ECSS-E-ST-35-03C
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Space engineering

Liquid propulsion for launchers

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Foreword

This Standard is one of the series of ECSS Standards intended to be applied together for the management, engineering and product assurance in space projects and applications. ECSS is a cooperative effort of the European Space Agency, national space agencies and European industry associations for the purpose of developing and maintaining common standards. Requirements in this Standard are defined in terms of what shall be accomplished, rather than in terms of how to organize and perform the necessary work. This allows existing organizational structures and methods to be applied where they are effective, and for the structures and methods to evolve as necessary without rewriting the standards.

This Standard has been prepared by the ECSS-E-ST-35-03 Working Group, reviewed by the ECSS Executive Secretariat and approved by the ECSS Technical Authority.

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Introduction

The requirements in this Standard ECSS-E-ST-35-03 (and in the 3 other space propulsion standards ECSS-E-ST-35, ECSS-E-ST-35-01 and ECSS-E-ST-35-02) are organized with a typical structure as follows:

- functional;
- constraints;
- development;
- interfaces;
- design;
- GSE;
- materials;
- verification;
- production and manufacturing;
- in-service (operation and disposal);
- deliverables.

This standard forms parts of ECSS-E-ST-35 series which has the following structure;

- ECSS-E-ST-35 Propulsion general requirements
- ECSS-E-ST-35-01 Liquid and electric propulsion for spacecrafts
- ECSS-E-ST-35-02 Solid propulsion for spacecrafts and launchers
- ECSS-E-ST-35-03 Liquid propulsion for launchers
- ECSS-E-ST-35-06 Cleanliness requirements for spacecraft propulsion components, subsystems, and systems
- ECSS-E-ST-35-10 Compatibility testing for liquid propulsion components, subsystems, and systems

ECSS-E-ST-35 contains all the normative references, terms, definitions, abbreviated terms, symbols and DRD that are applicable for ECSS-E-ST-35, ECSS-E-ST-35-01, ECSS-E-ST-35-02 and ECSS-E-ST-35-03.

In the use of this standard, the term ‘propulsion system’ is intended to be read and interpreted only and specifically for ‘liquid prolusion system’.

1
Scope

General requirements applying to all type of Propulsion Systems Engineering are defined in ECSS-E-ST-35. For Liquid propulsion for launchers activities within a space project the standards ECSS-E-ST-35 and ECSS-E-ST-35-03 are applied together.

This Standard defines the specific regulatory aspects that apply to the elements and processes of liquid propulsion for launch vehicles. It specifies the activities to be performed in the engineering of these propulsion systems and their applicability. It defines the requirements for the engineering aspects such as functional, physical, environmental, quality factors, operational and verification.

Other forms of propulsion (e.g. nuclear, nuclear-electric, solar-thermal and hybrid propulsion) are not presently covered in this issue of the Standard.

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

2
Normative references

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

ECSS-S-ST-00-01	ECSS system - Glossary of terms
ECSS-E-ST-10	Space engineering - System engineering general requirements
ECSS-E-ST-10-02	Space engineering - Verification
ECSS-E-ST-10-06	Space engineering - Technical requirements specification
ECSS-E-ST-32	Space engineering - Structural general requirements
ECSS-E-ST-32-01	Space engineering - Fracture control
ECSS-E-ST-32-02	Space engineering - Structural design and verification of pressurized hardware
ECSS-E-ST-32-10	Space engineering - Structural factors of safety for spaceflight hardware
ECSS-E-ST-35	Space engineering - Propulsion general requirements
ECSS-Q-ST-70	Space product assurance - Materials, mechanical parts and processes
ISO 15389:2001	Space systems - Flight-to-ground umbilicals

3
Terms, definitions and abbreviated terms

3.1 Terms from other standards

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

3.2 Abbreviated terms

For the purpose of this Standard, the abbreviated terms from ECSS-S-ST-00-01, ECSS-E-ST-35 and the following apply:

Abbreviation	**Meaning**
LPS	liquid propulsion system

4
Overview of a liquid propulsion system

- Main functions of a liquid propulsion system are:
    - To provide thrust
    - To provide thrust vector control
    - To provide multiple burn capability if necessary
    - To supply pressurized gas for auxiliary functions (e.g. roll control, stage orientation)
    - To supply fluid for pneumatic control (e.g. Helium)
    - To provide thrust for propellant settling
    - To provide information concerning its status (e.g. measurement)

- The liquid propulsion system generally consists in:
    - the engine
    - the tank
    - the feed system
    - the pressurisation system
    - the command system
    - the TVC
    - auxiliary systems such as the anti-POGO device, roll control system

- The typical life of a liquid propulsion system is the following:
    - Manufacturing and assembly
    - Acceptance test (if any)
    - Storage and transport
    - Launcher integration
    - Pre-launch activities (e.g. flushing, leak tightness checks)
    - Tanks filling
    - Main stage Chill down (for cryogenic liquid propulsion system)
    - Launch chronology (including launch-abort activities)

- Lift-off
- Chill-down (for cryogenic liquid propulsion upper stages)
- Boost phases
- Stage separation
- Ballistic phase
- Passivation
- De-orbiting, reaching a graveyard orbit, or both

NOTE The way how to write the technical specification is given in ECSS-E-ST-10-06.

5
Functional

5.1 Overview

The general functional specification coming from mission optimisation at system level provides values for:

- Thrust
- Isp
- Burning time

The additional functional requirements are:

- thrust level versus time (throttling)
- propellant budget management (e.g. mixture ratio variation)
- TVC (e.g. maximum angle, acceleration, response time)
- start-up and shutdown transient requirements (e.g. duration, impulse scatter)
- auxiliary power to be delivered to the launcher (e.g. electrical and fluids)
- re-startability
- propellant depletion

5.2 Mission

a. ECSS-E-ST-35 clause 4.2 shall apply.

5.3 Functions

a. The technical specification shall provide the values of thrust, Isp and burning time with their deviations.

6
Constraints

6.1 Acceleration

a. Accelerations in the axial and lateral directions, assessed at launch vehicle level, shall be specified as an input for the propulsion system.

NOTE The acceleration has an impact on the:

- functioning of the vortex suppression devices in the tank outlets;
- pressure at the pump inlets;
- flow pattern in the tank;
- mechanical loads.

6.2 Geometrical constraints

a. The dimensioning of the liquid propulsion system and its components shall conform to the overall launch vehicle dimensions, interfaces between stages, ground infrastructure and requirements for transportation.

6.3 Electrical constraints

a. The design of the prop system shall be such that the electrical continuity is ensured.

6.4 Safety

a. The design of the liquid propulsion system shall conform to the safety requirements of the launch system.

NOTE For Example, ground safety requirements, flight safety requirements.

7
Development

7.1 Overview

The phases of development for a liquid propulsion system are as follows:

- definition of system and subsystem requirements conforming to mission requirements
- establishment of the general concepts
- trade-off of various concepts
- preliminary design
- risk analysis of the preliminary design and trade-off of various options
- detailed design and definition
- manufacturing and assembly of
    - components,
    - subsystems.
- integration of subsystem and system
- testing of:
    - components,
    - subsystems,
    - engines, and
    - system (functional stage).
- selection of the design to be qualified
- qualification process
- review of first article

7.2 Development logic

a. The development logic shall include a requirement verification plan in conformance with ECSS-E-ST-10-02 ‘verification plan’.

