4:1999	Space systems — Fluid characteristics — Part 4: Helium

A.4 Simulants

ISO 14951-10:1999	Space systems — Fluid characteristics — Part 10: Water
ASTM-D1193	Reagent Water
MIL-C-81302D(1)	Cleaning, compound, solvent, trichlorotrifluoroethane

A.5 Cleaning agents

TT-I-735A(3) NOT 1	Isopropyl Alcohol
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Bibliography

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

ECSS-E-00	Space engineering — Policy and principles
ECSS-E-30 Part 2A	Space engineering — Mechanical — Part 2: Structural
ECSS-M-00-02A	Space project management — Tailoring of space standards
AIAA S-80-1998	Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components
CPTR 96-64	Electrical propulsion for space applications CPIA, Dec. 1996
CPTR 97-65	Electric thruster systems, CPIA , June 1997
ISO/CD 14623-1	Space systems — Pressure vessels structural design — Part 1: Metallic pressure vessels (Ed. 1)
ISO/AWI 14623-2	Space systems — Pressure vessels structural design — Part 2: Composite pressure vessels (Ed. 1)
ISO/CD 14952-1	Space systems — Surface cleanliness of fluid systems — Part 1: General terms and definitions (Ed. 1)
ISO/CD 14952-2	Space systems — Surface cleanliness of fluid systems — Part 2: Cleanliness levels (Ed. 1)
ISO/CD 14952-3	Space systems — Surface cleanliness of fluid systems — Part 3: Analytical procedures for the determination of non volatiles residues and particulate contamination (Ed. 1)
ISO/CD 14952-4	Space systems — Surface cleanliness of fluid systems — Part 4: Rough cleaning processes (Ed. 1)
ISO/CD 14952-5	Space systems — Surface cleanliness of fluid systems — Part 5: Drying process (Ed. 1)
ISO/CD 14952-6	Space systems — Surface cleanliness of fluid systems — Part 6: Precision cleaning process (Ed. 1)
JPL 82-62	Propellant/material compatibility program and results

JPL/AIAA S-081-1999	Composite-overwrapped pressure vessels (COPV) for space and launch vehicles
MIL-STD-1522A NOT 3	Standard general requirements for safe design and operation of pressurized missile and space systems
MIL-STD-1774 NOT 2	Process for cleaning hydrazine systems and components
NASA-MSFC-SPEC-522B	Design criteria for controlling stress corrosion cracking
NASA-HDBK-527B MSFC	Handbook, material selection list for space hardware systems
NASA-JSC-09604	Materials selection list for space hardware systems
NASA-JSC-HDBK-20810	Materials selection handbook

<h2 style="text-align: center;">ECSS Document Improvement Proposal</h2>		
1. Document I.D. ECSS-E-30 Part 5.1A	2. Document date 2 April 2002	3. Document title Mechanical — Part 5.1: Liquid and electric propulsion for spacecraft
4. Recommended improvement (identify clauses, subclauses and include modified text or graphic, attach pages as necessary)		
(Empty space for recommended improvement)		
5. Reason for recommendation		
(Empty space for reason for recommendation)		
6. Originator of recommendation		
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8. Send to ECSS Secretariat		
Name: W. Kriedte ESA-TOS/QR	Address: ESTEC, P.O. Box 299 2200 AG Noordwijk The Netherlands	Phone: +31-71-565-3952 Fax: +31-71-565-6839 e-mail: Werner.Kriedte@esa.int

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