> NOTE Example of verification methods are analyses, tests.

b. The development logic shall be structured into phases with a goal assigned to each phase.

c. Mathematical models shall be implemented during the preliminary design phase and used for system trade-off analysis.

NOTE 1 See clause 9.3.

NOTE 2 Preliminary design phase is Phase B of ECSS-M-ST-10.

d. Mathematical models shall be updated using component and subsystem results at milestones agreed by the customer.

e. Mathematical models shall be validated using test results.

f. Mathematical models shall be used to determine the design margins.

g. The development logic shall list the activities that are submitted to cross-check.

NOTE See ECSS-E-ST-35 clause 4.8.1.

h. The sequence of development activities shall include components and subsystem tests prior to system tests.

i. The development logic shall mention the difficulties and critical activities of the development.

NOTE In particular major development critical path.

j. The development logic shall include risk management activities for project and technical risks.

k. The development activities shall include verification that manufacturing and control processes lead to products that satisfy specified product-to-product variation limit.

l. Lessons learned from previous programs shall be introduced in the design development plan.

m. The critical technologies, manufacturing and control processes shall be listed and their qualification process described.

NOTE See ECSS-Q-ST-20.

n. Liquid propulsion system verification shall be obtained by testing the liquid propulsion system in conditions representative of flight.

NOTE Following the typical approach "Test as you fly".

o. Through the measurement plan of the qualification flight the LPS qualification shall be checked by post flight analysis.

p. The development test plan shall include limit testing and failure cases.

q. At the end of the development, the testing of the integrated system in its final configuration, including the electrical system, shall include tests with representative interfaces.

NOTE For example, typical interfaces are control computer, electrical interface, flight instrumentation.

r. Phase by phase analyses of the life cycle of the liquid propulsion system shall be performed in relationship with the launch vehicle system in support of the failure mode analysis and the mechanical and thermal load case selection.

s. A matrix of configuration of engine hardware versus subsystem hardware shall be produced.

t. An integrated schedule for subsystem hardware deliveries, engine integration, engine testing for all development and qualification hardware shall be produced.

u. The output of all the requirement of clause 7.2 shall be detailed in the SEP (System Engineering Plan) as defined in the ECSS-E-ST-10 Annex D DRD.

8
Interfaces

8.1 Overview

The interfaces of the liquid propulsion system are generally the following:

- Stage components (e.g. skirt, stage thermal protection)
- Other stages of the launch vehicle
- Launch vehicle on-board computer
- Electrical supply system
- Interfaces with GSE (including the flushing, venting, filling and draining systems)
- Transport

8.2 General

a. For interface requirements ECSS-E-ST-35 clause 4.4 shall apply.

b. The environmental conditions imposed to the liquid propulsion system shall be specified.

NOTE For example, temperature, humidity, salt content of the atmosphere, inter stage conditioning).

c. The loads induced by the liquid propulsion system acting on the launch vehicle and the payload shall be identified, evaluated and reported in the design definition file as defined in the ECSS-E-ST-10 Annex G DRD.

NOTE Examples of these loads are chugging, side loads, vibrations, blast wave, thermal radiation.

d. Interface requirements shall be derived from the extreme operating envelope.

9
Design

9.1 General

a. The statement of work shall provide a ranking and weights of the design criteria.

NOTE Criteria are for example performance, reliability and development cost and recurring cost.

b. The design resulting from the optimisation of the above criteria 9.1a shall be provided and justified.

9.2 Specification

a. The specification of a liquid propulsion system or subsystem shall be in conformance with ECSS-E-ST-10-06.

9.3 Propulsion system selection

9.3.1 Overview

The mixture ratio is derived from a system optimization analysis, taking into account the characteristics of the envisaged liquid propulsion system and rocket engines.

The mixture ratio and the total amount of propellants, is the determining factor for the sizing of the tanks, together with the pressure and temperature.

9.3.2 System selection

a. For the selection of the liquid propulsion system architecture, a trade-off analysis shall be performed using the following parameters:

1. type of propellants;
2. engine architecture and thermodynamic cycle;
3. propellant mixture ratio;
4. propellant storage;
5. pressurization and feed system;
6. any additional parameters specified by the customer.

9.3.3 Propellant selection

a. For the selection of the propellant, a trade-off analysis shall be performed using the following parameters:

1. conformance to the launch vehicle system requirements;
2. performance;
3. availability;
4. handling;
5. storage;
6. safety;
7. cost;
8. impact on the environment;
9. any additional parameters specified by the customer.

9.3.4 Engine selection

a. For the selection of the engine, a trade-off analysis shall be performed using the following parameters:

1. global stage performance (e.g. Isp, mass budget);
2. development costs;
3. recurring cost;
4. industrial infra structure;
5. test infra structure;
6. reliability;
7. strength;
8. architecture and overall dimensions;
9. the technical readiness level of the technologies;
10. any additional parameters specified by the customer.

9.3.5 Selection of the TVC system

a. For the selection of the TVC, a trade-off analysis shall be performed using the following parameters:

1. global mass;
2. strength;
3. performance losses;
4. power consumption;
5. costs;
6. reliability;

7. control loop stability;
8. geometrical constraints;
9. any additional parameters specified by the customer.

9.4 Propulsive system detailed design

9.4.1 Overview

The propulsive system is the part of the liquid propulsion system that deals with the:

- filling and draining system;
- feeding system from the tank to the engine inlets;
- pressurisation system;
- functional aspect of the tanks (e.g. propellant budget, propellant management).

The function of the propulsive system is to deliver the propellants to the engine in the specified thermodynamic conditions (e.g. aggregation state, pressure and temperature) and specified flow conditions (e.g. vorticity, and velocity distribution).

9.4.2 General

a. At liquid propulsion system level, functional and mechanical models shall be established and used to derive propulsive system components specifications and engine inlet conditions.

b. Propulsive system components shall provide inputs to the functional and mechanical models at various steps of the development.

c. The liquid propulsion system shall allocate reliability objective for each propulsive system component.

d. The liquid propulsion system test plan and instrumentation plan shall be established such that it can be demonstrated that the test objectives of propulsive system components are reached.

e. The liquid propulsion system shall assign pollution objective for each propulsive system component, in terms of distribution of size and numbers of incoming and exiting particles.

9.4.3 Filling and draining system

9.4.3.1 Filling and draining system on ground

a. The filling and draining subsystems shall conform to ISO 15389:2001(E) subclauses 4.4 to 4.7, and subclauses 4.9 and 4.20.

b. For cryogenic propellants, if the nominal draining lines between the liquid propulsion system and the GSE are disconnected before lift-off, the liquid propulsion system shall be provided with emergency draining possibilities that enable draining after a launch abort.

NOTE The filling subsystem can be combined with the draining functions.

9.4.3.2 Draining system in flight (passivation and degassing)

a. In-flight draining shall not create conditions that can lead to loss of performance of the launch vehicle.

b. If in-flight draining cannot be performed through the flow paths for the normal operation of the propulsion system, specific lines or valves shall be incorporated in the liquid propulsion system to enable in-flight draining.

9.4.3.3 Flushing, purging and venting

a. The subsystems or components of the liquid propulsion system for which flushing, purging or venting is performed during ground tests, launch activities (including launch-abort) and flight, shall be identified.

b. The liquid propulsion system shall provide valves and lines to flush, purge or vent the subsystems or components identified in 9.4.3.3a.

c. On ground, the flushed and purged fluids shall be collected.

d. The flushing and purging systems shall neither create hazards to personnel nor harm the environment.

e. Provisions shall be taken to ensure that vented fluids do not create hazards.

NOTE For example, burn-off of vented hydrogen.

f. Flushing, purging and venting in flight shall not create unwanted propulsive effects.

NOTE For example, non-propulsive venting.

9.4.4 Propellant tanks and management

9.4.4.1 General

a. the tank volume shall be designed using at least the following:

1. The amount of propellant to be used during nominal propulsion operations;
2. the amount of propellant provisions covering the liquid propulsion system and launch vehicle deviations;
3. losses and ejected propellants;
4. the amount of unusable propellant;
5. the ullage volume;

6. equipment and lines within the tank.

b. The tank volume shall be determined at the extreme temperature and pressure ranges.

c. The propellant loaded mass shall be measured with the accuracy requested by TS.

d. The tank shall be protected against over pressurisation.

9.4.4.2 Tank pressure and temperature and pressurisation system

9.4.4.2.1 General

a. The management of the tank pressure shall be such that the engine inlet thermodynamic conditions comply with the engine requirements for all phases of the mission.

b. The tank pressure analysis shall consider during all phases of the mission:

1. internal heat fluxes;
2. external heat fluxes;
3. pressurant conditions;
4. sloshing of propellant;
5. expelled fluids;
6. vehicle accelerations.

c. Tank heat balances shall be performed for all phases of the mission.

d. The pressurization system shall cover the worst case in terms of pressurant consumption.

NOTE The most usual worst case is when the:

- temperature of pressurant is minimum,
- final volume of propellant tank is maximum,
- pressure of propellant tank is maximum (based on pressure regulator characteristics).

e. Pressurant gas budget shall include provision for gas leakage through equipment of the pressurisation system.

f. For the initial design a 30 % margin shall be used on the pressurant mass.

g. The pressurization system shall not induce pressure oscillations in the liquid propulsion system or stage.

h. There shall not be back flow (gaseous or liquid) into the pressurization system.

i. The pressurization system shall prevent detrimental contact between dissimilar fluids.

9.4.4.2.2 Maximum tank pressure

a. A MEOP shall be calculated using at least the:

1. time history of the tank pressure during the mission;
2. acceleration;
3. tank geometrical deviations;
4. pressure regulator operation and deviation;
5. internal and external heat flux.

NOTE The maximum design pressure (MDP) is defined in ECSS-E-ST-32, term 3.2.27

9.4.4.2.3 Minimum tank pressure

a. The minimum tank operating pressure shall conform to with the tank structural requirement.

b. The minimum tank operating pressure shall conform to with the engine inlet requirement.

9.4.4.3 Tank draining

a. An emergency draining or depletion procedure shall be present in case the nominal draining operation fails.

b. For all tanks, the location of fill-and-drain valves and the piping layout shall be such that liquids are not trapped in the system by on-ground draining and dissimilar fluids do not come into contact with each other.

c. The tank design shall be such that the occurrence of a vortex is prevented.

NOTE This usually happens when the tank is nearly empty

d. If 9.4.4.3c. is not met an anti-vortex device shall be installed at the sump to avoid gas ingestion into the feed lines.

e. The acceptability of propellant depletion shall be integrated in the “development logic” clause 7.2.

9.4.4.4 Sloshing

a. Propellant sloshing shall be analysed during all phases of the mission.

b. The effects of propellant sloshing in tank shall be analysed at both launch vehicle and liquid propulsion system levels.

NOTE 1 The propellant sloshing can have an effect on for example:

- Guidance, navigation and control of the launch vehicle,
- Propellant thermal stratification,
- Tank pressurisation.

NOTE 2 Anti sloshing device can be introduced to limit the sloshing amplitude.

9.4.4.5 Propellant Management Device (PMD)

a. The adverse effect of propellant fluid motion and micro gravity shall be analysed.

NOTE PMD device can be introduced to limit the above effects (such as swirl and sloshing).

9.4.4.6 Common bulkheads

a. The management of the pressure of each tank shall demonstrate that, during the whole mission, the bulkhead does not fail.

9.4.4.7 Temperature management

a. For storable propellants, the temperature prevision accuracy shall be 0,5 K.

b. For cryogenic propellants, the temperature prevision accuracy shall be 0,1 K.

c. If there is thermal stratification, the temperature distribution shall be evaluated with the same accuracy as respectively 9.4.4.7a for storable propellants and 9.4.4.7b for cryogenic propellant.

d. A thermal balance shall be established for all phases of the mission.

9.4.5 Propellant feed system

9.4.5.1 General

a. The feed system shall ensure a homogeneous parallel flow at the engine inlet in the thermodynamic conditions defined in the engine technical specification.

9.4.5.2 Pressure drop

a. The pressure drops in the feed system shall be determined by calculations.

NOTE The calculation of the feed system pressure drop takes into account the characteristics of the components constituting the feed system.

b. The LPS measurement plan shall allow the measurement of feed system pressure drop.

c. The combination of the deviations and uncertainties shall be performed via a statistical approach.

NOTE Statistical approach can be quadratic combination or Monte Carlo.

9.4.5.3 Dynamic effect

9.4.5.3.1 Non-stationary effects

a. The occurrence of pressure fluctuations shall be analysed.

b. The liquid propulsion system shall be designed so that no adverse effects of the pressure fluctuations occur during the mission.

NOTE (Rapid) variations in the mass flow rate in the feed system can introduce pressure fluctuations. These are related to the time rate of change of the mass flow rate and to the geometry of the feed system (L, D). These pressure fluctuations can interact with the structure of the feed system or adversely affect motor operation, e.g. pump cavitation.

c. Water-hammer phenomena shall have no detrimental effect on the structural and the functional behaviour of the propulsion system.

d. Rapid decomposition of the propellant vapour shall be avoided.

NOTE This decomposition can be created by:

- adiabatic compression,
- contact with hot spots and catalyst materials.

9.4.5.3.2 Propulsion system dynamic interaction with launch vehicle structure (POGO)

a. The POGO phenomenon shall be analysed for the whole mission.

b. The result of the analysis in 9.4.5.3.2a shall be used to conclude regarding the need of an anti-POGO device.

c. POGO Mathematical modelling shall be reported as defined in the ECSS-E-ST-35 Annex I DRD.

9.5 Liquid engines

9.5.1 General

a. At engine system level, geometrical (CAD models), functional, mechanical, thermal models shall be established and used to derive subsystem specifications.

b. Subsystem shall provide inputs to the above models at various steps of the development.

c. The engine system shall allocate reliability objective for each subsystem.

d. The test plan of the liquid engine shall include subsystem test objectives when establishing test plan and allocate instrumentation channels accordingly.

e. The engine system shall assign pollution objective for each subsystem (including distribution of size and numbers of incoming and exiting particles).

f. The development of the engine subsystems shall be managed in the same way as the whole engine following the applied management rules.

NOTE 1 This means that the development of subsystem will also contain phasing, reviews and a complete set of documentation deliverables).

NOTE 2 A launch vehicle liquid engine is a system composed of subsystems and components.

NOTE 3 The engine design is based on the flow of information from the system to the subsystem and vice versa all along the development process.

9.5.2 Performance

a. The engine thrust shall be calculated as the vectorial sum of the thrusts generated by all engine components.

NOTE This concerns:

- the main nozzles,
- the contribution from dump cooling,
- the turbine exhaust gases,
- ventings, purgings.

9.5.3 Functional system analysis

9.5.3.1 General

a. Nominal engine performance and deviation shall be defined at a reference operating point.

b. Engine performance losses shall be analysed and reported in the design justification file in as defined in ECSS-E-ST-10 Annex K DRD.

c. Contributions to engine thrust shall be analysed and reported in the design justification file as defined in ECSS-E-ST-10 Annex K DRD.

d. The operating limits of each major subsystem shall be reported at engine definition file level.

NOTE For example, maximum rotating speed corresponding to disk burst, flow separation limit, combustion chamber mixture ratio limit.

9.5.3.2 Performance

a. The performances of the engine shall be determined and documented in the design justification file as defined in ECSS-E-ST-10 Annex K DRD.

b. The deviation and offsets of the performances shall be determined and documented in the design justification file, as defined in ECSS-E-ST-10 Annex K DRD.

NOTE For liquid rocket engine, the performance concerns at least:
- Thrust
- Isp
- Mixture ratio
- Dry mass
- Required NPSP
- Roll moment
- Fluid consumptions
- Electrical consumptions

9.5.3.3 Reference point and envelopes

9.5.3.3.1 Overview

For operational envelope see ECSS-E-ST-35 clause 4.5.3.1.

For qualification points see ECSS-E-ST-35 clause 4.5.3.2.

9.5.3.3.2 Operational envelope

a. In the initial design process, an operational envelope shall be selected in conformance to the stage or launch vehicle requirements.

b. The liquid propulsion system or subsystem shall operate within the operational envelope specified in 9.5.3.3.2a.

NOTE During the design process, the launch vehicle or stage requirements can change; it is therefore prudent to consider a project margin when defining the operational envelope.

c. The operational envelope shall be designed with the following parameters:

1. The range of functional parameters of the liquid propulsion system during flight and testing.

   NOTE In particular flow rate, mixture ratio, tank propellant pressure.

2. The range of interface parameters.

   NOTE In particular acceleration effect, inlet pressure and inlet temperature variations, temperature environment.

3. Deviations in the trimming and throttling of the propulsion system.
4. Deviations in the various modelling processes.
5. Deviations in component performances.
6. Deviations in manufacturing.
7. Deviations in measurements.

d. The operational envelope shall be used for the initial design of propulsion systems, subsystems and components.

e. The operational limits of the systems, subsystems or components shall be documented.

9.5.3.3.3 Qualification points (test)

a. The engine and its systems, subsystems and components shall be qualified to demonstrate that the engine, system, subsystems and components operate as specified in the whole operational envelope, including uncertainty and deviations.

NOTE This means that the qualification points are covering the operational envelope.

b. The qualification points shall be defined using the following parameters:

1. ground test facility conditions compared to the flight ones;
2. deviations in the trimming and throttling of the propulsion system;
3. deviations in the modelling processes;
4. deviations in the component performances;
5. deviations in manufacturing;
6. deviations in measurements.

c. If a rocket engine is expected to operate in disconnected envelopes (qualification envelopes which do not overlap) the following shall be performed:

1. the engine qualified in each envelope separately;
2. ensure that a transition between the two envelopes can be made;
3. the transient process specified in 9.5.3.3.3c.2. qualified.

9.5.3.3.4 Reference point

a. One or more reference points shall be defined.

b. The performance optimization point shall be required in the engine specification.

9.5.3.3.5 Extreme envelope

a. An extreme envelope shall be defined around the qualification points using:

1. hardware deviation;
2. test bench deviation.

b. The extreme envelope shall be reported from the PDR.

9.5.3.4 Transients

9.5.3.4.1 General

a. Transient analyses shall be reported in conformance with the DRD in ECSS-E-ST-35 Annex G 'Propulsion transients analysis report'.

9.5.3.4.2 Chill-down

a. Chill down criteria shall be defined.

b. The propellant consumption for chill down and chill down duration shall be considered as performance parameters.

9.5.3.4.3 Start-up

a. The supplier shall demonstrate that the engine functional parameters during ignition and start-up remain within the specified range.

NOTE In particular mixture ratio, pump rotational speed.

b. A test bench configuration representative of the stage configuration and flight environment shall be used.

c. If 9.5.3.4.3b. is not met, a justification shall be provided and cross checked.

d. The supplier shall demonstrate that any dynamic effect, generated during start-up, is kept within the specified ranges for the stage and launch vehicle.

e. For multi engine stage, criteria shall be defined for thrust profile deviations between engines.

f. The start-up sequence shall include the following:

1. pressurization of the propellant tanks,
2. settling of the propellants in the tanks,
3. performance of the OBCs,
4. complete filling of lines, pumps and cooling circuits.

g. If a liquid propulsion system is expected to be activated after a ballistic flight, a propellant settling analysis shall be carried out.

9.5.3.4.4 In-flight transients

a. In flight transient between two operated conditions shall not create adverse dynamic effects.

b. 9.5.3.4.4a. shall be verified by tests.

9.5.3.4.5 Shutdown

a. The supplier shall demonstrate that the engine functional parameters during shut-down remain within the specified range.

NOTE Functional parameters such as mixture ratio and pump rotational speed.

b. A test bench configuration representative of the stage configuration and flight environment shall be used.

c. If 9.5.3.4.5b. is not met, a justification shall be provided and cross checked.

d. The supplier shall demonstrate that any dynamic effect, generated during shut-down, is kept within the specified ranges for the stage and launch vehicle.

e. For multi engine stage, criteria shall be defined for thrust profile deviations between engines.

9.5.3.4.6 Thrust decay and tail off

a. The thrust decay of an engine at nominal shutdown shall be determined analytically and derived from test results.

b. The tail-off characteristics shall be reproducible within the specified range.

c. The total impulse and its deviation shall be determined.

9.5.4 Thrust chamber assembly (TCA)

9.5.4.1 Overview

The TCA of liquid rocket engine for launch vehicle is an engine subsystem with the following functions:

- to enable admission of propellants;
- to ignite the propellants, maintain combustion, and enable shutdown;
- to eject high-temperature, high-pressure gases;
- to act as a power source for turbo-pumps (e.g. for the expander bleed or tap-off cycle);
- to transfer thrust;
- to act as a structural support for engine components and subsystems.

In addition, the thrust chamber can have the following secondary functions:

- to enable the installation and functioning of transducers and measurement equipment;
- to provide pressurized fluids to subsystems (e.g. tank pressurization and TVC).

The main components of the thrust chamber assembly are:

- the injector,
- the igniter,
- the combustion chamber and
- the nozzle.

Combustion instability in liquid rocket engines involves:

- the feed system,
- the combustion chamber and
- the combustion process.

The different types of instabilities that are commonly found, are low frequency or chugging, POGO and high frequency combustion instability.

Low frequency oscillations related to the hydraulic coupling between the feed system and the combustion delay are designated as chugging.

Low frequency oscillations involving the complete hydraulic feed system up to the tank and the structure are designated as POGO.

Combustion instabilities related to the combustion process are usually high frequency (HF) acoustic oscillations. They are related to the mixing and evaporation processes. HF combustion instability is manifested by violent combustion chamber pressure oscillations.

Combustion instability damping devices can be used to:

- increase the engine stability margin,
- suppress the growth of oscillatory combustion,
- damp pressure oscillations, and
- limit the amplitude of pressure oscillations to values that conform to the engine requirements.

NOTE Instabilities often occur during transients, i.e. start-up and shutdown. Changing the valve sequence or timing can affect the instabilities. Gas purging also can affect the instabilities

An injector is generally composed of:

- inlet manifold or manifolds;
- propellant dome or domes;
- passages to feed the injector elements;
- the faceplate that contains the injector elements.

The main function of a combustion chamber are:

- to enable the combustion gases to attain the specified pressures with the specified efficiency;
- to enable the engine turbo machinery to be powered in the case of expander, bleed, and tap-off cycles;
- if specified, to provide gases for tank pressurization;

- to sustain all loads including thrust;
- to transmit forces and torques to the stage.

The function of the nozzle is to accelerate the combustion gases, thereby creating an additional thrust compared to a combustion chamber without a nozzle extension.

As an auxiliary function, the nozzle can support lines such as exhaust lines or drain lines.

The different types of nozzles are:

- Radiatively cooled nozzle,
- Regeneratively cooled nozzle and
- Film cooled nozzle.

9.5.4.2 General

a. TCA subsystem fire tests shall be included in the development plan.

b. The chemical effects of the propellants and of the burned gases shall be analysed in the TCA design and justification.

9.5.4.3 Performance

a. The values of the performance parameters (Isp, C*, CF), over the entire operational envelope of the TCA, shall be determined and reported in the design definition file, as defined in the ECSS-E-ST-10 Annex G DRD.

b. Losses and gains shall be used in determining or assessing the effective specific impulse, independently of the analysis approach taken.

c. A budget of each elementary losses and gains shall be established for at least the following terms:

   1. Deviation of propellant composition
   2. Kinetic effects
   3. Combustion pressure loss
   4. Wall heat loss and boundary layer effects
   5. Non-uniform flows and multi-phase flow effects (e.g. unburned droplets, condensation)
   6. Hot gas tap-off
   7. Ablative wall
   8. Temperature effects
   9. Film cooling effect
   10. Shock and flow separation
   11. Re-injection of gas

9.5.4.4 TCA contour

a. For determination of TCA contour, the performance requirements and the cooling capacity shall be used.

b. The TCA contour, including the length, the contraction ratio, the throat diameter and the throat area, shall be reported and justified in the TCA design justification file, as defined in the ECSS-E-ST-10 Annex K DRD.

9.5.4.5 Cooling system

a. The justification of the choice of the cooling principle shall be reported in the design justification file, as defined in the ECSS-E-ST-10 Annex K DRD.

b. The fluid cooling system shall be designed including the following parameters:

   1. pressure drop along the cooling channels;
   2. temperature rise along the cooling channels;
   3. the effect on the engine performance (I_{sp}).

c. The justification of the choice of the coolant fluid shall be reported in the design justification file, as defined in the ECSS-E-ST-10 Annex K DRD.

d. The following performance parameters shall be reported in the design justification file, as defined in the ECSS-E-ST-10 Annex K DRD:

   1. pressure drop along the cooling channels;
   2. temperature rise along the cooling channels;
   3. chamber wall temperature distribution.

e. Dissymmetric effects shall be reported in the design justification file, as defined in the ECSS-E-ST-10 Annex K DRD.

   NOTE For example including unbalance in coolant flow distribution.

f. It shall be demonstrated that ageing effects do not deteriorate the cooling performances (e.g. coking).

   NOTE Ageing effect such as coking.

g. Deviations of surface roughness shall not deteriorate the cooling performances.

   NOTE For example, roughness due to manufacturing processes.

h. Vapour blockage during transient shall not induce any adverse effect.

i. The external radiation heat flux shall be reported.

j. Manufacturing inspection and verification processes shall be defined in order to demonstrate that the cooling system is free of any residual flow blockage and leak.

k. After hot fire test, the check process shall detect flow blockage or leak in the cooling system.

l. For active cooling system, the outlet coolant flow temperature shall be measured.

m. During engine start-up, flow rate shall not block in the cooling channels.

n. During engine start-up, the verification that the cooling film is established and effective shall be performed.

o. In case of TRL lower than 5 the dedicated Technology plan, as defined in the ECSS-E-ST-10 Annex E DRD, shall include:

   1. Calorimetric tests;

   2. Flow tests.

9.5.4.6 Heat soak back

a. The effect of the transfer of heat of the TCA after shutdown of the engine, from the hot parts of the TCA to cooler parts, shall not overpass the design temperature range of the TCA.

b. The effect of the transfer of heat of the TCA after shutdown of the engine, from the hot parts of the TCA to cooler parts, shall not overpass the design temperature range of the engine components.

9.5.4.7 Combustion stability

a. The stability margin shall be a design criteria when designing a thrust chamber.

b. The stability margin of an engine design shall be determined before the thrust chamber CDR.

c. For low frequency oscillations, ΔP/P threshold shall be defined (ΔP: pressure drop across the injector and P: combustion chamber pressure).

d. For high frequency oscillations, the thresholds of propellant temperatures shall be defined.

NOTE For example, LH2 temperature for cryogenic engines.

e. The stability margin shall be demonstrated by tests over the extreme envelope at transients and steady state.

NOTE The preferred method is the artificial perturbation of the combustion process, bomb and gas bubble ingestion and the evaluation of the damping characteristics.

f. Oscillation in the combustor shall not damage the engine.

g. Oscillation in the combustor shall not adversely affect the engine performance.

h. The pressure oscillation history shall be reported in the design definition file, as defined in the ECSS-E-ST-10 Annex G DRD.

NOTE The pressure oscillation history is the level of pressure oscillation with respect to frequency and time.

9.5.4.8 TCA components

9.5.4.8.1 Injector

a. Flow homogeneity at the inlet of the injection elements and at faceplate exit shall be evaluated and reported.

b. The design of the injector shall ensure the absence of low and high frequency oscillation during steady state operation.

c. The design of the injector shall limit the heat load on the chamber wall to a level in compliance with the combustion chamber life requirement.

d. The risk induced by pollution and icing shall be estimated.

e. The mixing of propellants inside the injector shall be prevented during the whole mission.

f. Specific injector tests shall be performed and reported in the case of:

    1. new propellant, or
    2. new injection principle, or
    3. out of experience operating range.

g. In case of TRL lower than 5, the dedicated Technology plan, as defined in the ECSS-E-ST-10 Annex E DRD, shall include:

    1. injector flow pattern test;
    2. spray test of injector elements;
    3. single element fire test.

h. The manufacturing inspections and verifications shall confirm that the flow passages are free of flow blockage and leak.

i. After hot fire test, the check process shall detect if there is flow blockage or leak in the injector.

9.5.4.8.2 Ignition system

a. The ignition system shall ensure ignition over the whole extreme envelope.

b. A maximum level of pressure spikes (amplitude and frequency) in the combustion chamber shall be defined.

c. The ignition shall not lead to pressure spikes exceeding the specified level.

d. Ignition criteria shall be defined including deviations.

e. The limit of the ignition envelope shall be determined.

f. The development logic shall include the demonstration of the reliability requirement for ignition system.

g. Damage to the chamber wall which is initiated from the ignition system shall be prevented.

h. If there are specific requirements on the angular position of the igniter, the design shall be such that mounting can only be done in the specified position.

i. The measurement to ensure that proper operation of the ignition system is obtained shall be defined.

j. The actual ignition of the combustor shall be monitored with measurements and compared to the ignition criteria.

NOTE For pyrotechnic igniters, see ECSS-E-ST-33-11.

9.5.4.8.3 Combustion chamber

a. Static pressure shall be measured during operation.

b. Dynamic pressure fluctuations shall be measured during hot fire tests.

NOTE The implementation of the dynamic pressure sensors is such that the high frequencies are captured and the measurement signal is not dampened by the transmitting test port configuration or the high viscosity of the fluid.

c. The frequency range of the dynamic pressure fluctuations measurement shall cover the two first tangential acoustic modes, the two first radial acoustic modes and the two first longitudinal acoustic modes of the combustion chamber.

d. A risk analysis at TCA and engine levels of the consequences of chamber wall cracks shall be performed.

e. Combustion roughness requirement shall be defined in the technical specification.

9.5.4.8.4 Nozzle extension

a. For radiative nozzle, the self induced heat loads shall be assessed during operation and after shut-down of the engine.

b. For heat soak back (see 9.5.4.6) a risk analysis at nozzle extension and engine levels of the consequences of nozzle wall cracks shall be performed.

c. The mechanical design justification shall include an evaluation of the margin concerning buckling.

d. For deployable nozzle, the deployment time shall conform to the launch vehicle requirements.

e. For first stage engine, flow separation margins shall be demonstrated by tests.

f. The design justification file shall contain an evaluation of any torque or asymmetric effect that can be introduced by the nozzle.

NOTE For example, boundary layer interaction with spirally wound coolant channels, tangential fluid injection.

9.5.5 Gas generator and pre-burner

9.5.5.1 Overview

The main function of a gas generator or a pre-burner is to provide hot gas to drive the turbopump(s).

The propellants are usually burned at a mixture ratio lower than the nominal mixture ratio for limiting the temperatures in the turbines.

9.5.5.2 General

a. Requirements concerning non-uniformity of the flow pattern at the gas generator, pre-burner exit, or both, shall be expressed in the technical specification.

b. Injector requirements of clause 9.5.4.8.1 shall apply.

c. Combustion chamber requirements of clause 9.5.4.8.3 shall apply.

d. Combustion stability requirements of clause 9.5.4.7 shall apply

e. Performance requirements of TCA clause 9.5.4.3 shall apply.

f. Ignition system requirements of TCA clause 9.5.4.8.4 shall apply.

9.5.6 Turbomachinery subsystem

9.5.6.1 Overview

The main function of a turbopump is:

- to provide a pressure head to a given propellant mass flow.

The main constraints of a turbopump are:

- to operate within a given pressure and temperature domain at pump inlet,
- to operate within a given pressure and temperature domains at turbine inlet and outlet.

9.5.6.2 General

a. The pump hydraulic performance shall be established over the entire extreme envelope using dimensionless coefficients.

NOTE Pump hydraulic performance are pressure rise, efficiency and suction performance.

b. The turbine performance shall be established over the entire extreme envelope using dimensionless coefficients.

c. Pump and turbine performance losses shall be determined and reported in the design justification file, as defined in the ECSS-E-ST-10 Annex K DRD.

d. The pump and turbine characteristics shall be determined in the transient phases (start-up and shutdown) to ensure safe operation during these transient phases.

e. A safe operation domain shall be established in the (dimensionless flow coefficient, dimensionless cavitation coefficient) axis.

NOTE Safe operation can be defined as no cavitation (using for instance 5 % head loss criteria), no pressure oscillation and excessive vibration.

f. For stable pump operation, the pump shall operate in the part of the performance curve with a negative slope in the (dimensionless flow coefficient, dimensionless pressure head coefficient) axis.

g. Vibration limits shall be established.

h. There shall be no resonance between frequencies of rotating parts and first and second harmonics of excitation frequencies on the whole extreme envelope.

i. The safety margin regarding proximity of frequencies leading to a resonance shall be defined.

j. The safety margin regarding proximity between critical speed and the extreme envelope shall be defined.

k. During transient, if coincidence appears, the life of the concerned component (in terms of number of cycle and duration) shall be justified.

l. For rotating blades, aeroelastic stability shall be assessed.

m. When boost pump are used, the justification of their use shall be expressed at the liquid propulsion system level including performance, reliability and cost.

NOTE Performance includes mass, pressurisation system, mass budget.

n. If the suction performance is obtained using similitude tests transposition to real propellant shall be justified.

NOTE Similitude test such as water test for cryogenic propellant.

o. Requirements concerning non-uniformity of the flow pattern at the turbine exit shall be documented in the technical specification.

p. Requirements concerning non-uniformity of the flow pattern at the pump inlet shall be documented in the technical specification.

q. The acceptable level of radial loads, amplitudes and frequencies, due to cavitation shall be established, including the characteristics of the bearings, shaft vibration amplitude and the turbo pump life requirements.

r. The conditions at which pump flow blockage occurs shall be determined experimentally.

s. The pump hydraulic impedance shall be evaluated as an input to POGO analysis.

t. Bearing life shall be demonstrated by component tests.

u. Bearing assembly conditions shall be established such that stress corrosion cracking is prevented.

v. Barriers shall prevent contact between non-compatible fluids.

w. Dynamic seal package life shall be demonstrated by component tests.

x. The dynamic stability of the axial balancing system shall be analysed and verified experimentally for the conditions of the extreme envelope and the associated transients.

y. The uncertainty in the axial loads of the active axial balancing system shall be analysed and reported in the definition file.

z. The design of turbopump components shall consider design criteria applicable to the specific failure modes of these components.

9.5.7 Control and monitoring systems

9.5.7.1 Overview

Control systems can be used for steady operating point (looking for a given chamber pressure or mixture ratio) or for transient sequence.

Control systems can be passive or active and liquid propulsion system operated in an open or closed mode.

Control systems rely on flow control system such as:

- flow regulators, e.g. cavitating venturis;
- calibrated orifices or valves to introduce a pressure drop;
- specific damping devices.

Active control systems use information given by monitoring devices, e.g. pressure sensor, rotational speed sensor, temperature sensor, in order to react on the status of the propulsion system.

9.5.7.2 Stability

a. A stability analysis shall be made for the operating points of the extreme envelope of the liquid engine.

b. The analysis specified in 9.5.7.2a. shall be performed for every physical loop.

c. For every loop, the stability margins shall be established.

d. The damping ratio shall be less than -3 dB for the whole extreme envelope.

e. The minimum stability margins shall be established by analysis.

f. The design shall ensure that when the control system is operated, inadvertent couplings are not introduced:

    1. internally (pressure regulator and check valves);
    2. externally (e.g. tank pressurization system).

9.5.7.3 Control systems

a. The value of the critical parameters for the equilibrium points, or values derived from these shall be compared with the values specified.

NOTE Mixture ratio is an example of value derived from critical parameters.

b. If the parameter values, or derived parameter values, differ from the specified values, the control system shall react to suppress this deviation.

c. Actuator commands shall be generated by the control system to activate elements that reset the system parameters to their specified values.

NOTE Servo valves and flow control devices are example of elements to be activated.

d. An analysis shall be made to establish the

1. type of monitoring devices needed,
2. location of the monitoring devices,
3. type of passive or active control devices to use,
4. location of the control devices, and
5. type of activation for active control devices, e.g. hydraulic, pneumatic, electric.

e. Passive control devices shall be used if the only requirement is to ensure stable equilibrium points with a given stability margins.

f. Active control shall be implemented if the following apply:

1. It follows from the system requirements.

   NOTE Example of system requirements: thrust profile, performance optimization, and safety.

2. The start-up or shutdown sequence, or the thrust modulation cannot be performed without a closed loop control system.
3. It follows from the functional constraints.

   NOTE Example of functional constraints: limitation of hot gas temperatures.

g. The engine control system shall be developed and qualified together with the engine.

h. The environment in which the control equipment on the engine functions shall be determined.

NOTE Example of environment: temperature, vibration, shocks, humidity.

i. If closed loop systems are used, the sensors shall be characterized and validated.

9.5.8 Auxiliary functions supplied by the stage

9.5.8.1 Overview

On liquid engine, components and interfaces can be heated or cooled and lines flushed to remove any remainders of propellants, and to ensure that the lines are dry. Electric heaters or gas flows can be used for heating, and cooling and flushing can be done using fluid flows. On the launch pad, these services are provided by the GSE (see clause 10).

9.5.8.2 Electrical

a. The electrical functions to be supplied for the operation of the liquid propulsion system shall be identified and reported in the design definition file, as defined in the ECSS-E-ST-10 Annex G DRD.

> NOTE For example, heating, valve operation, actuator operation, transducers, control system, and ignition.

b. An electrical energy and power budget shall be made for the autonomous operation of the stage according to the extreme envelope.

c. A margin for 9.5.8.2b shall be established and specified.

9.5.8.3 Gases

a. The heating, cooling, purging or venting operations to be performed for the operation of the liquid propulsion system shall be identified.

> NOTE For example, purging of injectors, coolant channels, pipes, lines and combustion chamber, heating or cooling of components, and the environment of the engine or propulsion system.

b. The components to be dried, de-iced and cleaned of particles and remainders of propellants or combustion products shall be identified.

c. Accounting for the elements identified in accordance with 9.5.8.3a. and 9.5.8.3b., the amount of gas and the type of gas to be used during the autonomous operation of the stage shall be identified according to the extreme envelope.

d. A margin shall be established in order to guarantee that the operations identified in 9.5.8.3a. can be performed.

e. The gas storage for stage support may be combined with other, already present, gas storage devices.

9.5.9 Components

9.5.9.1 General

a. Standardized environment loads for components shall be applied.

NOTE 1 Acceleration spectrum is an example of standardized environment load.

NOTE 2 Standardized environment loads are given by a general specification at launch vehicle level.

b. If the operational loads are higher than the standardized environment loads, complementary qualification linked to these overloads shall be carried out.

NOTE 1 Standardized environment loads are defined as acceleration spectrum, environmental conditions to be applied whatever the location and the type of component for a given launch vehicle.

NOTE 2 The operational loads are the loads derived from a mechanical analytical model of the propulsion system and from test results as available.

c. Component functional requirements shall be verified by tests under environmental loads.

9.5.9.2 Valves

9.5.9.2.1 Overview

The functions of a valve are:

- to isolate a fluid volume or to admit fluid into a volume;
- to control a fluid flow rate.

9.5.9.2.2 General

a. The valve functional characteristics shall be established over the entire extreme envelope.

NOTE Example of functional characteristics: pressure drop, response times.

b. The valve life requirements shall include additional cycles for development tests and in service needs.

NOTE Example of service needs are leak tests, ground control operation at subsystem, liquid propulsion system and launch vehicle level.

c. A “normally open”, “normally closed” or bi-stable valve shall be selected according to the operational and safety analyses and the liquid propulsion system requirements.

NOTE Valves that provide the function to shut-off a line can be obtained in a “normally open” or “normally closed” configuration. In the “normal” condition no power is applied to the activation system. A bi-stable valve is a valve that remains in its position (open-closed) after the power to the activation system is switched off.

9.5.9.3 Pressure regulator

9.5.9.3.1 Overview

The pressure regulator function is to control the downstream static pressure to a prescribed level.

There are two types of pressure regulators:

- the mechanical regulator that balances the pressure forces with (an adjustable) spring-like load;
- the electronic pressure regulator that consists of a valve that can be opened and closed if the downstream pressure exceeds preset limits.

A pressure regulator usually opens at a pressure that is somewhat lower than the prescribed downstream pressure and closes at a pressure that is somewhat higher than the prescribed downstream pressure. The latter is called the "lock-up" pressure.

9.5.9.3.2 General

a. The pressure regulator functional characteristics shall be established over the entire extreme envelope.

NOTE For example downstream pressure versus mass flow rate curve.

b. The pressure regulator life requirements shall include additional life duration for development tests and in service needs.

NOTE Example of service needs are leak tests, ground control operation at subsystem, liquid propulsion system and launch vehicle level.

9.5.9.4 Ground board coupling devices

9.5.9.4.1 Overview

Ground-board coupling device function is to provide the interface between the launcher and the GSE for fluid and power supply, monitoring and command and, if necessary, for draining the launcher.

NOTE For ground board coupling devices, refer to ISO 15389:2001.

9.5.9.4.2 General

a. The fluid valves used in the ground-board decoupling devices shall be of the "normally closed" type.

9.5.9.5 Calibrating orifices

9.5.9.5.1 Overview

The functions of calibrating orifices can be:

- to control the mass flow rate,
- to decouple upstream conditions from fluctuations in downstream conditions.

There are several types of calibrating orifices, e.g.:

- cavitating venturi for liquids;
- venturi for gas;
- calibrating orifice for liquid;
- sonic orifice for gases.

9.5.9.5.2 General

a. The functional characteristic and the flow stability of the calibrating orifices shall be verified either by individual test or liquid propulsion system test.

9.5.9.6 Gimbal joint

9.5.9.6.1 Overview

The function of the gimbal joint is to orient the engine with respect to the launch vehicle in order to perform TVC.

The gimbal joint connects the engine to the stage.

9.5.9.6.2 General

a. The gimbal joint friction torque characteristics shall be established over the entire extreme envelope of thrust, temperature and environmental pressure including manufacturing tolerances.

b. Clearance variation shall be studied over the whole life of the engine including operating and non-operating engine conditions, environmental conditions and manufacturing tolerances.

9.5.9.7 Piping

a. It shall be verified that no cavitation occurs due to high flow velocities in piping.

b. The thermal insulation of LH2 and LHe cryogenic lines shall be designed in such a way that cryo-pumping is prevented.

NOTE For example bonding of the insulation to the piping, double insulation with ventilation.

c. The non uniformity of the flow introduced by elbows shall be characterized and reported in the design definition file, as defined in the ECSS-E-ST-10 Annex G DRD.

NOTE This non uniformity is used by downstream components.

d. Flow fluctuation induced by bellows shall be avoided.

9.5.9.8 POGO suppression device

9.5.9.8.1 Overview

The function of the POGO suppression device is to damp coupled pressure and mass flow fluctuations in the propellant feed line.

9.5.9.8.2 General

a. The functioning of the POGO suppression device shall be verified experimentally at stage level.

b. It shall be verified that the POGO suppression device does not adversely affect the functioning of the propulsion system.

NOTE For example gas ingestion into the feed line.

9.6 Mechanical design

a. Requirements 9.6b to 9.6w shall apply to all the subsystem and components of a propulsion system.

b. ECSS-E-ST-32-02 (Structural design and verification of pressurized hardware) and ECSS-E-ST-32-01 (Fracture control) shall not be applicable to the following liquid propulsion system components:

1. combustion chamber
2. gas generator
3. pre burner
4. turbopump
5. nozzle extension
6. igniter
7. mechanisms

c. A failure mode analysis of the mechanical failure modes of a liquid propulsion system shall be performed prior to completion of the detailed design and presented prior to the PDR and reported both in the FMECA, as defined in the ECSS-Q-ST-30-02 Annex A DRD, and the design justification file, as defined in the ECSS-E-ST-10 Annex K DRD.

NOTE The major failure modes are:

- Departure from elastic behaviour (gross yielding)
- Rupture
- Instability, plastic or elastic instability
- Progressive deformation, ratcheting

- Creep and relaxation
- Fatigue - crack initiation - crack propagation
- Excessive deformation leading to a loss of Serviceability
- Wear and tribological damage
- Ageing
- Oxydation for material sensitive to chemical deterioration with oxygen

d. The propulsion system mechanical design shall include at least the following environmental aspects:

1. pressure,
2. temperature,
3. vibration levels,
4. humidity,
5. corrosive environment,
6. vacuum.

e. Minimum material properties for yield strength, ultimate tensile strength and rupture elongation, defined as values with 99 % probability to be exceeded at 90 % confidence level, shall be used for strength justification i.e. departure from elastic behaviour (yielding), rupture, instability (plastic or elastic).

f. Local yielding shall not be allowed unless all the following conditions are met:

1. the material is ductile;
2. no detrimental deformations that adversely affect the component system function are present;
3. the service life requirements are met.

NOTE 1 Ductile material are defined on the basis of their notch sensitivity when performing a tensile test: Fnotch > or equal to Fsmooth, Fnotch and Fsmooth being respectively the rupture load for a notched and a smooth tensile specimen of same minimum cross section.

NOTE 2 For pressure vessel submitted to a temperature gradient across their wall (for instance the wall of the regenerative circuit of a combustion chamber or the wall of a gas generator) and made of a ductile material, the part of the stress due to the thermal gradient can be excluded from the yield margin verification. In this case the justification is based on a life verification which includes creep and ratcheting (progressive deformation).

g. As part of life justification of a propulsion system, the absence of crack initiation shall be demonstrated by performing fatigue analysis.

h. The nominal life shall be established with the internal loads which are taken at the edge of the operational domain.

i. The extreme envelope life shall be established with the extreme envelope internal loads.

j. Crack propagation analysis shall be used in the following cases:

  1. The manufacturing process leads to the presence of a significant number of flaws.

     NOTE Example of manufacturing process affected by the presence of a significant number of flaws are welds and castings.

  2. The structure is submitted to loads which cannot be reproduced in ground tests.

  3. Major parts of turbopump rotors.

k. For cases identified in 9.6j ECSS-E-ST-32-01 shall apply.

l. For parts defined in 9.6b safety factors used in the design process shall be listed in the propulsion system technical specification.

m. For propulsion system parts other than parts defined in 9.6b the safety factors specified in ECSS-E-ST-32-10 shall be applied.

n. For margin policy ECSS-E-ST-10 shall apply.

o. Project margins shall be accompanied by an action plan showing how they are reduced along the development.

   NOTE The reduction of project margins relies on an enhanced material characterization, component tests, analysis of engine tests, post test examination.

p. A qualification by test shall be performed for the strength demonstration of critical parts.

   NOTE There is no detrimental yielding at the maximum design load multiplied by the yield coefficient and no failure at the maximum design load multiplied by the ultimate safety coefficient, with a temperature correction, a material correction and geometry correction.

q. Dimensioning load cases shall be established by using a selection process of all load case combinations during the whole life of the propulsion system.

r. Internal loads used for strength analysis, designated as limit load in conformance with ECSS-E-ST-32, shall be taken at the edge of the extreme envelope.

s. Internal loads shall be derived from steady state and transient functional analysis of the propulsion system.

t. External loads shall be derived from launch vehicle and stage specification using analytical model of the engine and propulsive system.

u. Both internal and external load cases shall be used when establishing dimensioning load cases.

v. It shall be verified that all functional clearance requirements are met for the extreme envelope.

w. All pressurized connections and interfaces shall be designed such that they remain leak tight for all identified load cases.

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Ground support equipment

a. ECSS-ST-35 clause 4.6 shall apply.

b. Relief valves shall be installed on all pressurized vessels and major portions of the lines

c. The GSE design, functioning and procedures shall ensure that fluids are delivered to the launcher or spacecraft according to their specifications.

NOTE Examples of fluid specifications are contamination level, flow, pressure and temperature.

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Materials

a. ECSS-Q-ST-70 clause 5 shall apply.

b. The material characteristics shall be determined on material samples obtained by the same manufacturing process as the part themselves.

> NOTE During the early phase of the development when the number of material test data is not sufficient, the use of a statistical distribution applicable to a similar class of material is allowed in order to define minimum properties.

c. Hydrogen embrittlement effect on material characteristic shall be determined for parts exposed to hydrogen rich gases.

d. The possible adverse effect of vacuum shall be evaluated.

> NOTE For example, tribological deterioration, degassing.

e. Risk of wear and tribological damage shall be considered when selecting material.

f. Compatibility with oxidizer shall be examined with respect to the material potential to ignite.

g. The material selection shall be compatible with the contained fluids.

h. The material selection shall consider the possible galvanic effect between dissimilar materials.

> NOTE For minimum material characteristic see “Mechanical design” 9.6e.

12
Verification

a. For verification ECSS-E-ST-35 clause 4.8 shall apply.

b. The qualification process of the propulsion system shall include testing in the following conditions:

   1. four times the nominal life (i.e. four main life cycles in term of number of cycles and cumulated time) within the flight domain,

   2. at least one time the main life cycle within the extreme envelope.

13
Production and manufacturing

a. The functional parameters used to ensure the reproducibility of the hardware shall be defined and compared to acceptance criteria.

NOTE Examples of such functional parameters are vibration levels for turbopumps and ignition time.

b. All components and elements that are sensitive to pollution and contamination, and all components and elements that can create pollution and contamination in sensitive elements shall be cleaned purged and dried.

c. It shall be demonstrated that the components and elements that come into contact with reactive chemicals are cleaned.

NOTE For example oxygen.

d. After cleaning, purging and drying, the components and elements shall be sealed to avoid pollution and contamination.

e. The adverse effect of storage environmental conditions shall be analysed.

NOTE For example, creep, corrosion, oxidation.

14
In-service

14.1 General

a. Leakage criteria and leakage budget shall be defined.

NOTE A leakage budget is defined as an allowable leakage flow for each subsystem.

b. The liquid propulsion system shall be instrumented in such a way that in the case of a launch-abort, the cause of the launch-abort can be identified.

14.2 Operation

a. In case of launch abort, the following shall be performed:

1. the propulsion system reset to a safe condition;
2. cryogenic propulsion systems drained and flushed.

b. In case of launch abort, procedures shall be prepared, qualified and implemented to reset the propulsion system to a safe condition.

c. The number of launch aborts the propulsion system can undergo shall be specified.

d. After having performed its operational mission, each propulsion system shall be drained of the remaining propellants (passivation) in such a way that this does not lead to explosion or other hazardous situations.

15
Deliverables

a. For deliverables ECSS-E-ST-35 requirement 4.11a. shall apply.

Bibliography

ECSS-S-ST-00	ECSS system – Description, implementation and general requirements
ECSS-E-ST-33-11	Space engineering – Explosive systems and devices
ECSS-M-ST-10	Space project management - Project planning and implementation
ECSS-Q-ST-20	Space project assurance – Quality assurance